Expanded Research and Development of an Enhanced Rear Signaling System for Commercial Motor Vehicles

U.S. Department of Transportation
Federal Motor Carrier Safety Administration

April 2014

FOREWORD

The mission of the Federal Motor Carrier Safety Administration (FMCSA) is to reduce crashes, injuries, and fatalities involving large trucks and buses. According to FMCSA, the development, evaluation, and deployment of advanced safety technologies will be key to realizing this objective. In 2010, heavy trucks were found to be three times more likely than other vehicles to be struck from behind during two-vehicle fatal crashes.[(1)] These crashes occur with such sufficient frequency that they cause concern within regulatory agencies. In light of FMCSA's goal to reduce the overall number of truck crashes, this crash configuration is important to the Agency.

The purpose of this research is to further develop and refine the Enhanced Rear Signaling (ERS) system that was developed during the previous Phase III effort.[(2)] Although testing during Phase III indicated that the design was promising, results also indicated that expanded development and ERS system refinement were warranted prior to further field work. Expanded development efforts for the ERS system covered in this report included rear lighting brightness adjustments for nighttime conditions, modification of the system into a unit designed for simple truck and trailer installation, and activation subsystem refinements.

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16. Abstract

The purpose of the current study was to further develop and refine the prototype Enhanced Rear Signaling (ERS) system that was developed during the previous Phase III effort. Expanded development efforts for the ERS system included modification of the system into a unit designed for simple commercial motor vehicle (CMV) installation, collision-warning activation refinements, and rear lighting brightness adjustments for nighttime conditions. During the ERS system development process, the team successfully completed necessary modifications for improved CMV installation. Formal closed test-track and real-world testing were then performed to determine the ERS system collision-warning activation performance. Ultimately, the ERS system performed with a 100 percent correct detection rate and an 85.43 percent correct rejection rate during real-world testing. During all ERS system activations, no unsafe following vehicle driver reactions/behaviors were observed, indicating a promising system for follow-on research. A nighttime brightness level was selected at the conclusion of a ratings study and carried on into nighttime real-world testing. During ERS system nighttime activations, there were also no unsafe following-vehicle driver reactions/behaviors observed. Overall, the research team found that the ERS system is ready for further evaluation in a field operational test (FOT).

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SI* (MODERN METRIC) CONVERSION FACTORS

Table of APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	Inches	25.4	Millimeters	mm
ft	Feet	0.305	Meters	m
yd	Yards	0.914	Meters	m
mi	Miles	1.61	Kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yards	0.836	square meters	m^2
ac	Acres	0.405	Hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME	1000 L shall be shown in m^3	
fl oz	fluid ounces	29.57	Milliliters	mL
gal	Gallons	3.785	Liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		MASS		
oz	Ounces	28.35	Grams	g
lb	Pounds	0.454	Kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or “metric ton”)	Mg (or “t”)
		TEMPERATURE	Temperature is in exact degrees	
°F	Fahrenheit	5 × (F-32) ÷ 9 or (F-32) ÷ 1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	Lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		Force and Pressure or Stress		
lbf	Poundforce	4.45	Newtons	N
lbf/in^2	poundforce per square inch	6.89	Kilopascals	kPa

Table of APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
Mm	Millimeters	0.039	inches	in
M	Meters	3.28	feet	ft
m	Meters	1.09	yards	yd
km	Kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	Hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	Milliliters	0.034	fluid ounces	fl oz
L	Liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	Grams	0.035	ounces	oz
kg	Kilograms	2.202	pounds	lb
Mg (or “t”)	megagrams (or “metric ton”)	1.103	short tons (2000 lb)	T
		TEMPERATURE	Temperature is in exact degrees	
°C	Celsius	1.8c + 32	Fahrenheit	°F
		ILLUMINATION		
lx	Lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		Force & Pressure Or Stress		
N	Newtons	0.225	poundforce	lbf
kPa	Kilopascals	0.145	poundforce per square inch	lbf/in^2

* SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003, Section 508-accessible version September 2009)

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ABBREVIATIONS, ACRONYMS, AND SYMBOLS

Acronym	Definition
3D	three-dimensional
ABS	antilock brake system
ANOVA	analysis of variance
CAD	computer-aided design
CAN	controller area network
CFR	Code of Federal Regulations
CMV	commercial motor vehicle
CNC	computer numerical control
ConOps	concept of operations
COTR	Contracting Officer’s Technical Representative
CUT	combination unit truck
DAS	data acquisition system
DFMEA	design failure mode and effects analysis
DV	dependent variable
ERS	enhanced rear signaling
FCW	forward collision warning
FDM	fused deposition modeling
FET	field-effect transistor
FMCSA	Federal Motor Carrier Safety Administration
FOT	field operational test
GES	General Estimates System

Acronym	**Definition**
HSD	honestly significant difference
IRB	Institutional Review Board
IV	independent variable
LED	light-emitting diode
NHTSA	National Highway Traffic Safety Administration
OEM	original equipment manufacturer
RPN	risk priority number
SAE	Society of Automotive Engineers
SD	standard deviation
SME	subject matter expert
TTC	time-to-collision

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EXECUTIVE SUMMARY

PURPOSE

The purpose of the current project was to expand upon the research and development of the enhanced rear signaling (ERS) prototype system developed during the previous Phase III effort.[2] The Phase III prototype system was robust in real-world driving situations during real-world data collection. Results indicated that the system performed well at detecting and signaling rear-end crash threats and drawing the gaze of following-vehicle drivers to the forward roadway. Although performance was positive, further testing was warranted prior to data collection during a field operational test (FOT). Phase III only investigated rear lighting during daytime conditions. Therefore, the potential need for rear warning-light brightness adjustments for lower light conditions still needed to be investigated. Additionally, a limitation was found in the detection of oncoming vehicles traveling at lower speeds in high-traffic scenarios. The radar from the prototype system was not robust in identifying targets in such traffic conditions, which resulted in a high number of false alarms. That particular false alarm type needed to be addressed prior to large-scale, real-world data collection efforts.

PROCESS

Three ERS system development efforts were undertaken during the current project. The first effort involved the design and modification of the ERS system into a unit designed for simple truck and trailer installation. The second effort involved refinement of the radar target identification firmware to reduce the likelihood of false alarms in lower speed, high-traffic-density scenarios and to transfer the activation subsystem algorithm processing from the research team's data acquisition system (DAS) to the radar itself. The third effort involved testing different nighttime brightness levels to select the one with the best balance between attention-getting and discomfort-glare characteristics.

RATIONALE AND BACKGROUND

Data from the National Highway Traffic Safety Administration (NHTSA) General Estimates System (GES) from 2006 indicate that there were 135 fatalities and 1,603 incapacitating injuries resulting from rear-end crashes involving heavy trucks.[3] In 2010, heavy trucks were three times more likely than other vehicles to be struck from behind in two-vehicle fatal crashes.[1] Findings from naturalistic driving research indicate that many rear-end crashes result from following-vehicle drivers having long eyes-off-road glances (further underscoring the importance of countermeasures that are based on eye-drawing). There were three phases of ERS research performed prior to the current project. During Phase I, researchers performed crash database analyses to determine causal factors of rear-end collisions and to identify potential countermeasures. Phase II continued through prototype development based on recommendations from Phase I. During Phase II field testing, potential benefits of using such countermeasures were realized. During Phase III, a multi-phased approach was executed to design, develop, and test multiple types of countermeasures on a controlled test track and on public roadways. Phase

III resulted in positive results for a rear warning prototype system comprising 12 light-emitting diode (LED) units. The current project was focused on refining the Phase III prototype system in preparation for an FOT. Table 1 below describes the three phases of the ERS research.

Table 1. ERS Phases I, II, and III project descriptions.

Phase I (2004)	Phase II (2006)	Phase III (2010)
Performed a crash data analysis to determine causal factors of rear-end truck crashes and to identify auditory and visual countermeasures.	Development of prototype system that incorporated auditory and visual countermeasures identified in Phase I. Field testing in Phase II revealed potential benefits to using auditory and visual countermeasures that performed better than normal brake lights in preventing rear-end truck crashes. During this phase, a three rear-warning-light configuration performed the best in eye-drawing performance and in detecting rear-end crash threats, and was selected to move forward to the real-world dynamic data collection effort.	Analyzed characteristics of rear-end truck crashes, explored the benefits of auditory and visual countermeasures from Phases I and II in static and dynamic environments, and developed a plan for a large-scale ERS FOT.

STUDY FINDINGS

The research team modified the ERS system for improved trailer installation, refined the following-vehicle tracking firmware and transitioned all collision-warning algorithm logic to the radar itself, and tested and selected a brightness level for nighttime conditions.

Concept of Operations and a Design Failure Mode and Effects Analysis

Prior to the expanded development efforts of the ERS system, a concept of operations (ConOps) and a design failure mode and effects analysis (DFMEA) were completed. The purpose of the ConOps was to provide a conceptualization from the user’s perspective of the daily conditions and functions of the system during implementation. This document was successfully finalized and will likely be a useful guide for others in the future. The research team employed a DFMEA process to systematically explore the potential failure modes of the ERS system based on prior system testing and engineering experience with similar technologies. The findings of this analysis helped engineers and researchers prioritize and address potential design deficiencies early during the development process.

System Modification for Simple Installation

Prior to an FOT, a modification to the ERS system was warranted to improve truck and trailer installation/implementation. The goal was to reduce the numerous components of the Phase III ERS design and to reduce the potential for unnecessary failure modes. The Phase III prototype

ERS system and the final ERS system are shown in Figure 1 and Figure 2. The research team was successful in designing an ERS system that is simpler for truck and trailer implementation. This system included two light activation subsystems (i.e., open-loop or closed-loop). An open-loop system requires no measurements associated with the following vehicle; only lead-vehicle parameters are available. A closed-loop system includes the measurement of closing rate (velocity) and closing distance to the following vehicle (using radar), along with lead-vehicle velocity and deceleration.

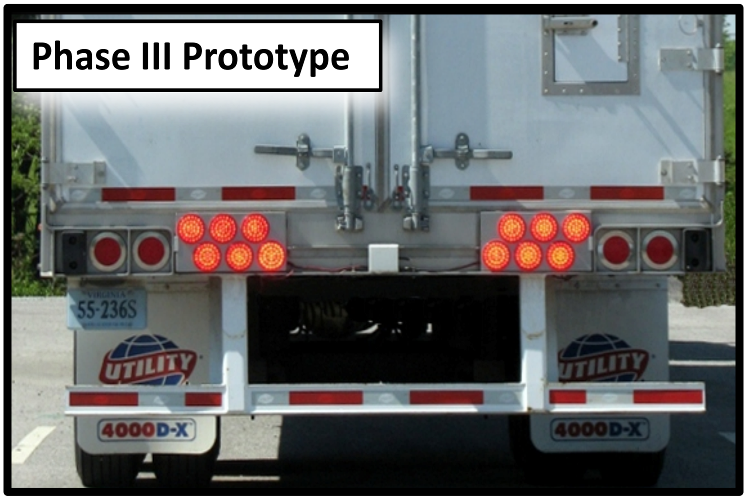

Figure 1. Photo. Phase III prototype ERS system.

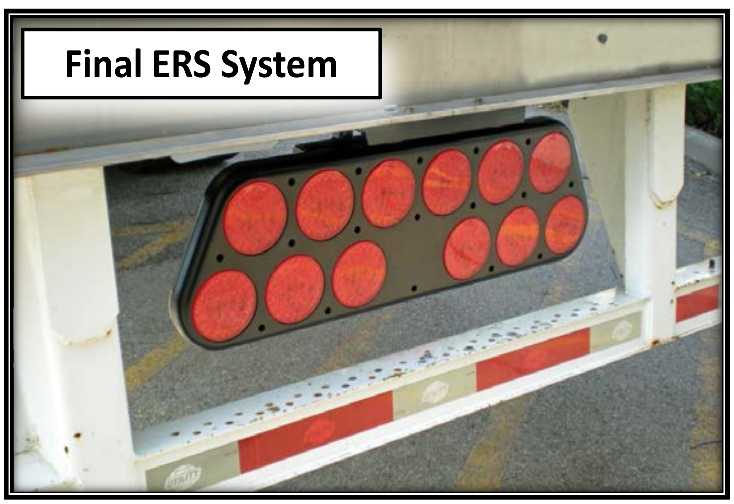

Figure 2. Photo. Final ERS system.

Closed-loop Activation Subsystem Refinement

As part of the current project, efforts were undertaken to improve the following-vehicle tracking firmware and to transition all collision-warning algorithm logic to the radar itself. The research team collaborated with a private radar design company and used the radar company's proprietary software to collect preliminary data during limited testing on the Virginia Smart Road (using the Phase III prototype system in low-speed, high-density scenarios). The initial tests consistently resulted in false alarms. Multiple refinements were successfully applied to the following-vehicle tracking firmware, resulting in improved tracking performance.

The research team also worked with the radar design company to transition the closed-loop activation algorithms into the radar firmware. As a first step, the research team cleaned up the programming code behind the closed-loop activation algorithms, then transferred the code to the radar company. The radar company engineers worked to incorporate these algorithms into the radar firmware. Several iterations of updated firmware were passed between the research team and the radar company until a working version of the refined firmware was completed and uploaded to the radar. Preliminary pilot testing on the Smart Road indicated that the firmware was ready for formal testing.

Two types of formal testing were performed: Smart Road and real-world. The purpose of formal Smart Road testing was to evaluate the refined radar firmware for improved target tracking along with the performance of the incorporated activation (triggering) algorithms. Both the open-loop activation subsystem and the closed-loop activation subsystem were tested in various rear-end and non-rear-end collision scenarios. The open-loop activation system performed with a 100 percent correct detection rate and a 100 percent correct rejection rate. The closed-loop activation system across all algorithm conditions performed with a 100 percent correct detection rate (for direct threats only) and a 95 percent correct rejection rate.

Real-world testing occurred on public roadways in southwest Virginia. Data were collected during a 5-hour period across approximately 150 mi (241.40 km). Performances of the activation subsystems were determined through a combination of video and sensor data collected using the research team's DAS installed in the rear of the trailer. Because this was an observational study, no drivers were recruited to participate. Rather, the experimental combination unit truck (CUT) joined other vehicles in the available traffic stream. The open-loop and closed-loop activation subsystems were fully functional with no experimenter input provided. A data reduction effort was performed for each following-vehicle scenario. No open-loop activations occurred during real-world testing (i.e., no events occurred requiring a heavy deceleration by the experimental CUT). The closed-loop activation system across all roadway types performed with a 100 percent correct detection rate and an 85.43 percent correct rejection rate.

Nighttime Warning-light Brightness Testing

Two studies were performed to evaluate the ERS system during nighttime conditions. The first study used following-vehicle drivers provide ratings on discomfort glare and "attention-getting" effectiveness for multiple nighttime brightness levels. The second study used the best brightness level candidate resulting from the ratings study and included the collection of real-world data on public roadways in southwest Virginia. During real-world testing, no following-vehicle unintended consequences were found.

CONCLUSIONS

The ConOps and DFMEA efforts completed in this project helped engineers and researchers perform a thorough development and refinement process. Potential design deficiencies were identified early in the development process, thus increasing the likelihood of system success once deployed in an FOT. In addition, the ConOps, DFMEA, and associated system requirements (shown in Appendix A) will likely act as useful guides for other researchers and engineers in the future. During the ERS system development process the research team, in collaboration with engineers from the radar company, successfully completed necessary modifications. Formal Smart Road and real-world testing were then performed to determine the ERS system activation performance. Ultimately, the ERS open-loop system performed with a 100 percent correct detection rate and a 100 percent correct reject rate. The ERS closed-loop system performed with a 100 percent correct detection rate and an 85.43 percent correct rejection rate during real-world testing. During all ERS system activations, no unsafe following-vehicle driver reactions/behaviors were observed. A nighttime brightness level was selected at the conclusion of a Smart Road ratings study and carried on into nighttime real-world testing. During ERS system nighttime activations, there were also no unsafe following-vehicle driver reactions/behaviors observed.

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1. INTRODUCTION

1.1 BACKGROUND AND RESEARCH OBJECTIVES

The enhanced rear signaling (ERS) system for commercial motor vehicles (CMVs) effort thus far has included three phases of work focused on the reduction of crashes which involve a heavy truck being struck in the rear by another vehicle. An analysis of the National Highway Traffic Safety Administration (NHTSA) General Estimates System (GES) using data from 2006 was performed during Phase III. It was found during the analysis that there were 135 fatalities and 1,603 incapacitating injuries resulting from this particular crash type.(3) Recent analyses found that during 2010, heavy trucks were three times more likely than other vehicles to be struck from behind in two-vehicle fatal crashes.(1)

The purpose of Phase I was to perform a crash data analysis to determine causal factors of rear-end collisions and to identify potential countermeasures. Phase II continued with the development of a prototype system that incorporated the countermeasure designs from Phase I. During Phase II field testing, potential benefits of using such countermeasures were realized. The purpose of Phase III was threefold:

- Conduct GES database analysis using the most recent data available to report various break-outs/characterizations of rear-end truck crashes.
- Explore the benefits of the countermeasures previously developed.
- Develop a plan for a large-scale field operational test (FOT) designed to assess countermeasures for rear-end truck crashes.

Phase III resulted in positive results for an ERS system comprising two types of activation subsystems (i.e., open-loop and closed-loop). Table 2 below describes the three phases of the ERS research.

Table 2. ERS Phases I, II, and III project descriptions.

Phase I (2004)	Phase II (2006)	Phase III (2010)
Performed a crash data analysis to determine causal factors of rear-end truck crashes and to identify auditory and visual countermeasures.	Development of prototype system that incorporated auditory and visual countermeasures identified in Phase I. Field testing in Phase II revealed potential benefits to using auditory and visual countermeasures that performed better than normal brake lights in preventing rear-end truck crashes. During this phase, a three rear-warning-light configuration performed the best in eye-drawing performance and in detecting rear-end crash threats, and was selected to move forward to the real-world dynamic data collection effort.	Analyzed characteristics of rear-end truck crashes, explored the benefits of auditory and visual countermeasures from Phases I and II in static and dynamic environments, and developed a plan for a large-scale ERS FOT.

1.1.1 ERS System and Open-loop and Closed-loop Activation Subsystems

The ERS system that was identified for further development during Phase III testing comprised a rear warning-light system of 12 light-emitting diode (LED) units positioned on the main rear bumper of the trailer (as shown in Figure 3). These LED units were positioned to maximize light output to the lane directly behind the trailer and to target following-vehicle driver eye-heights of both light vehicles and heavy vehicles. The rear warning-light system would flash lights at a frequency of 5 Hz when triggered. Light activation triggering was dependent upon which activation system was selected (i.e., open-loop or closed-loop). An open-loop system requires no measurements associated with the following vehicle; only lead-vehicle parameters are available. A closed-loop system includes the measurement of closing rate (velocity) and closing distance to the following vehicle (using radar), along with lead-vehicle velocity and deceleration. Further information about the exact conditions associated with rear warning-light activation for each subsystem can be found in the Phase III technical report.[2]

Figure 3. Photo. Phase III (prototype system) final rear-warning light configuration.

Although testing during Phase III indicated promise for both activation subsystems, results also indicated that expanded ERS development and system refinement were warranted prior to the initiation of an FOT. The purpose of the current project was to further develop and refine ERS system components. Expanded development efforts for the ERS system included:

- Modification of the system into a unit designed for simple truck and trailer installation.
- Closed-loop activation subsystem refinement, including:
  - Radar firmware refinement to reduce false alarms in lower speed, high-traffic density scenarios.
  - Transfer of algorithm processing to radar firmware unit.
- Adjustments required to rear warning-light brightness during nighttime conditions.

1.2 ORGANIZATION OF THE CURRENT REPORT

The current report details all major tasks completed during the project. These tasks are briefly described below so that the reader can understand the logical progression of events that occurred.

1.2.1 Concept of Operations

The research team developed a concept of operations (ConOps) document for the ERS system. The intent of this document was to provide a conceptualization from the user's perspective of the daily conditions and functions of the system during implementation.

1.2.2 Design Failure Mode and Effects Analysis

The research team employed a design failure mode and effects analysis (DFMEA) process to systematically explore the potential failure modes of the ERS system based on prior system testing and engineering experience with similar technologies. The findings of this analysis helped engineers and researchers prioritize and address potential design deficiencies early during the development process, thus increasing the likelihood of system success once deployed.

1.2.3 System Modification for Simple Installation

Prior to a FOT, a modification to the ERS system was warranted to improve truck and trailer installation/implementation. The goal was to reduce the numerous components of the Phase III ERS design and to reduce the potential for unnecessary failure modes.

