Enhanced Rear Signaling (ERS) for Heavy Trucks: Phase III – Development of Field Operational Test

Final Report

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

September 2010

FOREWORD

This project was directed at investigating methods of reducing or mitigating those crashes where a heavy truck has been struck in the rear by another vehicle. These crashes occur with sufficient frequency that they are a cause of concern within regulatory agencies. As part of the Federal Motor Carrier Safety Administration's (FMCSA) goal of reducing the overall number of truck crashes, this crash configuration is one that is important to the Agency.

Prior to the current effort, two phases of work had been completed on this project. Phase I entailed crash data analysis to determine causal factors of these crashes and the development or identification of countermeasures to aid in reducing them. Phase II entailed the development of a prototype system that incorporated the countermeasures from Phase I. The purpose of the current effort, Phase III, focused more closely on exploring the benefits of the countermeasures developed in Phases I and II. Phase III also had the objective of the development of a plan for a large scale Field Operational Test (FOT).

NOTICE

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16. Abstract

The Enhanced Rear Signaling (ERS) for Heavy Trucks project was directed at investigating methods to reduce or mitigate those crashes where a heavy truck has been struck in the rear by another vehicle. Prior to the current effort, two phases of work had been completed on this project. The purpose of the current effort, Phase III, focused on exploring the benefits of the countermeasures developed in previous phases, and to develop a plan for a large scale Field Operational Test (FOT). During crash database analyses in the current project it was found that, in 2006, there were approximately 23,500 rear-end crashes involving heavy trucks which resulted in 135 fatalities and 1603 incapacitating injuries. Many different types of ERSs were investigated in this study across both the auditory and visual modalities. Visual warning signals were found to be the most beneficial at signaling following-vehicle drivers (more specifically rear warning-light configurations). The research team recommended that one specific configuration be selected for real-world data collection based on its high performance and the potential success of future design implementation. Overall, the final radar-based cautionary ERS system was robust in real-world driving conditions and is recommended for an FOT.

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SI* (MODERN METRIC) CONVERSION FACTORS

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 yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
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
		NOTE: volumes greater than 1000 L shall be shown in 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 (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		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

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 (exact degrees)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and 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)

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ABBREVIATIONS, ACRONYMS, AND SYMBOLS

ABS	Antilock Braking System
ANOVA	Analysis of Variance
BTS	Bureau of Transportation Statistics
B/W	black and white
CDS	Crashworthiness Data System
CFR	Code of Federal Regulations
CMOS	Complementary Metal Oxide Semiconductor
CMV	Commercial Motor Vehicle
COTR	Contracting Officer's Technical Representative
CUTs	combination-unit trucks
CV	Commercial Vehicle
d	distance of following vehicle from rear of heavy truck trailer
D	Depth
dB	Decibels
DAS	Data Acquisition System
dBA	decibels
deg	degrees
DOT	Department of Transportation
DPS	digital pixel sensor
DV	dependent variable
ERS	Enhanced Rear Signaling
EST	Eastern Standard Time
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FMVSS	Federal Motor Vehicle Safety Standard
FOT	Field Operational Test
g	acceleration due to gravity (32.2 ft/s^2 [9.81 m/s^2])
GES	General Estimates System
GPS	Global Positioning System
h	hour(s)
H	Height
HSD	Honestly Significant Difference
Hz	hertz
IAP	Improved Alternating Pair
ICC	Interstate Commerce Commission

IHS	Dwight D. Eisenhower National System of Interstate and Defense Highways or Interstate Highway System
ISO	isometric
IRB	Institutional Review Board
IV	independent variable
IVBSS	Integrated Vehicle-Based Safety Systems
IT	Information Technology
KHz	kilohertz
km/h	kilometers per hour
LED	light-emitting diode
mi/h	miles per hour
mm	millimeters
ms	millisecond(s)
NASS	National Automotive Sampling System
NHTSA	National Highway Traffic Safety Administration
NTSC	National Television Systems Committee
PAL	phase alternating line
PARs	Police Accident Reports
PC	personal computer
PsF	Progressive segmented frame
PVC	polyvinylchloride
s	second(s)
SAE	Society of Automotive Engineers
SD	Standard Deviation
SOW	Statement of Work
SUTs	single-unit trucks
SUVs	Sport Utility Vehicles
TCL	Traffic Clearing Lamp
TV	time value
UFOV	Useful Field of View
U.S.	United States
V2V	Vehicle-to-vehicle communications
VTTI	Virginia Tech Transportation Institute
W	width
WAV	Waveform Audio Format

EXECUTIVE SUMMARY

PURPOSE

The focus of the Enhanced Rear Signaling (ERS) for Heavy Trucks project was to investigate methods to reduce or mitigate those crashes where a heavy truck has been struck in the rear by another vehicle. This particular collision type results in higher-than-usual rates of fatalities and injuries compared to collision types involving lighter lead vehicles. As part of the Federal Motor Carrier Safety Administration's (FMCSA) goal of reducing the overall number of truck crashes, this crash configuration is one that is important to the Agency. There were two phases of work completed on this project prior to the current effort. Phase I had the purpose of performing a crash data analysis to determine causal factors of these collision types and to identify potential countermeasures. (See references 1, 2, 3 and 4.) Phase II continued further with development of a prototype system that incorporated the countermeasures from Phase I.[(5)] In Phase II field testing**,** it was found that there appeared to be potential benefits of using such countermeasures. The purpose of the Phase III effort was threefold: (1) conduct a General Estimates System (GES) database analysis using the most recent data available to report various break-outs/characterizations of rear-end truck crashes, (2) explore the benefits of the countermeasures developed in Phases I and II, and (3) develop a plan for a large scale Field Operational Test (FOT) to assess countermeasures for rear-end truck crashes. Phase III utilized what has been learned in the rear-end crash avoidance work on light vehicles conducted by the National Highway Traffic Safety Administration (NHTSA).[(6)]

PROCESS

Phase III included a GES database analysis that was conducted using the most recent data available (2006), following a similar strategy used by Pierowicz and Damon.[(2,3,4)] A series of static and dynamic empirical data collection efforts were performed to test and evaluate potential countermeasures. A final ERS system was developed and tested on the public roadways of southwest Virginia. A detailed FOT plan was developed for the final ERS system. The purpose of the current report is to document all activities performed during Phase III.

STUDY FINDINGS

GES Database Analysis Update 2006

The research team conducted a GES database analysis, using the most recent data available, following the same strategy used by Pierowicz and Damon.[(2,3,4)] Pierowicz and Damon used GES data from 2001 to report various break-outs/characterizations of rear-end truck crashes. The current research team analyzed data from 2006, the most recent GES data available, to update these various break-outs/characterizations. The crash data used in this report were collected by NHTSA and compiled in the National Automotive Sampling System (NASS). NASS is comprised of two systems – the Crashworthiness Data System (CDS) and the GES. These systems represent a sample of police crash reports. While the CDS focuses on passenger vehicle crashes and is used to investigate injury mechanisms and identify potential improvements in vehicle design, GES focuses on presenting an overall crash analysis which can be used for assessing the size of problems and for tracking trends.(7)

Data included in the CDS and the GES have been drawn from select crashes using police accident reports (PARs) obtained from police agencies around the country. The reports are selected from randomly chosen areas of the country and include counties and major cities that are statistically representative of the United States as a whole. This report used 2006 NASS-GES data as the primary source of crash statistics cited within this report.

Overall Truck Statistics

- In 2006, there were 8,819,007 registered trucks in the United States. Of those, there were more than three times the number of single-unit trucks (SUTs; 6,649,337) than combination-unit trucks (CUTs; 2,169,670).

Heavy Truck Configuration

- Of the 10,584,000 total vehicles involved in all vehicle crashes, heavy trucks accounted for 385,000 vehicles.
- Of the 385,000 crashes involving heavy trucks, 23,508 were rear-end crashes.
- Trucks pulling one trailer unit accounted for 92 percent of the body types involved in rear-end crashes. A much smaller percentage (4 percent) occurred with the tractor pulling no trailer, or “bob tail” configuration. An even smaller percentage (3 percent) of rear-end crashes occurred with trucks pulling two trailer units.
- When looking at the rear-end crash configurations involving a single trailer unit, the most common trailer unit type was the van/enclosed box configuration. The van/enclosed box configuration accounted for 32.4 percent of the population of trucks pulling one trailing unit. Flatbed trailers made up the second largest configuration group with 12.8 percent of the population of trucks involved in rear-end crashes. Cargo tank trailers (4.8 percent), dump (5.5 percent), auto transporter (0.8 percent) and garbage/refuse (0.1 percent) accounted for the remainder of known vehicle configurations. Vehicles recorded as other or unknown accounted for 43.6 percent of the populations of trucks pulling one trailing unit.

Heavy Truck Rear-End Crash Types

- The three most common rear-end crash configurations were *Lead Vehicle Stopped*, *Lead Vehicle Traveling Slower*, and *Lead Vehicle Decelerating*. In each of these configurations the lead vehicle (i.e., the vehicle being struck) was the heavy truck.
    - The configuration *Lead Vehicle Stopped* resulted in 11,249 rear-end crashes. This was 47.9 percent of the rear-end crash population involving heavy trucks.
    - The configuration *Lead Vehicle Traveling Slower* resulted in 6,978 rear-end crashes. This was 29.7 percent of the rear-end crash population involving heavy trucks.
    - The configuration *Lead Vehicle Decelerating* resulted in 5,282 rear-end crashes. This was 22.5 percent of the rear-end crash population involving heavy trucks.
- When looking at the crash severity of rear-end crashes within those three crash configurations, there were 135 fatalities, 1,603 incapacitating injuries, 2,074 non-

incapacitating injuries, and 2,711 possible injuries. The most serious injuries (i.e., non-incapacitating injuries and incapacitating injuries) occurred within the *Lead Vehicle Stopped* configuration, which had 1,621 serious rear-end crashes.

Environmental Conditions

- When looking at the severity of injuries as a percentage of all the crash-related injuries occurring at nighttime versus the severity of all crashes occurring during daytime conditions, a greater percentage of fatal rear-end crashes occurred at nighttime (4.5 percent of all nighttime injuries) versus daytime conditions (0.5 percent of all daytime injuries). Additionally, of the nighttime injuries, 31.3 percent were serious injuries (i.e., non-incapacitating injuries and incapacitating injuries), almost double the percent of daytime rear-end crashes (16 percent).
- Rear-end crashes occurred during nighttime conditions 26.4 percent of the time and during daytime conditions 73.6 percent of the time. The greatest percentage (49.2 percent) of daytime rear-end crashes occurred when the CUT was stopped. Nighttime rear-end crashes occurred predominantly when the CUT was the *Lead Vehicle Traveling Slower* (54 percent).

Passenger Vehicles Versus CUTs

- There were a larger number of rear-end crashes for passenger vehicles (1,405,695) than for CUTs (11,833).
- In the majority of rear-end crashes, for both passenger vehicles and CUTs, there were no traffic controls present at the crash, the crashes occurred on roadways having straight alignment profiles and a level *Roadway Profile* in non-interchange/non-junction areas without a traffic control, and under good conditions (i.e., *No Adverse Atmospheric Conditions*).
- A much higher percentage of passenger vehicle rear-end crashes occurred on non-Interstate highways as compared to Interstate highways (approximately 90.6 percent versus 9.3 percent). Heavy-truck-related rear-end crashes were more evenly divided between non-Interstate highways and Interstate highways (58.1 percent and 41.9 percent).
- In more than 78 percent of both passenger vehicle and CUT rear-end crashes the striking vehicle was going straight in the lane of travel.

CUT Rear-End Crashes During Daytime and Nighttime Conditions

- Rear-end crashes occurred 26.4 percent of the time under nighttime conditions and 73.6 percent of the time during daytime conditions.
- Nighttime rear-end crashes occurred most often when the drivers of the striking vehicles were traveling greater than or equal to 46 mi/h (74.03 km/h; 57.5 percent). However, 34.6 percent of rear-end crashes occurred when drivers of striking vehicles were traveling at 26-35 mi/h (41.84-56.33 km/h). Daytime rear-end crashes occurred most often when the drivers of the striking vehicles were traveling 5-25 mi/h (8.05-40.23 km/h; 25.5 percent) or 46-55 mi/h (74.03-88.51 km/h; 23.8 percent).
- With the exception of the dump and flatbed body types, the 55-65 mi/h (88.51-104.61 km/h) *Speed Limit Range* had the greatest percentage of rear-end crashes involving a CUT. Within the dump body type, 58 percent of rear-end crashes occurred when the truck

was traveling 40-50 mi/h (64.37-80.47 km/h) as compared with 24 percent that occurred when the truck was traveling 55-65 mi/h (88.51-104.61 km/h). The peak speed range for flatbed rear-end crashes was 25-35 mi/h (4023-56.33 km/h; 34 percent).

Conclusions

Generally, the 2006 GES findings were consistent with those from the 2001 GES analysis; however, below is a summary of the primary discrepancies between these two data sets:

- In the 2006 GES data set, only 36 percent of daytime rear-end crashes occurred on Interstate highways. This marks a sharp reduction since 2001 when 67.3 percent of daytime rear-end crashes occurred on Interstates. Nighttime rear-end crashes that occurred on the Interstate increased from 38.5 percent in the 2001 GES data set to 55 percent in the 2006 GES data set.
- The percent of SUT rear-end crashes on two-lane roads decreased from 48.2 percent in the 2001 GES data set to 35.7 percent in the 2006 GES data set. The percent of rear-end crashes that occurred on four-lane roads increased from 8.6 percent in the 2001 GES data set to 13.3 percent in the 2006 data set.
- There has been a decrease in the number of rear-end crashes that occurred at dawn (8.9 percent in the 2001 GES versus 0.6 percent in the 2006 GES).
- There has been an almost 5 percent increase in the number of rear-end crashes that occurred on roadways with four or more lanes (19.8 percent in the 2006 GES compared to 15 percent in the 2001 GES).
- In the 2006 GES data set, CUT rear-end crashes had a higher occurrence of no avoidance maneuver than did SUTs (29.1 percent versus 16 percent, respectively). This is a change from the 2001 GES data set, which found no avoidance maneuver attempted in 36.5 percent and 21.9 percent of the SUT and CUT rear-end crashes, respectively.

Analysis of Countermeasures

A series of static and dynamic empirical data collection efforts were performed to test and evaluate potential rear-end crash countermeasures. Overall, two different exterior auditory signal devices were designed, developed, and tested in a static environment with the use of three signal types (sounds). The objective of this development process was to determine if an appropriate narrow-beam-width system could be built. Development and testing of multiple visual rear-signal types (normal brake lighting, rear warning-light configurations, and passive conspicuity markings) was performed in both static and dynamic environments. The purpose of both the static testing and the dynamic testing was to determine how well various rear-lighting configurations would provide improved eye-drawing capabilities, as well as to investigate the effects of two passive conspicuity markings on following distance behavior of drivers in a following vehicle. Prior to the successful development of an ERS system, an activation sub-system development effort was needed. This effort consisted of the modification of previously developed activation (triggering) algorithms and testing their performance. Both an open-loop activation sub-system and a closed-loop activation sub-system were chosen and tested in a dynamic setting on the Virginia Smart Road. Key findings from the analysis of countermeasures effort are as follows:

Auditory Warning Signal

The feasibility of generating a narrow-beam-width external auditory signal was investigated; however, the two proposed concepts (i.e., tube design and parabolic reflector) were unable to achieve the beam-width goal of ±5 degrees (deg). Because this narrow beam-width could not be obtained with either concept, further use of either concept may needlessly alert other drivers in adjacent lanes. Vehicle-to-vehicle communications (V2V) has the clear benefit over an external auditory signal in that more control of the signal's sound, directionality, and amplitude can be maintained inside the following vehicle. It was recommended that further ERS testing not include the external auditory signal component of this research project and that efforts be focused on visual countermeasures.

Visual Warning Signal (Static Testing)

Preliminary static testing was performed using various rear-lighting configurations with the objective of down-selecting to the most promising concepts to move forward in dynamic testing. Results from initial static testing indicated that three rear warning-light configurations performed the best. One of these was a configuration containing 12 light-emitting diode (LED) units ganged on the main bumper of a trailer (*Main Bumper*). The second configuration consisted of 12 LED units ganged on the main bumper combined with 6 LED units positioned on the cargo box (*Main Bumper/Cargo Box*). The third configuration consisted of 12 LED units ganged on the main bumper combined with 5 LED units positioned on the Interstate Commerce Commission (ICC) bumper (*Main Bumper/ICC Bumper*). All three of these rear warning-light configurations performed well with regard to eye-drawing and opinion ratings performance (labeled as A, B, and C, respectively, in figure 1). These results corresponded to previous research which has also shown that ganging multiple LED units together can improve eye-drawing performance.[(6)] After further consideration, researchers determined that new lighting configurations needed to be developed and tested in a second experiment to further explore ganging LED units in locations other than the main bumper area. It was determined that one lighting configuration should contain 12 LED units ganged and positioned high on each side of the cargo box (*Twelve-light Cargo Box*), and another configuration should contain 12 LED units ganged and positioned on the ICC bumper (*Twelve-light ICC Bumper*) (labeled as D and E respectively in figure 2). Testing these remaining two ganged-lighting configurations in a second static experiment would allow further insight into two areas: 1) determination of whether ganged lighting would also perform well in both in high and low locations on the trailer, and 2) selection of the final two most promising concepts to move forward to the dynamic testing on the Virginia Smart Road.

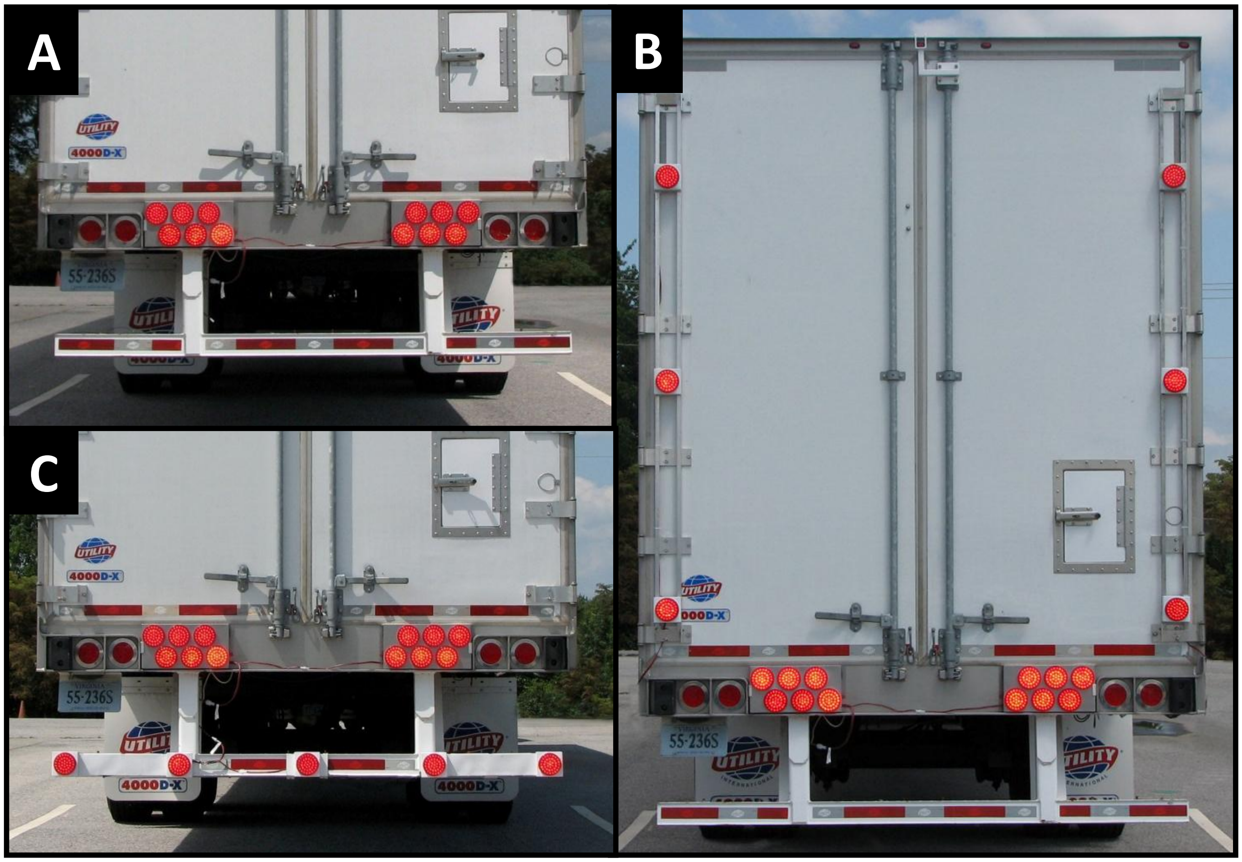

Figure 1. Grouped image. Rear warning-light configurations that performed well in initial static testing (A = *Main Bumper*, B = *Main Bumper/Cargo Box*, and C = *Main Bumper/ICC Bumper*).

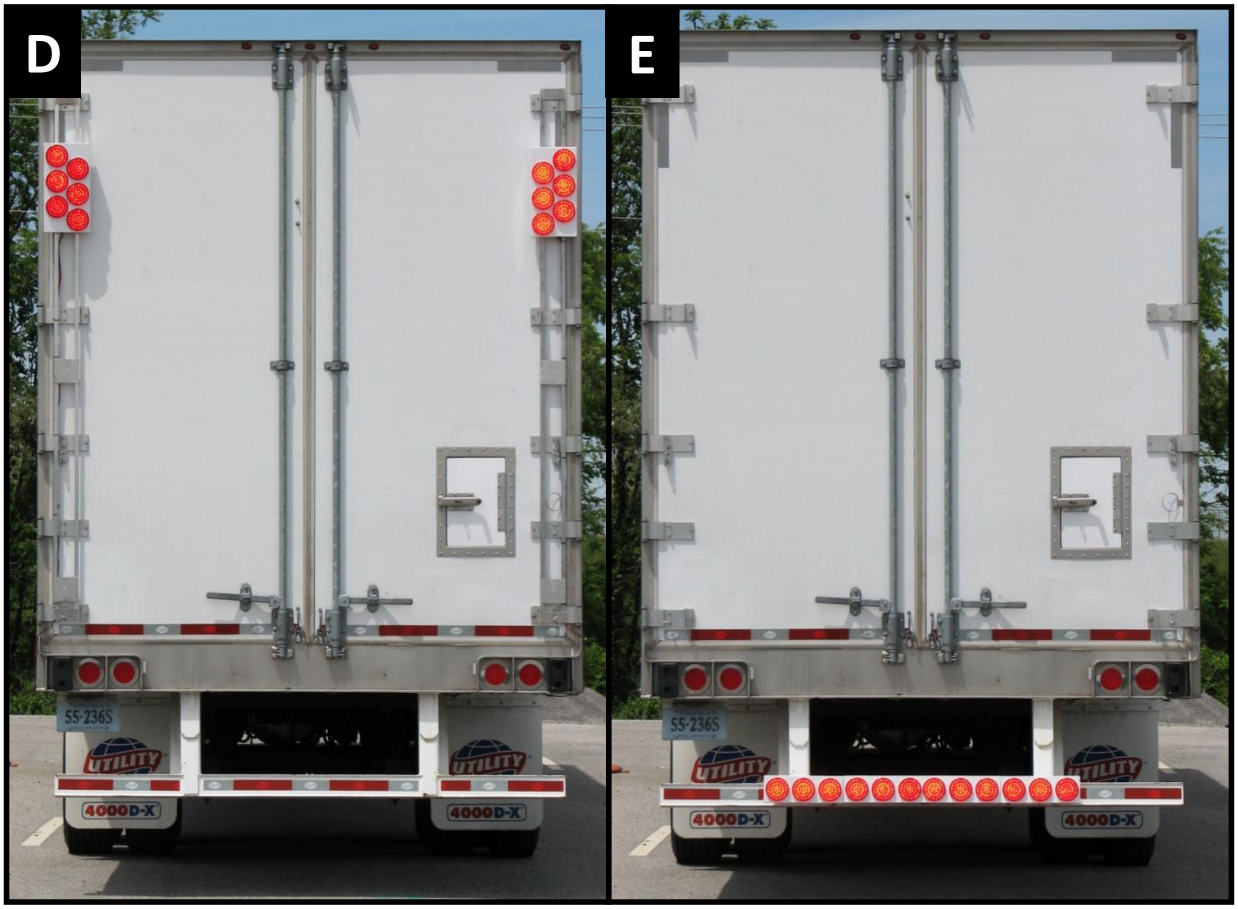

Figure 2. Grouped image. Additional rear warning-light configurations tested in follow-up static testing (D = *Twelve-light Cargo Box*, and E = *Twelve-light ICC Bumper*).