1.2.4 Closed-loop Activation Subsystem Refinement

During Phase III, all closed-loop activation algorithm conditions were processed using the research team's data acquisition system (DAS). As part of the current project, efforts were undertaken to improve following-vehicle tracking firmware and to transition all collision-warning algorithm logic to the radar itself.

1.2.5 Nighttime Warning-light Brightness Testing

During Phase III, the ERS system was not tested during nighttime conditions. Therefore, an investigation was conducted to determine whether adjustments of the brightness levels of the rear warning lights were necessary to reduce associated discomfort glare while maintaining eye-drawing capabilities. Two studies were performed to evaluate the ERS system during nighttime conditions. The first study used following-vehicle drivers to rate multiple nighttime brightness levels on discomfort glare and "attention-getting" effectiveness. Using the brightness level candidate deemed best by the ratings study, the second study included the collection of real-world data on public roadways in southwest Virginia.

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2. CONCEPT OF OPERATIONS

2.1 INTRODUCTION

This section describes the ConOps of the ERS system for CMVs. The intent of the ConOps was to provide a conceptualization from the user's perspective of the daily conditions and functions of the system during implementation. Specifically, the ConOps answered questions such as:

- What is the purpose of the ERS system for CMVs?
- Who will use it?
- For what will they use it?
- How will they use it?
- When will they use it?
- Where will they use it?
- In what environments will it be used?
- How will we know if it is effective?

A complete list of sources that were referenced within the ConOps document, as well as a list of other resources that were not directly referenced but were used for background and/or as a source for potential user needs during the ConOps development can be found in Appendix C.

2.2 BACKGROUND

Visual warnings have been shown to be effective in mitigating rear-end collisions, assuming the following driver is looking directly at the warning display or has his/her eyes drawn to it. Currently, the primary visual warnings on the rear of CMVs and all motor vehicles are the brake lights. The presence, quantity (i.e., two red lights), and activation (e.g., upon application of service brakes) of these stop lamps are governed by 49 Code of Federal Regulations (CFR) 571.108.

One of the primary limitations of the current visual warning system (standard brake lights) is the limited effectiveness across varying operational conditions. Because these brake lights are activated only with the service brakes, the visual warning is only provided during conditions when the lead vehicle is decelerating using its braking system. The brake lights may not be activated during other important conditions unique to CMVs wherein rear-end collisions can occur. These include:

- CMV stopped along roadway or in traffic.
- CMV traveling slower.
- CMV decelerating using engine retarder.

Because of the prevalence and severity of rear-end crashes, there have been advances made using safety systems such as forward collision warning (FCW) systems, during which the following vehicle is equipped with a collision detection system such as forward-facing radar. An in-vehicle alert is provided to the following driver when an impending collision is detected between the lead and following vehicles. These systems hold promise in reducing rear-end crashes and are currently being implemented in higher-end production vehicles (both light and heavy vehicles). However, these FCWs provide only a general, in-vehicle alert to the following vehicle of the impending crash. Once warned, the driver must scan the environment to identify and classify the immediacy of all threats present.

2.3 CONCEPT OF THE PROPOSED SYSTEM

To avoid a collision, a driver must recognize (i.e., quickly identify vehicles that are an imminent threat) and correctly react (i.e., take the appropriate evasion action) to a dangerous situation. Because of the limitations of the current brake system on CMVs (i.e. only activated during brake-pedal activation, not during other CMV decelerations) there is a need to provide supplemental warnings for following-vehicle drivers under the aforementioned conditions so that drivers can quickly recognize impending collision threats. Also, visual warnings that directly emanate from threats in the driving environment could help drivers improve their threat recognition and target identification.

The purpose of the ERS system for CMVs is to detect rear-end crash threats and to provide following-vehicle drivers with a supplemental visual warning of an impending collision with the rear of a CMV. There are two primary subsystems of the ERS system: the triggering unit and a visual warning unit. The triggering unit can be either open-loop or closed-loop.(2) Each triggering approach is described below.

An open-loop activation subsystem is one that uses only equipped-vehicle parameters (i.e., antilock brake system [ABS] signal, vehicle velocity, and the derivatives of velocity) to activate the rear lighting. Parameters used could include deceleration level, ABS activation, and a timeout feature (i.e., deactivate the rear warning lights), as shown in Figure 4.

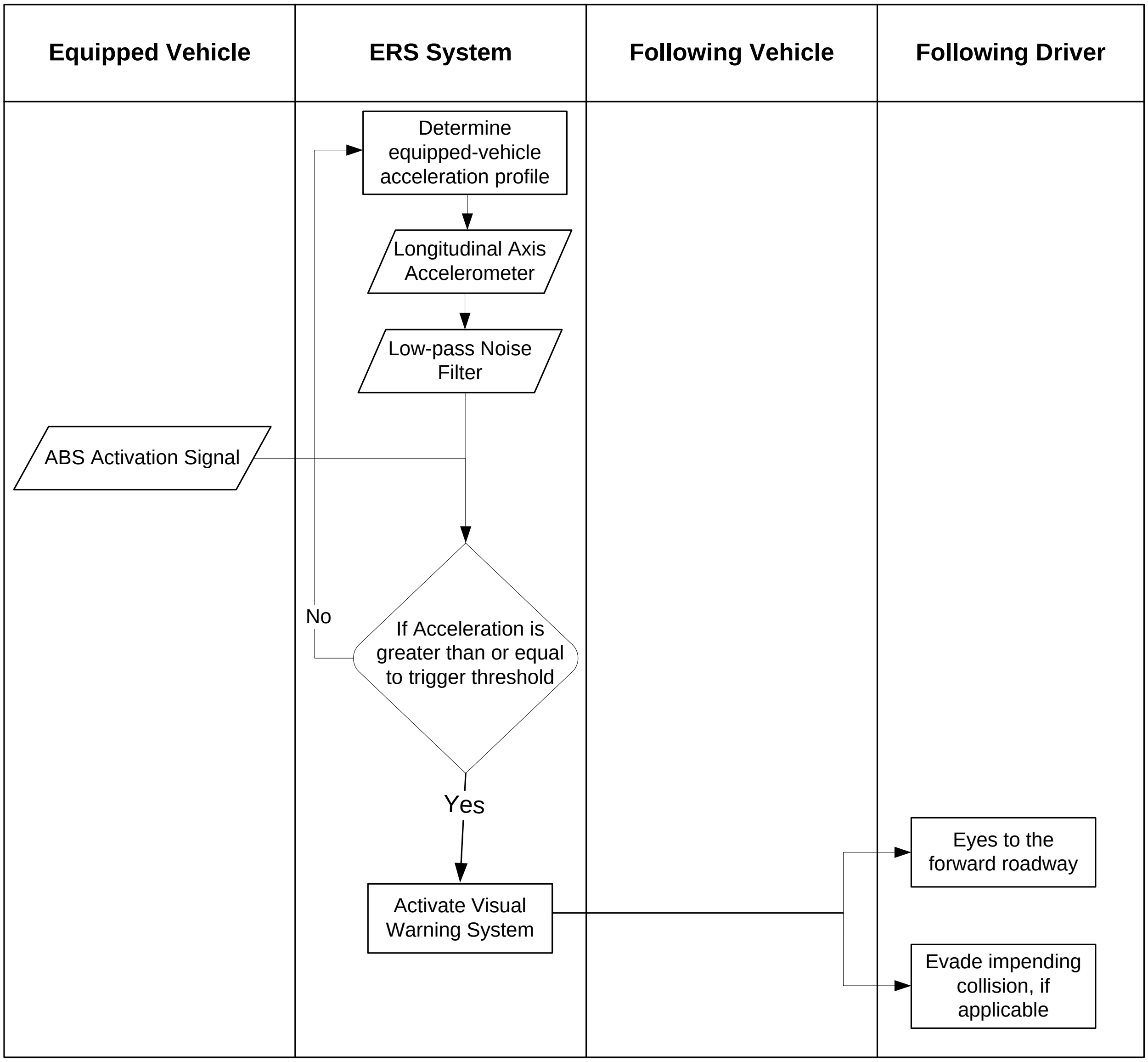

Figure 4. Flowchart. ERS system operational sequence diagram using an open-loop trigger.

A closed-loop activation subsystem is one that uses both equipped-vehicle parameters (i.e., vehicle velocity and derivatives of velocity) and measurements related to the following vehicle (e.g., closing rate and closing distance, as shown in Figure 5). Typical sensors for determining this closing rate and distance would be radar- or laser-based measurements taken from the rear bumper of the lead vehicle, aimed towards the rear. This system would provide the parameters necessary to ascertain the precise information needed to determine whether there is an immediate likelihood of a rear-end collision. It is likely that closed-loop activation would result in greater accuracy of activation (i.e., a more accurate detection of imminent collisions and fewer false alarms). However, implementation costs would be greater for closed-loop activation, as additional components such as a measurement sensor at the rear bumper and computational hardware software must be used.

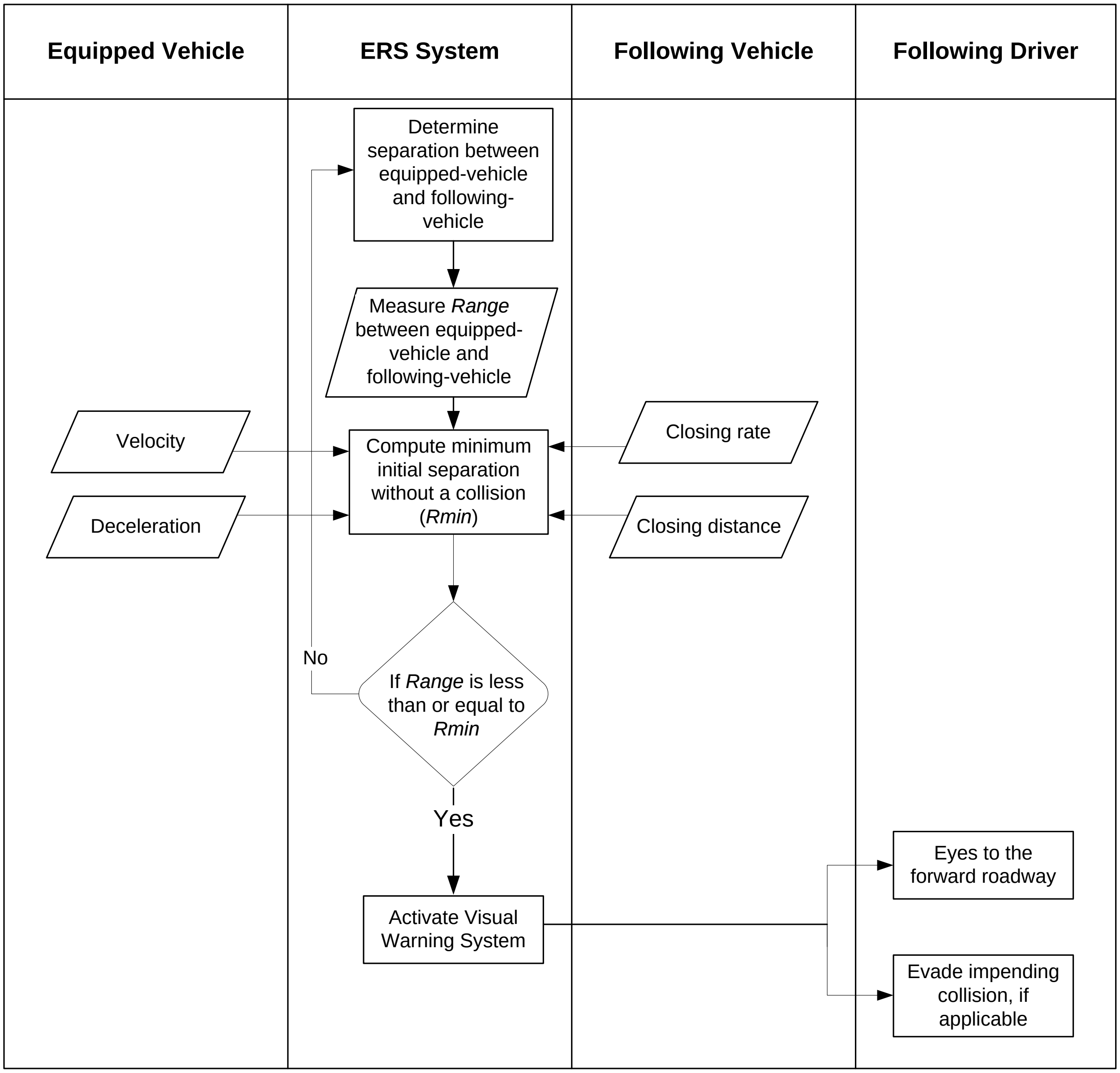

Figure 5. Flowchart. ERS system operational sequence diagram using a closed-loop trigger.

Regardless of the triggering subsystem, the ERS system uses an array of 12 LED units flashed at 5 Hz to provide a visual warning to the following-vehicle drivers indicating that, with continued closing rate and distance, a collision will occur with the lead vehicle. Figure 6 provides the operational scenario for the open-loop trigger system. Figure 7 and Figure 8 provide the operational scenarios for the closed-loop trigger system. The purpose of the visual warning is to draw the following-vehicle driver's attention to the forward roadway and to the equipped CMV. This will allow the following-vehicle driver to quickly recognize the threat and take the appropriate evasive action (e.g., braking, swerving, and/or a combination of actions).

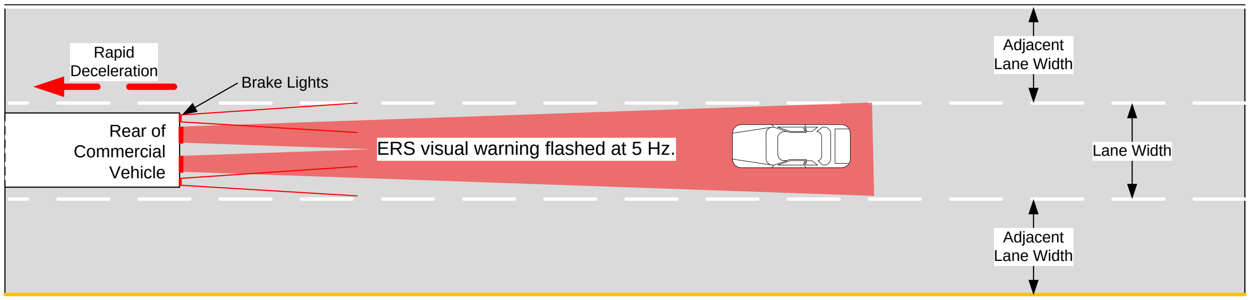

Figure 6. Diagram. ERS system operational scenario using an open-loop trigger during *warning* phase.

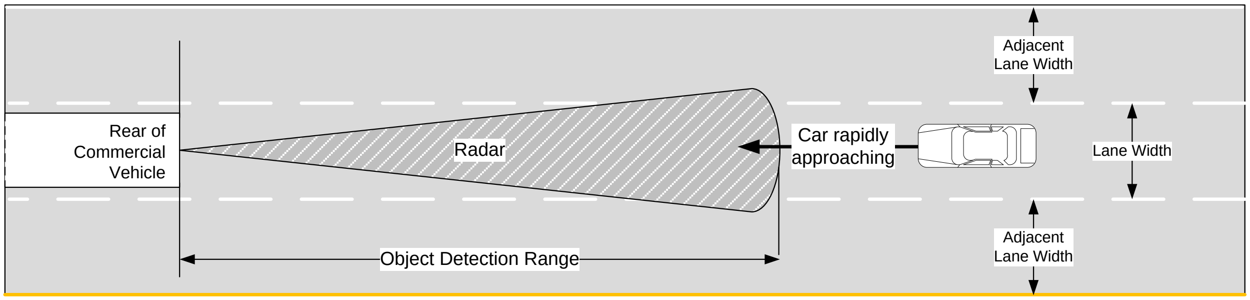

Figure 7. Diagram. ERS system operational scenario using a closed-loop trigger during *monitoring* phase.

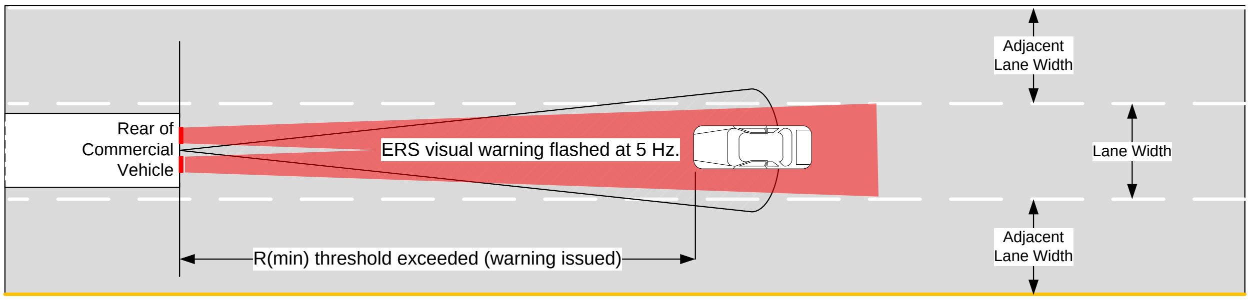

Figure 8. Diagram. ERS system operational scenario using a closed-loop trigger during *warning* phase.

The ERS system can be mounted on the rear of both combination vehicles (tractor-trailers) and straight trucks. As seen in the operational sequence diagrams (as shown in Figure 4 and Figure 5), the primary interface of the ERS system is with the host vehicle to determine its velocity profile (i.e., velocity and velocity derivatives such as acceleration) and the ABS activation signal. For the closed-loop system, the ERS system interfaces with a distance measurement sensor (e.g., radar) to determine the range and velocity profile of the following vehicle. There is no user input required for the proper functioning of the system. The only output is a visual signal from the array of 12 red LED units.

2.4 OPERATIONAL ENVIRONMENT

The ERS system for CMVs is intended for operation in a variety of commercial vehicles. Heavy trucks (a main focus of the ERS design) typically fall into two main types: combination vehicles (tractor-trailers) and straight trucks. These two types of CMVs have different purposes and operating characteristics. In general, straight trucks tend to be used for local/short hauls (i.e., 50–

100 mi radius from the home terminal), pick-up, and deliveries. These types of vehicles usually return to their home terminal every day or every couple of days. Combination vehicles are generally used in regional and long-distance (i.e., hundreds of miles from their home terminals) hauling of freight. These vehicles deliver goods and provide services during an extended period of time, often a week or more.

The trucking industry provides a vital service to the world's economy by transporting large quantities of raw materials, works in progress, and finished goods across a vast network of roads. The movement of goods by truck is conducted on all types of roads, at all hours of the day, and in all types of driving conditions. Since collisions with other vehicles or obstacles can occur along any route, many fleet types may benefit from using the ERS system. However, the ERS system may provide the most benefit for combination unit trucks (CUTs) since tractors pulling one trailer accounted for 92 percent of the 23,508 rear-end crashes occurring in 2006.(3)

2.5 OPERATIONAL SCENARIOS

As mentioned, there are two activation subsystems responsible for triggering the rear warning lights of the ERS system:

- Open-loop activation subsystem.
- Closed-loop activation subsystem.

The various inputs required to trigger the ERS system rear warning lights will depend on which activation subsystem is used. However, regardless of which activation subsystem is used, the output of the ERS system will be the same. That is, the ERS system rear warning lights will flash at a rate of 5 Hz for a period of 5 seconds. The purpose of the flashing warning lights is to alert a following-vehicle driver in the lane directly behind the CMV that he/she is approaching and that a rear-end collision is likely. As the output of the ERS system is the same for all operational scenarios, the inputs required to trigger the ERS system will be described in this section as they relate to real-world, on-road driving scenarios.

2.5.1 Open-loop Activation Subsystem Inputs

An open-loop system utilizes only lead-vehicle parameters. There are two main components for an open-loop activation subsystem used as the basis for development during this project: one associated with deceleration and one associated with ABS triggering. The accelerometer is used to determine when the vehicle is undergoing a high level of deceleration. The threshold used in the current ERS system is 0.4 g. To correct for potential noisy accelerometer signals that can cause thresholds to be exceeded even though a vehicle has not actually reached a 0.4 g threshold, a low-pass filter is used between the accelerometer and the threshold detector. A deceleration of 0.4 g was selected based on previous research.(2,4) A vehicle undergoing 0.4 g of deceleration or more will come to a stop relatively quickly. For that reason, a timeout feature is added to the ERS system. This feature continues the activation of the rear warning lights for a period of 5 seconds after the lead vehicle falls below 0.15 g in deceleration. The purpose of this feature is to continue activation of the rear warning lights while the vehicle is standing or moving slowly on the pavement after decelerating.