Results from the second static testing experiment showed that the *Main Bumper*, *Twelve-light Cargo Box*, and *Twelve-light ICC Bumper* lighting configurations were the only ones that caused any look-ups (i.e., had acceptable eye-drawing capability); however, the M*ain Bumper* was the only one that was significantly better at reducing the eye-drawing time. The other two test configurations did result in look-ups and the *Twelve-light ICC Bumper* lighting configuration performed a close second behind the *Main Bumper*. Based on the results of the static testing, it appeared there was diminished eye-drawing power as the ganged lighting was moved away, either above or below, the main bumper of the lead vehicle. Researchers determined that any further lighting configurations to be tested should contain ganged lighting. Based on results from both static experiments, the lighting configurations chosen to move forward to the dynamic Smart Road tests were the *Main Bumper*, and the new hybrid design *Main Bumper/Twelve-light ICC Bumper* (labeled as F and G, respectively, in figure 3).

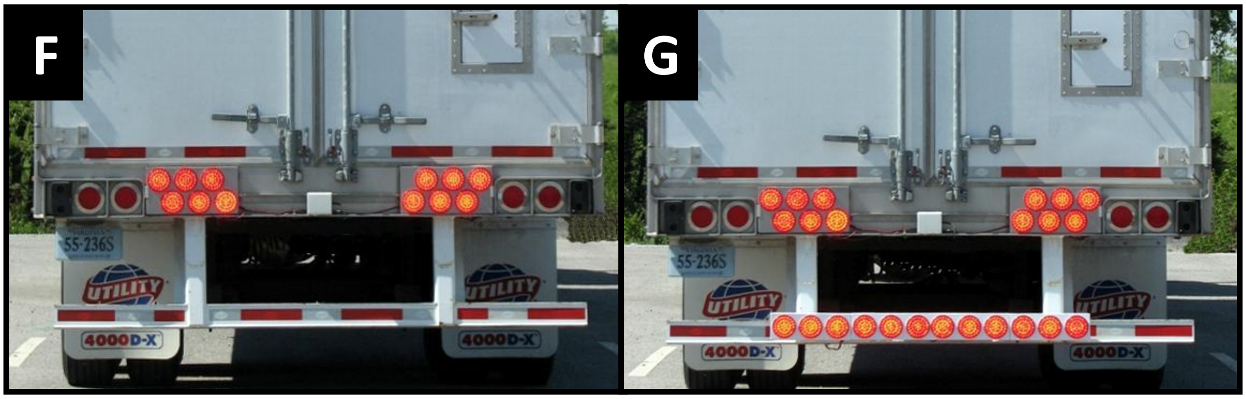

Figure 3. Grouped image. Rear warning-light configurations selected to move forward to dynamic testing on the Virginia Smart Road (F = *Main Bumper*, and G = *Main Bumper/Twelve-light ICC Bumper*).

Visual Warning Signal (Dynamic Testing)

The purpose of dynamic testing (i.e., a moving vehicle with an individual driving on the Smart Road) was to investigate the effects of a set of two retro-reflective octagonal passive conspicuity markings (*Conspicuity Markings*) on following distance behavior as well as to determine how well a selected group of rear-lighting configurations would provide improved eye-drawing capabilities. The purpose of the *Conspicuity Markings* was to provide additional visual cues, making heavy truck trailers more easily seen and distinguishable from the background. Two dynamic experiments were performed in total. Results from Experiment 1 showed that *Conspicuity Markings* did not provide a performance benefit in maintaining a demonstrated distance behind the experimental CUT. It was recommended that further ERS testing not include the *Conspicuity Markings* and that efforts be focused on rear-lighting configurations. Although attempted, the eye-drawing capability of rear-lighting configurations could not effectively be measured using the same methodology performed for the *Conspicuity Markings*. The method was revised by researchers for a follow-on experiment (Experiment 2). This follow-on experiment required the research team to coach each participant to maintain a following distance of approximately 120 ft (36.58 m) during Smart Road loops.

The follow-on Experiment 2 was successful at coaching participants to maintain a closer distance to the lead vehicle, resulting in a mean following distance of 125.71 ft (38.32 m). After the removal of outliers from the data, results indicated that a strong trend was found for improved eye-drawing performance of both rear warning-light configurations over that of normal brake lights. Various opinion ratings were also collected from participants. Overall, ratings indicated that both rear warning-light configurations were attention-getting and any discomfort-glare associated was acceptable. However, one rear warning-light configuration did not substantially show improved performance over that of the other. Both appeared to be good candidates for real-world data collection.

Activation (Triggering) System Development

In order to successfully develop an ERS system for heavy trucks, an effort was performed which consisted of researchers and engineers utilizing and modifying activation (triggering) algorithms and testing the performance of these on the Smart Road. Both an open-loop activation sub-system and a closed-loop activation sub-system were tested in potential rear-end crash scenarios.

An open-loop system requires no measurements associated with the following vehicle. Only lead vehicle parameters are available. For open-loop testing, the experimental CUT was driven five loops around the Smart Road while multiple braking events (at varying levels of braking) were initiated. Upon examination of the data collected, it was found that, as programmed, warning lights were initiated whenever braking levels were greater than or equal to 0.4 *g* of deceleration. Due to safety reasons, actual scenarios involving the activation of the tractor and trailer antilock braking systems (ABS) were not performed. However, these ABS signals were reproduced manually by experimenters during multiple scenarios and warning lights were initiated every time.

The main aspect of the closed-loop activation sub-system testing was determining the prototype algorithm performance under various rear-end crash scenarios. The main dependent measures investigated included correct detections, missed detections, false alarms, and correct non-detections. Rear-end crash scenarios were executed on a long, flat portion of the Smart Road. Overall, the closed-loop activation sub-system performed extremely well at correct detections and correct non-detections. There were no missed detections found, which also provided support of proper system function. The system did show five false alarms during following vehicle adjacent lane approaches. However, after further analysis, it was determined that these false alarms were due to the radar and not the algorithm performance. Researchers concluded that the closed-loop activation sub-system algorithm performed well and was ready for real-world data collection. However, the current radar implementation was producing clutter (identifying false objects) in the left adjacent lane and surrounding area, which was increasing the risk of false triggering. The propensity for these false triggers were further addressed prior to activation sub-system testing in the real-world data collection effort.

Conclusions

Many different types of ERSs were investigated in this study across both the auditory and visual modalities. The testing of narrow-beam-width external auditory signals was performed and it was found that the development of a narrow beam-width could not be obtained. Further use of an external auditory signal that does not have directional characteristics may needlessly alert other drivers in adjacent lanes. It was recommended that further ERS testing not include the external auditory signal component and that efforts be focused on visual countermeasures.

Visual warning signals were developed and tested in both static and dynamic experiments. Nine different rear-lighting configurations were investigated as well as a set of *Conspicuity Markings*. The two rear warning-light configurations moved forward to dynamic tests on the Virginia Smart Road were the *Main Bumper* and *Main Bumper/Twelve-light ICC Bumper* configurations. During dynamic tests it was found that both of these rear warning-light configurations performed equally well and better than normal trailer brake lighting. It was also found that *Conspicuity Markings* did not provide a performance benefit in maintaining a demonstrated distance behind the experimental CUT. It was recommended that further ERS testing not include the *Conspicuity Markings* and that efforts be focused on rear-lighting configurations. Both final rear warning-light configurations appeared to be good candidates for real-world data collection. Based on the results of these experiments, there were two options for moving forward to the real-world data collection. The first option consisted of testing both of the final candidate rear warning-light configurations along with a baseline (normal trailer brake lights) configuration. This would result in a reduction of on-road data collection hours per condition (less data for analyses), but in the end would possibly help in evaluating the performance benefits of one rear warning-light configuration over the other. The second option consisted of selecting one of the rear warning-light configurations based on the potential success of future design implementation (e.g., cost of overall system, trailer structural constraints, etc.).

With regard to closed-loop and open-loop activation sub-system testing, both systems performed well. The closed-loop system was the recommended candidate to move forward to real-world data collection. This system had the greater potential for mitigating rear-end crashes involving heavy trucks over that of the simpler open-loop system. The closed-loop system did show five false alarms during tests. However, after further analysis, it was determined that these false alarms were due to the radar limitations and not the algorithm performance. Researchers concluded that the closed-loop activation sub-system algorithm performed well and was ready for real-world data collection. However, the radar implementation was producing clutter (identifying false objects) in the left adjacent lane and surrounding area which was increasing the risk of false triggering. The propensity for these false triggers would need to be addressed prior to activation sub-system testing in the real-world data collection effort.

Real-world Data Collection

The final dynamic evaluation of the ERS system was conducted on public roadways in order to observe and measure the reaction of the driving public. Observations of following-vehicle driver behavior behind an experimental CUT took place on multiple road types and in various driving scenarios. While both final rear warning-light configurations appeared to be potential candidates for the real-world data collection effort, the research team recommended that one configuration be selected based on the potential success of future design implementation. Researchers recommended that the *Main Bumper* configuration be selected to move forward to the real-world data collection effort (figure 4). This recommendation was supported by the project's Contracting Office Technical Representative (COTR) from FMCSA. The final ERS system consisted of a *Main Bumper* rear warning-light system as well as a radar-based closed-loop activation sub-system (figure 4). There were three areas of investigation in this study: (1) following-vehicle unintended consequences, (2) closed-loop activation sub-system performance, and (3) eye-drawing capability. Key findings from the real-world data collection effort are presented below.

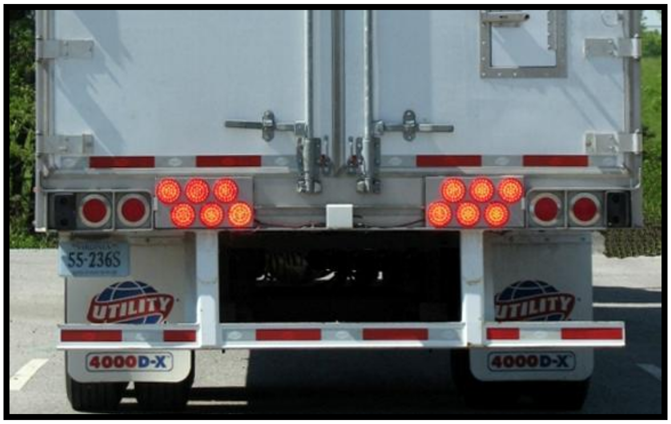

Figure 4. Photo. *Main Bumper* selected as final rear warning-light configuration for the real-world data collection effort.

Following-vehicle Unintended Consequences

The presence or absence of following-vehicle unintended consequences during *Main Bumper* warning-light activation was investigated. After unintended consequences were identified, data were compared to typical baseline brake-lighting events (*Baseline*). There were two categories of interest for investigation with regard to roadway type. The first roadway type investigated was a *Single-lane Roadway*, while the second roadway type investigated was a *Multi-lane Roadway*. For an event to be considered an unintended consequence in the single-lane roadway category the following vehicle had to be positioned in the same lane directly behind the experimental CUT and perform an unintended following-vehicle behavior (i.e., heavy deceleration, acceleration, swerve, lane deviation, or lane change). An event considered to be an unintended consequence in the *Multi-lane Roadway* category required the following vehicle, when positioned in the same lane directly behind the experimental CUT, to perform an unintended following-vehicle behavior such as a heavy deceleration, acceleration, swerve, lane deviation, or lane change. When the following vehicle was positioned in an adjacent lane behind the experimental CUT, an unintended following-vehicle behavior was required such as a heavy deceleration, deceleration, acceleration, swerve, lane deviation, or lane change.

- The occurrence of following-vehicle unintended consequences during both normal brake light and rear warning-light activation was minor.
- Of the unintended consequences that did occur across all roadway categories, all were labeled as decelerations and accelerations (that is, no heavy braking (brake lock-ups), swerves, lane deviations, or lane changes were found).
- Overall, the results indicated that the *Main Bumper* rear warning-lights did not result in an increase of unintended consequences over that of normal brake lights during the real-world data collection effort.

Closed-loop Activation Sub-system Performance

During the analysis of countermeasures effort, the research team recommended that a closed-loop activation sub-system be the final candidate to move forward to the real-world data collection effort. This system was determined to have greater potential for mitigating rear-end crashes involving heavy trucks over that of the simpler open-loop system. A closed-loop activation sub-system includes the measurement of closing rate (velocity) and closing distance to the following vehicle, along with lead-vehicle velocity and deceleration, regardless of speed and distance between vehicles (usually obtained through radar). The closed-loop activation sub-system was tested on three different roadway types in the real-world data collection effort. The first roadway type on which the closed-loop activation sub-system was tested was an *Interstate Highway* (Interstate 81). The second roadway type on which the closed-loop activation sub-system was tested was a *State Highway* (Virginia Highway 460). The third roadway type on which the closed-loop activation sub-system was tested included all *Other* lower-speed roadways; these consisted of rural/town single-lane and multi-lane roads with traffic lights. A signal detection theory experimental design was used to evaluate the closed-loop activation sub-system performance.[8,9] The activation and de-activation of a rear warning-light system is a critical component of an effective ERS system. If such a system is activated correctly, it should provide the warning only when a rear-end crash is likely to occur and not at any other time. Additionally, it must not miss situations where a rear-end crash is likely to occur. There are four aspects to such a system, as with any other detection system, when applied to rear-end crashes:

- Activation when a crash would otherwise occur (correct detection).
- Non-activation when a crash would otherwise occur (missed detection).
- Activation when a crash would not otherwise occur (false alarm).
- Non-activation when a crash would not otherwise occur (correct non-detection).

The objective was to maximize the probabilities of occurrence of correct detections and correct non-detections, and minimize the probabilities of occurrence of missed detections and false alarms. Results indicated that the closed-loop activation sub-system performed well at rear-end crash detection and rear warning-light activation. In all three roadway types, the closed-loop activation sub-system performed with a 100-percent correct detection rate. Other findings are presented below:

- During events in which there were no rear-end crash threats present, the closed-loop activation sub-system performed well on the *Interstate Highway* and *State Highway* roadways. For the *Interstate Highway* roadway category, the resulting estimated probability of correct rejections found was 98.22 percent (false alarm rate of 1.78 percent). For the *State Highway* roadway category, the resulting estimated probability of correct rejections found was 93.26 percent (false alarm rate of 6.74 percent).
- During the *Other* roadway category testing, the performance of the closed-loop activation sub-system resulted in a reduction in the estimated probability of correct rejections and, therefore, an increase in false alarm rates as compared to the previous two roadway categories. The estimated probability of correct rejections found was 61.65 percent (false alarm rate of 38.35 percent). Upon further investigation, it was found that a majority of the false alarms occurred when there was more than one following vehicle within 200 ft (60.96 m) of the rear of the experimental CUT (46 of the 51 false alarms). This indicated that primary target identification by the newly modified radar firmware may still need refinement for lower speed, high following-vehicle density scenarios before implementation in an FOT.

Eye-drawing Capability

The third area of investigation was the eye-drawing capability of the *Main Bumper* rear warning-lights in comparison to *Baseline* brake lights. With regard to rear-end crashes, the most prevalent contributing factor is that of the following-vehicle driver looking away, either into the vehicle interior or to the outside (but not the forward view).[10] Most previous work on prevention of rear-end crashes has been directed toward attention-getting and eye-drawing; that is, trying to get the following-vehicle driver to look forward instead of continuing to look away. The time taken for a participant to redirect his/her skewed gaze back to the forward roadway (*Time To Look-up*) was measured and served as the main dependent measure.

- The duration between the initiation of the rear lighting and the participant's look-up response was obtained. The mean *Time To Look-up* for the *Main Bumper* configuration was found to be 0.579 s with a standard deviation (SD) of 0.225. The mean *Time To Look-up* for the *Baseline* configuration was found to be 0.7 s (SD.= 0.323). The first analysis performed using *Time To Look-up* as the primary variable of interest was a one-way between-subjects Analysis of Variance (ANOVA). Although not significant at $p < 0.05$, results demonstrated a positive trend with $F(1,46) = 2.26$, $p = 0.1392$. Participants receiving the *Main Bumper* configuration took less *Time To Look-up* to the forward roadway than did participants receiving the *Baseline* configuration (although this was not a statistically significant difference, this may have resulted from insufficient statistical power).
- The mean *Time To Look-up* values did show an observed practical difference and benefit. Converting the mean *Time To Look-up* values (0.579 s for main bumper and 0.7 s for baseline brake lights) to distance traveled at 55 mi/h (88.51 km/h) equates to 46.72 ft and 56.47 ft, respectively (14.24 m and 17.21 m, respectively). Therefore, drivers, on average, were traveling approximately 10 ft (3.05 m) further without looking at the roadway when exposed to the baseline brake light condition as compared to the main bumper rear warning-light configuration. According to the results found from the GES analysis performed, of the crashes for which attempted crash avoidance maneuvers were known, the driver of the striking vehicle attempted a braking maneuver in 70.7 percent of SUT rear-end crashes and in 61.6 percent of CUT rear-end crashes. The additional 10 ft (3.05 m) afforded by the main bumper rear warning-light configuration may reduce the occurrence (or crash severity) of rear-end crashes by providing additional time and distance needed for the following vehicle to successfully come to a stop.

Conclusions

Overall, the ERS system was robust in real-world driving conditions. Results indicated that the system in its current state performed well at detecting rear-end crash threats and drawing the gazes of following-vehicle drivers back to the forward roadway, and resulted in minor following-vehicle unintended consequences during fair weather and daylight hours. Although the analysis of eye-drawing capability was not statistically significant, there appears to be a strong trend that the *Main Bumper* configuration reduces the *Time To Look-up*. Radar target identification problems that produced higher number of false alarms were found during closed-loop activation sub-system testing at lower speeds and in high-traffic-density scenarios. The propensity of these false alarms should be addressed prior to data collection in an FOT with further radar firmware modifications, or other design modifications could be implemented such as non-activation or switching to an open-loop application at low travel speeds. Also, the current study's testing included real-world data collection during daylight hours and in fair weather (no rain or fog). Future work should investigate the potential need of rear warning-light brightness adjustments for adverse weather and lower-light conditions.

DEVELOPMENT OF FIELD OPERATIONAL TEST

Although much has been learned in Phase III of this project, a requirement prior to regulation is the conduct of a large-scale data collection effort in a real-world, naturalistic environment. Although Phase III does not involve collection of any data to address this requirement, the current report represents a detailed FOT plan to test the most promising countermeasure in a fleet environment. The research team has identified three ERS system development efforts that should be performed prior to data collection in an FOT: (1) testing the eye-drawing capability and associated discomfort glare of the proposed rear warning-light system during nighttime conditions, (2) refinement of the radar target identification firmware as well as transfer the activation sub-system algorithm processing from the vehicle data acquisition system (DAS) to the radar firmware unit, and (3) design and modify the ERS system into a unit designed for simple truck and trailer installation. In regard to the FOT plan, research questions were developed. The key research topics to be focused on include (1) ERS Activation Sub-system Performance and (2) Following Vehicle Driver Behavior. The performance of the ERS Activation Sub-system should be assessed through questions about correct detections and correct rejections. The following vehicle driver behavior will be assessed through acceleration data, the system's eye-drawing capability, and the occurrences of unintended actions by adjacent traffic. This testing will involve recruiting carriers, instrumenting 32 heavy trucks, collecting operational data for one year, and testing the hypotheses of the aforementioned research topics. The results of this evaluation will be used to develop preliminary estimates of reliability and effectiveness of the ERS system prior to regulatory decisions by the U.S. Government.

1. INTRODUCTION

The Enhanced Rear Signaling (ERS) for Heavy Trucks project was directed at investigating methods to reduce or mitigate those crashes where a heavy truck has been struck from behind by another vehicle. During crash database analyses in the current project it was found that, in 2006, there were approximately 23,500 rear-end crashes involving heavy trucks which resulted in 135 fatalities and 1603 incapacitating injuries. This particular collision type results in higher-than-usual rates of fatalities and injuries compared to rear-end accidents in which the lead vehicle is a light vehicle. In 2008, heavy trucks were found to be 3.2 times more likely than other vehicles to be struck from behind in two-vehicle fatal crashes.[11] These crashes occur with sufficient frequency that they are a cause of concern within regulatory agencies. As part of the Federal Motor Carrier Safety Administration's (FMCSA) goal of reducing the overall number of truck crashes, this crash configuration is one that is important to the Agency.

Prior to the current effort, two phases of work had been completed. Phase I entailed a crash data analysis to determine the causal factors of these crashes and the development or identification of countermeasures to aid in reducing them. (See references 1, 2, 3 and 4.) These countermeasures included: adjustable intensity light-emitting diode (LED) brake lights with high-contrast, grime-resistant lenses, an ambient light sensor to make the lamps brighter in direct sunlight, brake lamps that were activated by engine braking, additional conspicuity markings, and a system that consisted of a sensor that detected and tracked a following vehicle with radar, as well as sounded an audible signal and illuminated a traffic-clearing lamp when the vehicle was following too closely or approaching at too high a rate of closure. Phase II entailed the development of a prototype system that incorporated the countermeasures from Phase I.[5] Each element of the prototype was evaluated and rated by 25 volunteers (licensed drivers) and by limited field testing (approximately 100 h on the road). In Phase II**,** it was found that there appeared to be potential benefits from using these countermeasures.

The purpose of the Phase III effort was threefold: (1) conduct a General Estimates System (GES) database analysis using the most recent data available to report various break-outs/characterizations of rear-end truck crashes, (2) explore the benefits of the countermeasures developed in Phases I and II, and (3) develop of a plan for a large-scale Field Operational Test (FOT) to assess countermeasures for rear-end truck crashes. In addition, Phase III utilized what had been learned in the rear-end crash avoidance work with light vehicles that was conducted by the National Highway Traffic Safety Administration (NHTSA).[6]

1.1 REPORT STRUCTURE

The current report details all steps completed during Phase III. These steps are briefly described in this section so that the reader can understand the logical progression of events that took place.

GES Database Analysis Update 2006

A GES database analysis using data from 2006 was performed to report various break-outs/characterizations of rear-end truck crashes. A selection of this analysis will be reported in this section.

Auditory Warning System

Overall, two different exterior auditory signal devices were designed, developed, and tested in a static environment with the use of three signal types (sounds). The objective of this development process was to determine if an appropriate narrow-beam-width system could be built in order to maintain the majority of the signal in the lane directly behind a heavy truck.

Visual Warning System

Development and testing of multiple visual rear-signal types (normal brake lighting, rear warning-light configurations, and passive conspicuity markings) was performed in both static and dynamic environments. The purpose of both the static testing and the dynamic testing was to determine how well various rear-lighting configurations would provide improved eye-drawing capabilities, as well as to investigate the effects of two passive conspicuity markings on following distance behavior of drivers in a following vehicle.

Activation Sub-system

This effort consisted of the modification of previously developed activation (triggering) algorithms and testing their performance. Both an open-loop activation sub-system and a closed-loop activation sub-system were selected, developed, and tested in a dynamic setting on an experimental combination-unit truck (CUT) on the Virginia Smart Road.

Real-world Data Collection

A dynamic evaluation of a final ERS system was conducted on public roadways in order to observe and measure the reaction of the driving public. Observations of following-vehicle driver behavior behind an experimental CUT took place on multiple road types and in various driving scenarios. The final ERS system consisted of a "main bumper" rear warning-light system as well as a radar-based closed-loop activation sub-system.

Field Operational Test Plan

A requirement prior to regulation is the conduct of a large-scale data collection effort in a real-world, naturalistic environment. Although Phase III did not involve collection of any data to address this requirement, work included the development of a detailed FOT plan to test the final ERS system in a fleet environment.

2. GES DATABASE ANALYSIS UPDATE 2006

2.1 INTRODUCTION

The research team completed analyses of rear-end crashes involving trucks using 2006 crash data. The crash data used were collected by NHTSA and compiled in the National Automotive Sampling System (NASS). NASS is comprised of two systems – the Crashworthiness Data System (CDS) and the GES. These systems represent a sample of police crash reports. While the CDS focuses on passenger-vehicle crashes and is used to investigate injury mechanisms and identify potential improvements in vehicle design, GES focuses on presenting an overall crash analysis which can be used for assessing the size of problems and for tracking trends.(7)

Data included in the CDS and the GES have been drawn from select crashes using police accident reports (PARs) obtained from police agencies around the country. The reports are selected from randomly chosen areas of the country and include counties and major cities that are statistically representative of the United States as a whole. The PARs from which the GES data are coded are a probability sample of police-reported crashes, and because each crash had a chance of being selected, the national estimates and probable errors associated with the estimates can be calculated.(12) The national estimates may differ from the actual values because they are based on a probability sample of crashes, not a true census of crashes in the United States.(12) This report used 2006 NASS-GES data as the primary source of crash statistics cited within this report. A selection of the GES analyses performed are presented in this section of the report. All remaining analyses are provided in appendix A. Most statistics reported are rounded to one decimel point (tenths) in order to maintain similarity in presentation to work reported in Phase I.(2,3,4)

2.2 OVERALL TRUCK STATISTICS

2.2.1 Truck Population

Each year, the Bureau of Transportation Statistics (BTS) compiles and publishes the *National Transportation Statistics.*(13) The *National Transportation Statistics*, which is a presentation of statistics on the U.S. transportation system, including its physical components, safety record, economic performance, the human and natural environment, and national security. BTS distributes the truck population into two primary categories:

- Single-unit trucks (SUTs), those non-articulated trucks designed to carry cargo on the same chassis as the power unit.
- CUTs, those fifth-wheel-equipped tractor-trailer power units.(12)

Table 1 shows that in 2006 there were 8,819,007 registered trucks in the United States. Additionally, there were more than three times as many SUTs as compared to CUTs.

Table 1. Breakdown of Heavy-Truck Population in 2006

Truck Type	Registered
SUT	6,649,337
CUT	2,169,670
Total	8,819,007

2.2.2 Trucks as Part of the Crash Population

According to NHTSA's *Traffic Safety Facts*, in 2006, there were 10,584,000 total vehicles involved in all vehicle crashes.[(14)] Figure 5 provides a breakdown of the population of all vehicle crashes by vehicle type. *Passenger Cars,* as defined by NHTSA, were involved in 5,864,000 of all vehicle crashes. *Light Trucks* (including sport utility vehicles [SUVs], minivans, and pick-up trucks) accounted for 4,156,000 of all vehicle crashes. Heavy trucks, including both CUTs and SUTs, comprised 385,000 of all vehicle crashes. Figure 6 shows the truck categories involved in all vehicle crashes, specifically:

- 1,142 crashes involved step vans.
- 3,540 crashes involved medium/heavy truck-based motor homes.
- 136,737 crashes involved SUTs.
- 176,108 crashes involved truck-tractors (cab only, or any trailing units).

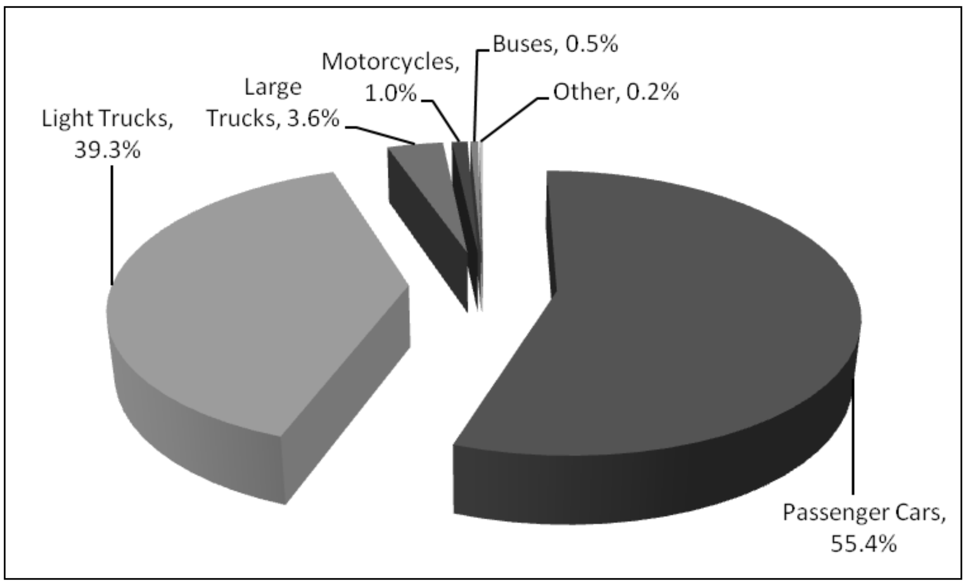

Figure 5. Pie chart. All crash types population by vehicle type.

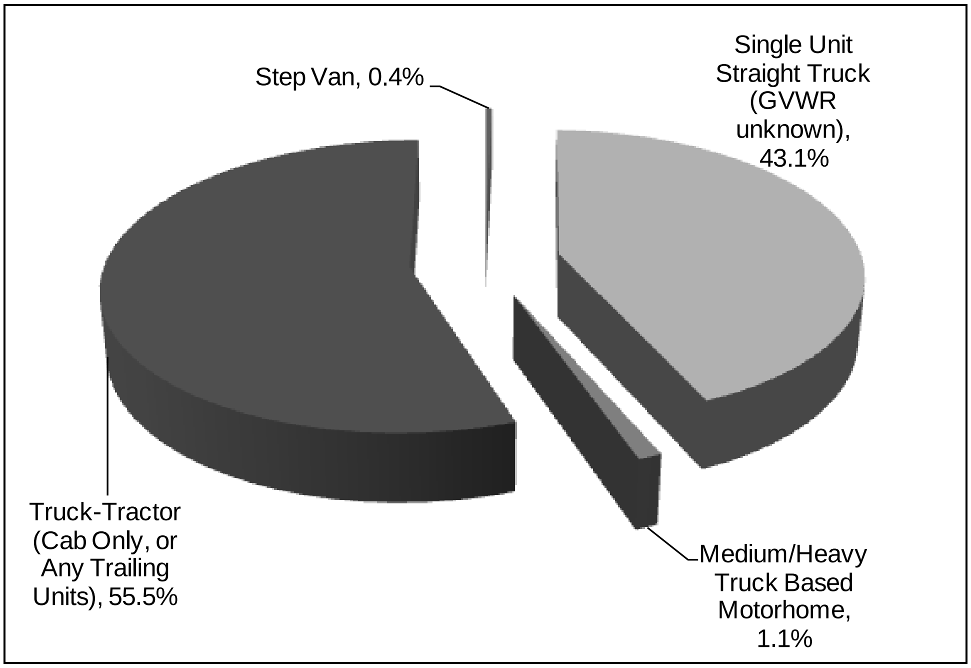

Figure 6. Pie chart. Population of heavy trucks involved in all crash types.

2.3 OVERALL REAR-END CRASH STATISTICS FOR HEAVY TRUCKS

The analyses in this section focused on rear-end crashes with primary focus on the variable *Accident Type*. Additionally, the distribution of rear-end *Accident Types* for heavy trucks was explored.

2.3.1 Rear-end Crashes as Part of the Heavy-truck Crash Population

This analysis used the GES variable *Accident Type* to examine crashes based on category, configuration, and type.

Crash categories include:

- *Single Driver*
- *Same Trafficway – Same Direction*
- *Same Trafficway – Opposite Direction*
- *Changing Trafficway – Vehicle Turning*
- *Intersecting Paths – Vehicle Damage*
- *Miscellaneous*

Crash categories were further broken down by crash configurations. The rear-end crash configuration, the focus of this analysis, fell within the *Same Trafficway-Same Direction* crash category.

Configurations were then narrowed into the 14 variables (GES numbers 20 – 33) as follows:[12]

- (20) *Rear-End: Stopped*: Vehicle impacts another vehicle from the rear when the impacted vehicle was stopped in the trafficway.

- (21) *Rear-End: Stopped, Straight*: When a rear-impacted vehicle was stopped in the trafficway, and was intending to proceed straight ahead.
- (22) *Rear-End: Stopped, Left*: When a rear-impacted vehicle was stopped in the trafficway and was indicating to make a left turn.
- (23) *Rear-End: Stopped, Right*: When a rear-impacted vehicle was stopped in the trafficway, intending to make a right turn.
- (24) *Rear-End: Slower*: When a vehicle impacts another vehicle from the rear when the impacted vehicle was going slower than the striking vehicle.
- (25) *Rear-End: Slower, Going Straight*: When a rear-impacted vehicle was going slower than the other vehicle while proceeding straight ahead.
- (26) *Rear-End: Slower, Going Left*: When a rear-impacted vehicle was going slower than the other vehicle while turning left.
- (27) *Rear-End: Slower, Going Right*: When a rear-impacted vehicle was going slower than the other vehicle while turning right.
- (28) *Rear-End: Decelerating (Slowing)*: When a vehicle impacts another vehicle from the rear when the impacted vehicle was slowing down.
- (29) *Rear-End: Decelerating (Slowing), Going Straight*: When a rear-impacted vehicle was slowing down while proceeding straight ahead.
- (30) *Rear-End: Decelerating (Slowing), Going Left*: When a rear-impacted vehicle was slowing down while turning left.
- (31) *Rear-End: Decelerating (Slowing), Going Right*: When a rear-impacted vehicle was slowing down while turning right.
- (32) *Rear-End: Specifics, Other*: When rear-end crashes cannot be described as in 20-31.
- (33) *Rear-End: Specifics, Unknown*: When the PAR indicates a rear-end collision but no further classification is possible.

Figure 7 provides an illustration of the rear-end crash configurations. The intended motion of the lead vehicle (i.e., the heavy truck) is noted.(12)

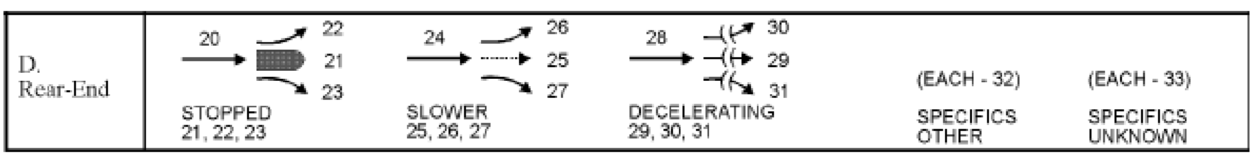

Figure 7. Diagram. Illustration of GES coding of rear-end crashes.

The distribution of crash types for heavy trucks is presented in figure 8. *Single Driver-Right Roadside Departure* was the largest component of the crash population, followed by *Same Direction Rear-end*, *Same Direction Sideswipe Angle*, and *Miscellaneous*.

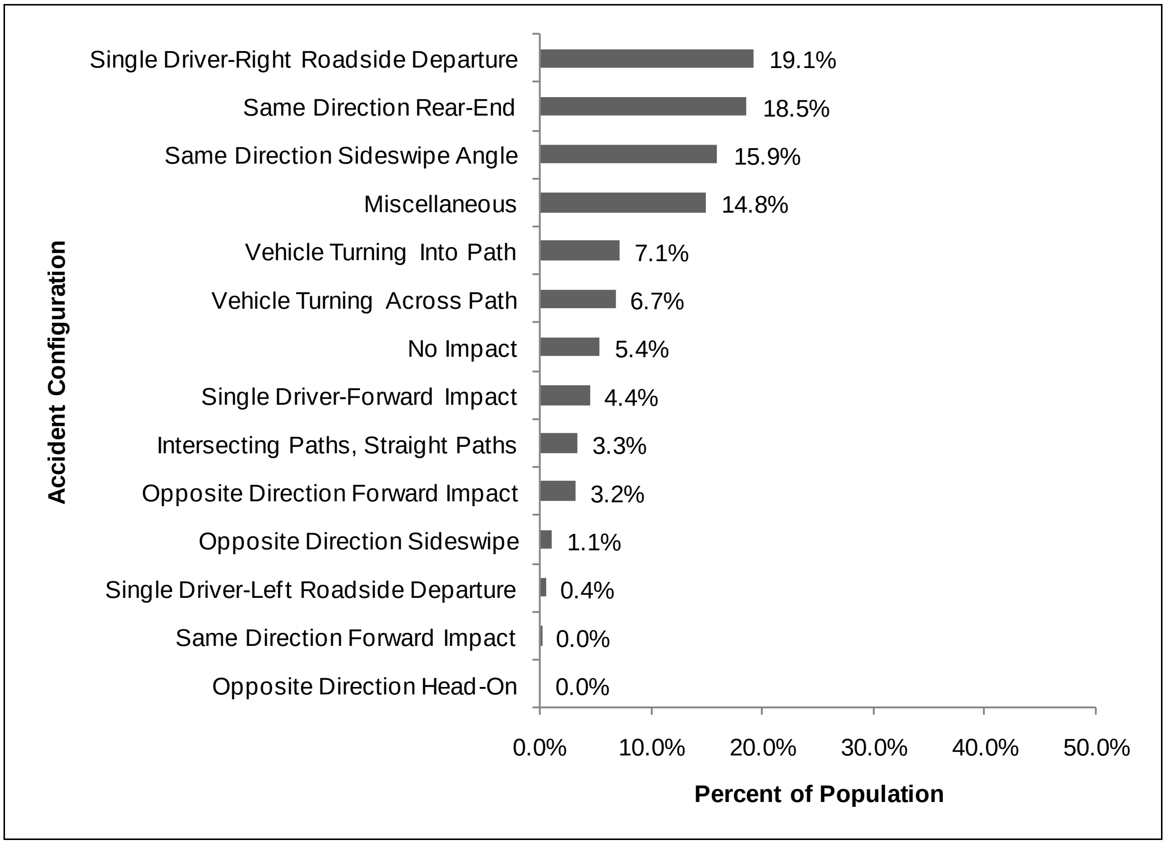

Figure 8. Bar graph. *Accident Type* populations for heavy trucks.

In each of these configurations, the struck vehicle was the heavy truck. The three most common configurations of rear-end crashes were:

- *Rear-End Stopped* (struck vehicle is at rest) (47.9 percent).
- *Rear-End Slower* (struck vehicle is moving at a slower speed than the striking vehicle) (29.7 percent).
- *Rear-End Decelerating* (struck vehicle is slowing to a stop) (22.5 percent).

When looking at the crash severity of rear-end crashes within those three configurations, there were 135 fatalities, 1,603 incapacitating injuries, 2,074 non-incapacitating injuries, and 2,711 possible injuries. The most serious injuries (i.e., non-incapacitating injuries and incapacitating injuries) occurred within the *Lead-vehicle Stopped* configuration, which had 1,621 serious rear-end crashes. The laws of physics may provide an explanation for the larger proportion of serious injuries for the *Lead Vehicle Stopped* configuration. Kinetic energy, which is derived from the mass and speed of the vehicles, is directly proportional to the speed differential between the lead and striking vehicles. Since the kinetic energy involved in the rear-end crash varies as the square of the vehicle's velocity, a small increase in the speed will lead to large increases in injury risk.[15]

Table 2 provides a listing of the counts and percentages for each rear-end crash configuration Accident Type. The values listed in each of the accident types were a percentage of those crashes where the truck was struck.

Table 2. Expansion of Rear-End Accident Type for Heavy Truck Categories

Configuration	Count	Percent
Rear-end – Stopped (21)	9,919	42.2
Rear-end – Stopped (22)	812	3.5
Rear-end – Stopped (23)	518	2.2
Rear-end – Slower (25)	6,734	28.6
Rear-end – Slower (26)	83	0.4
Rear-end – Slower (27)	161	0.7
Rear-end – Decelerating (29)	4,358	18.5
Rear-end – Decelerating (30)	384	1.6
Rear-end – Decelerating (31)	540	2.3
Total	23,508	100
Note. All figures rounded to the nearest integer.		

2.4 REAR-END CRASH CHARACTERISTICS BY TRUCK BODY TYPE

The team examined rear-end crash characteristics based on heavy-truck body type. Two separate analyses were performed, one for SUTs and one for CUTs, which explored crash location, roadway, environment and lighting characteristics, and actions of the heavy truck. Actions of the truck included the truck's movement prior to the critical event and corrective action attempted by the driver in the heavy truck. Maximum injury severity data were also included. The section concludes with two concurrent analyses, one for SUTs and one for CUTs, which present data regarding the striking vehicle's maneuvers.

SUTs and CUTs comprised 98.6 percent of the rear-end crashes involving heavy trucks. However, SUTs and CUTs are fundamentally different – in both body design and use. Consequently, rear-end crash characteristics for both SUTs and CUTs will be presented separately in the sections that follow.

2.4.1 Population of Rear-end Crashes Involving SUTs

Table 3 presents the rear-end crash statistics for SUTs. These data are a subset of the data presented in table 2. Just as the majority of the crashes for all heavy trucks occurred in the *Rear-end Stopped*, *Slower*, and *Decelerating* crash configurations, so too did most of the SUT crashes. Half of all SUT rear-end crashes occurred in the *Rear-End Stopped* configuration. The *Rear-End Slower* and *Rear-End Decelerating* crash configurations accounted for a combined 50 percent of the SUT-involved rear-end crashes.

Table 3. Expansion of Rear-End Accident Type for SUT Category Body Type

Configuration	Count	Percent
Rear-end – Stopped (21)	5,538	43
Rear-end – Stopped (22)	728	6
Rear-end – Stopped (23)	180	1
Rear-end – Slower (25)	3,679	29
Rear-end – Slower (26)	29	0
Rear-end – Slower (27)	70	1
Rear-end – Decelerating (29)	2,214	17
Rear-end – Decelerating (30)	256	2
Rear-end – Decelerating (31)	123	1
Total	12,818	100
Note. All figures rounded to the nearest integer.		

2.4.2 Where Do SUT Rear-end Crashes Occur?

Using the GES *Land Use* variable it was possible to determine whether or not a crash occurred in a rural, suburban, or urban area through the use of population indicators. Potential values for the *Land Use* variable were 25,000 to 49,999 residents (i.e., rural crashes), 50,000 to 100,000 residents (i.e., suburban crashes), and more than 100,000 residents (i.e., urban crashes). The *Other* category was used to represent a location within a city or town that does not match the other listed values.

The distribution of SUT rear-end crashes with respect to location is shown in figure 9. The largest percentage of SUT rear-end crashes occurred in areas described as *Other*. When combined with the rear-end crashes that occurred in urban areas of more than 100,000 residents, 70 percent of the SUT rear-end crashes were accounted for. A moderate percentage, 19.1 percent, occurred in suburban areas. Only 10.9 percent of rear-end SUT crashes occurred in rural areas.

Figure 10 illustrates the distribution of rear-end crashes between the Interstate Highway System (IHS) and other roadways. The term *Interstate Highway* is a Federal Highway Administration (FHWA) designation for those roadways that are part of the Dwight D. Eisenhower System of Interstate and Defense Highways.(12) As shown in figure 10, almost six times as many rear-end crashes occurred on non-IHS roadways as on IHS roadways.

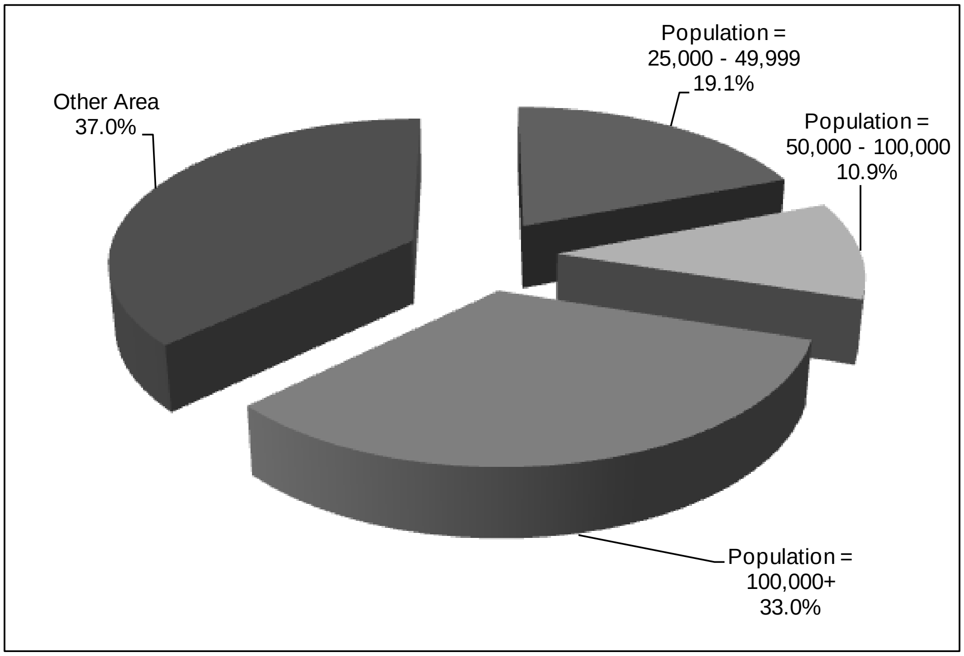

Figure 9. Pie chart. Location of SUT rear-end crashes.

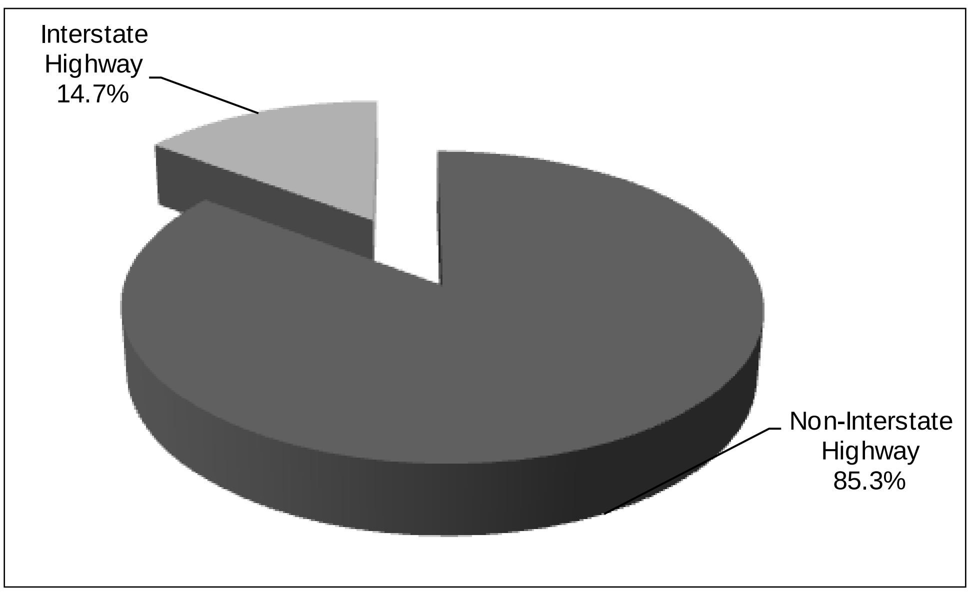

Figure 10. Pie chart. SUT rear-end crashes occurring on *Interstate Highways*.

The data file *Relation to Junction* allows one to determine where in the roadway SUT rear-end crashes occur. *Relation to Junction* describes where the first event occurred that led to the rear-end crash and is divided into *Interchange* and *Non-Interchange* areas.[(12)] The *Interchange* is defined as the area around a grade separation that involves at least two trafficways, and includes all ramps which connect the roadway and each roadway entering or leaving the interchange to a point 30 m beyond the gore or curb return at the outermost ramp connection for the roadway.

Of the SUT rear-end crashes, 55.5 percent occurred at *Non-interchange/Non-junction* areas. These are areas described as being between intersections and excluded from other categories. As shown in figure 11, 27.7 percent of the SUT rear-end crashes were *Non-interchange – Intersection Related*, meaning the rear-end crash occurred on the approach to the intersection. Only 3 percent of the rear-end crashes occurred within the intersection.