ABS activation indicates that one or more wheels of the vehicle are slipping on the pavement. Consequently, ABS activation is an indication that the lead vehicle (or trailer) is encountering a situation involving lack of adhesion or instability while braking. ABS activation may occur with or without high deceleration. Therefore, using this activation supplements those cases during which the deceleration threshold for activation has not been reached. An example is lack of adhesion on ice or snow. When using ABS it is also desirable to use a timeout feature as ABS activation is usually short in duration. ABS activation can be detected at the tractor and at the trailer by tapping a signal from the ABS control module at each location.

To summarize, Figure 9 shows the major elements of the open-loop activation subsystem. This system can also be used for straight trucks. Two real-time inputs are used: sensed deceleration level and activation of ABS.

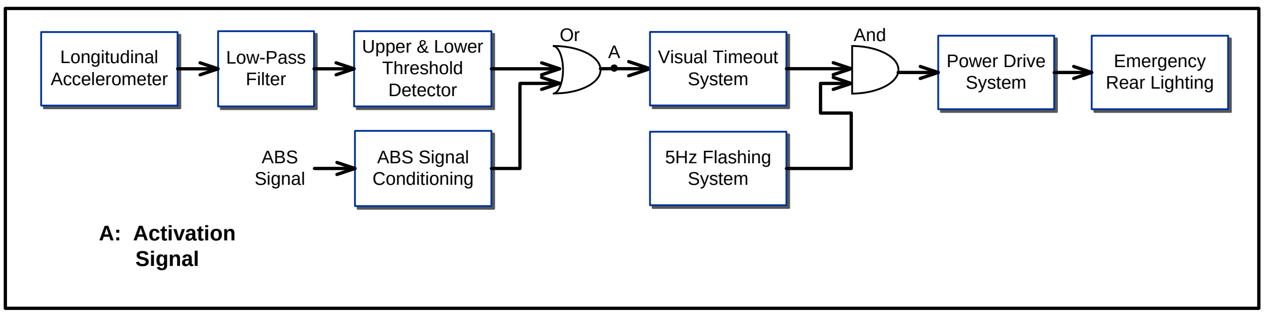

Figure 9. Flowchart. Open-loop activation subsystem for use on a CMV.

2.5.2 Closed-loop Activation Subsystem Inputs

A closed-loop activation subsystem includes the measurement of the closing rate (velocity) and closing distance of the following vehicle and the lead-vehicle velocity and deceleration regardless of speed and distance between vehicles. The inputs required for the closed-loop activation subsystem to trigger the ERS rear warning lights are initially dependent upon (and closely tied to) five acceleration and deceleration conditions of the lead vehicle. These conditions are as follows:

- *Condition 1*: The lead vehicle is standing on the pavement and has zero velocity.
- *Condition 2*: The lead vehicle is moving at a constant forward speed.
- *Condition 3*: The lead vehicle is slowly decelerating but does not come to a complete stop.
- *Condition 4*: The lead vehicle decelerates to a stop and stands on the pavement.
- *Condition 5*: The lead vehicle is slowly accelerating.

For each condition, there is a corresponding closed-loop activation subsystem algorithm used to calculate appropriate thresholds for warning-light activation based on measures of the following-vehicle velocity and range. Whenever the truck ignition is on (i.e., the ERS system is on), an algorithm for one of the five above conditions will be selected and calculated. The inputs required for ERS system rear warning-light activation for each of the five conditions are detailed below.

2.5.2.1 Condition 1: The Lead Vehicle Has Zero Velocity

During this scenario, the lead vehicle is standing on the roadway and has zero velocity. It is important to note that during this scenario the lead-vehicle driver may or may not be activating the brake pedal. It is common for a CMV driver to apply a trailer and/or vehicle parking brake after he/she has come to a complete stop. Scenarios during which it is common for a CMV to be stopped on the roadway are numerous and may include:

- CMV stopped at a traffic signal.
- CMV stopped due to other stopped traffic ahead.
- CMV stopped due to object blocking roadway.
- CMV stopped due to involvement in a safety-critical event.
- CMV stopped due to vehicle malfunction.

According to work performed during Phase III, Condition 1 is the most common in CMV rear-end collisions.(2) Data estimates from 2006 indicated that approximately 48 percent of all crashes during which a CMV was struck from behind occurred when the CMV was stopped/standing on the roadway. During this scenario, the Condition 1 algorithm evaluates multiple parameters to determine if there is an instantaneous likelihood of a rear-end collision. These parameters are as follows:

- Measure if there is a negative closing rate (i.e., a following vehicle is closing in on the lead vehicle).
- Determine (in units of g) the deceleration capability of the following vehicle during braking (a positive value for deceleration).
- Input into appropriate calculations the acceleration due to gravity.
- Input a constant value for the estimated driver perception-reaction time (including the time taken to bring eyes back to forward roadway from the associated visual distraction task).
- Measure the approach angle of the following vehicle (used to determine if the following vehicle is approaching in the lane directly behind the lead vehicle).
- Measure the time-to-collision (TTC).

Any following vehicle that approaches a stopped CMV and exceeds the set thresholds as calculated by the Condition 1 algorithm will trigger the rear warning-light activation.

2.5.2.2 Condition 2: The Lead Vehicle is Moving at a Constant Forward Speed

During this scenario the lead vehicle is moving forward at a constant speed. In terms of the closed-loop activation subsystem operation, this scenario is similar to Condition 1 in that the calculations are performed in a comparable manner. Therefore, the Condition 2 algorithm evaluates the same parameters as Condition 1 for determining if there is an instantaneous likelihood of a rear-end collision. Any following vehicle that exceeds the set thresholds while approaching a CMV and moving at a constant forward speed as calculated by the Condition 2 algorithm will trigger the rear warning-light activation.

2.5.2.3 Condition 3: The Lead Vehicle is Slowly Decelerating but Does Not Come to a Complete Stop

The Condition 3 algorithm will be used when the lead vehicle is slowly decelerating. During this scenario, the Condition 3 algorithm evaluates the same parameters as the previous two conditions. This scenario is common on many types of U.S. roadways and generally occurs when a CMV slowly decelerates when traveling up a hill while carrying a heavy load. A following-vehicle driver traveling in a light vehicle can easily maintain or even accelerate up a hill, which can result in a following vehicle approaching the rear of a CMV.

2.5.2.4 Condition 4: The Lead Vehicle Decelerates to a Stop and Stands on the Pavement

The Condition 4 algorithm is used when the lead vehicle is quickly decelerating to a stop (i.e., hard braking). This condition algorithm will remain active until the lead vehicle is truly stopped, at which point Condition 4 will shift to Condition 1. The Condition 4 algorithm evaluates the same parameters as previous conditions. This scenario can occur often during traffic jams on all types of U.S. roadways. Even if the CMV driver is attentive and keeping his/her eyes on the forward roadway, there are times when the traffic ahead suddenly stops and requires the driver to decelerate quickly. Sudden deceleration can also occur when traffic ahead starts to slow and a CMV driver is not attentive and does not perceive the slowing traffic until the last possible second. During this situation, the driver must decelerate quickly to avoid rear-ending the vehicle directly ahead. Similarly, traffic signals that transition from green to yellow, and finally to red, may result in a CMV driver decelerating quickly because he/she did not properly perceive the signal transition in time, possibly due to performing another visual task. One final scenario that is common for CMV drivers involves other vehicles merging into the lane directly ahead and reducing the space required for a CMV driver to slow properly in the case of sudden-stopping traffic. This scenario often occurs during high-traffic-density situations and is usually initiated by aggressive drivers of other vehicles.

2.5.2.5 Condition 5: The Lead Vehicle is Slowly Accelerating

Although less frequent, one potential scenario during which a CMV may be struck from behind is when the CMV is slowly accelerating while a following vehicle is closing in at a higher rate. The Condition 5 algorithm evaluates the same parameters as the previous conditions. Although this scenario is less likely to occur than the other four, it is possible and is accounted for in the closed-loop activation subsystem. A likely scenario that meets the Condition 5 requirements is when a CMV passes another vehicle on a multi-lane roadway and, even though the CMV is accelerating, a following vehicle approaches at a greater speed. For example, CMVs will commonly move from the right lane to the left lane before beginning a passing maneuver. Although a CMV does have ample power, its ability to accelerate while carrying a heavy load is limited in comparison to a light vehicle. Typically, these CMV passing maneuvers take longer to be completed. It is common for a following-vehicle driver to approach the rear of the passing CMV and find it necessary to slow to avoid a rear-end collision or find that it is too late and strike the rear of the CMV.

2.6 ASSUMPTIONS

During all conditions presented, it is assumed that the following vehicle maintains constant velocity during perception-reaction time, and the braking thereafter creates constant deceleration. These assumptions appear reasonable and make it unnecessary to determine the acceleration of the following vehicle.

2.7 SUMMARY

The ERS system provides a countermeasure for reducing the number and severity of rear-end collisions during which a CMV is struck from behind. The ERS is a standalone system that requires no input from the driver of the equipped vehicle and only provides visual feedback (i.e., a flashing red-light warning) to drivers following the equipped vehicle. The primary metric used to assess system performance is a reduction of rear-end collisions or near-collisions with the equipped vehicle. Other possible metrics include:

- The ERS activation subsystem performance (both the closed-loop and open-loop systems).
- The following-vehicle driver behavior (acceleration data, eye-drawing capability, and unintended consequences).

To supplement the ConOps, a system requirements document was written by the research team and can be found in Appendix A. This document provides high-level functional requirements and detailed performance requirements of the ERS system.

3. DESIGN FAILURE MODE AND EFFECTS ANALYSIS

A DFMEA was conducted to help ERS design engineers and researchers recognize and evaluate the potential deficiencies of the ERS system. Using this analysis, the research team identified possible actions to mitigate design deficiencies.

The research team met on several occasions to develop two separate DFMEA efforts. The first effort examined the utility of the ERS at the system level (Utility DFMEA). The second effort examined the functionality of the ERS at the subsystem level (Functional DFMEA).

The research team used guidance from Society of Automotive Engineers (SAE) J1739—Potential Failure Mode and Effects Analysis in Design (Design FMEA) and Potential Failure Mode and Effects Analysis in Manufacturing and Assembly Processes (Process FMEA) and Effects Analysis for Machinery (Machinery FMEA) to perform the DFMEAs.[(5)] First, the team met to identify all subsystem and principal components of the ERS system (as shown in Appendix B). During the next several meetings, the research team identified the function performed by these principal components and the potential failure modes. Based on group consensus, rankings for severity (*S*), occurrence (*O*), and detection (*D*) were assigned to each component. The team agreed to provide separate rankings for detection occurring at the manufacturing facility (production) or in the field. This was conducted to ensure that difficulties in detecting system defects during use were captured. A risk priority number (*RPN*) was derived as the product of the *S*, *O*, and *D* rankings (as shown in Figure 10).

$$RPN = S \; x \; O \; x \; D$$

Figure 10. Equation. *RPN*.

Because there were two detection rankings provided (i.e., production and field), there were two RPNs per failure mode (i.e., Production RPN and Field RPN).

The resulting RPNs ranged from 1 to 1,000; therefore, the team agreed that an RPN of 100 or more would be assigned a corrective action. These corrective actions were addressed during the system development to reduce the overall risk of the ERS system and to increase user satisfaction through improved system design.

The Utility DFMEA resulted in the identification of 15 failure modes with RPNs ranging from 28 to 172. Of these 15, there were 3 failure modes with an RPN of 100 or greater. These were addressed during the development phase, resulting in RPNs less than 100 (ranging from 32 to 54). The Functional DFMEA identified 49 failure modes with RPNs ranging from 4 to 576. Of these 49, there were 10 failure modes with an RPN of 100 greater. These were also addressed during the development phase and resulted in RPNs less than 100 (ranging from 20 to 72).

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4. SYSTEM MODIFICATION FOR SIMPLE INSTALLATION

The ERS system designed during Phase III had numerous components, many of which required separate weatherproof housings and wiring harnesses. At the time, this design was necessary in order to test different lighting configurations and to facilitate access to and control of components. Prior to an FOT, a modification to the system was necessary to improve truck and trailer installation/implementation.

Appendix B contains a breakdown of the five ERS subsystems (i.e., vehicle detection, embedded firmware, LED unit, housing, and ERS interface). Only activities involving the LED unit, housing, and ERS interface will be described in this section. Modification activities involving the vehicle detection and embedded firmware subsystems will be described in Section 5 of this report, as they were more complex and required substantial test-track and on-road testing.

4.1 LED UNIT

The same off-the-shelf LED units used during Phase III of the ERS program were ordered for the ERS system tested in this study. Engineers used computer-aided design (CAD) as the primary tool during the initial design stages. The resulting CAD models provided the information needed to identify hardware and materials prior to fabrication. Figure 11 and Figure 13 include an original photo of the heavy-vehicle LED unit and the resulting CAD model rendering.

Figure 11. Photo. Heavy-vehicle LED unit.

Figure 12. Diagram. CAD model rendering of the LED unit.

4.2 HOUSING

Once the LED unit was modeled, engineers were able to design a housing to fit all 12 LED units, the necessary wiring, and radar bracketry.

Figure 13 shows preliminary CAD model renderings of the front of the ERS system housing (one with the protective cover and one without it). Figure 14 shows an interior view of the ERS housing with LED unit positions and the radar mount position. The four most outwardly positioned LED units were designed to be mounted 1.5 degrees inwards. The four LED units surrounding the radar were designed to be mounted flat (0 degrees). The remaining LED units were designed to be mounted 0.75 degrees inwards. After the housing design was complete, a trailer mount was designed. This "housing-to-trailer" mounting bracket is shown in Figure 15.

Figure 13. Diagram. ERS system housing CAD model without cover.

Figure 14. Diagram. ERS system housing CAD model rendering—with cover.

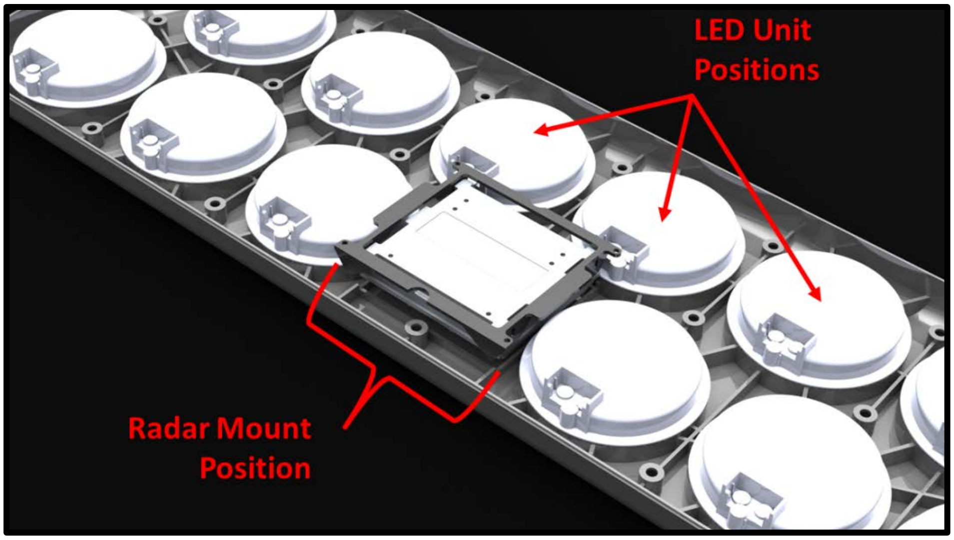

Figure 15. Diagram. CAD model rendering of LED unit and radar mount positions.

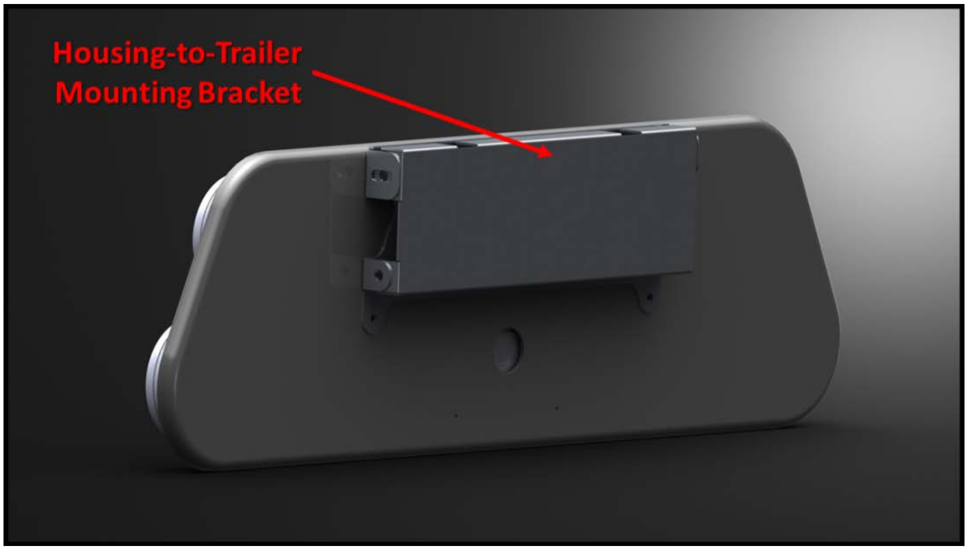

Figure 16. Diagram. CAD model rendering of the ERS housing-to-trailer mounting bracket.

Next engineers ordered the materials needed for fabrication of the ERS system housing, including:

- Fused deposition modeling (FDM) three-dimensional (3D) printed front piece (as shown in Figure 17A).
- Computer numerical control (CNC)-machined aluminum back piece (as shown in Figure 17B).
- Water-jetted sheet metal bracketry.

Figure 17. Diagram. Delivered materials: (A) FDM 3D printed front piece (B) CNC-machined aluminum back piece with mounted LED units.

Figure 18 illustrates the final installed housing containing all LED units and the radar mounted under the trailer main bumper above the underride guard. The entire housing was mounted 1 degree upwards to focus the light intensity for following drivers of low-sitting and high-sitting eye-heights (passenger car and heavy truck, respectively). To power the LED units, a miniature weatherproof plastic connector was used between the housing and the trailer power source. A standard weatherproof barrel connector was used to communicate radar data to and from the ERS interface (as explained in Section 4.3).

Figure 18. Photograph. Final ERS system housing.

4.3 ERS INTERFACE

The ERS interface collects and processes data (from external and internal sensors), and relays processed information back to the ERS housing. During the development effort undertaken in this study, a wheel speed sensor (0 degrees) was mounted to the trailer to measure lead-vehicle speed. The ERS interface collected these speed data and converted them to radar format. Converted data were then relayed to the radar (lead-vehicle speed data were required for improved radar tracking accuracy and closed-loop activation subsystem algorithm conditions). The ERS interface also collected ABS activation data directly from the trailer ABS controller. However, constraints existed based on the type of ABS controllers equipped on trailers. The ERS interface also contained two additional internal sensors. The first was an ambient light sensor. Data from this sensor were relayed to the digital signal processor of the ERS interface, which then determined the LED unit brightness levels. A high-power field-effect transistor (FET) was used to provide power to the LED units and to make them flash at a rate of 5 Hz. The second internal sensor was an accelerometer used to measure the lead-vehicle deceleration behavior. Accelerometer data were only used for the open-loop activation subsystem.

Engineers designed the ERS interface controller board at the research team’s facility. Figure 19 provides a rendering of the controller board design. The controller board development was then outsourced and refined upon delivery. The main components of the ERS interface were housed in a printed circuit board enclosure with a radial flange seal for environmental protection. This enclosure was mounted under the trailer behind the ERS housing for protection.