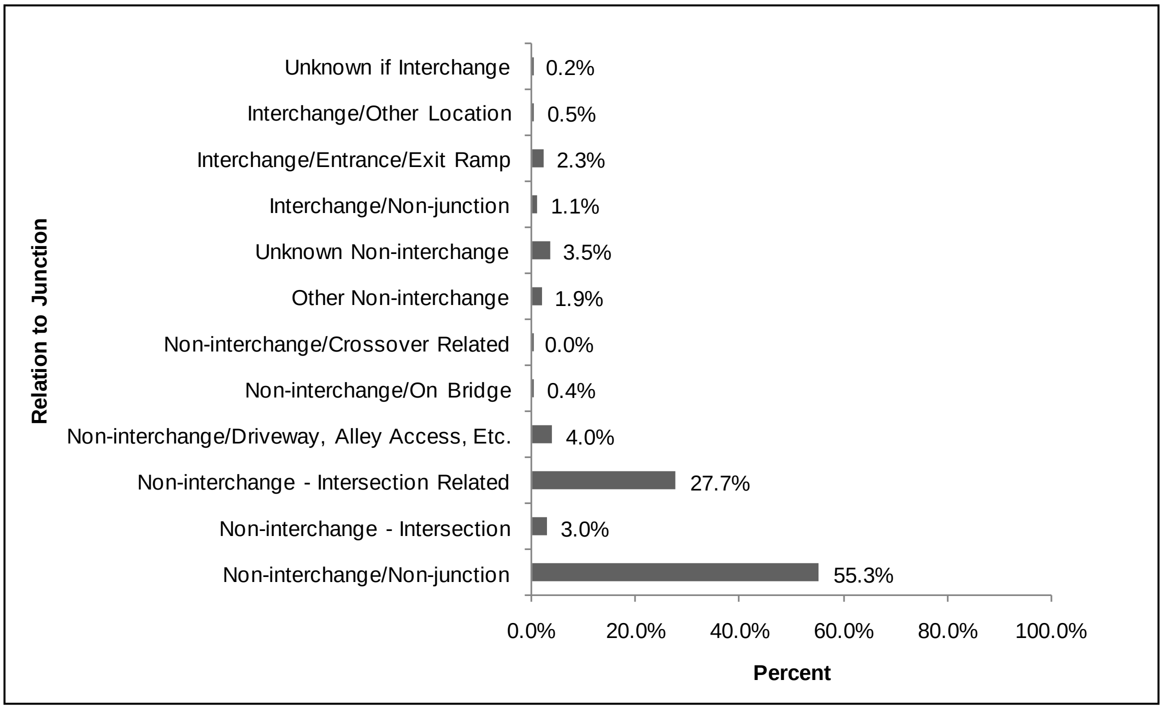

Figure 11. Bar graph. *Relation to Junction* for SUT rear-end crashes.

2.4.3 Roadway Characteristics Where Rear-end Crashes Occur

Characteristics such as trafficway flow, the number of traffic lanes on the road, roadway alignment, and *Speed Limit Range* were determined for the roadways where SUT rear-end crashes occurred.

The variable *Trafficway Flow* was used to describe the configuration of the roadway.[(12)] Possible configurations were *One-Way Trafficway*, *Divided Highway* (i.e., those highways that are physically divided by a median or barrier), *Not Physically Divided*, and *Unknown*. Figure 12 illustrates the distribution of roadway types where SUT rear-end crashes occurred. Rear-end SUT crashes occurred 46.1 percent of the time on *Not Physically Divided Trafficways* versus the 37.2 percent which occurred on *Divided Highways*. These numbers reflect an increase in the number of rear-end crashes on *Not Physically Divided Trafficways* since 2001. In 2001, rear-end crashes occurring on *Not Physically Divided Trafficways* (41.4 percent) and *Divided Highways* (42.2 percent) were almost equally distributed.

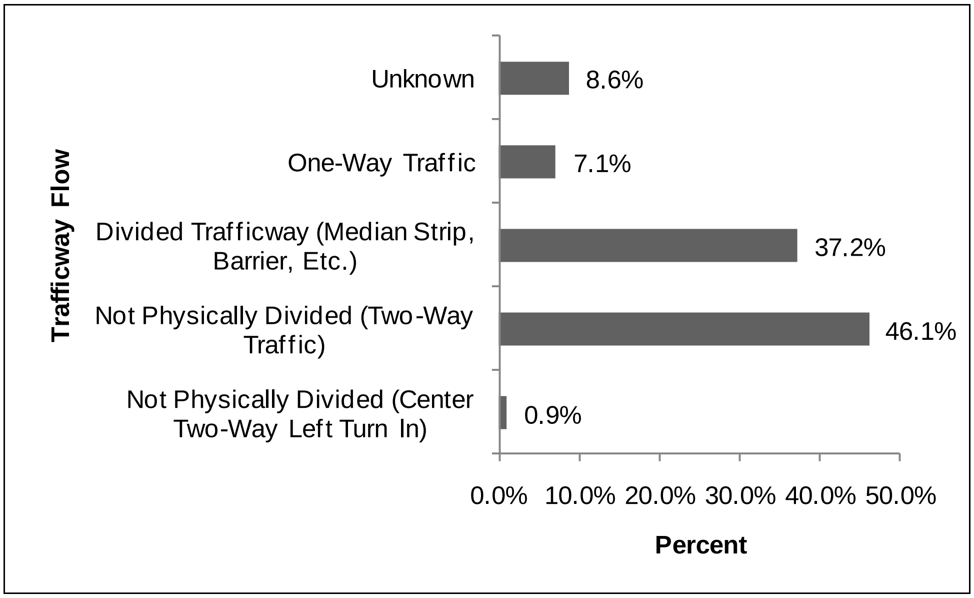

Figure 12. Bar graph. *Trafficway Flow* for SUT rear-end crashes.

The number of traffic lanes on the roads where the SUT rear-end crashes occurred is illustrated in figure 13. SUT rear-end crashes on two-lane roads decreased from 48.2 percent in 2001 to 35.7 percent in 2006. Conversely, the percent of rear-end crashes that occurred on four-lane roads increased from 8.6 percent in 2001 to 13.3 percent in 2006. The percent of rear-end crashes that occurred on all two-lane, three-lane, four-lane and unknown roadways for 2006 was 91.1 percent (compared to 96.6 percent in 2001). In both instances, few rear-end crashes occurred on roadways with very few lanes (i.e., one-lane) or very high numbers of lanes (i.e., six or seven).

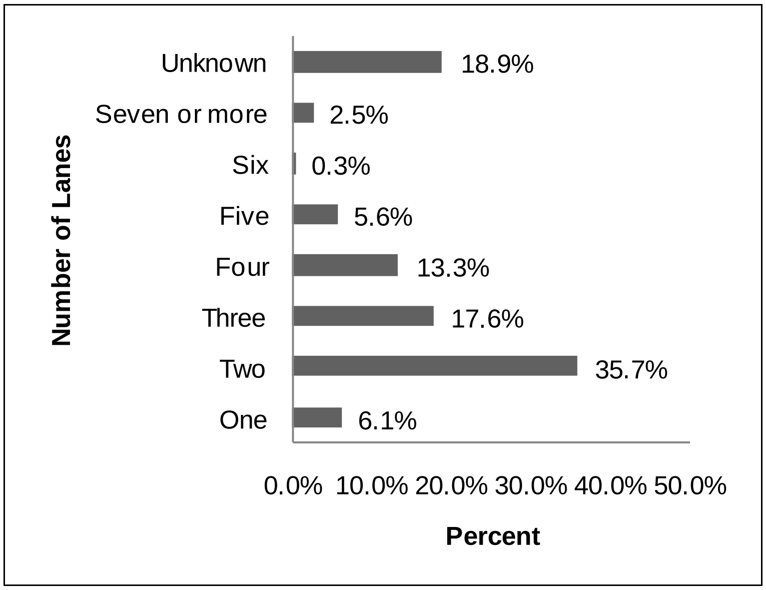

Figure 13. Bar graph. Number of lanes for SUT rear-end crashes.

2.4.4 Actions of the Truck Involved in the Crash

This section explored the actions of the struck SUTs immediately before the rear-end crash occurred. Actions of the SUTs (in this case, the vehicle being rear-ended) were determined using the *Movement Prior to the Critical Event* and *Corrective Action* variables. The *Movement Prior to the Critical Event* variable explored the action of the struck SUT just before it was hit from behind.(12) Figure 14 illustrates that the highest percentage (44.1 percent) of SUT rear-end crashes occurred when the SUT was stopped in a traffic lane, followed by the SUT going straight (24.5 percent) and decelerating in the traffic lane (18.8 percent).

The variable *Corrective Action* can be used to determine whether or not the driver of the SUT knew that a crash was inevitable and what, if any, actions were taken to avoid the crash.(12) As noted in figure 15, *No Avoidance Maneuver* was attempted in more than 54 percent of the rear-end crashes. This finding is consistent with the rear-end crash configuration *Rear-end Stopped*. It is unknown if the driver attempted an avoidance maneuver in 46.1 percent of the rear-end crashes.

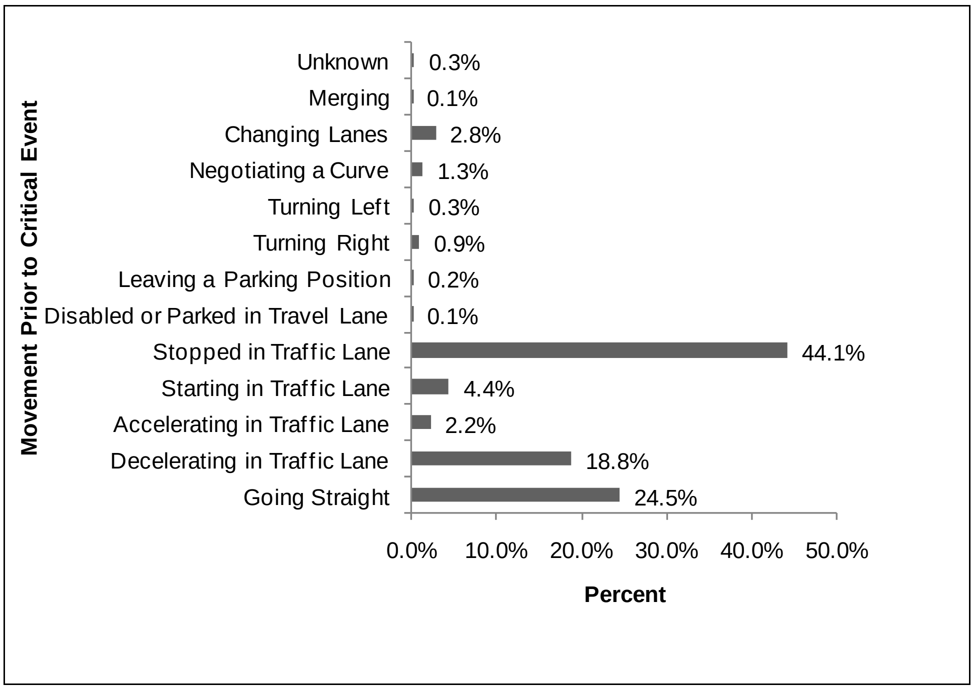

Figure 14. Bar graph. Truck movements prior to critical event for SUT rear-end crashes.

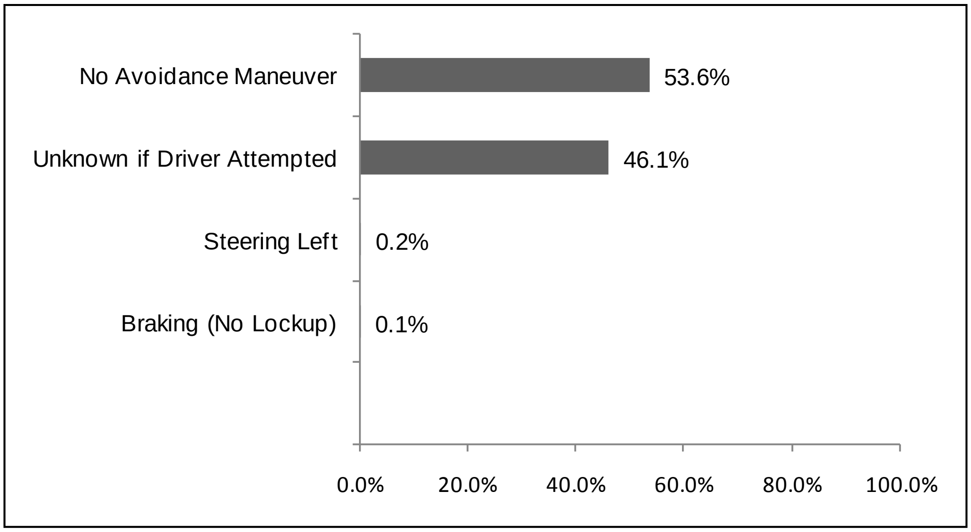

Figure 15. Bar graph. *Corrective Actions* attempted by truck drivers for SUT rear-end crashes.

2.4.5 Population of Rear-end Crashes Involving CUTs

Table 4 presents the rear-end crash statistics for CUTs. These data are a subset of the data presented in table 2. Just as the majority of the crashes for all heavy trucks and SUTs occurred in the *Rear-end Stopped*, *Slower*, and *Decelerating* categories, so too did most of the CUT rear-end crashes. Looking at the CUT rear-end crashes, 46 percent occurred in the *Rear-end Stopped* configuration. *Rear-end Slower* and *Rear-end Decelerating* crash configurations accounted for a combined 55 percent of the CUT-involved rear-end crashes.

Table 4. Expansion of Rear-End Accident Type for CUT Category Body Type

Configuration	Count	Percent
Rear-end – Stopped (21)	4261	42
Rear-end – Stopped (22)	60	1
Rear-end – Stopped (23)	337	3
Rear-end – Slower (25)	2767	27
Rear-end – Slower (26)	54	1
Rear-end – Slower (27)	90	1
Rear-end – Decelerating (29)	2143	21
Rear-end – Decelerating (30)	128	1
Rear-end – Decelerating (31)	416	4
Total	10257	100
Note. All figures rounded to the nearest integer.		

2.4.6 Where Do CUT Rear-end Crashes Occur?

The distribution of CUT rear-end crashes with respect to location is shown in figure 16. The largest percentage of CUT rear-end crashes occurred in the category of *Other Areas* (47.3 percent). When combined with the 26.1 percent of CUT rear-end crashes that occurred in urban areas of more than 100,000 residents, 73.4 percent of the CUT rear-end crashes were accounted for. A moderate percent of CUT rear-end crashes, 21.3 percent, occurred in suburban areas, while only 5.2 percent of rear-end CUT crashes occurred in rural areas.

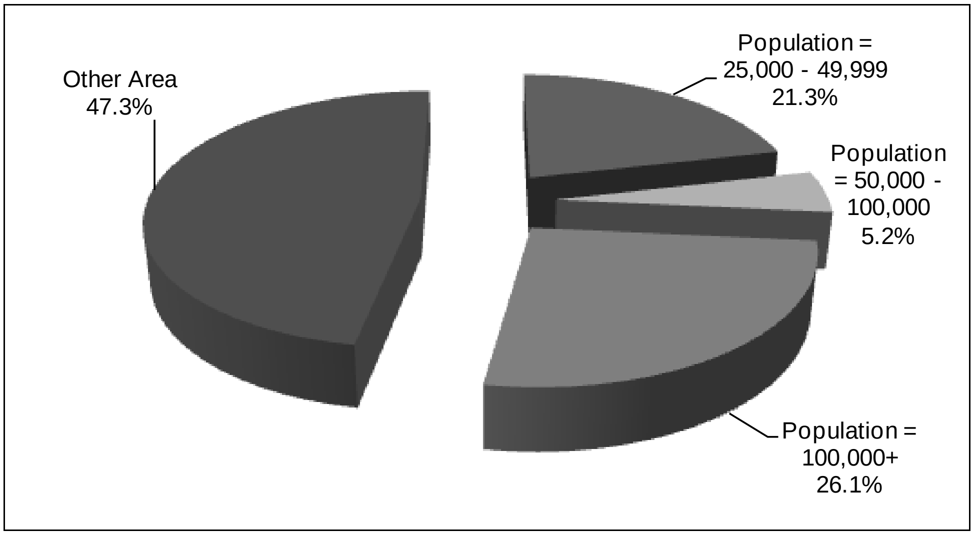

Figure 16. Pie chart. Location of CUT rear-end crashes.

Figure 17 illustrates the distribution of CUT rear-end crashes between the IHS and other roadways. While a much higher percentage of SUT rear-end crashes occurred on non-IHS roadways versus the IHS (approximately 85.3 percent versus 14.7 percent, respectively), CUT rear-end crashes were more evenly divided between non-IHS and IHS (58.1 percent versus 42 percent, respectively). This finding is consistent with the 2001 data and suggests that CUTs are used more commonly for long-haul and other shipping purposes than SUTs, which are used more for short-haul means.

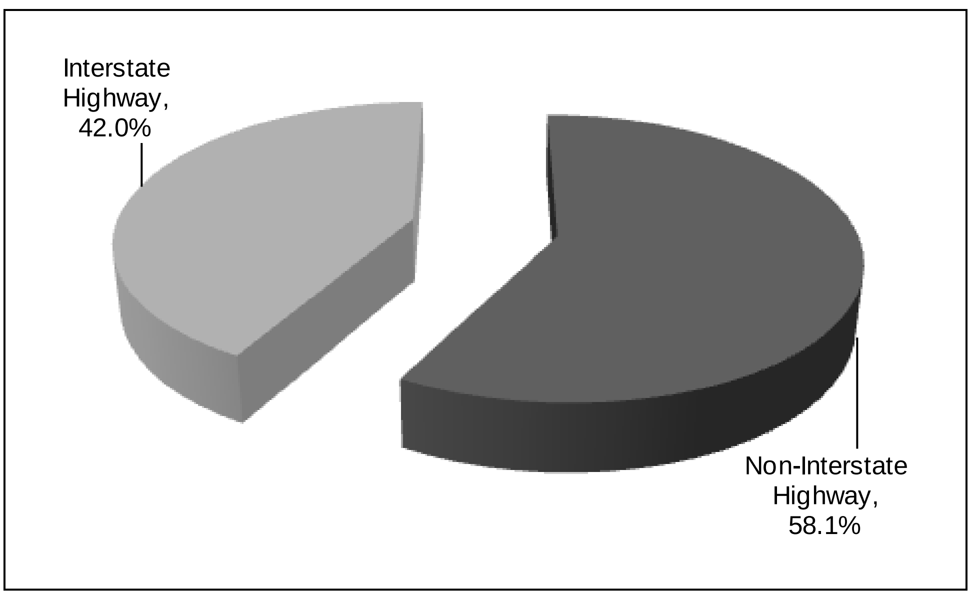

Figure 17. Pie chart. Percentage of CUT rear-end crashes occurring on *Interstate Highways*.

Using the data file *Relation to Junction*, one can determine where in the roadway the CUT rear-end crashes occurred. As shown in figure 18, 58.8 percent of the CUT rear-end crashes occurred at *Non-interchange/Non-junction* areas. These were areas described as being between intersections and excluded from other categories. For 25.8 percent of CUT rear-end crashes, the rear-end crash occurred in an area designated *Non-Interchange – Intersection Related*, meaning the crashes occurred on the approach to the intersection, while only 1.4 percent of the CUT rear-end crashes occurred within an *Intersection*.

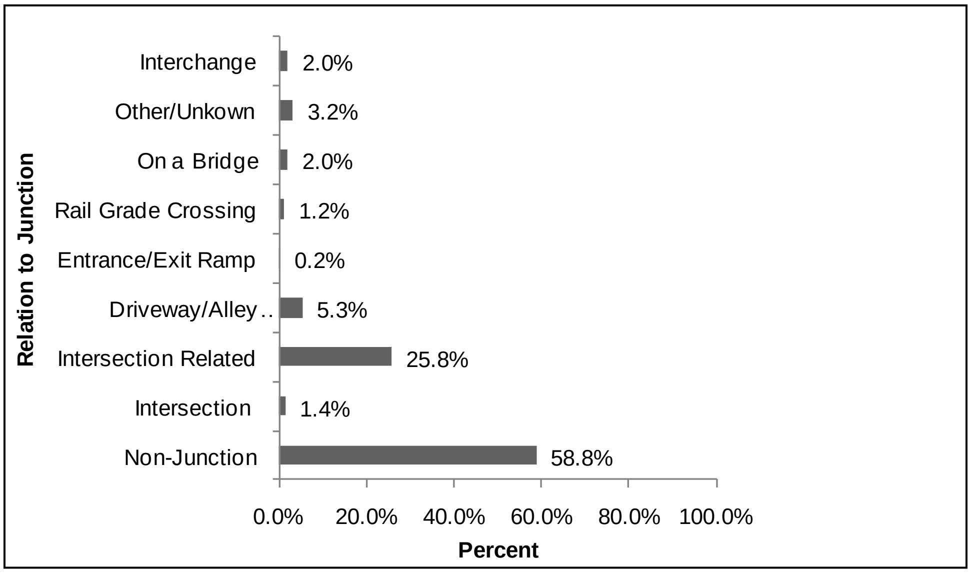

Figure 18. Bar graph. *Relation to Junction* for CUT rear-end crashes.

2.4.7 Roadway Characteristics Where Rear-end Crashes Occur

Characteristics such as trafficway flow, the number of traffic lanes on the road, *Roadway Alignment*, and *Speed Limit Range* can be determined for the roadways where CUT rear-end crashes occurred. The variable *Trafficway Flow* was used to describe the configuration of the roadway.[(12)] Figure 19 illustrates the distribution for roadway types for CUT rear-end crashes. Contrary to SUT rear-end crashes, which occurred primarily on *Not Physically Divided Trafficways*, CUT rear-end crashes occurred predominantly on *Divided Highways*. As shown in figure 19, most CUT rear-end crashes (62.2 percent) occurred on *Not Physically Divided Trafficways* versus 22.3 percent which occurred on *Divided Highways*.

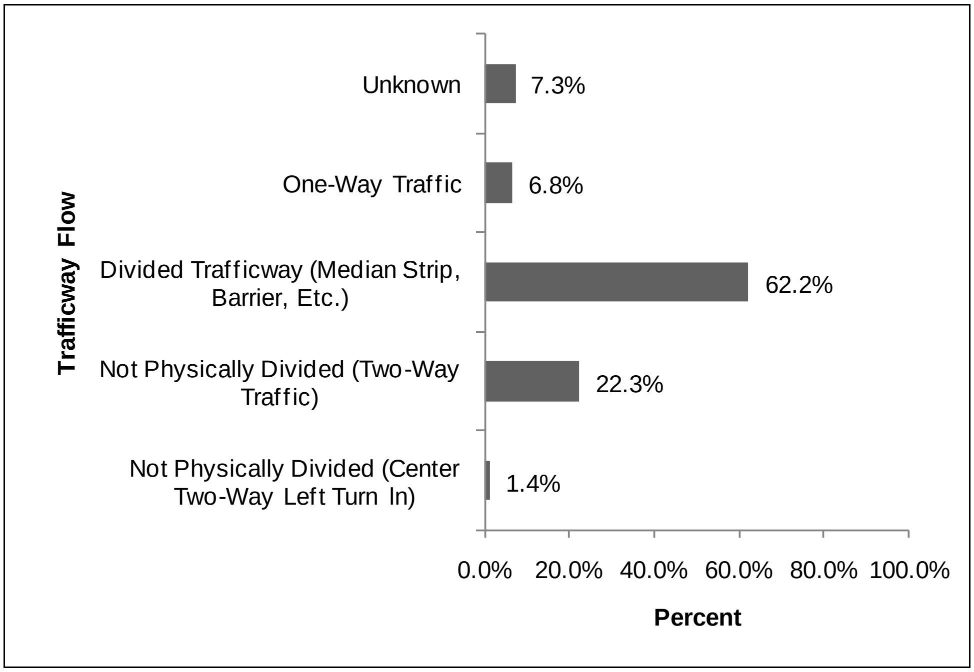

Figure 19. Bar graph. *Trafficway Flow* for CUT rear-end crashes.

The number of traffic lanes on the roads where the CUT rear-end crashes occurred is illustrated in figure 20. More than 44 percent of CUT rear-end crashes occurred on two-lane roadways. Since 2001, there has been an almost 5 percent increase in the number of CUT rear-end crashes occurring on roadways with four or more lanes (19.8 percent in 2006 compared to 15 percent in 2001).