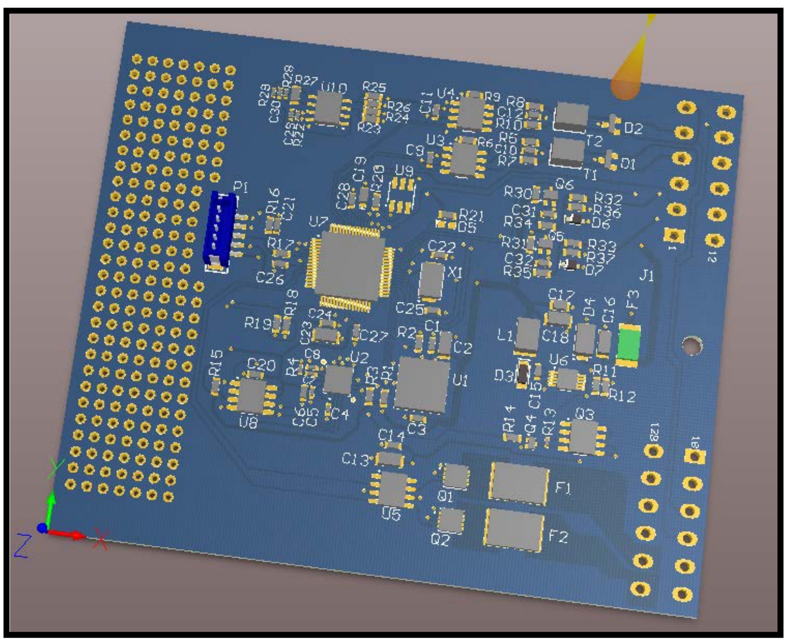

Figure 19. Diagram. ERS interface controller board.

5. CLOSED-LOOP ACTIVATION SUBSYSTEM REFINEMENT

The vehicle detection and embedded firmware subsystems were designed and developed in collaboration with a private radar design company. These two subsystems are relevant only for closed-loop activation. During Phase III, all closed-loop activation algorithm conditions were processed using the research team's DAS. As part of the current project, an effort was undertaken to improve following-vehicle tracking firmware and to transition all collision-warning algorithm logic to the radar itself. This section describes the activities performed during these efforts and all performance testing completed.

5.1 TRACKING FIRMWARE REFINEMENT

The research team worked with the radar design company to improve the rear-facing radar tracking firmware based on results found during Phase III. A limitation was found during Phase III closed-loop activation subsystem testing at lower speeds in high-traffic scenarios due to radar target identification problems. This resulted in a greater number of false alarms. The purpose of the tracking refinement effort made during the current project was to reduce the propensity of these false alarms.

The research team used the radar company's proprietary software to collect data on the Virginia Smart Road using the Phase III prototype system in low-speed, high-traffic-density scenarios (that consistently resulted in false alarms). These data were sent to the radar company for use in refining the firmware. The radar company sent back an initial firmware revision, which was tested in similar scenarios on the Smart Road. Minor issues were found, and data were returned for a second set of revisions. After refinement efforts were completed a second time, a final tracking firmware revision was sent back and tested by researchers. Initial testing indicated improved tracking performance, and the firmware was deemed ready for formal Smart Road testing.

5.2 CLOSED-LOOP ACTIVATION ALGORITHM TRANSLATION

The research team worked with the radar design company to transition the closed-loop activation algorithms into the radar firmware. As a first step, the research team revised the programming code behind the closed-loop activation algorithms and transferred the code to the radar company. Radar company engineers worked to incorporate these algorithms into the radar firmware. Several iterations of updated firmware were passed between the research team and the radar company. Many of these firmware iterations were evaluated on the Smart Road. Researchers and engineers simultaneously collected data with the new firmware and the firmware from Phase III and all collected data were transferred to the radar company for review. A working version of the refined firmware was completed and uploaded to the radar. Preliminary pilot testing conducted on the Smart Road indicated that the firmware was ready for formal testing.

5.3 FORMAL TESTING: SMART ROAD

The purpose of formal testing on the Smart Road was to evaluate the refined radar firmware for improved target tracking in addition to the performance of the incorporated activation (triggering) algorithms. Both the open- and closed-loop activation subsystems were tested.

5.3.1 Open-loop Activation Sub-system Testing

Open-loop testing used only lead-vehicle deceleration for system activation and excluded the ABS. There were two reasons for excluding ABS data from the ERS open-loop activation testing:

- The ABS controller on the research team’s trailer would have required a substantial redesign to measure any broadcasted ABS activation signals. Upon further investigation, it was found that recent advances in original equipment manufacturer (OEM) ABS controllers include signal broadcasting that will meet the requirements of an ERS open-loop activation system implementation.
- Due to safety reasons, actual scenarios involving the activation of the trailer ABS were not performed.

5.3.1.1 Method

Study Design

All testing was conducted with researchers and engineers. As mentioned, an open-loop system requires no measurements associated with the following vehicle. Only lead-vehicle parameters are available. The lead-vehicle parameter tested was deceleration (measured by an accelerometer). The main purpose of the open-loop activation subsystem testing was to determine how well the system could detect a rear-end crash threat, and the subsequent activation of the rear warning lights. A signal detection theory experimental design was used. Categories for open-loop activation performance were defined as follows:

- Correct detections.
- Missed detections.
- False alarms.
- Correct non-detections.

The main dependent variable (DV) was light activation (*Yes* or *No*). The main independent variable (IV) was the braking level. The different levels of the IV are as follows:

- Braking Level.
  - *Low-level* (< 0.4 g).
  - *High-level* (≥ 0.4 g).

The instrumented CMV was driven one loop around the Smart Road. Each variable above was tested 10 times for a total of 20 samples.

Apparatus

The ERS system was installed on the rear of an experimental CUT trailer (below the main bumper and above the underride guard, see Figure 20). Light-activation logic was calculated by the ERS interface installed on the trailer. An accelerometer was used to measure the level of braking.

Figure 20. Diagram. ERS system position on rear of trailer.

Procedure

As mentioned, the experimental CUT was driven one loop around the Smart Road. A loop on the Smart Road is approximately 2.2 mi (3.54 km).

5.3.1.2 Open-loop Activation System Results

Table 3 shows the results for the braking level conditions. Results indicated that all threats were correctly detected and that lighting activated appropriately. No false alarms occurred and no missed detections occurred. Therefore, the estimated probability of the system correctly identifying a threat based on *High-level* braking and activating the lights was 100 percent, P(hit) = 10/10 = 1.0. The estimated probability of the system correctly rejecting *Low-level* braking and not activating the lights was 100 percent, P(cr) = 10/10 = 1.0.

Table 3. Detection results from brake level testing for the open-loop activation subsystem.

Light Activation	Threat	No Threat
Yes	10	0
No	0	10

5.3.2 Closed-loop Activation Subsystem Testing

The main objective of the closed-loop activation subsystem testing was to determine system performance under various rear-end crash scenarios. During this project, rear-end crash scenarios involved approaching vehicles of various sizes (e.g., mid-sized sedans and motorcycles). These approaching vehicles re-created rear-end crash scenarios both when the experimental CUT was standing still (static) and moving (dynamic).

The closed-loop activation subsystem is designed to operate based on the five algorithm conditions as follows:

- *Condition 1:* The lead vehicle is standing on the pavement and has zero velocity.
- *Condition 2:* The lead vehicle is moving at a constant forward speed.
- *Condition 3:* The lead vehicle is slowly decelerating but does not come to a complete stop.
- *Condition 4:* The lead vehicle decelerates to a stop and stands on the pavement.
- *Condition 5:* The lead vehicle is slowly accelerating.

5.3.2.1 Static Testing

Method

Study Design: Condition 1 does not require the experimental CUT to be in motion, making it an ideal candidate for preliminary tests. Rear-end crash scenarios were executed on a long, flat portion of the Smart Road. All testing was performed using researchers and engineers. Testing was completed during low-traffic-density (e.g., single approaching vehicle) and high-traffic-density (e.g., one stationary vehicle behind trailer and one approaching vehicle) scenarios. A detection paradigm was used that is similar to signal detection theory. Four occurrences of detection were categorized as follows:

- Correct detections.
- Missed detections.
- False alarms.
- Correct non-detections.

The main DV was light activation (*Yes* or *No*). The main IVs were light-vehicle type, light-vehicle approach scenario, and light-vehicle approach speed. Each scenario was performed four times. The different levels of each IV are as follows:

- Light-Vehicle Type.
  - Motorcycle.
  - Mid-Sized sedan.
- Light-Vehicle Approach Speed.
  - *5 mi/h* (*8.05 km/h*).
  - *15 mi/h* (*24.14 km/h*).
  - *25 mi/h* (*40.23 km/h*).
- Light-Vehicle Approach Scenario.
  - Same Lane.
  - Left Lane.
  - Right Lane.
  - Left-to-right merge at *75 ft* (*22.86 m*) from trailer (*100 ft* [*30.48 m*] for the *25 mi/h* [*40.23 km/h*] approaches).
  - Left-to-right merge at *75 ft* (*22.86 m*) behind stationary light vehicle (*100 ft* [*30.48 m*] for the *25 mi/h* [*40.23 km/h*] approaches).
  - Right-to-left merge at *75 ft* (*22.86 m*) from trailer (*100 ft* [*30.48 m*] for the *25 mi/h* [*40.23 km/h*] approaches).
  - Right-to-left merge at *75 ft* (*22.86 m*) behind stationary light vehicle (*100 ft* [*30.48 m*] for the *25 mi/h* [*40.23 km/h*] approaches).

Apparatus: The ERS system was installed on the rear of the experimental CUT trailer, below the main bumper and above the underride guard, as shown in Figure 20. Light-activation logic was calculated by the radar. The approaching light vehicle used for initial static testing was a mid-sized sedan (as shown in Figure 21). The approaching motorcycle used for initial static testing is shown in Figure 22. A second mid-sized sedan (as shown in Figure 23) was positioned directly behind the experimental CUT in the same lane, approximately 15 ft (4.57 m) from the rear bumper for the high-traffic condition testing.

Figure 21. Photo. Mid-sized sedan (approach vehicle) used for Smart Road testing.

Figure 22. Photo. Motorcycle used during Smart Road testing.

Figure 23. Photo. Mid-sized sedan used during Smart Road testing as a following vehicle positioned directly behind the experimental CUT.

Procedure: As mentioned, a detection paradigm similar to signal detection theory was used in these tests. In this situation, the closed-loop activation subsystem acts as an observer and initiates the warning lights when certain conditions are met. The two types of static testing that occurred during the current performance period are as follows:

- Testing performed during low-traffic density (i.e., mid-sized sedan or motorcycle approaching the experimental CUT).
- Testing performed during high-traffic density (i.e., motorcycle or mid-sized sedan approaching the stationary mid-sized sedan parked directly behind the experimental CUT).

During low-traffic-density testing an approaching vehicle demonstrated a rear-end crash threat (*direct threat*) when approaching the rear of the experimental CUT in the same lane. During high-traffic-density testing the approaching vehicle demonstrated an indirect rear-end crash threat (*indirect threat*). The latter scenario was classified as an *indirect threat* as the stationary light vehicle was the primary vehicle threatened by a rear-end collision, not the experimental CUT. However, the ERS system is still somewhat capable of detecting an approaching vehicle even with a stationary vehicle blocking the direct line of sight of the system radar. Therefore, researchers decided that these scenarios were important to evaluate. Figure 24 presents a diagram of rear-end crash scenarios used during the low-traffic static-density testing, while Figure 25 presents a diagram of the rear-end crash scenarios used during the high-traffic-density static testing.

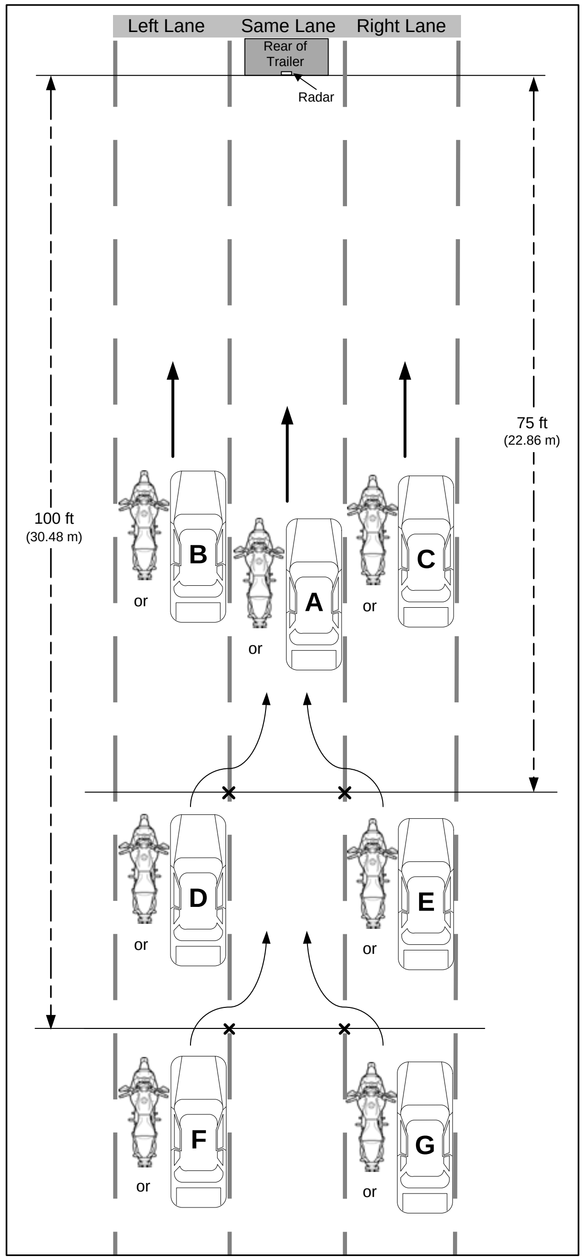

Figure 24. Diagram. Rear-end collision and adjacent-lane passing scenarios for low-traffic-density conditions during closed-loop activation subsystem testing (static only).

- **Scenario A (*direct threat*)**: Mid-sized sedan or motorcycle approached the rear of the experimental CUT in the *Same Lane* four times at each closing speed (*5 mi/h* [*8.05 km/h*], *15 mi/h* [*24.14 km/h*], and *25 mi/h* [*40.23 km/h*]).

- **Scenario B (*no threat*)**: Mid-sized sedan or motorcycle approached the rear of the experimental CUT in the *Left Lane* four times at each closing speed (*5 mi/h* [*8.05 km/h*], *15 mi/h* [*24.14 km/h*], and *25 mi/h* [*40.23 km/h*]).

- **Scenario C (*no threat*)**: Mid-sized sedan or motorcycle approached the rear of the experimental CUT in the *Right Lane* four times at each closing speed (*5 mi/h* [*8.05 km/h*], *15 mi/h* [*24.14 km/h*], and *25 mi/h* [*40.23 km/h*]).

- **Scenario D (*direct threat*):** Mid-sized sedan or motorcycle approached the rear of the experimental CUT in the *Left Lane* and merged into the *Same Lane* at a distance of *75 ft* (*22.86 m*). This scenario was conducted four times for each closing speed of *5 mi/h* (*8.05 km/h*) and *15 mi/h* (*24.14 km/h*).
- **Scenario E (*direct threat*)**: Mid-sized sedan or motorcycle approached the rear of the experimental CUT in the *Right Lane* and merged into the *Same Lane* at a distance of *75 ft* (*22.86 m*). This scenario was conducted four times for each closing speed of *5 mi/h* (*8.05 km/h*) and *15 mi/h* (*24.14 km/h*).
- **Scenario F (*direct threat*)**: Mid-sized sedan or motorcycle approached the rear of the experimental CUT in the *Left Lane* and merged into the *Same Lane* at a distance of *100 ft (30.48 m)*. This scenario was conducted four times at the *25 mi/h* (*40.23 km/h*) closing speed.
- **Scenario G (*direct threat)***: Mid-sized sedan or motorcycle approached the rear of the experimental CUT in the *Right Lane* and merged into the *Same Lane* at a distance of *100 ft (30.48 m)*. This scenario was conducted four times at the *25 mi/h* (*40.23 km/h*) closing speed.

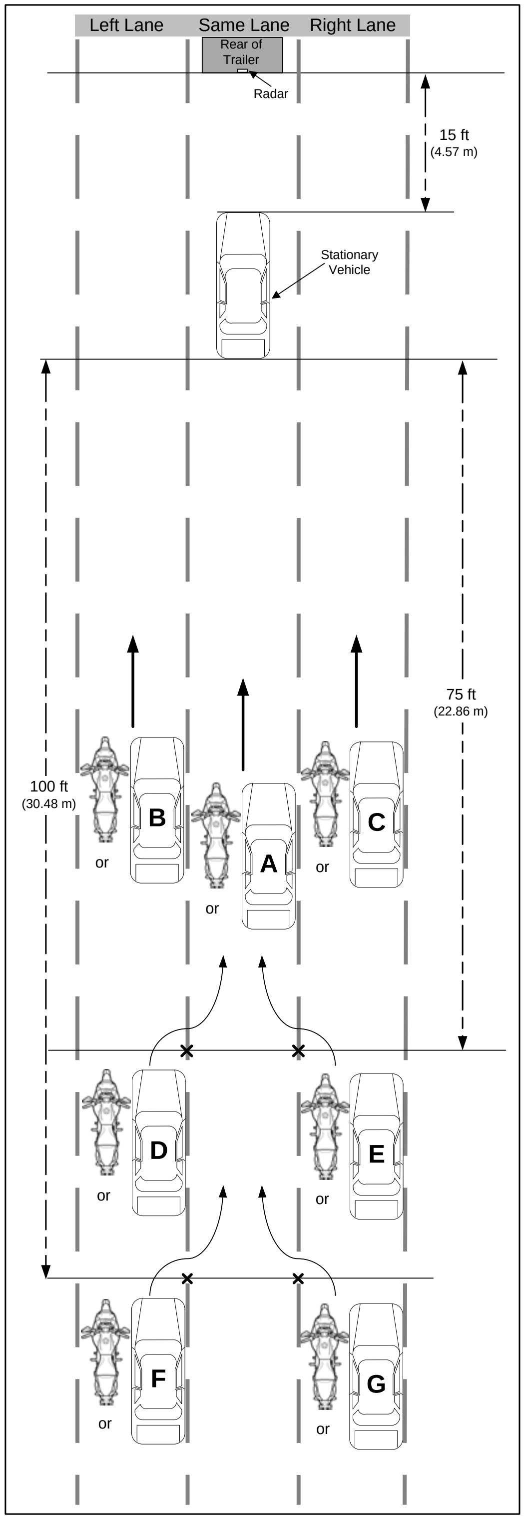

Figure 25. Diagram. Rear-end collision and adjacent-lane passing scenarios for high-traffic-density conditions during closed-loop activation subsystem testing (static only).

- **Scenario A (*indirect threat*)**: Mid-sized sedan or motorcycle approached the rear of the stationary light vehicle in the *Same Lane* four times at each closing speed (*5 mi/h* [*8.05 km/h*], *15 mi/h* [*24.14 km/h*], and *25 mi/h* [*40.23 km/h*]).

- **Scenario B (*no threat*)**: Mid-sized sedan or motorcycle approached the rear of the stationary light vehicle in the *Left Lane* four times at each closing speed (*5 mi/h* [*8.05 km/h*], *15 mi/h* [*24.14 km/h*], and *25 mi/h* [*40.23 km/h*]).
- **Scenario C (*no threat*)**: Mid-sized sedan or motorcycle approached the rear of the stationary light vehicle in the *Right Lane* four times at each closing speed (*5 mi/h* [*8.05 km/h*], *15 mi/h* [*24.14 km/h*], and *25 mi/h* [*40.23 km/h*]).
- **Scenario D (*indirect threat*)**: Mid-sized sedan or motorcycle approached the rear of the stationary light vehicle in the *Left Lane* and merged into the *Same Lane* at a distance of *75 ft* (*22.86 m*). This scenario was conducted four times for each closing speed of *5 mi/h (8.05 km/h*) and *15 mi/h* (*24.14 km/h*).
- **Scenario E (*indirect threat*)**: Mid-sized sedan or motorcycle approached the rear of the stationary light vehicle in the *Right Lane* and merged into the *Same Lane* at a distance of *75 ft* (*22.86 m*). This scenario was conducted four times for each closing speed of *5 mi/h (8.05 km/h*) and *15 mi/h* (*24.14 km/h*).
- **Scenario F (*indirect threat*)**: Mid-sized sedan or motorcycle approached the rear of the stationary light vehicle in the *Left Lane* and merged into the *Same Lane* at a distance of *100 ft (30.48 m)*. This scenario was conducted four times at the *25 mi/h* (*40.23 km/h*) closing speed.
- **Scenario G (*indirect threat*)**: Mid-sized sedan or motorcycle approached the rear of the stationary light vehicle in the *Right Lane* and merged into the *Same Lane* at a distance of *100 ft (30.48 m)*. This scenario was conducted four times at the *25 mi/h* (*40.23 km/h*) closing speed.

Algorithm Condition 1: Low-traffic-density Results

There were 60 motorcycle approach scenarios and 60 mid-sized sedan approach scenarios performed. These scenarios included 72 *direct threats* and 48 *no threats.* Results indicated that 72 of the total 72 *direct threats* were correctly detected, and 48 of the total 48 *no threats* were correctly rejected (as shown in Table 4). Therefore, the estimated probability of the system correctly detecting a rear-end crash *direct threat* and activating the lights when a motorcycle or mid-sized sedan approached was 100 percent, P(hit) = 72/72 = 1.0. The estimated probability of the system correctly rejecting a non-rear-end crash threat and not activating the lights when a motorcycle or mid-sized sedan approached was 100 percent, P(cr) = 48/48 = 1.0.

Table 4. Detection results from algorithm Condition 1 testing in low-traffic density.

Light Activation	Threat	No Threat
Yes	72	0
No	0	48

Algorithm Condition 1: High-traffic Density Results

All *indirect threats* (motorcycle or mid-sized sedan approaching the stationary light vehicle in the same lane) at 5 mi/h (8.05 km/h) did not result in an ERS system activation, as the minimum activation threshold could not be met (approaching vehicles at 5 mi/h [8.05 km/h] stopped before an activation was warranted). Although this result was expected, the scenarios were still performed to exercise the system performance. Therefore, scenarios A, D, and E (as shown in Figure 25) at 5 mi/h (8.05 km/h) have been reclassified as *no threat* for the sake of results presentation below. Consequently, there were 60 motorcycle approach scenarios and 60 mid-sized sedan approach scenarios performed that included 48 *indirect threats* and 72 *no threats*. Results indicated that 45 of the total 48 *indirect threats* were correctly detected, and 71 of the total 72 *no threats* were correctly rejected (as shown in Table 5). Therefore, the estimated probability of the system correctly detecting a rear-end crash *indirect threat* when a motorcycle or mid-sized sedan approached was 93.75 percent, P(hit) = 45/48 = 0.94. The estimated probability of the system correctly rejecting a non-rear-end crash threat when a motorcycle or mid-sized sedan approached was 98.61 percent, P(cr) = 71/72 = 0.99.

Table 5. Detection results from algorithm Condition 1 testing in high-traffic density.

Light Activation	Threat	No Threat
Yes	45	1
No	3	71

5.3.2.2 Dynamic Testing

Method

Study Design: Rear-end crash scenarios for algorithm Conditions 2–5 (lead vehicle and following vehicles in motion) were executed on the Smart Road. All testing was performed using researchers and engineers. The same signal detection paradigm from static testing was used. The main DV was light activation (*Yes* or *No*). The main IVs were algorithm condition, light-vehicle type, vehicle speed, and light-vehicle approach scenario. Each scenario was performed four times. The different levels of each IV are as follows:

- Algorithm Condition.
  - *Condition 2*: The lead vehicle is moving at a constant forward speed.
  - *Condition 3*: The lead vehicle is slowly decelerating but does not come to a complete stop.
  - *Condition 4*: The lead vehicle decelerates to a stop and stands on the pavement.
  - *Condition 5*: The lead vehicle is slowly accelerating.
- Light-vehicle Type
  - *Mid-sized sedan—Approaching* (as shown in Figure 21).
  - *Motorcycle* (as shown in Figure 22).

  - *Mid-sized sedan—Following* (as shown in Figure 23).

- Vehicle Speed.
  - Approach Speeds.
    - *40 mi/h* (*64.37 km/h*) and *50 mi/h* (*80.47 km/h*).
  - Experimental CUT Speeds.
    - Maintaining, accelerating, and decelerating between *0 mi/h (0 km/h)* and *35 mi/h (56.33 km/h).*

- Light-vehicle Approach Scenario.
  - Same Lane.
  - Left Lane.
  - Right Lane.
  - Left-to-right merge at *75 ft* (*22.86 m*) from trailer (*125 ft* [*38.1 m*] from trailer during high-traffic-density scenarios).
  - Right-to-left merge at 75 ft (22.86 m) from trailer (*125 ft* [*38.1 m*] from trailer during high-traffic-density scenarios).

Apparatus: The ERS system was installed on the rear of the experimental CUT trailer (as shown in Figure 20). The mid-sized sedan used for approach scenarios is presented in Figure 21. The motorcycle used for approach scenarios is presented in Figure 22. A second mid-sized sedan (as shown in Figure 23) was used to follow directly behind the experimental CUT in the same lane at approximately 35 ft (10.67 m) from the rear bumper for the high-traffic-density condition testing.

Procedure: Two types of dynamic testing were performed, as follows:

- Low-traffic density (i.e., mid-sized sedan or motorcycle approaching the experimental CUT).

- High-traffic density (i.e., mid-sized sedan approaching a second mid-sized sedan that followed directly behind the experimental CUT).

During low-traffic-density testing, an approaching vehicle demonstrated a *direct threat* when approaching in the same lane. During high-traffic density, testing the approaching vehicle demonstrated an *indirect threat*. The latter scenario was classified as an *indirect threat*, as the following vehicle was the primary vehicle threatened by a rear-end collision, not the experimental CUT. However, as mentioned previously, the ERS system is still somewhat capable of detecting an approaching vehicle even with another vehicle blocking the direct line of sight of the system radar, so the research team decided to evaluate these scenarios. Figure 26 presents a diagram of rear-end crash scenarios used during the low-traffic-density testing, while Figure 27 presents a diagram of the rear-end crash scenarios used during the high-traffic-density testing.

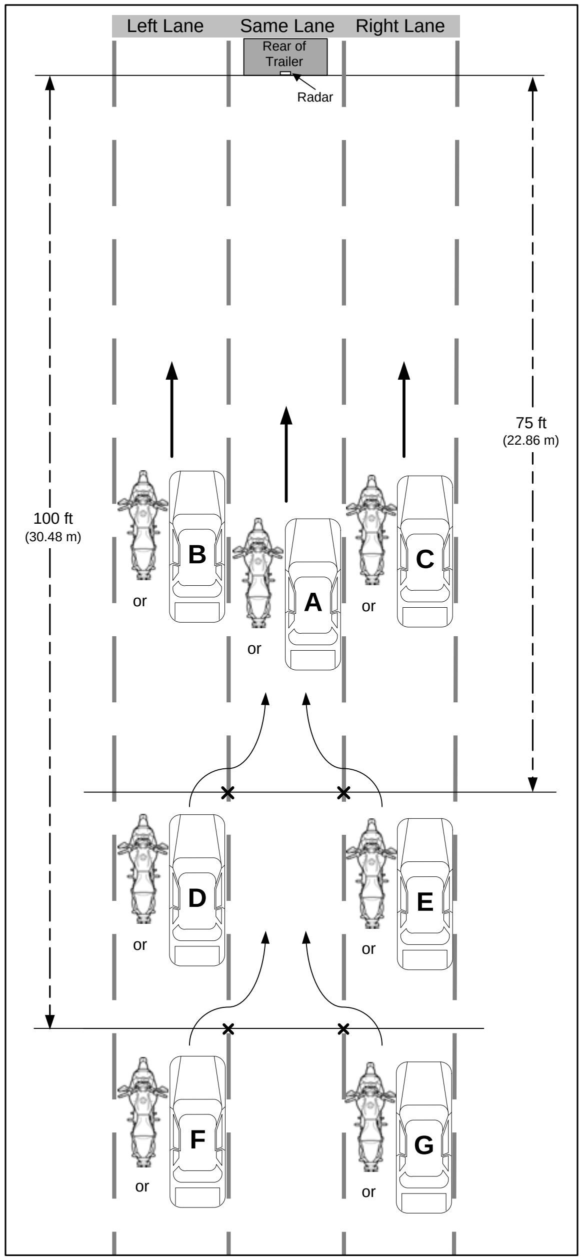

Figure 26. Diagram. Rear-end collision and adjacent-lane passing scenarios for low-traffic-density conditions during closed-loop activation subsystem testing (dynamic only).

- **Scenario A (*direct threat*)**: Motorcycle or mid-sized sedan approached the rear of the experimental CUT in the *Same Lane* four times.
  - *Condition 2:* Motorcycle or mid-sized sedan traveling at *40 mi/h (64.37 km/h)*; experimental CUT traveling at *25 mi/h (40.23 km/h)* closing rate.
  - *Condition 3:* Motorcycle or mid-sized sedan traveling at *40 mi/h (64.37 km/h)*; experimental CUT decelerating from *25 mi/h (40.23 km/h)* to *15 mi/h (24.14 km/h)*.
  - *Condition 4:* Motorcycle or mid-sized sedan traveling at *40 mi/h (64.37 km/h)*; experimental CUT heavily decelerating from *25 mi/h (40.23 km/h)* to *0 mi/h (0 km/h)*.

- *Condition 5:* Motorcycle or mid-sized sedan traveling at *40 mi/h (64.37 km/h)*; experimental CUT accelerating from *25 mi/h (40.23 km/h)* to *35 mi/h (56.33 km/h)*.

- **Scenario B (*no threat*)**: Motorcycle or mid-sized sedan approached the rear of the experimental CUT in the *Left Lane* four times.
  - Characteristics of Conditions 2–5 same as Scenario A.
- **Scenario C (*no threat*)**: Motorcycle or mid-sized sedan approached the rear of the experimental CUT in the *Right Lane* four times.
  - Characteristics of Conditions 2–5 same as Scenario A.
- **Scenario D (*direct threat*):** Motorcycle or mid-sized sedan approached the rear of the experimental CUT in the *Left Lane* and merged into the *Same Lane* at a distance of *75 ft (22.86 m)*. This scenario was performed four times.
  - Characteristics of Conditions 2–5 same as Scenario A.
- **Scenario E (*direct threat*)**: Motorcycle or mid-sized sedan approached the rear of the experimental CUT in the *Right Lane* and merged into the *Same Lane* at a distance of *75 ft (22.86 m)*. This scenario was performed four times.
  - Characteristics of Conditions 2–5 same as Scenario A.

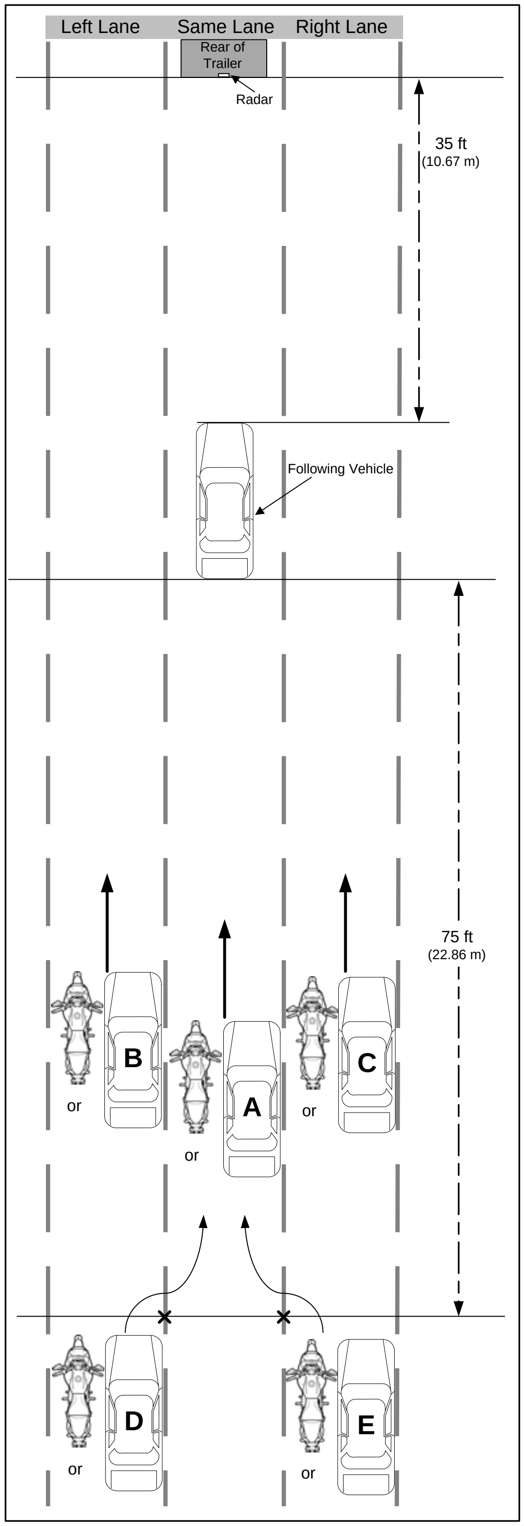

Figure 27. Diagram. Rear-end collision and adjacent-lane passing scenarios for high-traffic-density conditions during closed-loop activation subsystem testing (dynamic only).

- **Scenario A (*indirect threat*)**: Motorcycle or mid-sized sedan approached the rear of the following light vehicle in the *Same Lane* four times.

- *Condition 2:* Light vehicle traveling at *50 mi/h (80.47 km/h)*; experimental CUT and following vehicle traveling at *25 mi/h (40.23 km/h)* closing rate.
- *Condition 3:* Light vehicle traveling at *50 mi/h (80.47 km/h)*; experimental CUT and following vehicle decelerating from *25 mi/h (40.23 km/h)* to *15 mi/h (24.14 km/h)*.
- *Condition 4:* Not performed due to safety concerns.
- *Condition 5:* Light vehicle traveling at *50 mi/h (80.47 km/h)*; experimental CUT and following vehicle accelerating from *25 mi/h (40.23 km/h)* to *35 mi/h (56.33 km/h)*.

- **Scenario B (*no threat*)**: Motorcycle or mid-sized sedan approached the rear of the following light vehicle in the *Left Lane* four times.
  - Characteristics of Conditions 2–5 same as Scenario A.
- **Scenario C (*no threat*)**: Motorcycle or mid-sized sedan approached the rear of the following light vehicle in the *Right Lane* four times.
  - Characteristics of Conditions 2–5 same as Scenario A.
- **Scenario D (*indirect threat*):** Motorcycle or mid-sized sedan approached the rear of the following light vehicle in the *Left Lane* and merged into the *Same Lane* at a distance of *75 ft (22.86 m)*. This scenario was performed four times.
  - Characteristics of Conditions 2–5 same as Scenario A.
- **Scenario E (*indirect threat*)**: Motorcycle or mid-sized sedan approached the rear of the following light vehicle in the *Right Lane* and merged into the *Same Lane* at a distance of *75 ft (22.86 m)*. This scenario was performed four times.
  - Characteristics of Conditions 2–5 same as Scenario A.

Low-traffic Density Results for Algorithm Conditions 2–5

There were 160 motorcycle and mid-sized sedan approach scenarios performed that included 96 *direct threats* and 64 *no threats*. Results indicated that 96 of the total 96 *direct threats* were correctly detected, and 64 of the total 64 *no threats* were correctly rejected (as shown in Table 6). Six false alarms did occur between approach scenarios; these have been added to the table below. Therefore, the estimated probability of the system correctly detecting a rear-end crash *direct threat* when a motorcycle or mid-sized sedan approached was 100 percent, P(hit) = 96/96 = 1.0. The estimated probability of the system correctly rejecting a non-rear-end crash threat was 91.43 percent, P(cr) = 64/70 = 0.91.

Table 6. Detection results from algorithm Conditions 2–5 testing in low-traffic density.

Light Activation	Threat	No Threat
Yes	96	6
No	0	64

High-traffic Density Results for Algorithm Conditions 2–5

In contrast to static testing results, only 1 of 36 *indirect threats* (i.e., vehicle approaching another vehicle that is following directly behind the experimental CUT in the same lane) resulted in ERS system activation. The research team was confident that all same-lane approach scenarios (*indirect threat* scenarios) met the minimum activation threshold. However, it appears that while the CUT is in motion the radar does not ideally detect the approach of *indirect threat* vehicles (second following vehicles). There were 60 approach scenarios performed that included 36 *indirect threats* and 24 *no threats.* Results indicated that 1 of the total 36 *indirect threats* was correctly detected, and 24 of the total 24 *no threats* were correctly rejected (as shown in Table 7). Two false alarms were observed between approach scenarios; these have been added to the table below. Therefore, the estimated probability of the system correctly detecting a rear-end crash *indirect threat* is 2.78 percent, P(hit) = 1/36 = 0.03. The estimated probability of the system correctly rejecting a non-rear-end crash threat is 92.31 percent, P(cr) = 24/26 = 0.92.

Table 7. Detection results from algorithm testing (Conditions 2–5) in high-traffic density.

Light Activation	Threat	No Threat
Yes	1	2
No	35	24

5.3.3 Discussion: Smart Road Formal Testing

The performance of the open-loop activation subsystem was positive. The ERS system refinement included transitioning the activation system logic from the DAS to a standalone ERS interface. This design and development effort appears to have been successful as indicated by the excellent performance of the open-loop activation system.

The closed-loop activation subsystem correctly detected rear-end crash *direct threats* in both static and dynamic conditions, P(hit) = 168/168 = 1.0, and performed well at rejecting non-rear-end crash threats, P(cr) = 112/118 = 0.95. The closed-loop activation subsystem also performed well at detecting *indirect threats* during static conditions. However, subsystem detection of *indirect threats* decreased when the CUT was in motion. The ERS system also performed well at non-detections (i.e., low false alarm rates across all approach scenarios). The false alarms that did occur were triggered when there were no vehicles surrounding the CUT.

5.4 FORMAL TESTING: REAL-WORLD

The final evaluation of the ERS system was conducted on public roadways. The primary area of investigation was the performance of the activation subsystems (both closed-loop and open-loop) in a real-world environment.

5.4.1 Method

5.4.1.1 Study Design

This study occurred on public roadways in southwest Virginia. Data were collected during a 5-hour period across approximately 150 mi (241.40 km). Performances of the activation subsystems were determined through a combination of video and sensor data collected using the research team's DAS installed in the rear of the trailer. Because this was an observational study, no drivers were recruited to participate. Rather, the experimental CUT joined other vehicles in the available traffic stream. Approval for this observational study was granted by the research team's Institutional Review Board (IRB) Human Assurances Committee. Data were collected from 12 p.m. to 5 p.m. Eastern Standard Time (EST).

A signal detection theory experimental design was used to evaluate activation subsystem performance. A similar methodology was used during Phase III testing. As was performed during Phase III, the research team drove the experimental CUT on three categories of roadway. The first roadway type tested was an *Interstate Highway* (i.e., Interstate 81). The second roadway type tested was a *State Highway* (i.e., Virginia Highway 460). The third roadway type tested included all other lower-speed roadways (i.e., single- and multi-lane rural and town roads with traffic lights). This third roadway type was categorized as *Other*. Further details about each of the three roadway types on which the activation subsystems were tested are below:

- *Interstate Highway*: Interstate 81 (multi-lane roadway, speed limit *65 mi/h* [*104.61 km/h*]).
- *State Highway*: Virginia Highway 460 (single- and multi-lane roadways, speed limit *45–55 mi/h* [*72.42–88.51 km/h*]).
- *Other*: Lower-speed single-lane and multi-lane roadways with traffic lights (*25–45 mi/h* [*40.23–72.42 km/h*]).

The main objective of this testing was to determine the activation subsystem performance on each roadway type under normal public driving conditions. Four occurrences of detection were categorized, as follows:

- Correct detections.
- Missed detections.
- False alarms.
- Correct non-detections.

The main DV was light activation (*Yes* or *No*). The main IV was following-vehicle lane position (*Same*, *Right*, *Left*).

5.4.1.2 Apparatus

The ERS system was positioned on the rear of the experimental CUT (as shown in Figure 20) during real-world testing. A small camera was placed on the bumper aimed directly rearward back to record video of following-vehicle activity. This video was recorded using the research team's DAS (as shown in Figure 28). This DAS can capture three general groups of measures, as follows:

- DAS measures.
- Vehicle network measures.
- Add-on measures.

For the purposes of this study, the DAS did not measure the vehicle network (i.e., speed data obtained from the trailer). The add-on measures included during this real-world evaluation involved ERS system activation data and lead-vehicle speed obtained via the wheel speed sensor installed on the trailer. During the evaluation, the DAS collected all data to assist in determining the operational performance of the ERS system. Data collection by the DAS began as soon as the trailer received power from the tractor, and data were saved continuously throughout the data collection period. The DAS was unobtrusively installed inside the trailer.

Figure 28. Image. The research team's DAS.

5.4.1.3 Procedure

The experimental CUT joined other vehicles in the available traffic stream on multiple roadway types. Two experimenters were located in the experimental CUT: one drove the experimental CUT and the second selected the routes and maintained the data collection equipment. The open-loop and closed-loop activation subsystems were fully functional with no experimenter input provided. A data reduction effort was performed for each following-vehicle scenario. The primary goal of the data reduction effort was to appropriately assign each event that occurred into one of the signal detection theory categories.