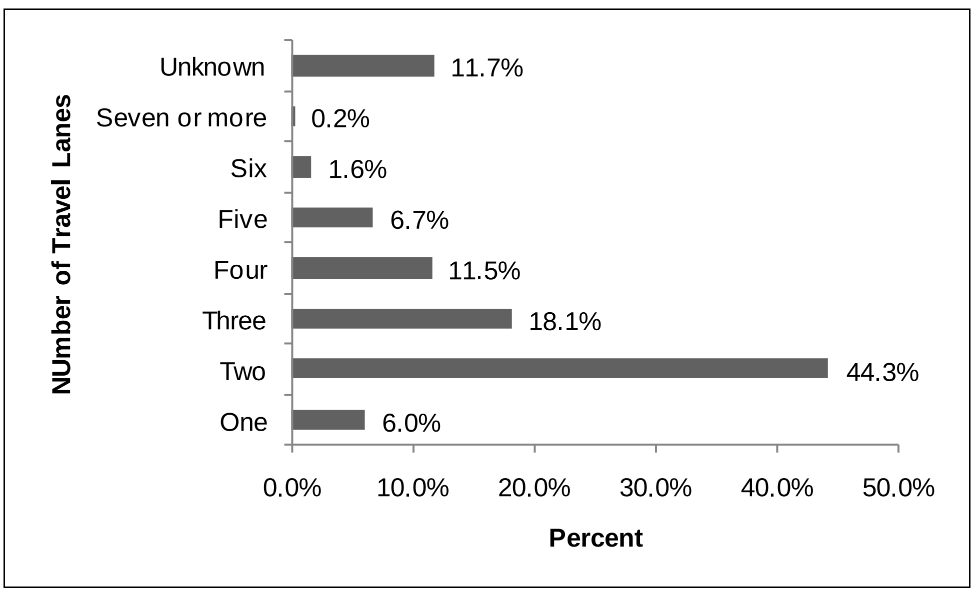

Figure 20. Bar graph. Number of lanes for CUT rear-end crashes.

2.4.8 Actions of the Truck Involved in the Crash

This section explores the actions of the CUTs immediately before the rear-end crash occurred. Actions of the CUTs – in this case, the vehicle being rear-ended – were determined using the *Movement Prior to the Critical Event* and *Corrective Action* variables. In 43.1 percent of the CUT rear-end crashes the CUT was stopped in a traffic lane (figure 21). The configurations *CUT Decelerating in the Traffic Lane* and *CUT Going Straight* were coded in approximately 24 percent of the CUT rear-end crashes.

The *Corrective Action* variable can be analyzed to determine whether or not the driver of the CUT knew that a crash was inevitable and what, if any, actions were taken to avoid the crash. Figure 21 illustrates the actions of the CUT drivers. As shown in figure 22, in 54.8 percent of the CUT rear-end crashes the driver took no *Corrective Action* to avoid the crash. In less than 5 percent of the CUT rear-end crashes the driver recognized the impending crash and made an attempt to avoid the crash.

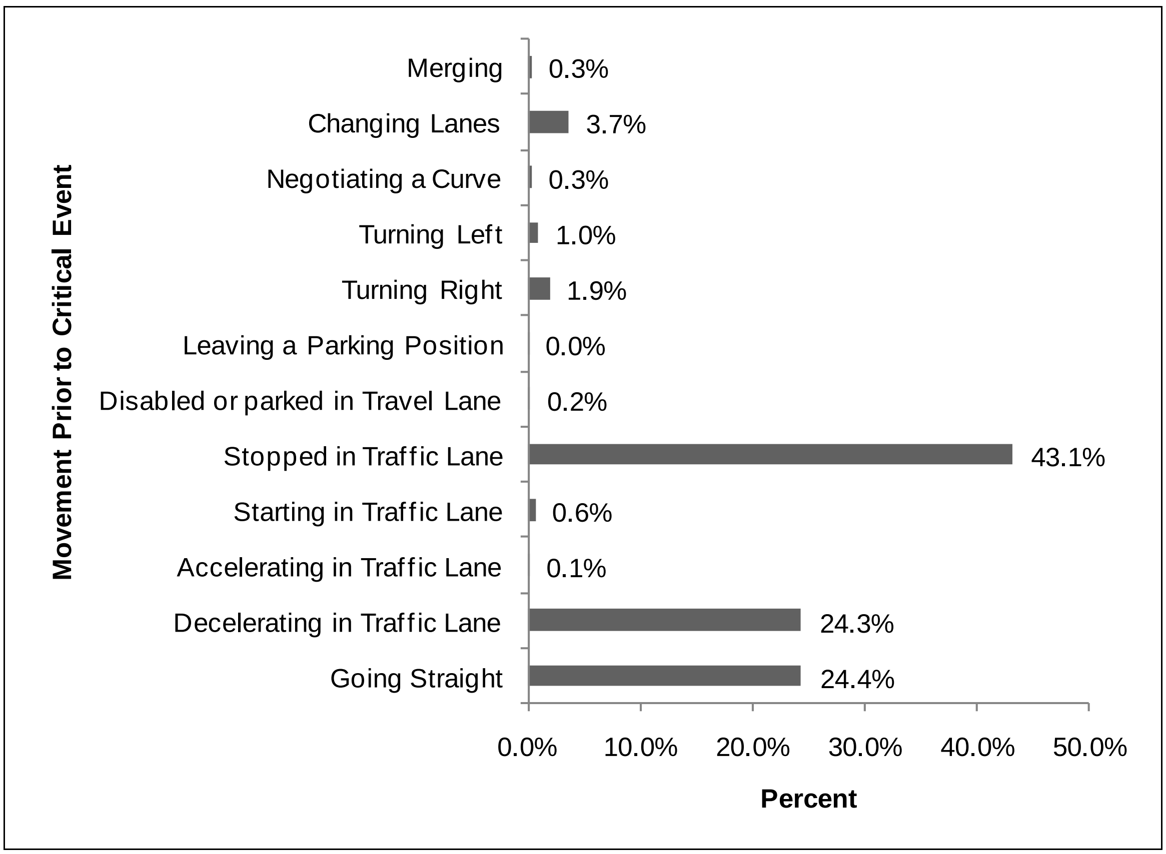

Figure 21. Bar graph. Truck movements prior to critical event for CUT rear-end crashes.

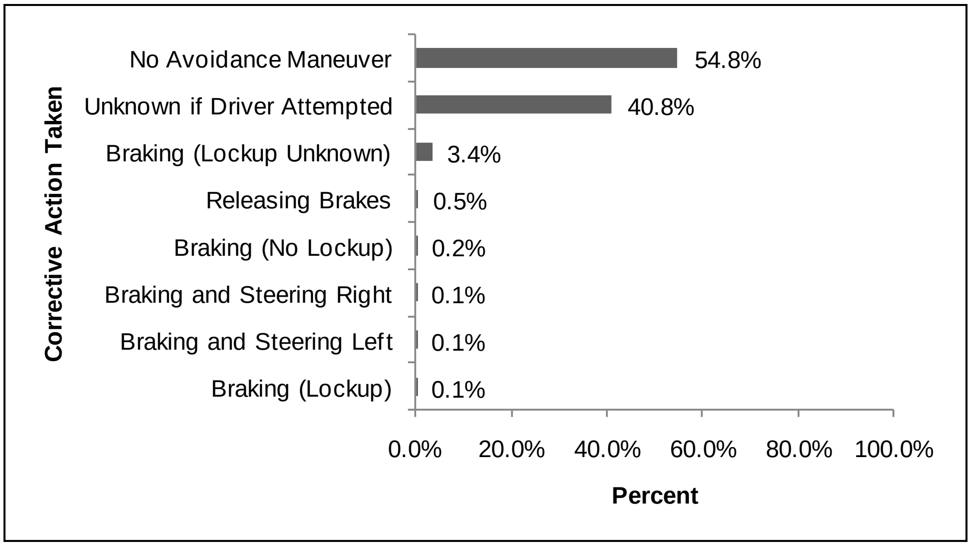

Figure 22. Bar graph. *Corrective Actions* attempted by truck drivers for CUT rear-end crashes.

2.4.9 Actions of Striking Vehicles in SUT and CUT Rear-end Crashes

When examining the actions of the striking vehicles in SUT and CUT rear-end crashes, the following findings stand out:

- In both SUT and CUT rear-end crashes, the majority of crashes occurred when both vehicles were traveling straight prior to the crash. For SUTs, the second most common movement was starting in the traffic lane. For CUTs, the second most common movement was decelerating in the traffic lane.
- For SUTs, more than 34 percent of rear-end crashes occurred when the striking vehicle was traveling 5 to 35 mi/h (8.05 to 56.33 km/h). CUT rear-end crashes were more likely than SUT rear-end crashes to have occurred when the traveling speed of the striking vehicle was 36 mi/h (57.94 km/h) or greater (21 percent for CUTs versus 13.6 percent in SUTs).
- For both SUTs and CUTs, the critical event for the striking vehicles was that the SUT or CUT was in a stopped position.
- Of the crashes for which attempted crash avoidance maneuvers were known, the driver of the striking vehicle attempted a braking maneuver in 70.7 percent of SUT rear-end crashes and 61.6 percent of CUT rear-end crashes. In CUTs, almost 12 percent of the braking maneuvers were accompanied by a steering maneuver.
- CUT rear-end crashes had a higher occurrence (29.1 percent versus 16 percent) of no avoidance maneuver than did SUT rear-end crashes.
- In approximately 90 percent of both SUT and CUT rear-end crashes, the driver of the striking vehicle was tracking, indicating that the driver had control of the vehicle and was not in a panic mode.
- In neither SUT nor CUT rear-end crashes were vehicle contributing factors significant contributors to the crash.

2.5 REAR-END CRASHES BY VEHICLE TYPE – PASSENGER VEHICLES VERSUS CUTS

Analyses included an examination of the overall rear-end crash profile for passenger vehicles and CUTs. As with the previous sections, the GES variable *Accident Type* was used to categorize rear-end crashes and consolidate these crashes into the three most common configurations. For the purposes of this report, passenger vehicle statistics were compiled using GES *Vehicle Attribute Codes 01-29*.[12] Additionally, for the remainder of the GES Truck Crash Statistics 2006 section, analyses involving heavy trucks refer to CUT body type heavy trucks.

2.5.1 Rear-end Crash Configurations for Passenger Vehicles and CUTs

Table 5 provides the *Accident Type* and the counts and percentages for each of these configurations as well as for a rear-end other/unknown category. Additionally, the values for each *Accident Type* are shown as a percentage of the rear-end problem in passenger vehicles and CUTs and are illustrated in figure 23 and figure 24, respectively.

There were a larger number of rear-end crashes involving passenger vehicles than CUTs. This is consistent with the larger number of passenger vehicles versus CUTs on the road. For both passenger vehicles and CUTs, the primary configuration was *Rear-End Stopped*. For passenger vehicles, the second most common configuration was *Rear-End Decelerating*. *Rear-End Stopped* and *Rear-End Decelerating* accounted for more than 86 percent of the passenger vehicle rear-end crashes. Within the CUT population, the *Rear-End Stopped* configuration was followed by the *Rear-End Slower* and *Rear-End Decelerating* configurations, of which the latter two account for a combined 52 percent of the rear-end crashes.

Table 5. Comparison of Rear-End Crash Populations for Passenger Vehicles and CUTs

Configuration	Passenger Vehicles (Count)	Passenger Vehicles (Percent)	CUTs (Count)	CUTs (Percent)
Rear-end – Stopped (21-23)	865,126	62	4,658	39
Rear-end – Slower (25-27)	123,042	9	2,912	25
Rear-end – Decelerating (29-31)	353,544	25	2,687	23
Rear-end – Other / Unknown (32-33)	63,982	5	1,576	13
Total	1,405,695	100	11,833	100
Note. All figures rounded to the nearest integer.				

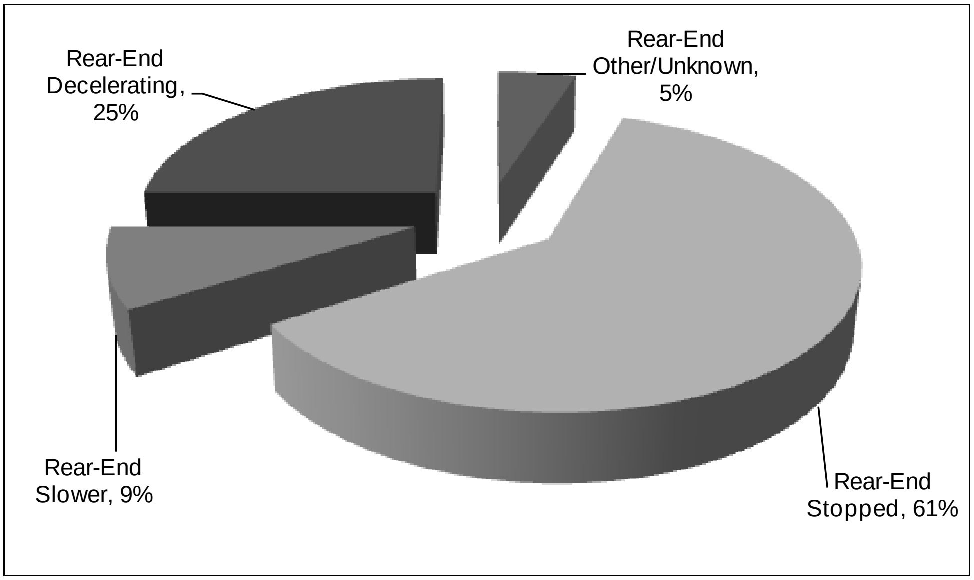

Figure 23. Pie chart. Rear-end crash distributions for passenger vehicle rear-end crashes.

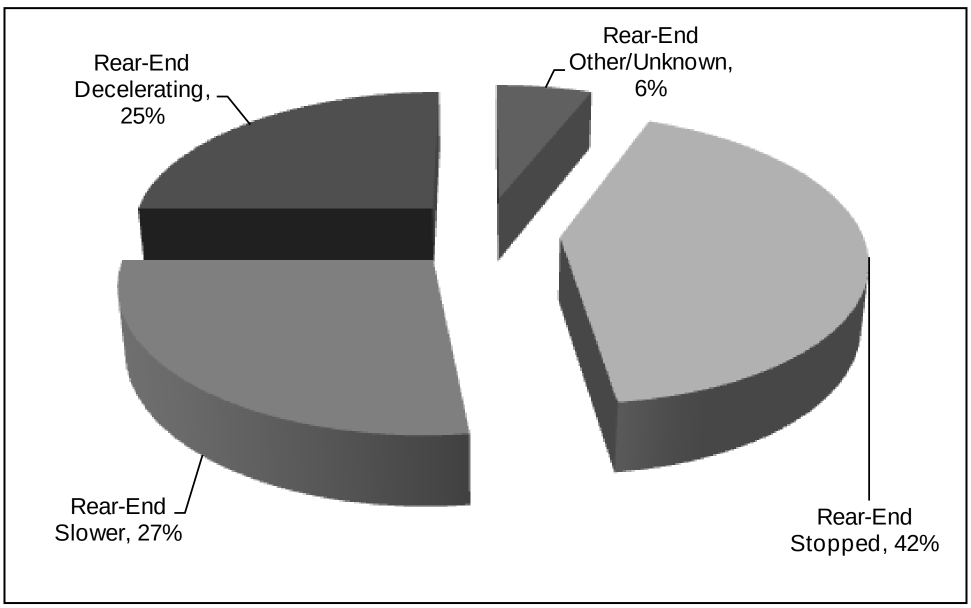

Figure 24. Pie chart. Rear-end crash distributions for CUT rear-end crashes.

2.5.2 Examining Rear-end Crash Characteristics

While both figure 22 and figure 23 illustrated that the majority of rear-end crashes in both passenger vehicles and CUTs were classified as *Rear-End Stopped,* the percentage of *Rear-End Stopped* crashes was much greater for passenger vehicles (61 percentage) than for CUTs (42 percent). Additionally, passenger vehicles and CUTs have very different configurations and purposes. Therefore, the following sections will look more closely at the differences in the crash records for these two vehicle configurations. Data will be presented first for passenger vehicles and then for CUTs in the following discussion.

2.5.3 Actions of the Vehicles Involved in the Crash

Figure 25 and figure 26 examine the *Corrective Action Attempted* variable in passenger vehicle and CUT rear-end crashes, respectively; that is, those actions attempted by the driver of the struck vehicle in response to impending danger. Looking at the *Corrective Action* variable provides insight as to whether or not the driver of the vehicle about to be struck recognized an impending rear-end crash and reacted to it (note that actions of the drivers striking both passenger vehicles and CUTs are examined in a later section). In 54.8 percent of both passenger vehicle rear-end crashes and CUT rear-end crashes, no avoidance maneuver was attempted.

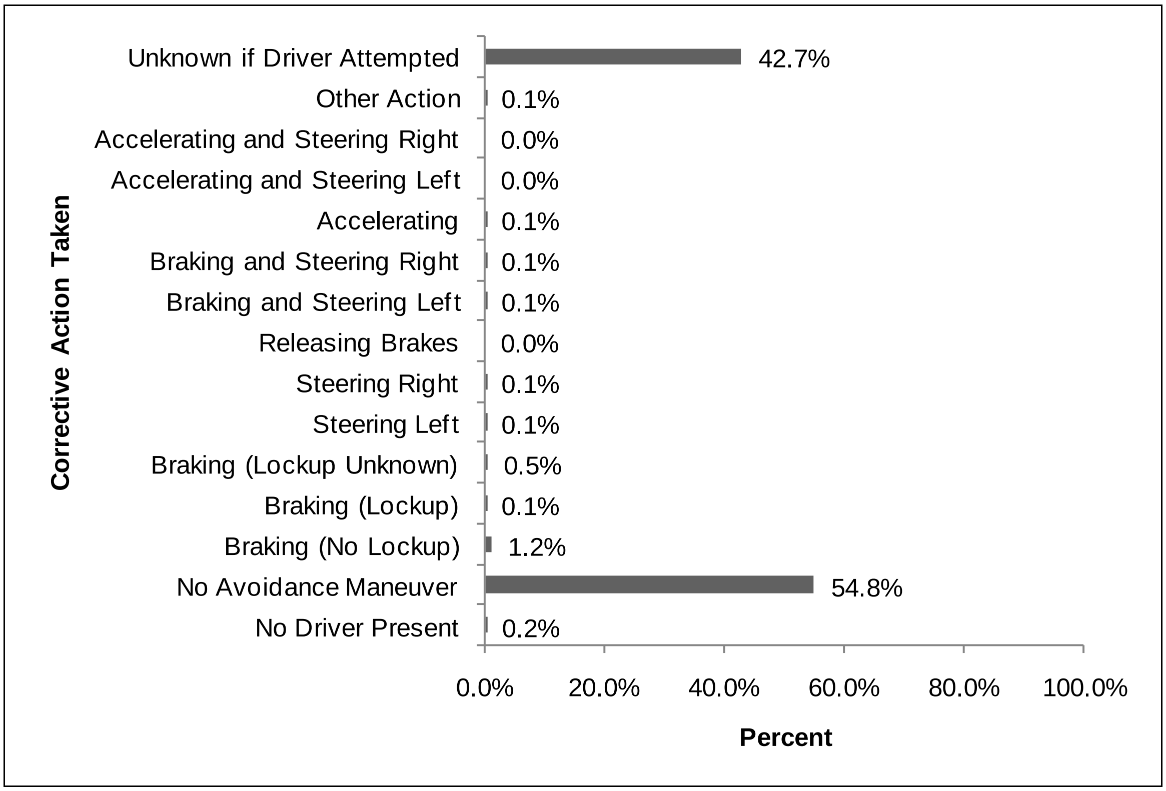

Figure 25. Bar graph. *Corrective Actions* attempted by passenger vehicle drivers in rear-end crashes.

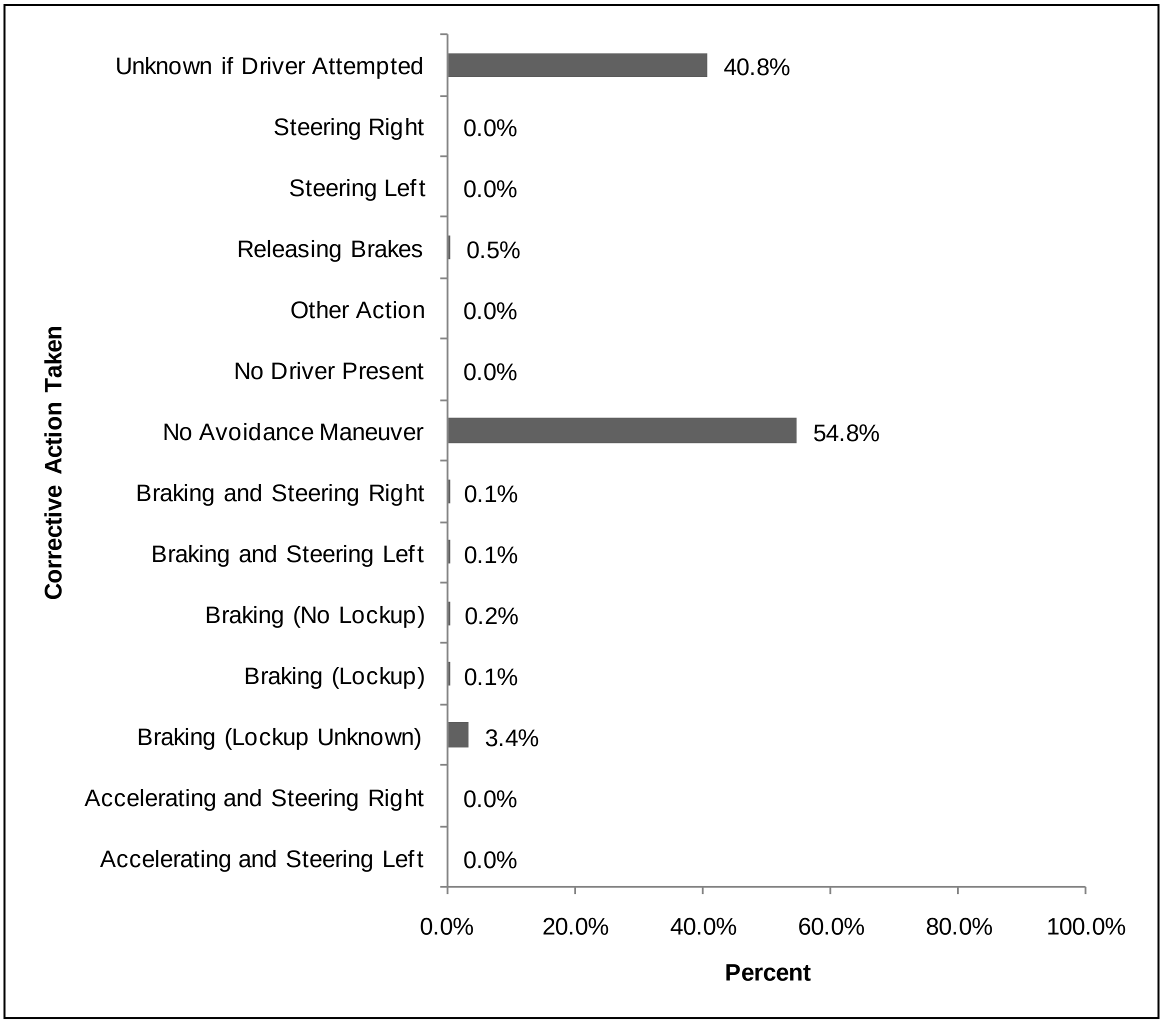

Figure 26. Bar graph. *Corrective Actions* attempted by CUT drivers in rear-end crashes.

2.5.4 Actions of the Striking Vehicle

This section examined the actions of the striking vehicle (i.e., those vehicles striking the passenger vehicle and those vehicles striking the CUT). Analyses are presented on the striking vehicle population, the movement of the striking vehicle, the *Corrective Action* attempted by the striking vehicle, and the violations charged against the striking vehicle driver.

2.5.4.1 Striking Vehicle Population

The population of striking vehicles is identified by searching the GES database for rear-end crashes and then filtering the vehicle role to equal *Striking*. The product of this search is the population of vehicles and the actions that the vehicle performed prior to the rear-end crash. For passenger vehicle rear-end crashes, the majority of crashes were the result of another passenger vehicle (54.9 percent) or light truck (41.3 percent) striking the passenger vehicle (figure 27). In CUT rear-end crashes, the largest percentage of striking vehicles was also passenger vehicles (42.6 percent); however, light trucks and CUTs struck the rear of CUTs at an almost even percentage (27.4 percent and 26.7 percent, respectively; see figure 28). It is interesting to note that CUTs strike other CUTs in approximately 27 percent of the CUT rear-end crashes, yet CUTs only strike passenger vehicles in 2.2 percent of passenger vehicle rear-end crashes.

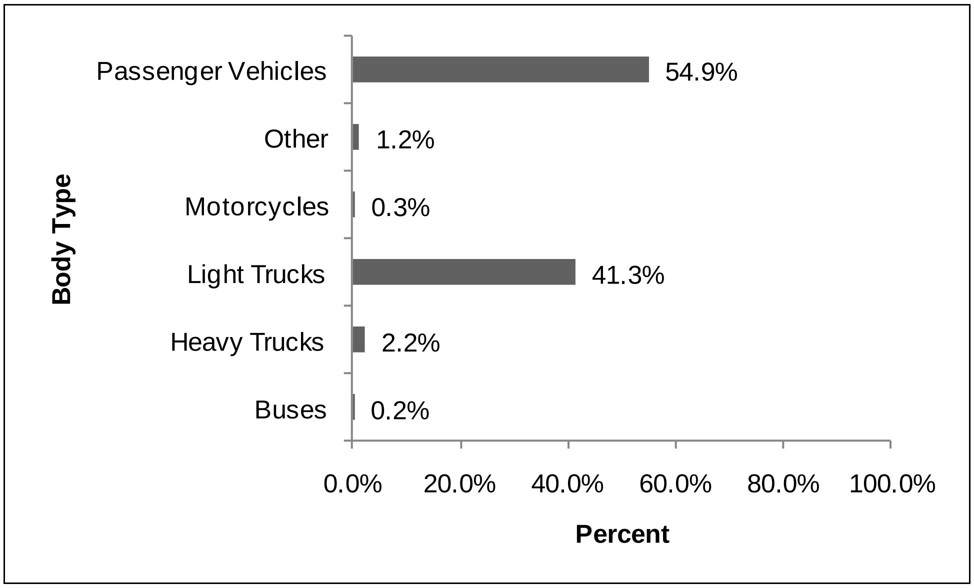

Figure 27. Bar graph. Population of vehicles *Striking* passenger vehicles in rear-end crashes.

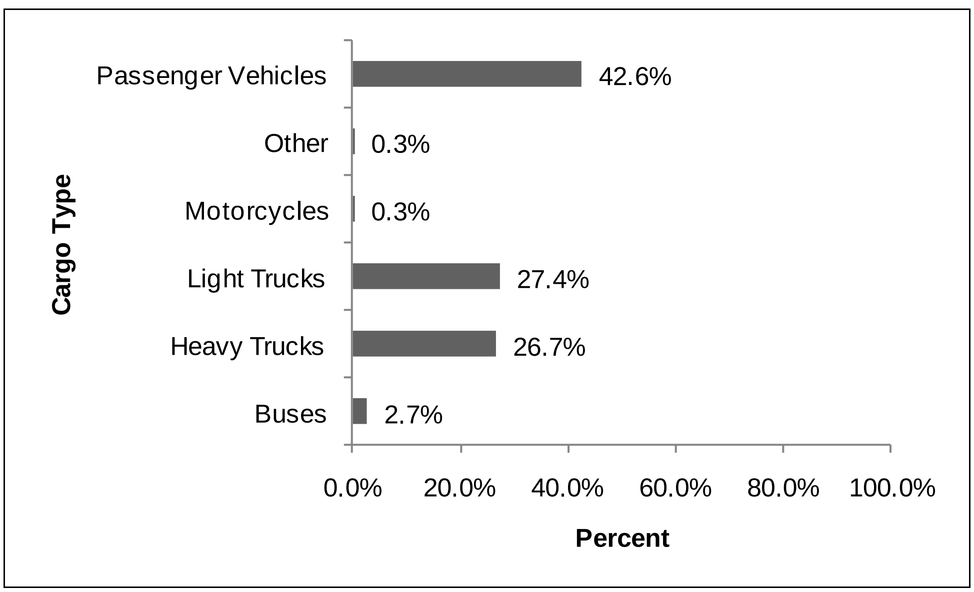

Figure 28. Bar graph. Population of vehicles *Striking* CUTs in rear-end crashes.

2.5.4.2 Movement of the Striking Vehicle

Figure 29 and figure 30 depict the movement of the striking vehicles in passenger vehicle and CUT rear-end crashes, respectively. This movement refers to the movement immediately preceding the critical event. In more than 78 percent of both the passenger vehicle and CUT rear-end crashes, the striking vehicle was going straight in the lane of travel. For passenger vehicles, this movement was followed by the striking vehicle decelerating in the traffic lane (8.7 percent) and starting in the traffic lane (5.3 percent). Decelerating in the traffic lane was also the second most common movement for striking vehicles in CUT rear-end crashes (5.3 percent).

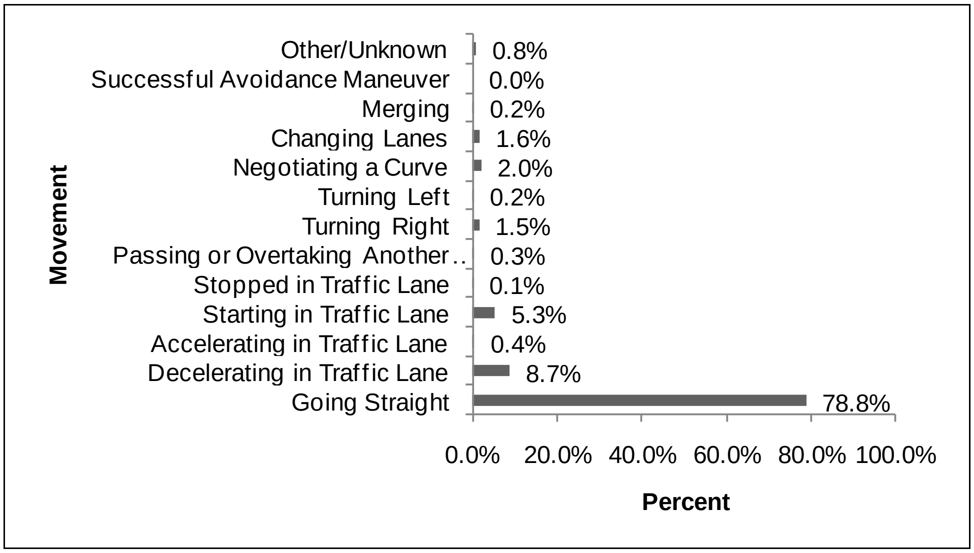

Figure 29. Bar graph. Movements prior to critical event in passenger vehicle rear-end crashes - passenger vehicle *Striking* vehicle.

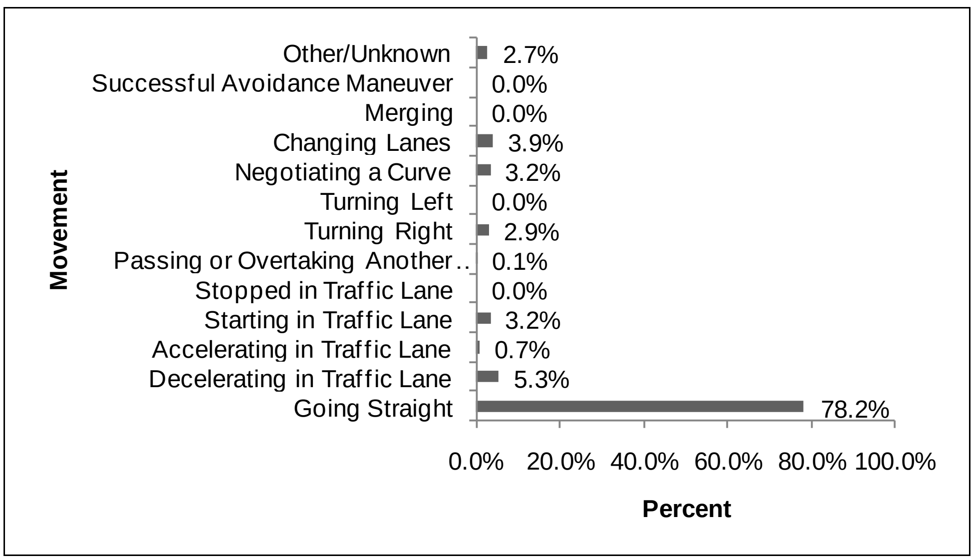

Figure 30. Bar graph. Movements prior to critical event in CUT rear-end crashes – CUT *Striking* vehicle.

2.5.4.3 Corrective Action Attempted by the Striking Vehicle

The *Corrective Action* attempted variable for the striking vehicle provides insight as to whether or not the driver of the striking vehicle recognized a rear-end crash was imminent and attempted a *Corrective Action*. In both passenger vehicle and heavy-truck rear-end crashes, there was a high percentage of unknowns. The unknown response is common given the design of the GES database. Because GES data are drawn from PARs, *Corrective Actions* are only included for those rear-end crashes where police obtained a response from the driver of the striking vehicle and included those data on the report. Figure 31 illustrates the *Corrective Actions* attempted by the striking vehicle in passenger-vehicle crashes and figure 32 illustrates the *Corrective Actions* attempted by the striking vehicle of CUT rear-end crashes.

In 11.9 percent of passenger vehicle rear-end crashes the striking vehicle attempted a braking-related maneuver. However, 9.1 percent of the time no *Corrective Action* was attempted (figure 31). The striking vehicle attempted a braking-related action at a slightly greater percentage (13.2 percent) in CUT rear-end crashes.

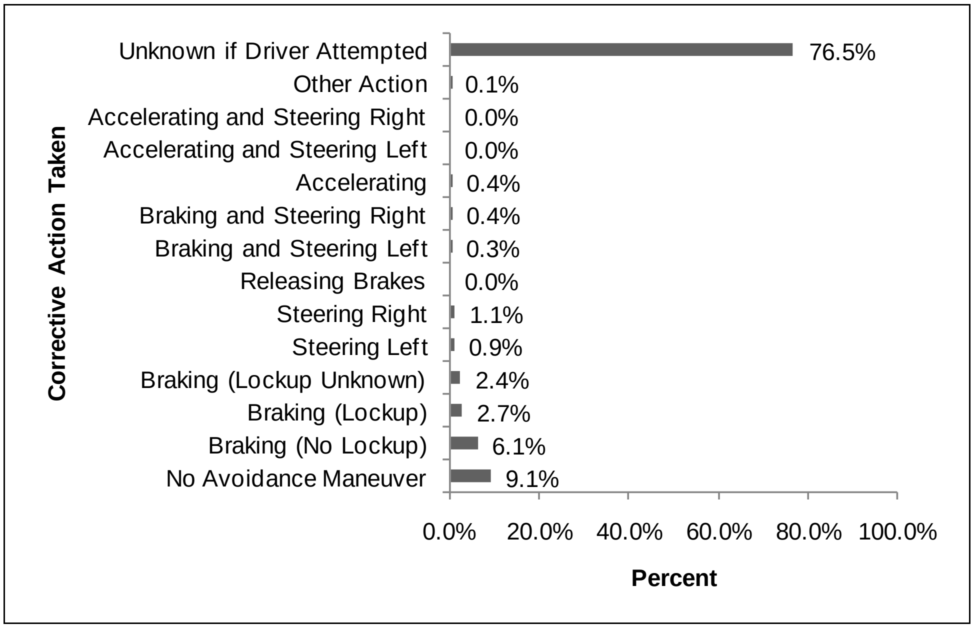

Figure 31. Bar graph. *Corrective Actions* attempted by the *Striking* vehicle driver in passenger vehicle rear-end crashes.

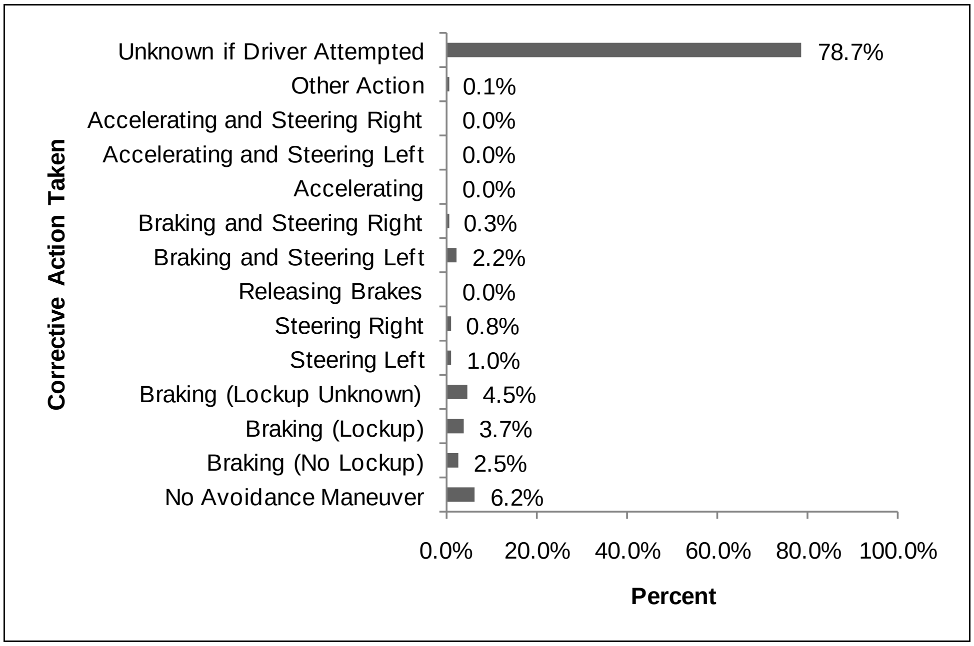

Figure 32. Bar graph. *Corrective Actions* attempted by the *Striking* vehicle driver in CUT rear-end crashes.

2.6 CONCLUSIONS

Generally, the 2006 GES findings were consistent with those from the 2001 GES analysis; however, there were some discrepancies in these two data sets. The first discrepancies seen related to *Roadway Type*. In the 2006 GES data set, only 36 percent of daytime rear-end crashes occurred on *Interstate Highways*. This marked a sharp reduction since 2001 when 67.3 percent of daytime rear-end crashes occurred on Interstates. Nighttime rear-end crashes that occurred on the *Interstate Highways* increased from 38.5 percent in the 2001 GES data set to 55 percent in the 2006 GES data set. The percent of SUT rear-end crashes on two-lane roads decreased from 48.2 percent in the 2001 GES data set to 35.7 percent in the 2006 GES data set. The percent of rear-end crashes that occurred on four-lane roads increased from 8.6 percent in the 2001 GES data set to 13.3 percent in the 2006 data set. There has been an almost 5 percent increase in the number of rear-end crashes that occurred on roadways with four or more lanes (19.8 percent in the 2006 GES compared to 15 percent in the 2001 GES). One other interesting discrepancy found was in regard to time of day. There has been a decrease in the number of rear-end crashes that occurred at dawn (8.9 percent in the 2001 GES versus 0.6 percent in the 2006 GES).

The final major discrepancy found relates to truck driver attempted avoidance maneuvers. In the 2006 GES data set, CUT rear-end crashes had a higher occurrence of no avoidance maneuver than SUTs (29.1 percent versus 16 percent, respectively). This is a change from the 2001 GES data set, which found no avoidance maneuver attempted in 36.5 percent and 21.9 percent of the SUT and CUT rear-end crashes, respectively. Generally, it is understood that a truck driver can be limited to what avoidance maneuvers may be available during a rear-end crash scenario (other vehicle striking the rear of the truck). However, it was interesting to find that, according to 2006

GES statistics, truck drivers appear to be making more frequent attempts to avoid these rear-end crash scenarios.

3. AUDITORY WARNING SYSTEM

3.1 BACKGROUND

It is generally recognized in human factors engineering that the auditory modality is the most appropriate for initial warnings and alarms.[16] The reason for this is because an auditory warning signal is largely independent of the orientation of the listener. Consequently, an operator who is looking away can be redirected to a relevant display or environmental view. Other modalities generally do not have this property, with the possible exception of haptic systems (that is, those that vibrate the seat or controls). Because of this redirecting property, auditory displays are often used for warnings or alarms.

With regard to rear-end crashes, the most prevalent contributing factor is that of the following-vehicle driver looking away, either into the vehicle interior or to the outside (but not the forward view).[10] Most of the earlier work on prevention of rear-end crashes has been directed toward attention-getting and eye-drawing; that is, trying to get the following-vehicle driver to look forward instead of continuing to look away. The purpose of introducing an auditory warning is to supplement the visual stimulus to increase the probability of redirecting the driver's attention and visual glance to the forward view. Similarly, if a driver is "daydreaming" while looking forward, an auditory system may help to re-alert the driver to an emergency situation ahead. There were two possibilities determined for development of an auditory warning for this scenario. One of these involved use of vehicle-to-vehicle (V2V) communications, in which the lead vehicle sends a signal to the following vehicle. In such a case, the following vehicle detects the signal and warns the driver by means of an in-vehicle auditory warning. The other possibility was to generate an auditory warning sound at the lead vehicle and focus it directly backward (external auditory signal). This sound would then directly warn the driver of the following vehicle. The advantage of this latter system is that the following vehicle need not be equipped with a receiver and an in-vehicle auditory warning system (V2V system). On the other hand, the latter system has the disadvantage that other drivers may be needlessly alerted by the external auditory warning if it is transmitted by means of a loudspeaker or similar device. This would occur if the sound is not sufficiently directional. Another possible shortcoming is that the sound level may not be in the correct range of amplitude (volume) for the following driver to hear it.

Earlier work in Phase I and II attempted to use a sound system,[1,5] but specifications recommended large beam-widths; that is, beam-widths on the order of 90 deg or more (45 deg to the right and left of the rear longitudinal axis of the heavy truck). A potentially better alternative would be to use a much narrower beam-width. A narrower beam-width would transmit the sound directly rearward only, so that it has less chance of alerting drivers who are not involved in following behind the heavy truck. The development of a narrow beam-width (± 5 deg) was therefore one of the objectives of the current effort.

Another important consideration was the sound wave to be used. The description reported during Phase II was technically vague and described as a siren, or possibly a sine wave with frequency swept across a narrow frequency band. The current research team took the position that the sound should cover a band of frequencies such that standing waves generated at a given fixed frequency would not pose a problem. Because so little previous work had been done on sound development for the current application, a development effort was required. With the above parameters, the research team began the development of signal types (sounds) and directional capabilities and tested them in a static environment. It was essential to determine if an appropriate narrow-beam-width system could be developed before further investigation continued with sound levels and signal types.

3.2 SIGNAL DEVELOPMENT

Three signal types (sounds) were used for testing. Two of these sounds were acquired and one was developed in a laboratory. The research team has had previous experience in this area, specifically with regard to the development of alarm sounds to re-alert drowsy drivers. In this previous research, several signals were synthesized and then tested.(17) To accomplish this, the signals were recorded, played back, and then rated by individuals trained in human factors engineering. Based on that research, it was determined that a more limited range of candidate warning sounds should be tested in the current effort. It was also determined that the sounds should cover a band of frequencies, rather than just a single frequency; accordingly, individuals with notch hearing deficiencies could still hear the sounds. The literature reports various optimal bands of human hearing sensitivity. For instance, Sanders and McCormick(18) report that human hearing is most sensitive in the range of 1 KHz to 5 KHz, while Deatherage(19) and Mudd(20) state that the range of 500 Hz to 3 KHz should be used for greatest human hearing sensitivity. For localizing sound, the midrange frequencies (1.5 KHz to 3 KHz) can make it difficult as frequencies in this range tend to have no effective phase or intensity difference cues.(18) By taking all of the above into consideration, researchers incorporated all of these auditory signal design principles and used sounds containing the majority of a frequency band of 500 Hz to 2 KHz (although, due to one sound being an already recorded waveform audio format [WAV] file making it difficult to measure, it is possible that it did at times move below 500 Hz). This band of frequencies would encapsulate good human hearing sensitivity, the ability to better localize the sound, all the while containing wavelengths that are in the range from 0.55 to 2.2 ft (.16 to .67 m). Wavelengths in this range would make it possible to obtain reasonable directionality of the sound, thereby allowing minimization of disturbances to drivers in adjacent lanes (that is, drivers who are not likely to be involved in a rear-end crash with the heavy truck).

A total of three sounds were used during testing. Each sound used consisted of a narrow band of frequencies, rather than just one frequency. Each sound is further defined as follows:

- *Tire Screech*: This WAV file simulated the sound of a vehicle locking up its brakes.
- *Piercer*: This sound was developed by an engineering company and contained both low and high frequency sound waves.
- *Dual Frequency Tone*: This sound was created by the research team and consisted of two tones simultaneously played, each with its own frequency.

Further detailed specifications of the three sounds used for testing can be found in appendix B.

3.3 DEVELOPMENT OF DIRECTIONAL CAPABILITIES

Development of directional capabilities involved testing with actual transducers and with physical focusing equipment. A power amplifier was needed to drive each transducer. The concept was to input the sound to the power amplifier and then adjust the focusing equipment across a range likely to produce a narrow beam-width. In the work plan, two concepts were proposed for focusing. The first concept tested involved positioning the transducer inside a tube, the length of which would be determined experimentally. A diagram of the tube design is provided in figure 33 that presents both an isometric (ISO) view and side view. Another concept that was explored was to reverse the direction of the transducer and use a parabolic reflector. A diagram of the parabolic reflector design is provided in figure 34 that presents both an ISO view and side view. The adjustment, in this case, would be the position of the transducer on the axis of the reflector. This adjustment would allow focus of the sound such that the audio energy is focused in a beam straight backward, much like the use of a reflector in a flashlight. Adjustment would allow the beam-width to be set to a narrow angle of coverage. There exists a possible trade-off in beam-width determination between disturbance of adjacent lane drivers and adequate coverage of the lane behind the heavy truck.

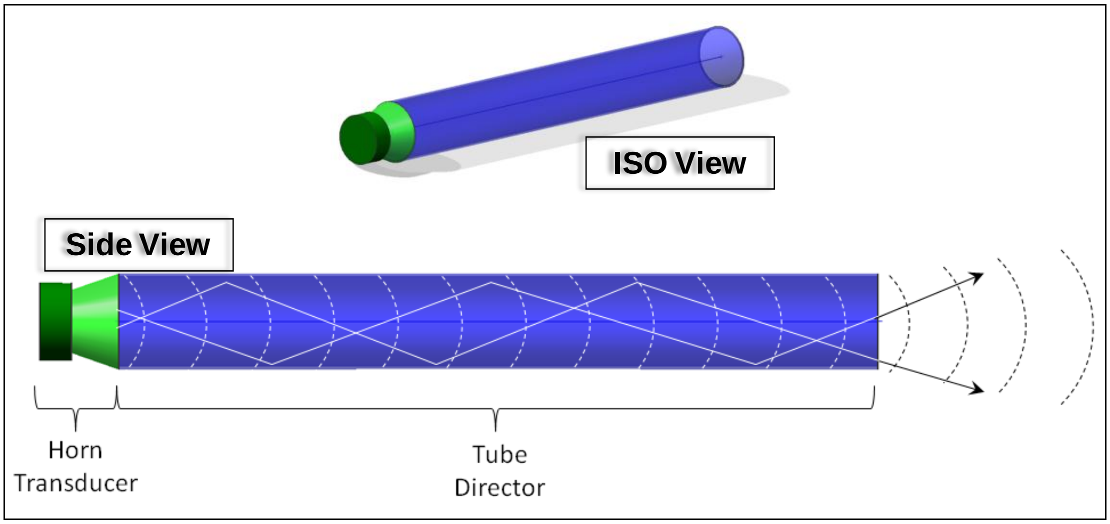

Figure 33. Diagram. Tube-type directional transducer concept.