5.4.2 Results: Real-world Testing

The activation subsystems were tested on three different roadway types (*Interstate Highway, State Highway, Other*). Results are presented below by roadway type.

5.4.2.1 Interstate Highway

Overall, there were 96 events captured during the *Interstate Highway* portion of data collection. Results in this section will be presented in three tables, each representing one of the following-vehicle lane positions (*Same*, *Right*, *Left*). An event for following vehicles positioned in the *Same Lane* directly behind the experimental CUT was defined as a following vehicle approaching (reducing following distance) the rear of the experimental CUT or maintaining a set following distance (following). An event for following vehicles positioned in one of the two adjacent lanes was defined as a following vehicle attempting to overtake the experimental CUT (passing) or maintaining a set following distance (hovering). Each event consisted of at least the primary vehicle traveling within 200 ft (60.96 m) of the rear of the experimental CUT.

For the *Same Lane* following-vehicle condition, 14 events were captured (10 rear-end crash threats and 4 non-threats). Results indicated that all threats were correctly detected, and 4 non-threats were correctly rejected (as shown in Table 8). Therefore, the estimated probability of the system correctly detecting a rear-end crash threat and activating the warning lights on an *Interstate* was 100 percent, P(hit) = 10/10 = 1.0. The estimated probability of the system correctly rejecting a non-rear-end crash threat in the *Same Lane* and not activating the lights on an *Interstate* was 100 percent, P(cr) = 4/4 = 1.0.

Table 8. Detection results from *Interstate Highway—Same Lane* testing.

Light Activation	Threat	No Threat
Yes	10	0
No	0	4

For the *Right Lane* following-vehicle condition, two events were captured (zero rear-end crash threats and two non-threats). Results indicated that both non-threats were correctly rejected, and no false alarms occurred (as shown in Table 9). Therefore, the estimated probability of the system correctly rejecting a non-rear-end crash threat in the *Right Lane* on the *Interstate* and not activating the lights was 100 percent, P(cr) = 2/2 = 1.0.

Table 9. Detection results from *Interstate Highway—Right Lane* testing.

Light Activation	Threat	No Threat
Yes	0	0
No	0	2

For the *Left Lane* following-vehicle condition, 80 events were captured (0 rear-end crash threats and 80 non-threats). Results indicated that 69 non-threats were correctly rejected, and 11 false alarms occurred (as shown in Table 10). Therefore, the estimated probability of the system correctly rejecting a non-rear-end crash threat in the *Left Lane* on the *Interstate* and not activating the lights was 86.25 percent, P(cr) = 69/80 = 0.86.

Table 10. Detection results from *Interstate Highway—Left Lane* testing.

Light Activation	Threat	No Threat
Yes	0	11
No	0	69

5.4.2.2 State Highway

Overall, there were 73 events captured during the *State Highway* portion of data collection. Results in this section will be presented in three tables, each representing one of the following-vehicle lane positions (*Same*, *Right, Left*). Events for following vehicles were defined identically in the *Interstate Highway* portion of this data collection effort. Each event consisted of at least the primary vehicle traveling within 200 ft (60.96 m) of the rear of the experimental CUT.

For the *Same Lane* following-vehicle condition, 27 events were captured (13 rear-end crash threats and 14 non-threats). Results indicated that all threats were correctly detected, nine non-threats were correctly rejected, and five false alarms occurred (as shown in Table 11). Therefore, the estimated probability of the system correctly detecting a rear-end crash threat in the *Same Lane* on a *State Highway* and activating the lights was 100 percent, P(hit) = 13/13 = 1.0. The estimated probability of the system correctly rejecting a non-rear-end crash threat in the *Same Lane* on a *State Highway* and not activating the lights was 64.29 percent, P(cr) = 9/14 = 0.64.

Table 11. Detection results from *State Highway—Same Lane* testing.

Light Activation	Threat	No Threat
Yes	13	5
No	0	9

For the *Right Lane* following-vehicle condition, 27 events were captured (0 rear-end crash threats and 27 non-threats). Results indicated that 26 non-threats were correctly rejected, and 1 false alarm occurred (as shown in Table 12). Therefore, the estimated probability of the system correctly rejecting a non-rear-end crash threat in the *Right Lane* on a *State Highway* and not activating the lights was 96.30 percent, P(cr) = 26/27 = 0.96.

Table 12. Detection results from *State Highway—Right Lane* testing.

Light Activation	Threat	No Threat
Yes	0	1
No	0	26

For the *Left Lane* following-vehicle condition, 19 events were captured (0 rear-end crash threats and 19 non-threats). Results indicated that 15 non-threats were correctly rejected, and 4 false alarms occurred (as shown in Table 13). Therefore, the estimated probability of the system correctly rejecting a non-rear-end crash threat in the *Left Lane* on a *State Highway* and not activating the lights was 78.95 percent, P(cr) = 15/19 = 0.79.

Table 13. Detection results from
***State Highway—Left Lane* testing.**

Light Activation	Threat	No Threat
Yes	0	4
No	0	15

5.4.2.3 Other

Overall, there were 74 events captured during the *Other* roadway type portion of data collection. Results in this section are presented in three tables, each representing one of the following-vehicle lane positions (e.g., *Same*, *Right*, *Left*). Events for following vehicles were defined identically in the two previous sections (*Interstate Highway* and *State Highway*). Each event consisted of at least the primary vehicle traveling within 200 ft (60.96 m) of the rear of the experimental CUT.

For the *Same Lane* following-vehicle condition, 26 events were captured (21 rear-end crash threats and 5 non-threats). Results indicated that all threats were correctly detected, and five non-threats were correctly rejected (as shown in Table 14). Therefore, the estimated probability of the system correctly detecting a rear-end crash threat in the *Same Lane* on an *Other* roadway type and activating the lights was 100 percent, P(hit) = 21/21 = 1.0. The estimated probability of the system correctly rejecting a non-rear-end crash threat in the *Same Lane* on an *Other* roadway type and not activating the lights was 100 percent, P(cr) = 5/5 = 1.0.

Table 14. Detection results from
***Other Same—Lane* testing.**

Light Activation	Threat	No Threat
Yes	21	0
No	0	5

For the *Right Lane* following-vehicle condition, 23 events were captured (0 rear-end crash threats and 23 non-threats). Results indicated that 20 non-threats were correctly rejected, and 3 false alarms occurred (as shown in Table 15). Therefore, the estimated probability of the system correctly rejecting a non-rear-end crash threat in the *Right Lane* on an *Other* roadway type and not activating the lights was 86.96 percent, P(cr) = 20/23 = 0.87.

Table 15. Detection results from
***Other—Right Lane* testing.**

Light Activation	Threat	No Threat
Yes	0	3
No	0	20

For the *Left Lane* following-vehicle condition, 25 events were captured (0 rear-end crash threats and 25 non-threats). Results indicated that 20 non-threats were correctly rejected, and 5 false alarms occurred (as shown in Table 16). Therefore, the estimated probability of the system correctly rejecting a non-rear-end crash threat in the *Left Lane* on an *Other* roadway type and not activating the lights was 80 percent, P(cr) = 20/25 = 0.8.

Table 16. Detection results from *Other—Left Lane* testing.

Light Activation	Threat	No Threat
Yes	0	5
No	0	20

5.4.3 Discussion: Real-world Formal Testing

No open-loop activations occurred during real-world testing (i.e., no events occurred requiring a heavy deceleration by the experimental CUT). Results indicated that the closed-loop activation subsystem performed well at rear-end crash detection and rear warning-light activation. On all three roadway types, the closed-loop activation subsystem performed with a 100 percent correct detection rate (zero missed detections), thus indicating excellent performance in rear-end collision-threat scenarios. False alarm rates in non-rear-end collision-threat scenarios were fairly equal across roadway types, ranging from 12.79 percent to 16.67 percent. These false alarm rates led researchers to investigate the video and radar data collected for each scenario. Upon further investigation, it was found that a majority of the false alarms triggered on the *Interstate* occurred when other CMVs were passing the experimental CUT (i.e., a scenario not tested for during formal Smart Road tests). No other unusual patterns emerged during data investigation. Table 17 contains a summary of the probabilities found for correct detections and correct rejections collapsed across lane position for each roadway type investigated.

Table 17. Probabilities found for correct detections and correct rejections collapsed across lane position.

Roadway Type	Estimated Probability of Correct Detection (P[hit])	Estimated Probability of Correct Rejection (P[cr])
Interstate Highway	10/10 = 100%	75/86 = 87.21%
State Highway	13/13 = 100%	50/60 = 83.33%
Other	21/21 = 100%	45/53 = 84.91%

5.5 CLOSED-LOOP ACTIVATION SUBSYSTEM REFINEMENT DISCUSSION

During real-world testing, the ERS activation subsystems were evaluated while joining the normal traffic stream on different roadway types (i.e., *Interstate Highway*, *State Highway*, and *Other*). Only closed-loop activation subsystem events occurred. Therefore, real-world findings do not support any open-loop activation subsystem conclusions.

Results found that the closed-loop activation subsystem correctly detected all rear-end crash threats (100 percent detection rate) during all events and across all roadway types. This indicated that the most safety-critical component of the closed-loop activation subsystem (i.e., the capability of the system to correctly detect and signal all rear-end crash threats) performed as designed. During events in which there were no rear-end crash threats present, the closed-loop activation subsystem performed similarly on all roadway types (83.33, 84.91, and 87.21 percent correct rejection rates for *State Highway, Other,* and *Interstate Highway*, respectively). Overall, the ERS system was robust in real-world driving situations. Results indicated that the system in its current state performed well at detecting and signaling rear-end crash threats. Of the false alarms that occurred, none resulted in any observed unintended consequences in following-vehicle driver behavior.

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6. NIGHTTIME WARNING-LIGHT BRIGHTNESS TESTING

During Phase III, the ERS system was not tested during nighttime conditions. Therefore, prior to an FOT, an investigation was conducted to determine whether adjustments of the brightness levels of the rear warning lights were necessary to reduce associated discomfort glare while maintaining eye-drawing capabilities. Two studies were performed to evaluate the ERS system during nighttime conditions. The first study used following-vehicle drivers to provide ratings on discomfort glare and “attention-getting” effectiveness for multiple brightness levels. The second study used the brightness level candidate deemed best by the ratings study and included the collection of real-world data on public roadways in southwest Virginia.

6.1 BRIGHTNESS LEVEL RATINGS STUDY

6.1.1 Method

6.1.1.1 Study Design

Nighttime rear warning-light brightness testing was performed on the Virginia Smart Road. The purpose of this testing was to determine if the current brightness of the daytime ERS system resulted in similar (or improved) eye-drawing capability when tested in low-light conditions (nighttime), and to determine the level of perceived discomfort glare. This testing was performed using 12 volunteers who filled out rating scales designed to measure the performance of 5 rear-lighting countermeasures (1 baseline [normal brake lights], 4 warning-light brightness levels). During pilot testing, it was determined by subject-matter experts (SMEs) that the brightness level of the daytime ERS system was too intense for nighttime conditions. Although the attention-getting properties were high, the associated discomfort-glare properties were unbearable (brightness measured at night in a dark lab [*M* = 17.92 lux, *SD* = 5.48 lux, Min = 7.28 lux, Max = 29.04 lux]). Four brightness levels were selected to be included in the experiment, ranging from low to high (as perceived by SMEs). The main DVs were attention-getting and discomfort glare. The main IVs were gaze direction, lane, following-vehicle distance from the experimental CUT, and countermeasure type. The different levels of the IVs are as follows:

- Gaze direction.
  - Directly ahead.
  - 30 degrees off-center to right.
- Lane.
  - Same lane.
  - Right adjacent lane.
- Following-vehicle distance.
  - *100 ft* (*30.48 m*).
  - *40 ft* (*12.19 m*).
- Countermeasure.

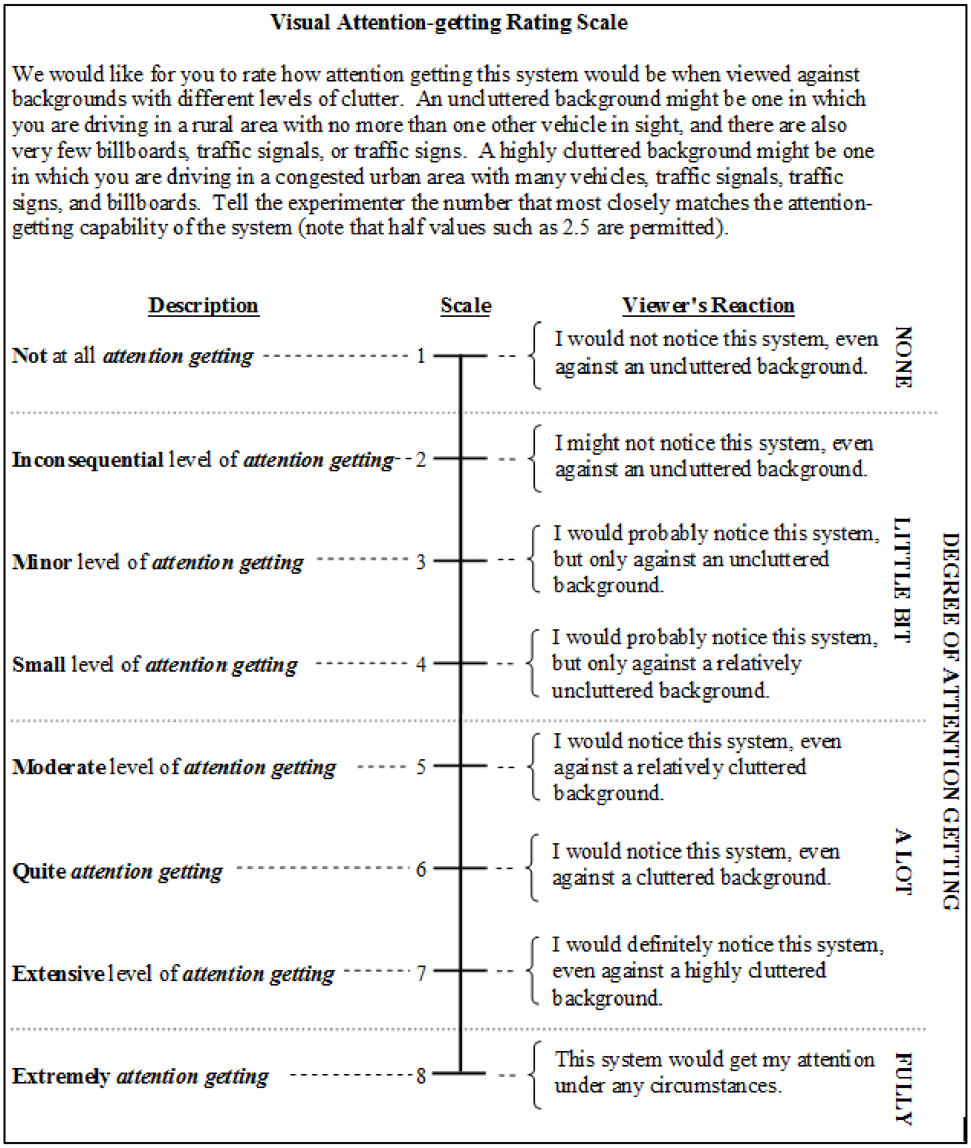
- *Normal brake lights* (*M* = 1.88 lux, *SD* = 0.16 lux, Min = 1.44 lux, Max = 2.37 lux).
- *Warning-light brightness level A* (*M* = 0.83 lux, *SD* = 0.18 lux, Min = 0.48 lux, Max = 1.3 lux).
- *Warning-light brightness level B* (*M* = 1.49 lux, *SD* = 0.38 lux, Min = 0.55 lux, Max = 2.48 lux).
- *Warning-light brightness level C* (*M* = 2.36 lux, *SD* = 0.45 lux, Min = 1.12 lux, Max = 3.05 lux).
- *Warning-light brightness level D* (*M* = 6.96 lux, *SD* = 1.29 lux, Min = 3.57 lux, Max = 9.35 lux).

6.1.1.2 Apparatus

Five rear-lighting conditions were used during testing (four rear warning-light brightness conditions, one normal brake-light condition). All testing was performed using an experimental CUT with the ERS system mounted on the trailer. Rear warning-light activation was controlled by an experimenter positioned near the trailer of the experimental CUT (nearby, but out of sight). A laptop was connected to the experimental CUT DAS and was used to select pre-determined brightness levels and to activate the rear warning lights. Upon activation of each rear warning-light configuration, lights flashed simultaneously at a 5 Hz frequency for a period of 5 seconds. For the normal brake-light condition, the experimenter walked to the front of the experimental CUT, entered the cab, and manually pressed the brake pedal for 5 seconds.

6.1.1.3 Procedure

Participants sat in the driver seat of a mid-sized sedan (with headlights activated) while the lead experimenter sat in the passenger seat. Each participant filled out rating scales at multiple, stationary light-vehicle positions behind the experimental CUT. These sessions were performed during clear, nighttime conditions. As mentioned, the two rating scales that participants used were attention-getting (an 8-point ordinal scale; as shown in Figure 29) and discomfort glare (a modified DeBoer 9-point scale; as shown in Figure 30). Participants provided their ratings verbally, and the in-vehicle experimenter wrote them down. Participants rated each brightness level twice using the attention-getting scale while positioned in the same lane 100 ft (30.48 m) behind the trailer (once looking directly ahead at the lighting and once looking 30 degrees off-axis to the right). Participants rated the level of discomfort glare of each brightness level once while positioned 100 ft (30.48 m) behind the trailer in the same lane, once while positioned 40 ft (12.19 m) behind the trailer in the same lane, and once while positioned 40 ft (12.19 m) behind the trailer in the adjacent lane to the right. The discomfort-glare ratings were provided while participants were positioned in the same lane and looking directly ahead at the lighting of the experimental CUT. Discomfort-glare ratings while positioned in the adjacent lane were provided while looking directly ahead in the lane (i.e., not focusing directly on the lighting of the experimental CUT). The vehicle positions for the rating scale portion of this experiment are depicted in Figure 31.



Visual Attention-getting Rating Scale

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

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

Figure 29. Screenshot. Attention-getting rating scale.

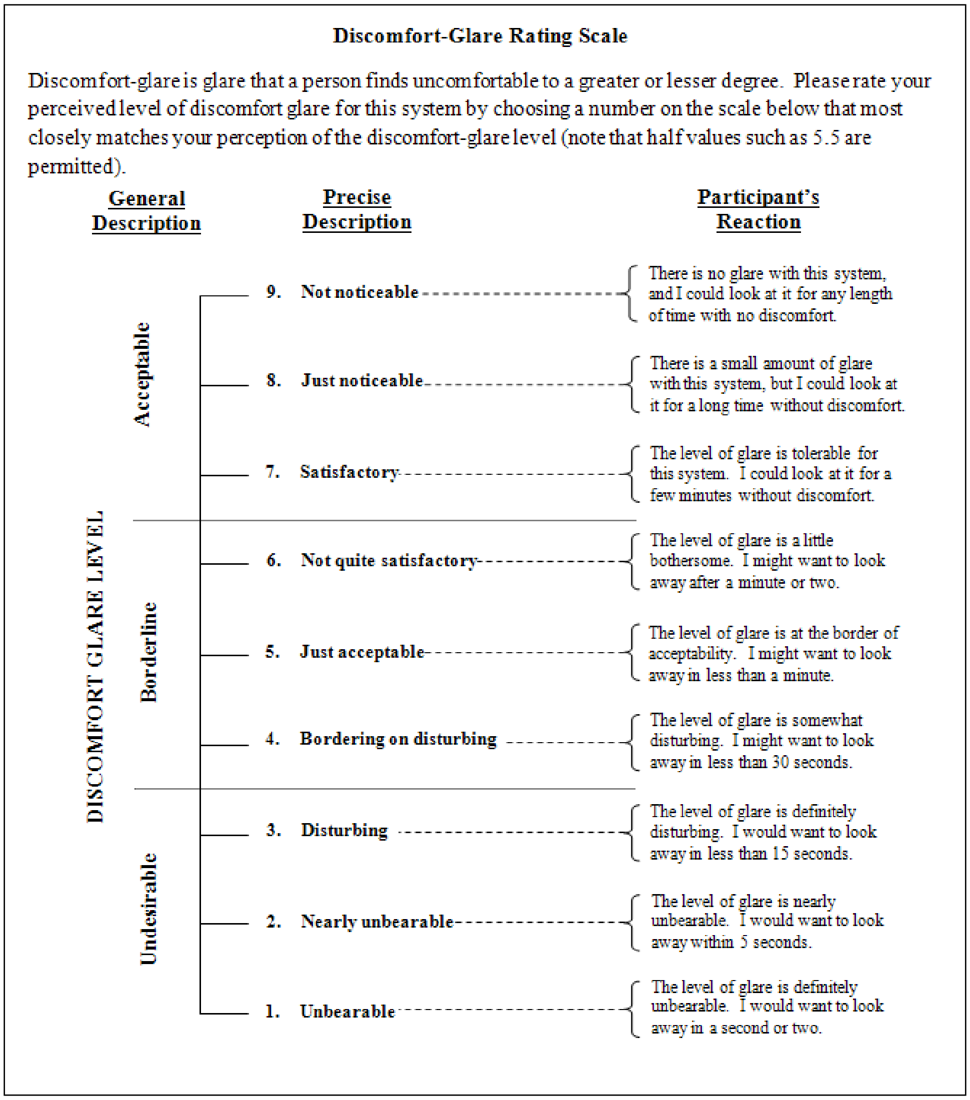


Figure 30. Screenshot. Discomfort-glare rating scale.