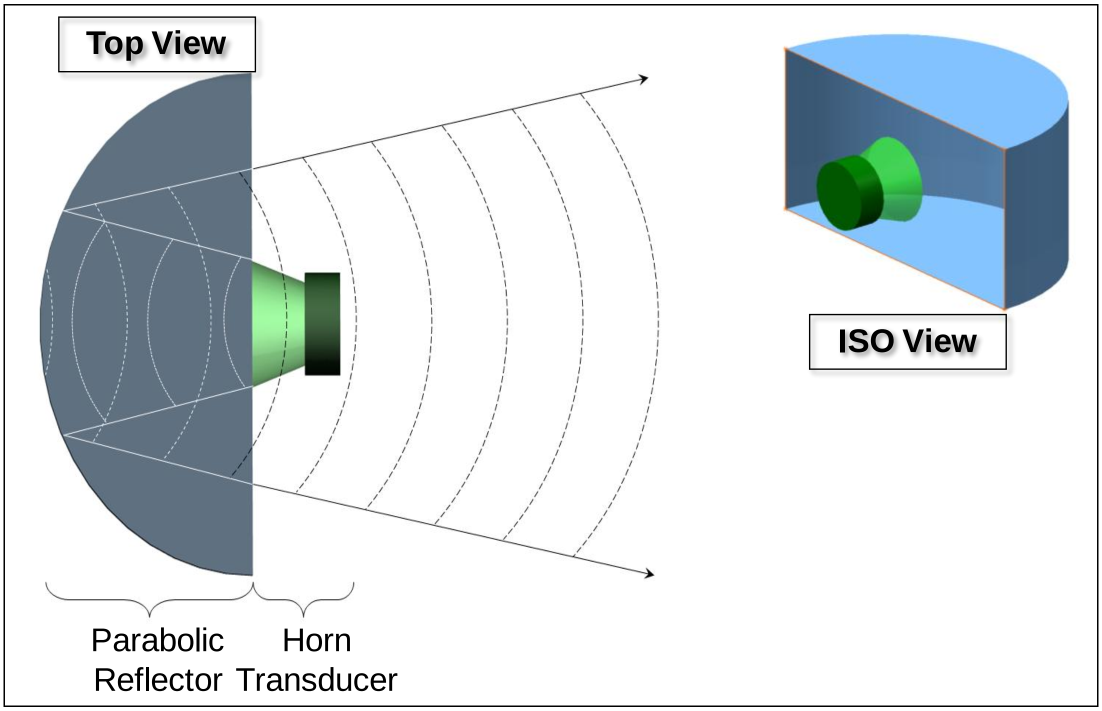

Figure 34. Diagram. Reflector-type directional transducer concept.

The transducers used for both the tube design and the parabolic reflector design were similar to a typical "ballpark public address horn." Such a horn has the characteristics needed, including power handling capability, some intrinsic directionality, and no back-wave to suppress. Back-waves occur when a speaker is open in both the front and back, as in the case of a typical cone speaker. Because the warning sounds were narrow-band, there was no need to use a wide-band speaker to reproduce them. A wide-band speaker has the problem of requiring back-wave suppression or phase reversal at emanation from its enclosure. Further detailed specifications of the tube type directional design, the parabolic reflector type design, and the actual transducers used can be found in appendix B.

Two separate experiments on directionality were performed outside. The reason for outside testing was that interiors of buildings produce reflections that do not exist on roadways. Roadways, of course, have their own reflections; therefore, to simulate authentic conditions, it was necessary to work on pavement outside.

3.4 EXPERIMENT 1

The objective of Experiment 1 was to investigate whether the tube design and parabolic reflector design could provide a narrow beam-width. This was done by moving the transducer inside the tube to multiple fixed positions, and by moving the transducer to fixed distances from the face of the parabolic reflector and measuring sound level.

3.4.1 Method

3.4.1.1 Apparatus

All auditory experimental testing was performed in a large blacktopped area at the research facility. Both the tube design (figure 35) and parabolic reflector design (figure 36) were tested for directionality. Six sound-level meters were used to determine the on-axis level of each of the three sounds as well as in the area ±5 deg about the vehicle centerline locations (2 m at each of the three locations). All meters were positioned at 100 ft (30.48 m) back from the device's location. An overhead diagram of the testing scenario for both the tube and parabolic reflector designs is provided in figure 37.

Figure 35. Photo. Tube-type directional transducer (photographed on grass for report; actual testing was performed on pavement).

Figure 36. Photo. Reflector-type directional transducer (photographed on grass for report; actual testing was performed on pavement).

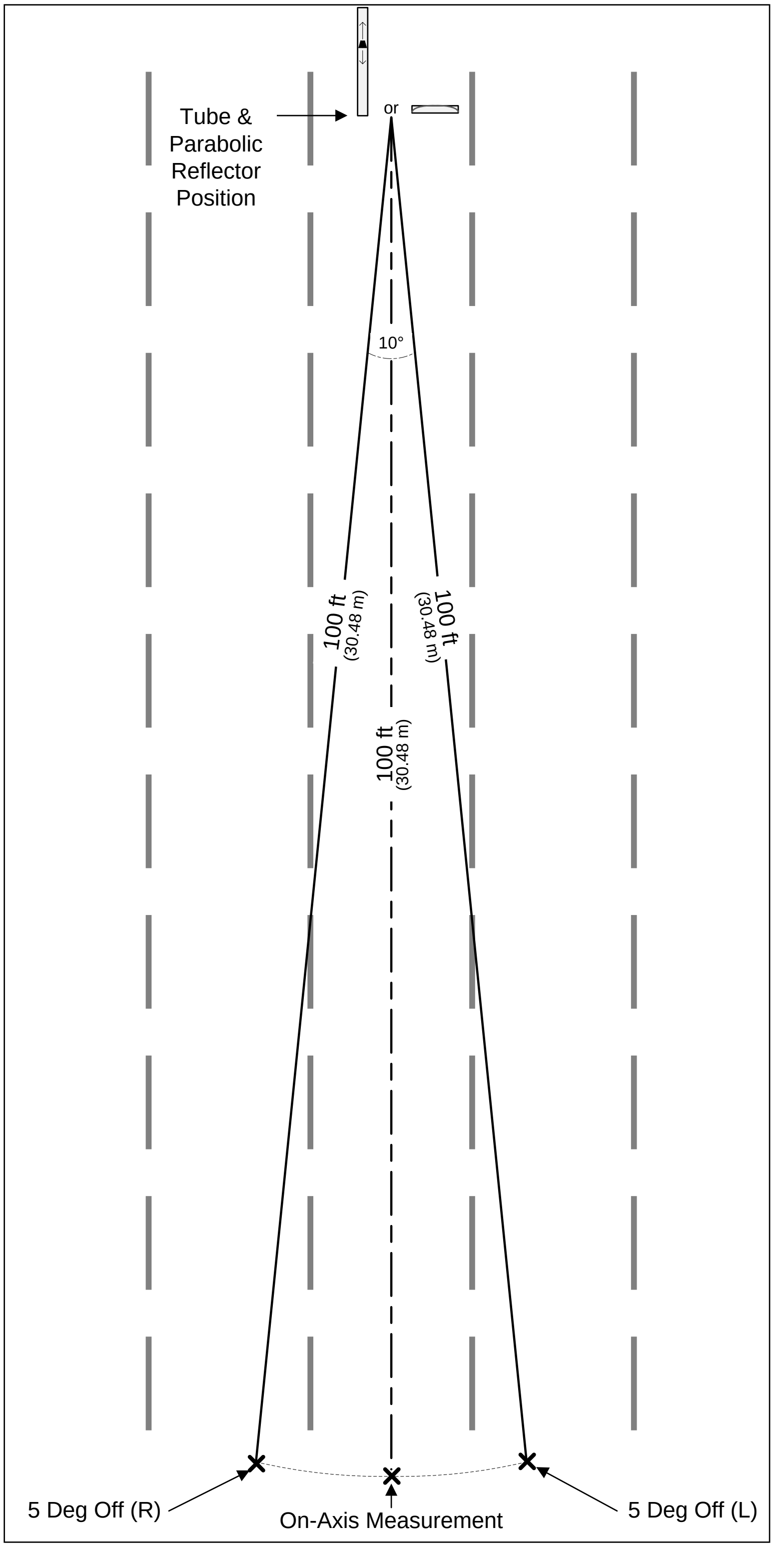

Figure 37. Diagram. Experiment 1 testing scenario for the tube design and parabolic reflector design.

3.4.1.2 Procedure

It was determined that a narrow beam-width of ±5 deg would be sufficient (maintaining the majority of the signal in the lane directly behind the trailer) and would be defined where the sound level was 5 to 10 dBA lower than the on-axis level (a clear perceptual drop in sound level in comparison to the on-axis level). For the tube design, the maximum dBA was recorded from each sound level meter at multiple transducer positions inside the tube. The transducer was positioned at the very front of the tube and then incrementally moved back every 6 in (15.24 cm) until a final distance of 72 in (182.88 cm) was reached. This process was performed for each of the three selected sounds. For the parabolic reflector design, the maximum dBA was recorded from each sound-level meter at multiple transducer distances from the front of the reflector. The distances tested were 15 in (38.1 cm), 16.75 in (42.55 cm), 18.5 in (46.99 cm), 20.25 in (51.44 cm), 22 in (55.88 cm), 23.75 in (60.33 cm), and 25.5 in (64.77 cm). This process was performed for each of the three selected sounds.

3.4.2 Experiment 1 Results

As mentioned previously, six sound-level meters were used (two at each location). Although each meter was calibrated prior to use, researchers determined that using two meters at each location and calculating the mean of the values obtained would reduce potential data collection errors from unexpected noise such as wind gusts.

3.4.2.1 Tube Design

After means were calculated for the recorded values at each location, line graphs were created for each of the three sounds tested. As previously described, the three sounds were *Tire Screech*, *Piercer*, and *Dual Frequency Tone*. Figure 38 shows results for the *Tire Screech*, figure 39 shows results for the *Piercer*, and figure 40 shows results for the *Dual Frequency Tone*. During testing, the position of the transducer was incrementally moved backward inside the tube. Results indicated that for each sound, a narrow beam-width (greater directionality) was not obtained. If the tube had provided directionality, a substantial increase in vertical distance would be seen between the on-axis line (blue diamond) from the other 5 deg off-axis lines (red square and green triangle) as the transducer distance inside the tube increased. As it turned out, the transducer positioned at the front of the tube provided just as much directionality as any other position.

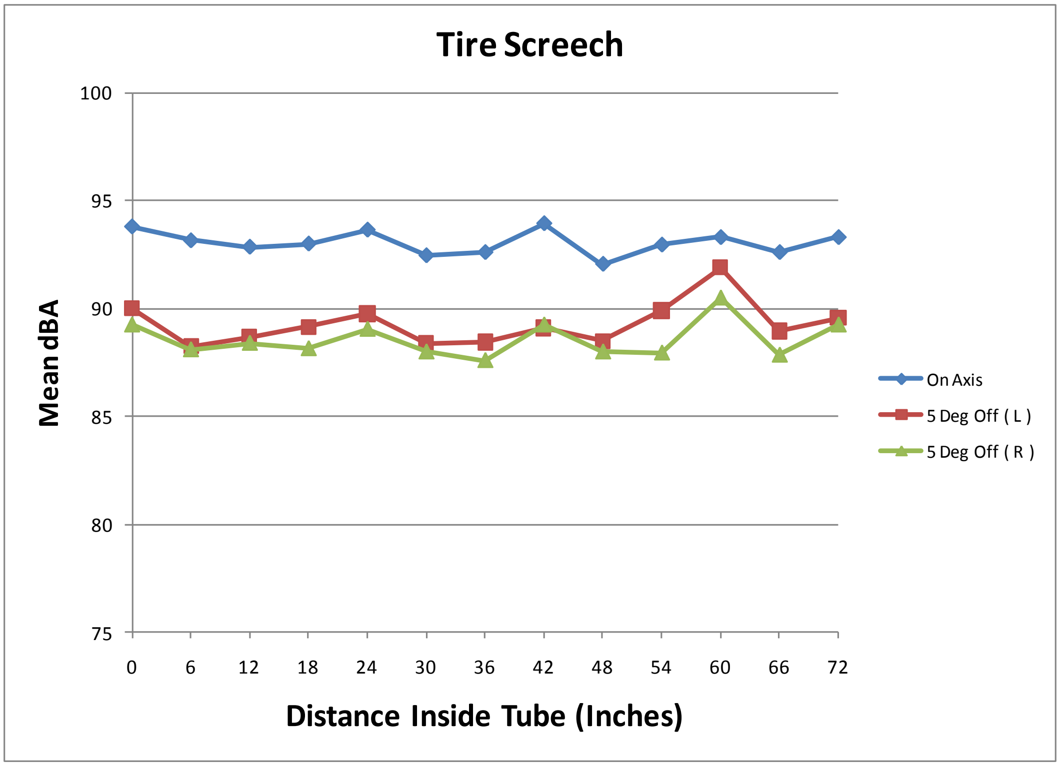

Figure 38. Line graph. Mean maximum dBA values collected during testing of the tube design while using the *Tire Screech*.

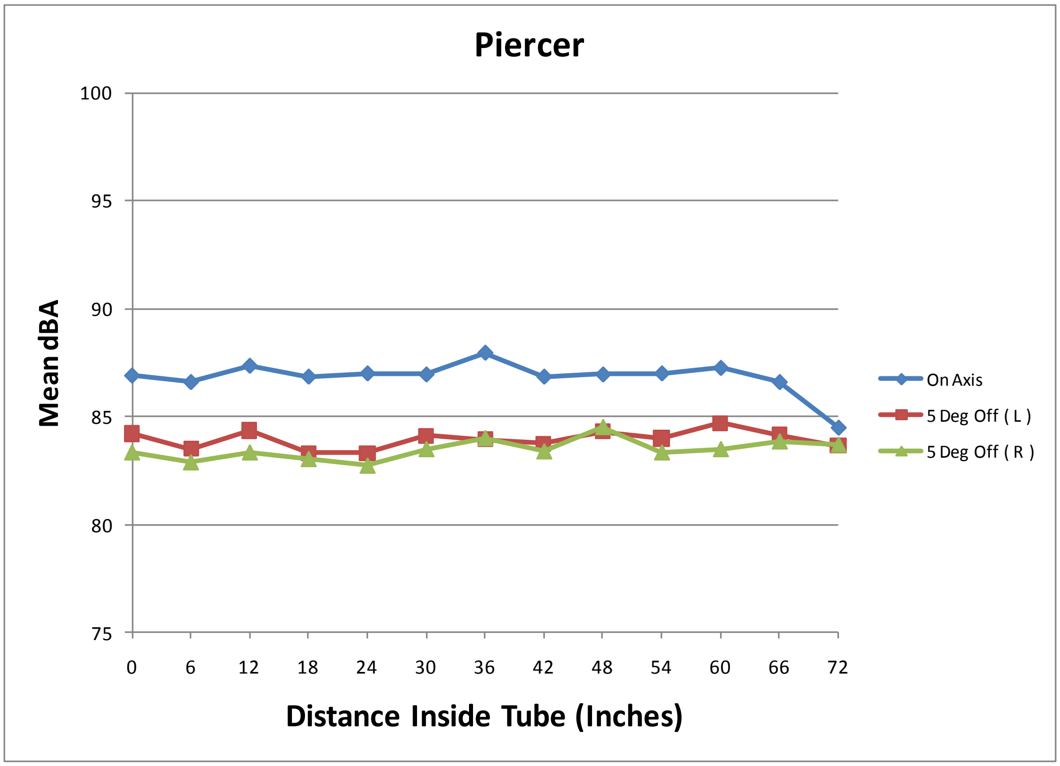

Figure 39. Line graph. Mean maximum dBA values collected during testing of the tube design while using the *Piercer*.

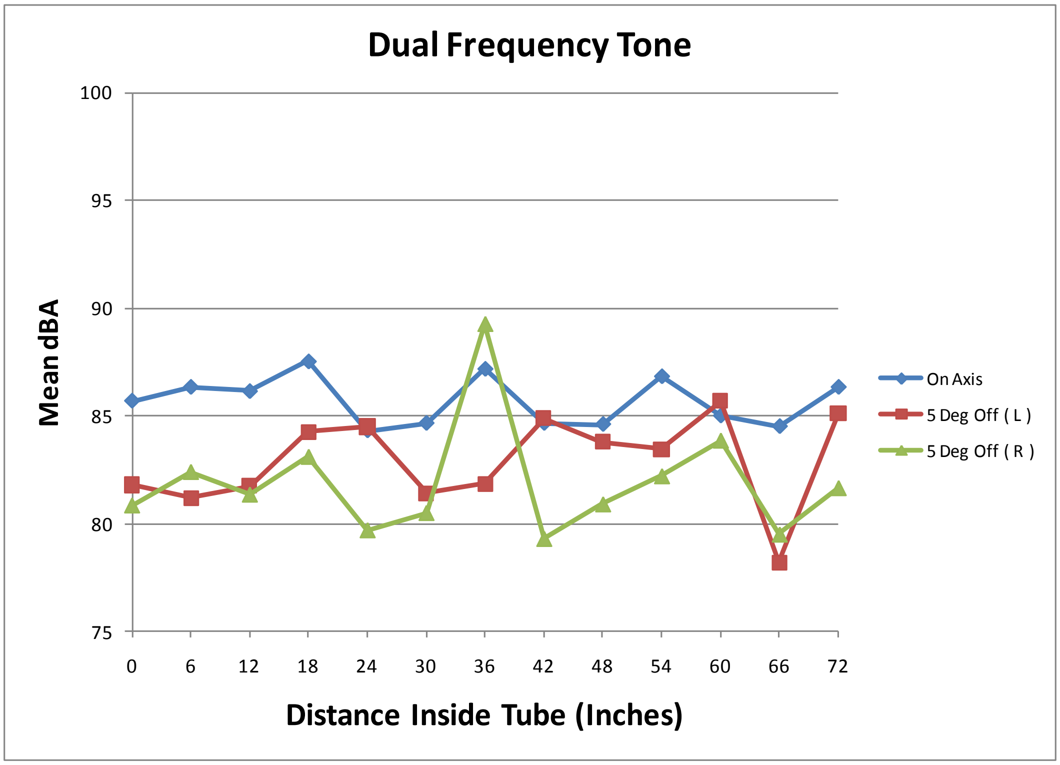

Figure 40. Line graph. Mean maximum dBA values collected during testing of the tube design while using the *Dual Frequency Tone*.

3.4.2.2 Parabolic Reflector Design

For the parabolic reflector testing, the means of the recorded values were calculated at each location and line graphs were created for each of the three sounds tested. Figure 41 shows results for the *Tire Screech*, figure 42 shows results for the *Piercer*, and figure 43 shows results for the *Dual Frequency Tone*. Results indicated that for each sound, a narrow beam-width (greater directionality) was not obtained at the selected transducer distances from the reflector. If the parabolic reflector had provided directionality, an increase in vertical distance would be seen between the on-axis line (blue diamond) from the other 5 deg off axis lines (red square and green triangle) at one or more of the distances along the x-axis. It was apparent to researchers that outside the 10-degree beam-width tested there was a clear drop in sound level, indicating that the parabolic reflector might have directionality to some extent. To obtain the actual characterization of the beam-width, a follow-up experiment was conducted.

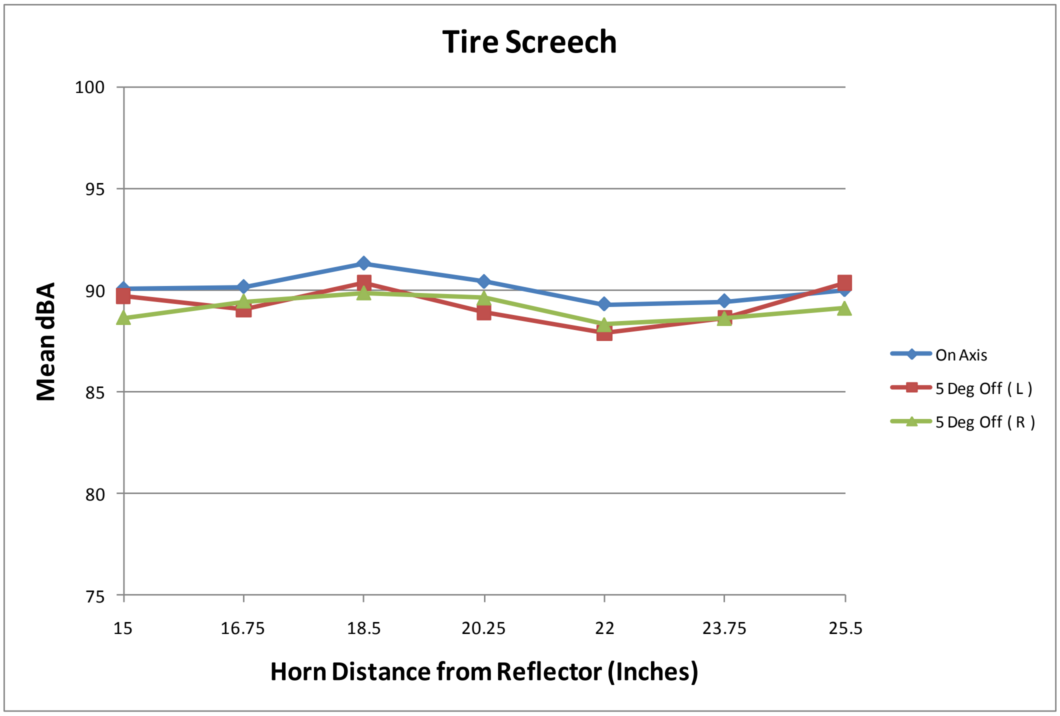

Figure 41. Line graph. Mean maximum dBA values collected during testing of the parabolic reflector design while using the *Tire Screech*.

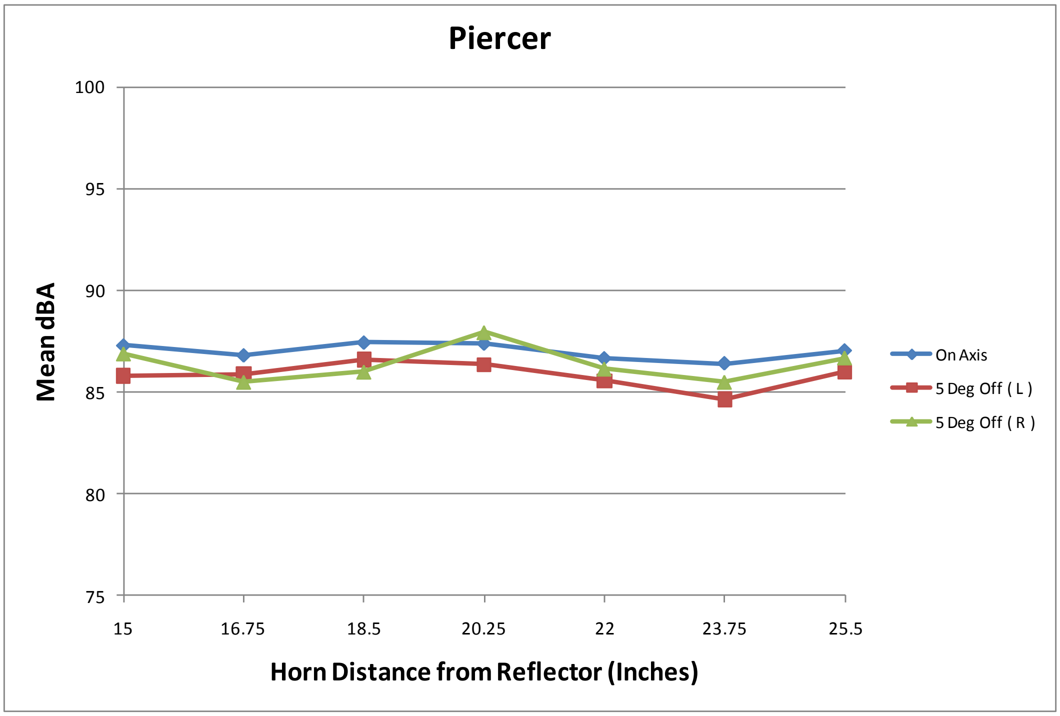

Figure 42. Line graph. Mean maximum dBA values collected during testing of the parabolic reflector design while using the *Piercer*.