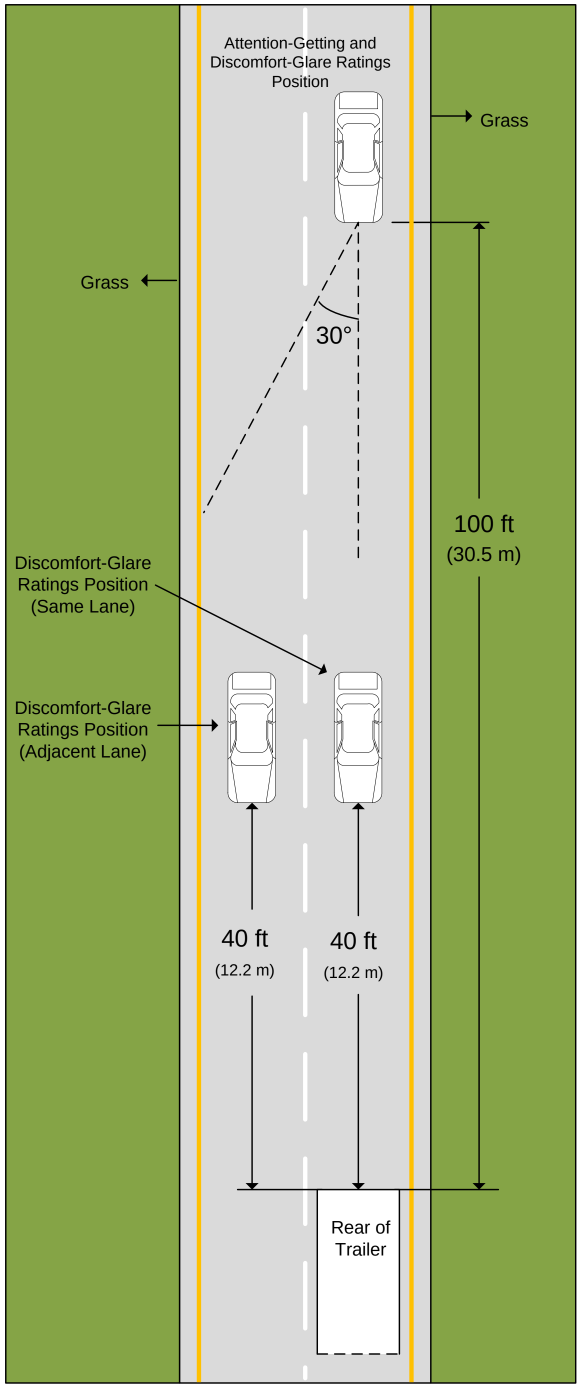


Figure 31. Diagram. Light-vehicle positions for the brightness level ratings session.

6.1.2 Ratings Results

Participants provided an attention-getting rating for each rear-lighting condition while fixating directly ahead at the lighting and another while fixating 30 degrees off-axis. Participants provided a discomfort-glare rating for each rear-lighting condition while in the same lane and fixating directly ahead at the lighting (from distances of both 100 ft [30.5 m] and 40 ft [12.2 m]). In addition, participants provided a discomfort-glare rating for each rear-lighting configuration while stationary in an adjacent lane and fixating ahead in the lane (i.e., looking past the lighting display).

For the attention-getting ratings taken while participants fixated directly at the lighting, a one-way, within-subject analysis of variance (ANOVA) was performed and was found to be significant ($F[5,50] = 13.83$, $p < 0.0001$). A Tukey's Studentized Range Honestly Significant Difference (HSD) post hoc test was performed, and results are shown in Figure 32. The attention-getting ratings were based on a scale of 1–8 (1 being not at all attention-getting and 8 being extremely attention-getting). The figure shows that the highest-rated countermeasures while fixating directly at the lighting were *Warning Light Brightness Levels D* and *C*.

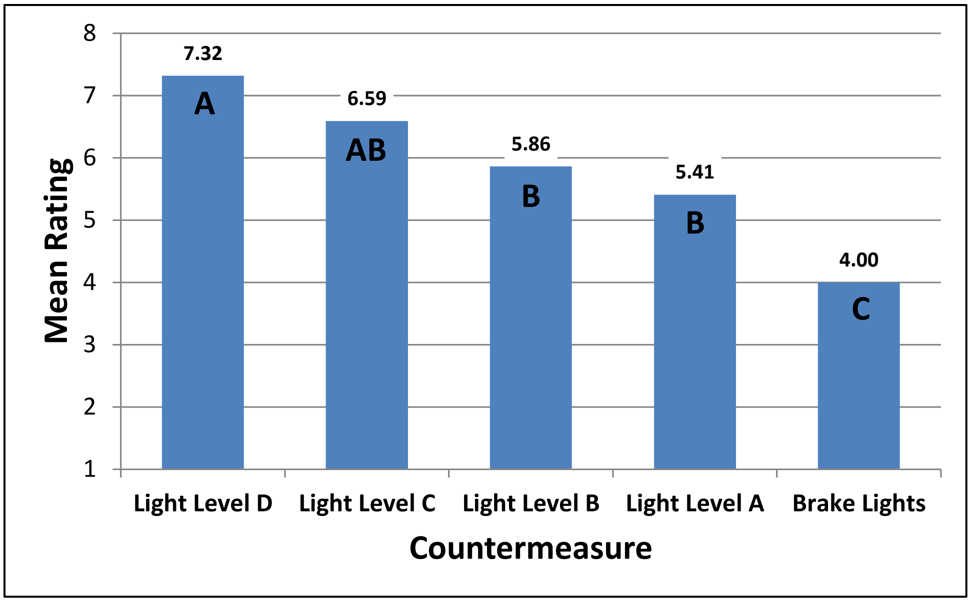


Figure 32. Bar graph. Mean attention-getting ratings of participants fixating on lighting as a function of countermeasure.

For the attention-getting ratings taken while participants fixated 30 degrees off-axis, a one-way, within-subject ANOVA was performed and was found to be significant ($F[5,50] = 15.51$, $p < 0.0001$). A Tukey's Studentized Range HSD post hoc test was performed, and results are shown in Figure 33. The figure shows that the highest rated countermeasures while fixating off-axis were *Warning Light Brightness Levels D* and *C*.

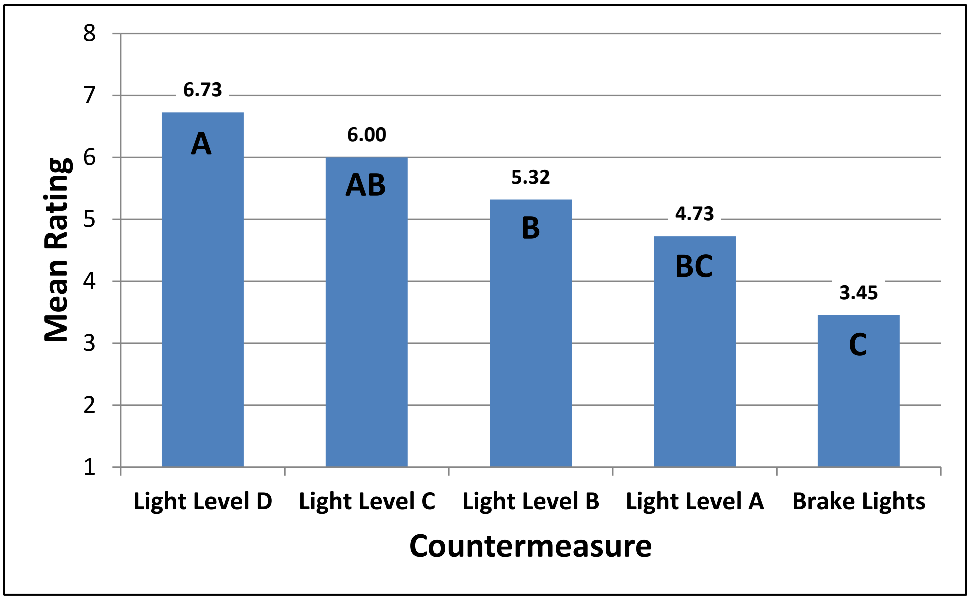


Figure 33. Bar graph. Mean attention-getting ratings of participants fixating 30 degrees off-axis as a function of countermeasure.

For the discomfort-glare ratings taken while participants fixated directly at the lighting from a distance of 100 ft (30.48 m), a one-way, within-subject ANOVA was performed and was found to be significant ($F[5,50] = 22.39$, $p < 0.0001$). A Tukey's Studentized Range HSD post hoc test was performed, and results are shown in Figure 34. The discomfort-glare ratings were based on a scale of 1 to 9 (1 being unbearable and 9 being not noticeable). The two countermeasures that resulted in the greater amount of discomfort glare were *Warning Light Brightness Levels D* and *C.* The mean rating for these higher-rated countermeasures fell in the middle range for glare.

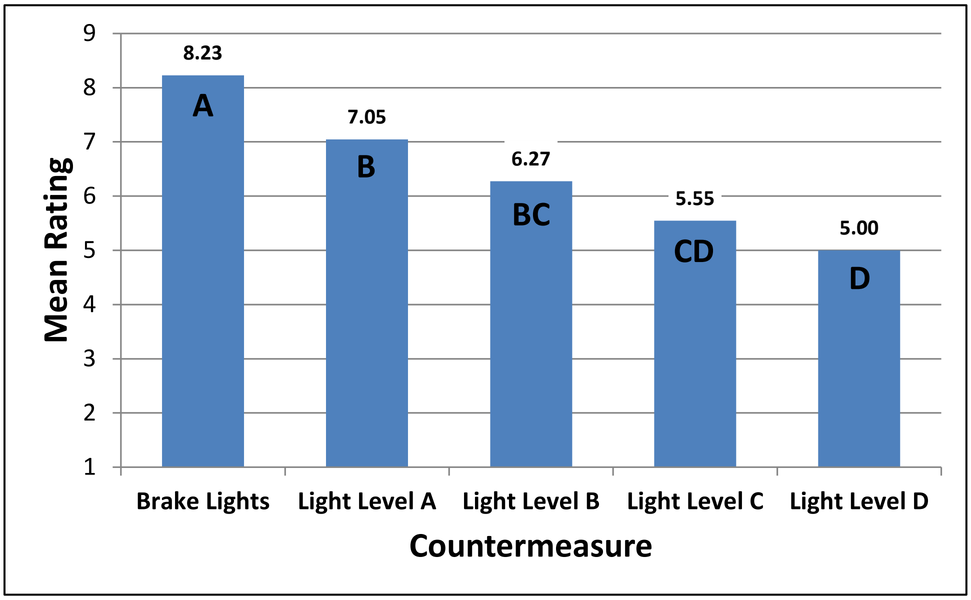


Figure 34. Bar graph. Mean discomfort-glare ratings of participants fixating on lighting at a distance of *100 ft* (*30.48* m) as a function of countermeasure.

For the discomfort-glare ratings taken while participants fixated directly at the lighting from a distance of 40 ft (12.2 m), a one-way, within-subject ANOVA was performed and was found to be significant ($F[5,50] = 18.92$, $p < 0.0001$). A Tukey's Studentized Range HSD post hoc test was performed, and results are shown in Figure 35. The countermeasure that resulted in the greatest amount of discomfort glare was *Warning Light Brightness Level D.* It is important to note that the mean ratings for these rear warning-light conditions fell in the middle range for glare.

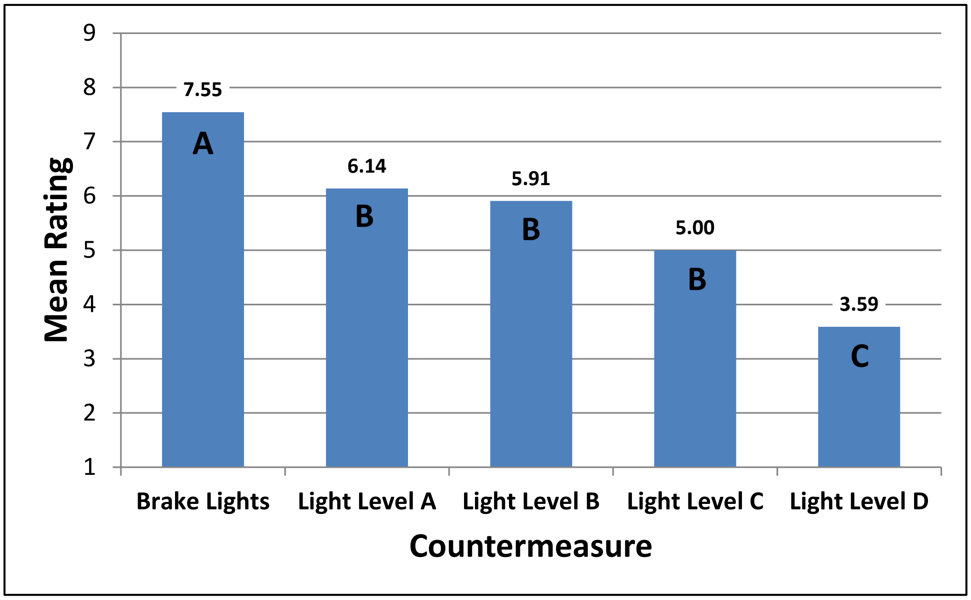


Figure 35. Bar graph. Mean discomfort-glare ratings of participants fixating on lighting at a distance of *40 ft* (*12.2 m*) as a function of countermeasure.

For the discomfort-glare ratings taken while participants were stationary in an adjacent lane and fixating ahead in the lane (i.e., looking past the lighting display), a one-way, within-subject ANOVA was performed and was found to be significant ($F[5,50] = 9.45$, $p < 0.0001$). A Tukey's Studentized Range HSD post hoc test was performed, and results are shown in Figure 36. The countermeasures that resulted in greater amounts of discomfort glare were *Warning Light Brightness Levels D*, *Brake Lights*, and *C.* It is important to note that the mean ratings for all countermeasures fell within the low range for glare (thus indicating above-satisfactory levels of glare).

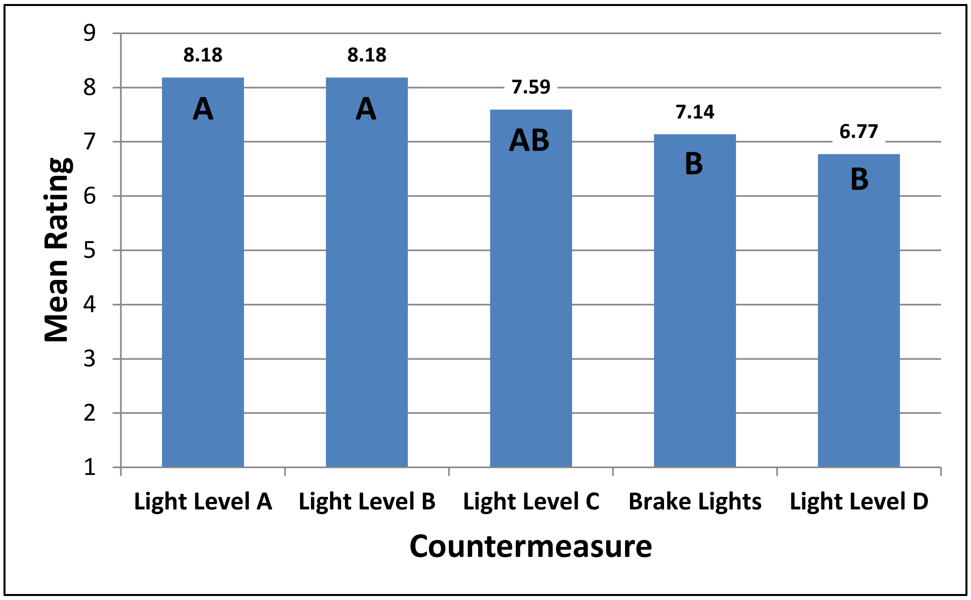


Figure 36. Bar graph. Mean discomfort-glare ratings of participants positioned in adjacent lane fixating forward in the lane (i.e., not looking directly at lighting) as a function of countermeasure.

6.1.3 Ratings Study Discussion

Based on the results above and in comparison to the Phase III daytime ratings results, it was determined that *Warning Brightness Level B* should be selected as the nighttime brightness level for the ERS system.

6.2 NIGHTTIME REAL-WORLD DATA COLLECTION

The nighttime brightness level selected from the ratings study was observed on public roadways. The purpose of this evaluation was to identify any following-vehicle unintended consequences resulting from ERS nighttime activations. ERS activations were not manually performed by experimenters. Following-vehicle behavior was observed when the ERS system activated under normal operating conditions. Unintended consequences were determined through a combination of video and sensor data collected using the DAS. The main DV was the presence or absence of an unintended consequence (*Yes* or *No*). The main IV was following-vehicle lane position during activations (*Same*, *Right*, *Left*).

Data were collected at night across approximately 75 mi (120.70 km). A total of 27 ERS activations occurred; no following-vehicle unintended consequences were observed (e.g., no following-vehicle heavy decelerations or accelerations, no swerves, etc.). Measuring the eye-drawing performance of each ERS activation for the following-vehicle driver was not feasible due to the low-light conditions and the glare from following-vehicle headlights.

6.3 NIGHTTIME TESTING DISCUSSION

The research team was successful at investigating alternative nighttime brightness levels for the ERS system. A ratings study was performed to identify the brightness level encompassing the ideal balance between attention-getting and discomfort-glare characteristics. This level was selected for real-world evaluation on public roadways in southwest Virginia. During real-world testing, no following-vehicle unintended consequences were found.

7. CONCLUSIONS

The primary visual warnings currently installed on the rear of all CMVs are the stop lamps, or brake lights. A significant limitation of CMV brake lights is the limited effectiveness across varying operational conditions. Because these brake lights are activated only with the service brakes, the visual warning is only provided during conditions where the lead vehicle is decelerating using its braking system. The brake lights may not be activated during other important conditions that are unique to CMVs wherein rear-end collisions can occur (i.e., CMV is stopped, traveling slower, or decelerating using an engine retarder). Due to visual distraction combined with the limitations of the current visual warning system (brake lights) on CMVs, there is a need to provide supplemental warnings for following-vehicle drivers under the aforementioned conditions so drivers can quickly recognize impending collision threats. The purpose of the ERS system for CMVs is to detect rear-end crash threats and to provide following drivers with a supplemental visual warning (located on the lead vehicle *in addition* to the current brake lights). This project successfully refined a prototype ERS system in preparation for an FOT.

The ConOps and DFMEA efforts completed in this project helped engineers and researchers perform a thorough development and refinement process. Potential design deficiencies were identified early in the development process, thus increasing the likelihood of system success once deployed in an FOT. In addition, the ConOps, DFMEA, and associated system requirements (as shown in Appendix A) will likely act as useful guides for other researchers and engineers in the future.

The next step in the development process was to modify the prototype ERS system to simplify installation on CMVs. Researchers and engineers, in collaboration with engineers from the radar company, successfully completed the ERS system modification. Finally, closed-loop activation subsystem testing (on the Virginia Smart Road and public roadways) was performed, in addition to nighttime warning-light brightness testing.

7.1 CLOSED-LOOP ACTIVATION SUBSYSTEM TESTING

Formal tests were performed on the Smart Road and on the public roadways of southwest Virginia (real-world testing). The purpose of formal Smart Road testing was to evaluate the refined radar firmware for improved target tracking, as well as the performance of the incorporated activation (triggering) algorithms. The open-loop activation system performed with a 100 percent correct detection rate and a 100 percent correct rejection rate (equal performance as the prototype system during Phase III). The closed-loop activation system across all algorithm conditions performed with a 100 percent correct detection rate (for *direct threats*) and a 95 percent correct rejection rate (equal performance to formal Smart Road testing during Phase III).

Real-world testing occurred across approximately 150 mi (241.40 km) of public roadways in southwest Virginia. The closed-loop activation system across all roadway types performed with a 100 percent correct detection rate and an 85.43 percent correct rejection rate. Although this performance was slightly better than real-world results from the prototype system in Phase III (100 percent correct detection rate and an 84.66 percent correct rejection rate), there were some reductions in performance found when broken out by roadway type. Table 18 contains a comparison of correct rejection rates between the Phase III real-world testing and the current real-world testing broken out by roadway type. As shown, a slight increase in false alarm rates was found during following-vehicle approaches on *Interstate Highway* and *State Highway* roadway types. However, a significant reduction in false alarms was found on the *Other* roadway type.

Table 18. Correct rejection rate comparisons from Phase III real-world testing to current project real-world testing by roadway type.

Roadway Type	Phase III Estimated Probability of Correct Rejection (P[cr])	Current Estimated Probability of Correct Rejection (P[cr])
Interstate Highway	166/169 = 98.22%	75/86 = 87.21%
State Highway	83/89 = 93.26%	50/60 = 83.33%
Other	82/133 = 61.65%	45/53 = 84.91%
TOTAL	331/391 = *84.66%*	170/199 = *85.43%*

These results indicate that while a significant improvement to the closed-loop activation subsystem performance was found in lower speed, high-traffic-density scenarios (*Other* roadway type), slight reductions in performance resulted on the *Interstate Highway* and *State Highway* roadways. Although these performance reductions are not desired, there were no unintended consequences observed from following-vehicle drivers (e.g. swerves, hard brakes). Overall, the ERS system performed with a 100 percent correct detection rate, an 85.43 percent correct rejection rate, and no unsafe following-vehicle driver reactions/behaviors were observed, indicating a promising system for implementation in an FOT.

7.2 NIGHTTIME WARNING-LIGHT BRIGHTNESS TESTING

Two studies were performed to evaluate the ERS system during nighttime conditions. The first study used following-vehicle drivers to provide ratings on discomfort glare and “attention-getting” effectiveness for multiple nighttime brightness levels. The second study used the brightness level candidate deemed best by the ratings study and included the collection of real-world data on public roadways in southwest Virginia. During real-world testing, no following-vehicle unintended consequences were observed. Overall, the research team concludes that during low ambient conditions (nighttime), the ERS system should switch to the lower brightness level recommended.

7.3 FUTURE RESEARCH

This preliminary research has identified a more basic issue of poor brake light conspicuity on current CMVs. First, brake lights are not designed to draw the following-vehicle drivers’ eyes to the forward roadway (rather, they are designed to signal the following driver only when looking directly ahead at the rear of the CMV). Results from Phase III found that the standard brake-light system installed on CMVs provides little benefit to following-vehicle drivers when they are not looking directly ahead. Current brake lights may benefit from improved conspicuity design.

Second, as the industry has moved from lamps with a single incandescent bulb to lamps with multiple LEDs, the decision to service the brake light has changed from binary (lit and not lit for legacy incandescent lamps) to driver/technician judgment. As the array of LEDs age, the number of LEDs lit continues to decrease within the lamp. A driver or service technician must make a judgment for when to replace or repair the brake light. It is recommended that the decrease in working LEDs within a lamp be evaluated to determine the acceptable level of performance degradation and incorporated into an industry standard or recommended practice. A more concentrated effort to survey current brake light conspicuity across types and performance is recommended.

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APPENDIX A—SYSTEM REQUIREMENTS

This appendix comprises the high-level functional requirements and detailed performance requirements for the ERS system for CMVs. The ConOps for the ERS for Heavy Trucks serves as the source for these specified or derived requirements. Again, the purpose of the ERS system for CMVs is to detect rear-end crash threats and to provide following drivers with a supplemental visual warning (located on the lead vehicle in addition to the current brake lights) of an impending collision with the rear of CMVs. Because there are two distinct activation (i.e., triggering) systems (open-loop and closed-loop) proposed for the ERS system, the requirements will be presented by applicable triggering systems.

OPEN-LOOP ACTIVATION LOGIC

Open-loop activation logic uses only equipped-vehicle parameters (i.e., ABS signal, vehicle velocity, and the derivatives of velocity) to activate the rear lighting. Parameters used could include deceleration level, ABS activation, and a timeout feature (i.e., deactivate the rear warning lights) succeeding these parameters reaching the activation levels (as shown in Figure 4).

Functional Requirements

The functional requirements describe what tasks must be completed using the ERS system with open-loop activation logic. This is the core functionality of the system. These functional requirements will be provided for the two identified purposes, as follows:

- Determine from the equipped vehicle a hard-braking event.
- Alert the following-vehicle driver.

Determine from the Equipped Vehicle a Hard-braking Event

For the ERS system using an open-loop triggering algorithm, the primary task is to determine from the equipped vehicle the occurrence of a hard-braking event. The ERS system performs this task by monitoring both the vehicle ABS activation signal and data from the ERS interface's internal accelerometer. If either the ABS signal is activated or the ERS accelerometer indicates that the equipped vehicle is rapidly decelerating, the ERS system activates the visual warning system. Therefore, the functional requirements for this purpose are:

- The ERS system shall detect ABS signal activation of the equipped vehicle.
- The ERS system shall determine the acceleration profile of the equipped vehicle.

Alert Following-vehicle Driver

Once the ERS system is activated, a visual warning (i.e., the red LED array) is triggered to alert the following-vehicle driver of an impending collision. This warning is independent of, and supplemental to, the foundation brake lights of the vehicle. This warning will be provided under all environmental (e.g., rain, frozen precipitation, fog) and ambient lighting (e.g., day and night) conditions. Therefore, the functional requirements for this purpose are:

- The ERS system must activate the LED unit when either the ABS signal of the equipped vehicle is activated or the equipped vehicle is rapidly decelerating.
- The ERS system must de-activate (timeout) the LED unit once the vehicle has sufficiently slowed or completely stopped.
- The ERS system shall dim the warning light output during low levels of ambient illumination (e.g., nighttime).

Performance Requirements

The following are the minimum acceptable thresholds of performance for the ERS system using open-loop activation logic.

Determine from the Equipped Vehicle a Hard-braking Event

- The ERS system interface unit will need an instantaneous input from the ABS controller of the trailer via an interrupt driven state change or sampled at 10 Hz.
- The internal sample rate of the accelerometer shall be 100 Hz. This data stream shall be filtered to 10 Hz for algorithm computation.

Alert Following-vehicle Driver

- The ERS system must activate the LED unit when either the ABS signal of the equipped vehicle is activated or the equipped vehicle is rapidly decelerating at a minimum of 0.4 g.
- The LED unit must have a minimum lit surface area of 0.97 m^2 (150.0 in^2).
- The LED unit must be red in color.
- The ERS system must simultaneously flash the LED unit at 5 Hz.
- The ERS system will continue the activation of the LED unit for a period of 5 seconds after the deceleration rate of the vehicle falls below 0.15 g.
- The LED unit must have a mean brightness of 17.92 lux for the daytime setting (SD = 5.48) and dim to a mean brightness of 1.49 lux for the nighttime setting (SD = 0.38).
- The horizontal centerline of the ERS housing must be between 0.8 m (31.5 in) and 1.14 m (45 in) above the ground.
- The individual LED bulbs or the entire LED unit must be aimed vertically and horizontally so that the eyes of the following-vehicle driver will be within the main beam while minimizing adjacent-lane light scatter.

Interface Requirements

The following section lists the primary hardware and user interfaces between the components of the ERS system using open-loop activation logic, the equipped vehicle, and the driver of the equipped vehicle.

ERS System Interface/Equipped Vehicle

- There is a hardware interface between the ERS system and the ABS signal of the equipped vehicle that is activated via the trailer brakes.
- There is also a hardware interface between the ERS system and the power supply of the equipped vehicle. A minimum of six amps will be required when the lights are activated.

ERS System Interface/Following-vehicle Driver

- The LED unit is the user interface between the ERS system and the following-vehicle driver.

Data Requirements

The following section lists the data elements shared between the components of the ERS system using open-loop activation logic and the equipped vehicle.

Determine from the Equipped Vehicle a Hard-braking Event

- ABS signal activation.
- Accelerometer.

Alert Following-vehicle Driver

- ERS interface activation signal.
- Ambient light sensor signal.

Closed-Loop Activation Logic

Closed-loop activation logic uses both equipped-vehicle parameters (i.e., vehicle velocity and derivatives of velocity) and measurements related to the following vehicle (e.g., closing rate and closing distance, as shown in Figure 5). Typical sensors for determining this closing rate and distance are radar- or laser-based measurements taken from the rear bumper of the lead vehicle (aimed towards the rear). This system will provide the parameters needed to ascertain the precise information to compute whether or not there is an instantaneous likelihood of a rear-end collision. It is likely that closed-loop activation will result in greater accuracy of activation (i.e., an accurate detection of imminent collisions and fewer false alarms [defined as activations for cases during which rear-end collisions are not likely to occur]). However, implementation costs are greater for closed-loop activation in that the measurement sensor at the rear bumper must be present and computational hardware and software must be used.

Functional Requirements

The functional requirements describe what tasks must be completed using the ERS system with closed-loop triggering. These functional requirements will be provided for three identified purposes, as follows:

- Detect a following vehicle.

- Determine the minimum safe range between the following vehicle and the equipped vehicle.
- Alert the following-vehicle driver.

Detect Following Vehicle

For the ERS system using a closed-loop activation algorithm, the first task is to determine the presence of a potential rear-end collision threat. The ERS system performs this task by scanning the rear of the equipped vehicle for the presence of an approaching vehicle. Therefore, the functional requirements for this purpose are as follows:

- The ERS system shall detect the presence of a following vehicle.
- The ERS system shall operate under all environmental (e.g., precipitation, debris) and ambient lighting (e.g., day and night) conditions.

Determine Minimum Safe Range Between Following Vehicle and Equipped Vehicle

Once a following vehicle has been detected, the ERS system computes its range and closing speed and compares those data to the speed of the equipped vehicle to determine if a threat is imminent. The ERS system interrogates each of the detected objects in this manner to determine the primary threat of a rear-end collision. If the approach of any following objects is such that the minimum safe range is compromised, the ERS system activates a visual warning to the following-vehicle driver. Therefore, the functional requirements for this purpose are as follows:

- The ERS system shall determine the speed and distance of the following object.
- The ERS system must be able to discern the primary rear-end collision threat from numerous detected following objects.

Alert Following-vehicle Driver

Once the ERS system has been activated, a visual warning (i.e., the red LED array) is activated to alert the following-vehicle driver of an impending collision. This warning is independent of, and supplemental to, the foundation brake lights of the vehicle. This warning will be provided under all environmental (e.g., rain, frozen precipitation, fog) and ambient lighting (e.g., day and night) conditions. Therefore, the functional requirements for this purpose are as follows:

- The ERS system must activate the LED unit when the minimum safe range falls below a predetermined threshold.
- The ERS system must deactivate (timeout) the LED unit once the rear-end collision threat is no longer present.
- The ERS system shall dim the warning light output during low levels of ambient illumination (e.g., nighttime).

Performance Requirements

The following are the minimum acceptable thresholds of performance for the ERS system using closed-loop activation logic.

Detect Following Vehicle

- A detection zone capable of viewing the current travel lane plus one adjacent lane on each side at a minimum of ± 20.0 degrees.
- The sensor shall not be mounted lower than 0.4 m (1.3 ft) above ground level.
- The detection zone shall be a minimum of 150.0 m (492.1 ft).
- The sampling rate shall be a minimum of 20 Hz.
- The detection system shall operate under various traffic conditions such as:
  - Stop-and-go traffic.
  - Free-flow freeway.
  - Rural, two-lane roadways.
- The detection system shall operate under various atmospheric conditions (e.g., rain, frozen precipitation, fog).

Determine Minimum Safe Range Between Following Vehicle and Equipped Vehicle

- The ERS system must compute the speed and distance of the following vehicle at a minimum of 20 Hz.
- The ERS system must be able to identify from all detected targets the primary threat as determined by range, closing speed, and approach angle.
- The ERS system must capture the speed (at 10 Hz) of the equipped vehicle and max latency of 50.0 ms on update.

Alert Following-vehicle Driver

- The LED unit must have a minimum lit surface area of 0.97 m^2 (150.0 in^2).
- The LED unit must be red in color.
- The ERS system must simultaneously flash the LED unit at 5 Hz.
- The LED unit must have a mean brightness of 17.92 lux for the daytime setting (SD = 5.48) and dim to a mean brightness of 1.49 lux for the nighttime setting (SD = 0.38).
- The horizontal centerline of the ERS housing must be between 0.8 m (31.5 in) and 1.14 m (45 in) above the ground.
- The individual LED bulbs or the entire LED unit must be aimed vertically and horizontally so that the eyes of the following-vehicle driver will be within the main beam while minimizing adjacent-lane light scatter.

Interface Requirements

The following section lists the primary hardware and user interfaces between the components of the ERS system using closed-loop activation logic, the equipped vehicle, and the driver of the equipped vehicle.

ERS System Interface/Equipped Vehicle

- The ERS system interfaces with the equipped vehicle to determine the speed of the vehicle. This is accomplished through a link with either the controller area network (CAN) bus of the equipped vehicle (J1939; preferred due to higher quality data) or the trailer wheel speed sensor of the equipped vehicle.
- There is also a hardware interface between the ERS system and the power supply of the equipped vehicle. A minimum of six amps will be required when the lights are activated.

ERS System Interface/Following-vehicle Driver

- The interface between the ERS system and the following-vehicle driver is the LED unit.

Data Requirements

The following section lists the data elements shared between the components of the ERS system using closed-loop activation logic and the equipped vehicle.

Detect Following Vehicle

- Location and relative speed of the following vehicle.

Determine Minimum Safe Range Between Following Vehicle and Equipped Vehicle

- Location, relative speed, and approach angle of the following vehicle.
- Speed and acceleration profiles of the equipped vehicle.

Alert Following-vehicle Driver

- ERS interface activation signal.
- Ambient light sensor signal.

APPENDIX B—SUBSYSTEMS AND COMPONENTS

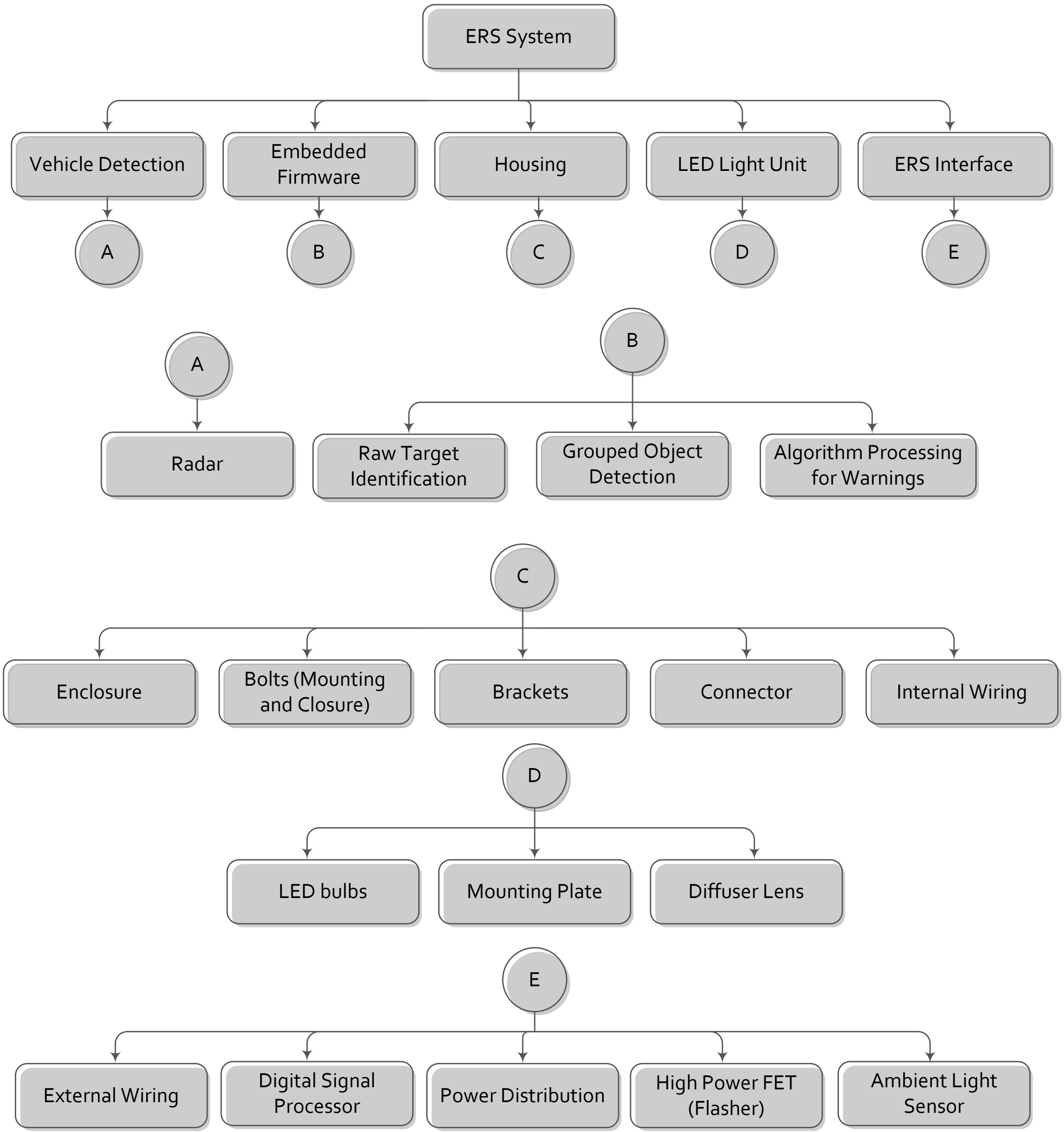

Figure 37. Flowchart. Subsystems and components.

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APPENDIX C—OTHER REFERENCED RESOURCES

BACKGROUND DOCUMENTATION

This section comprises two parts. The first lists the sources that are referenced within the ConOps document. The second lists documents or other resources that may not be directly referenced that were used for background information and/or as a source for potential user needs during the ConOps development.

Referenced Sources

- Lee, S. E., Llaneras, E., Klauer, S. G., and Sudweeks, J. (2007). Analyses of Rear-End Crashes and Near-Crashes in the 100-Car Naturalistic Driving Study to Support Rear-Signaling Countermeasure Development. Report No. DOT HS 810 846. Washington, DC: U.S. Department of Transportation, National Highway Traffic Safety Administration.
- Schaudt, W.A., Bowman, D., Trimble, T.E., Medina, A.F., Bocanegra, J., Baker, S., Marinik, A., Wierwille, W.W., and Hanowski, R.J. (in press). Enhanced rear signaling (ERS) for heavy trucks: Phase III—development of field operational test; final report. Contract No. DTMC75-07-D-00006, Task Order 2. Washington DC: U.S. Department of Transportation, Federal Motor Carrier Safety Administration (Submitted September, 2010).
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Resource Documents

- Freese, J. and Freese, S. (October, 2006). *Enhanced rear signaling for commercial motor vehicles; Final report*. Contract No. 1406-04-06-PO-60596. Prepared for the Federal Motor Carrier Safety Administration.
- Pierowicz, J., and Damon, G. (2004). *Enhanced rear signaling for commercial vehicles: Task 2a report: Problem assessment; Determine crash conditions in which heavy trucks are involved in rear-end crashes*. Contract No. DTMC75-03-C-00018. Washington, D.C.: U. S. Dept. of Transportation, Federal Motor Carrier Safety Administration.
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- Wolf, K. and Damon, G. (March, 2005). *Enhanced rear signaling for commercial vehicles; Task 5 report: Design, Test and Evaluation Planning.* Contract No. DTMC75-03-C-00018. Prepared for the Federal Motor Carrier Safety Administration.

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4. Wierwille, W. W., Lee, S. E., and DeHart, M. C. (2003). *Testing and optimization of high-level and stopped/slowly-moving vehicle rear-signaling systems: Enhanced rear lighting and signaling systems, Task 2 Report.* Report no. DOT HS 809 597. Washington, DC: US Dept. of Transportation, National Highway Traffic Safety Administration.
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6. Freese, J. and Freese, S. (October, 2006). *Enhanced rear signaling for commercial motor vehicles; Final report.* Contract No. 1406-04-06-PO-60596. Prepared for the Federal Motor Carrier Safety Administration.
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