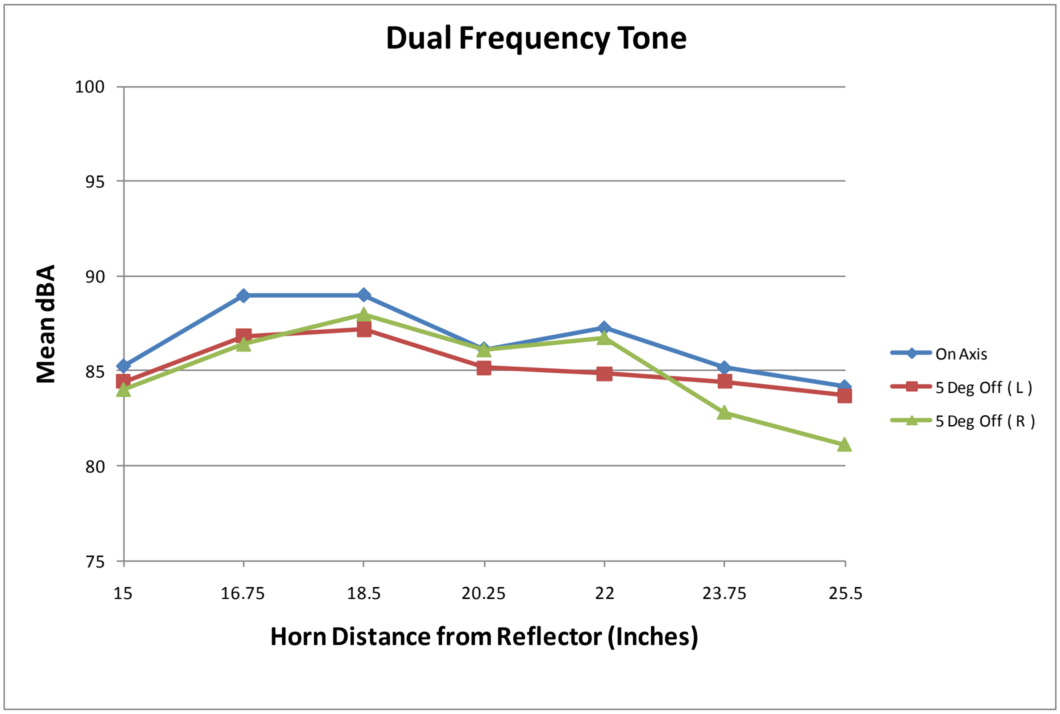

Figure 43. Line graph. Mean maximum dBA values collected during testing of the parabolic reflector design while using the *Dual Frequency Tone*.

3.5 EXPERIMENT 2

During Experiment 1, it was apparent to researchers that the parabolic reflector system produced a more directional signal than did the tube design even though neither system met the target beam-width of ±5 deg. Therefore, researchers determined that characterization of the actual beam-widths of each system should be further defined. Experiment 2 had the purpose of characterizing the actual beam-width for both the tube design and the parabolic reflector.

3.5.1 Method

3.5.1.1 Apparatus

Experiment 2 was also performed in a large blacktopped area at the research facility. Two sound-level meters were used to measure sound levels at 5-degree increments for an area covering ±45 deg about the vehicle centerline (90-degree beam-width). All sound level measurements were taken at 75 ft (22.86 m) back from transducer's location. A distance of 75 ft (22.86 m) was used (in contrast to the previous distance of 100 ft [30.48 m] that was used in Experiment 1) due to the width constraint of the blacktopped area used for testing. Figure 44 shows an overhead diagram of the testing scenario used for the tube design and the parabolic reflector design.

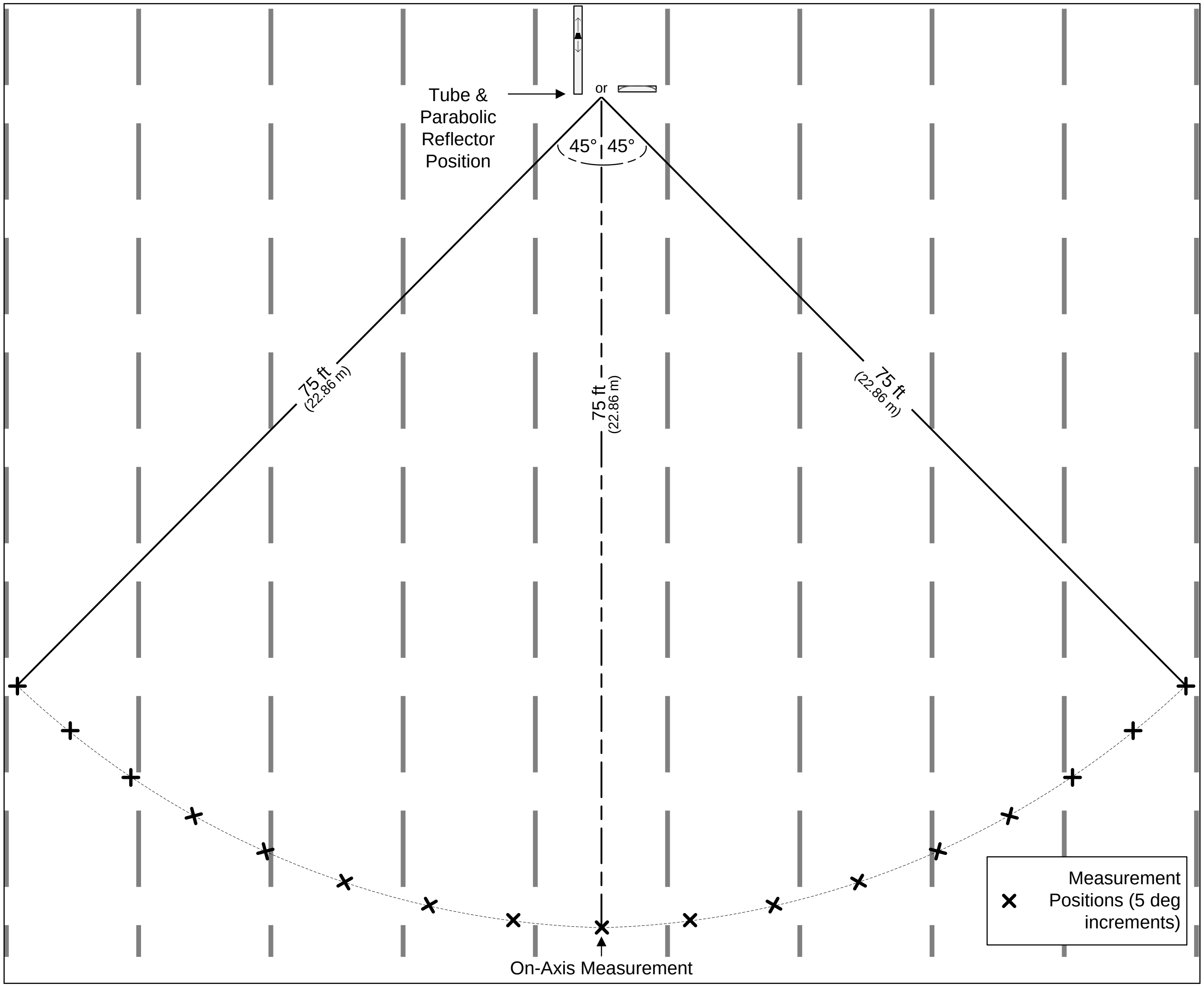

Figure 44. Diagram. Experiment 2 testing scenario for the tube design and parabolic reflector design.

3.5.1.2 Procedure

At each 5-degree measurement position, the maximum and minimum dBA values were recorded with one sound level meter. The value falling in the middle of the maximum and minimum dBA values was used as the final data point for that measurement position. The same procedure was used a second time at each position with a different sound level meter. Although each meter was calibrated prior to use, researchers determined that performing one measurement at each location with a different meter (two measurements in total per location) and calculating the mean of the values obtained would reduce data collection errors from unexpected noise such as wind gusts. The transducer position inside the tube was located at 72 in (182.88 cm) (the furthest distance back inside the tube tested in Experiment 1). This process was performed for two of the three previously selected sounds: the *Tire Screech* and the *Piercer*. The *Dual Frequency Tone* was removed from further testing as results from Experiment 1 indicated poor performance in directionality and measurement capability. For the parabolic reflector design, the transducer distance from the front reflector was located at the nominal position of 22 in (55.88 cm). This process was performed with the same two sounds as was the tube design.

3.5.2 Experiment 2 Results

3.5.2.1 Tube Design

Bar graphs were created for each of the two sounds tested. As previously described, the two sounds were the *Tire Screech* and the *Piercer*. Figure 45 shows results for the *Tire Screech* and figure 46 shows results for the *Piercer*. Results indicated that for each sound, the narrow beam-width (i.e., greater directionality) goal of ±5 deg could not be achieved (defined as a 5 to 10 dBA drop from the on-axis measurement at any off-axis position).

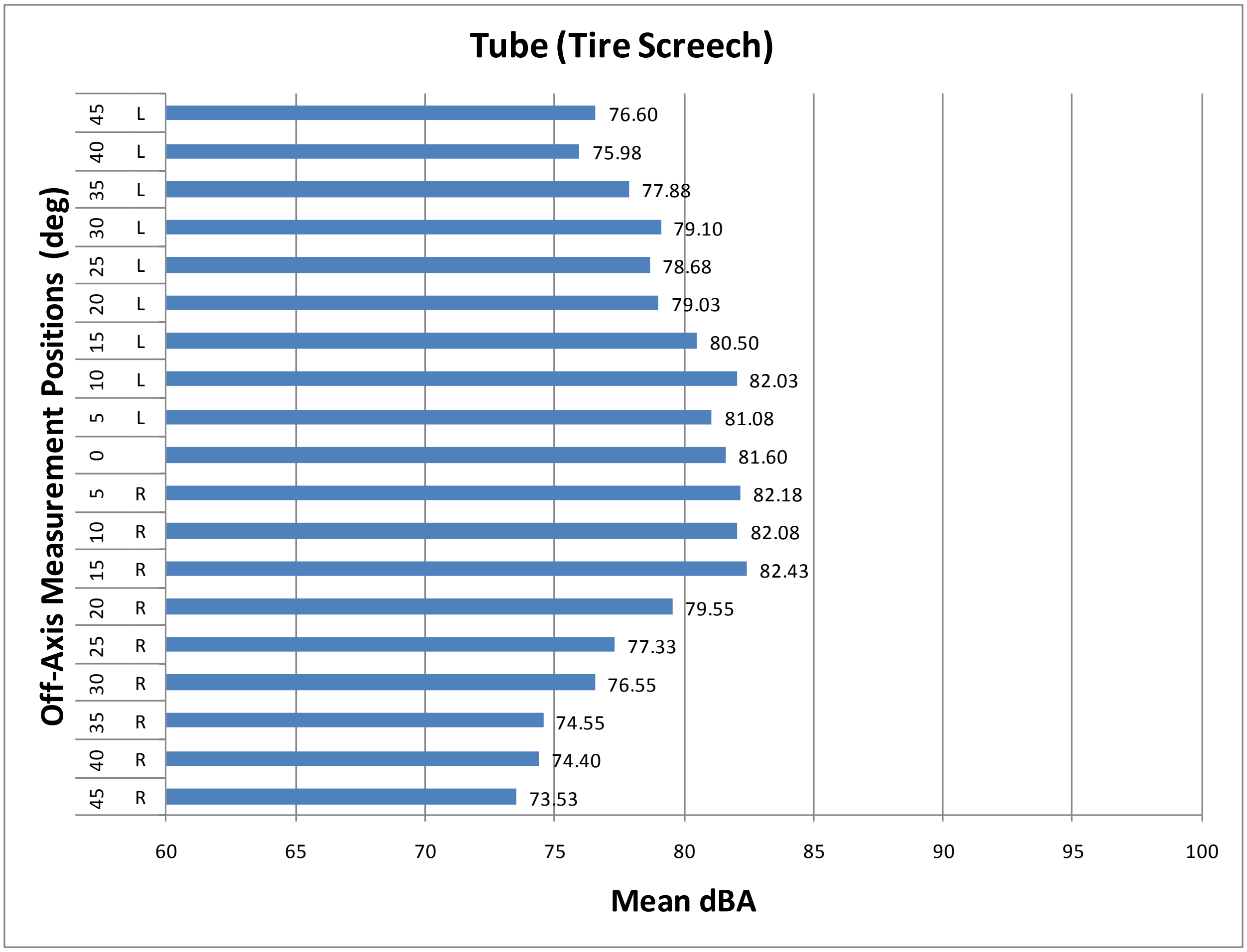

Figure 45. Bar graph. Mean dBA values collected during the beam-width characterization of the tube design while using the *Tire Screech*.

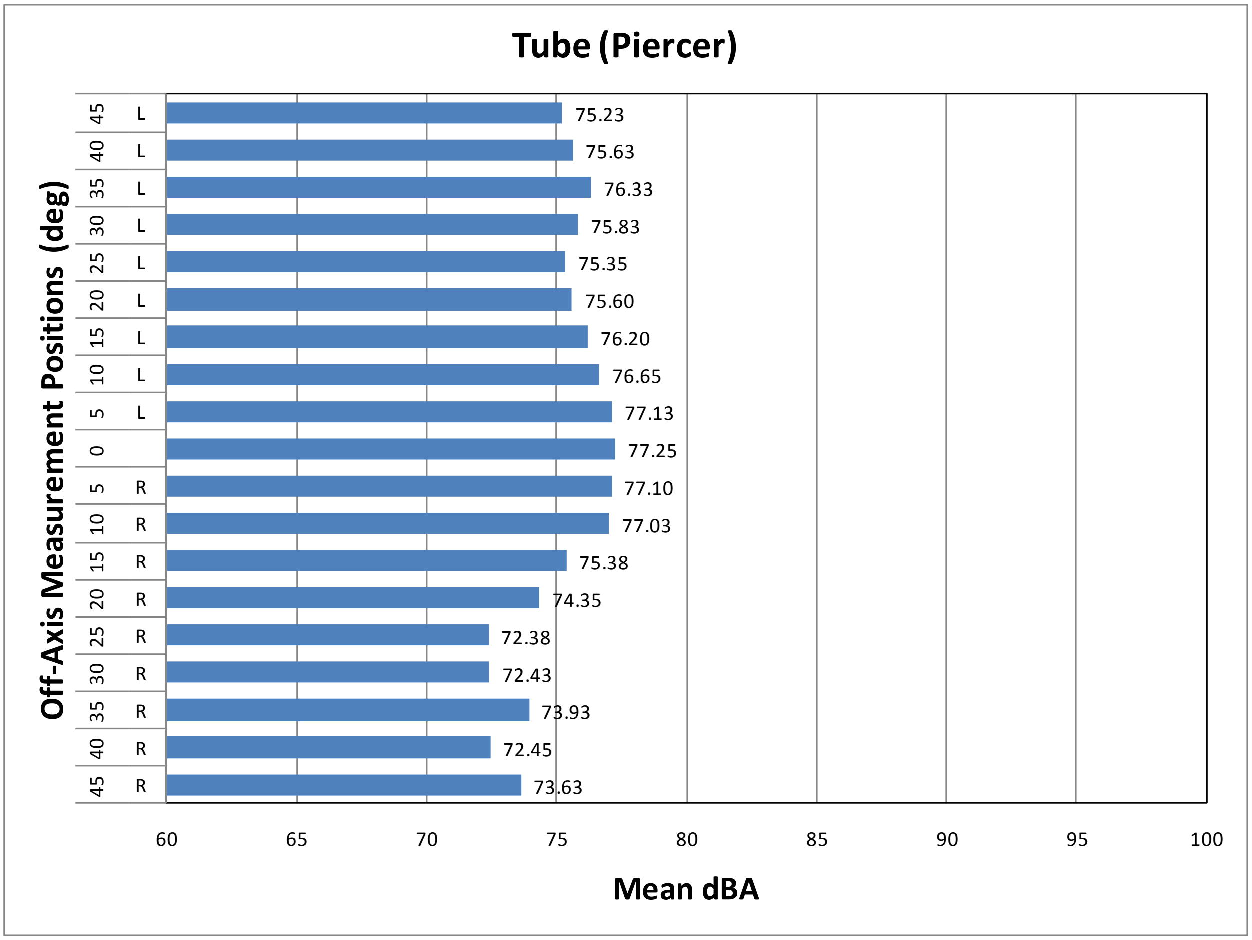

Figure 46. Bar graph. Mean dBA values collected during the beam-width characterization of the tube design while using the P*iercer*.

3.5.2.2 Parabolic Reflector Design

Bar graphs were created for each of the two sounds tested. As previously described, the two sounds were a *Tire Screech* and the *Piercer*. Figure 47 shows results for the *Tire Screech* and figure 48 shows results for the *Piercer*. Results indicated that for each sound type, the narrow beam-width (i.e., greater directionality) goal of ±5 deg could not be achieved, but could be characterized as providing a directional beam-width closer to 15 to 20 deg.

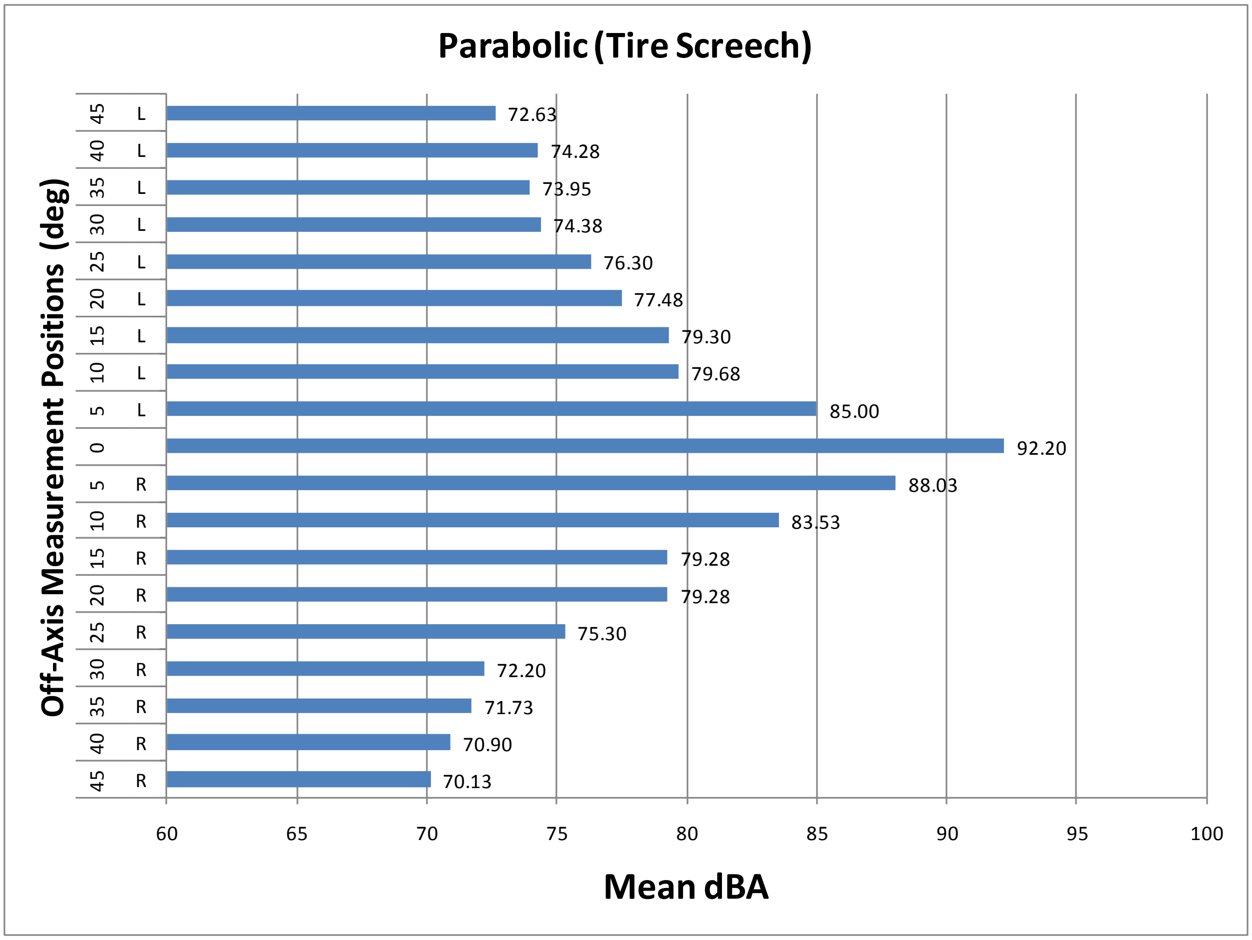

Figure 47. Bar graph. Mean dBA values collected during the beam-width characterization of the parabolic reflector design while using the *Tire Screech*.

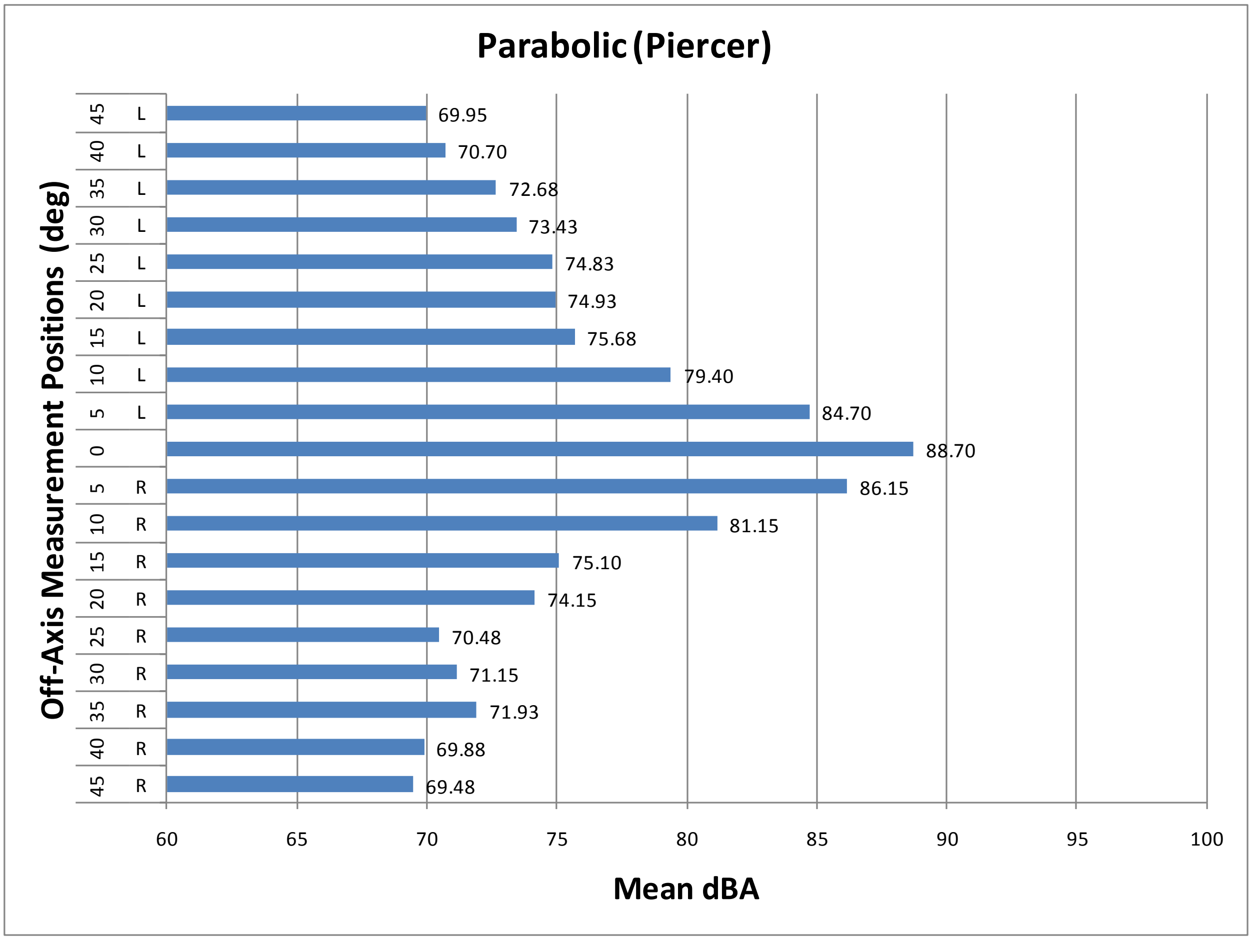

Figure 48. Bar graph. Mean dBA values collected during the beam-width characterization of the parabolic reflector design while using the *Piercer*.

3.6 CONCLUSIONS

Investigating the feasibility of generating a narrow-beam-width external auditory signal was one of the objectives; however, the two proposed concepts (i.e., tube design and parabolic reflector) were not able to achieve the narrow-beam-width goal of ±5 deg. Because this narrow beam-width could not be obtained, further use of either concept may needlessly alert other drivers in adjacent lanes. The parabolic reflector design was shown to provide directionality of 15 to 20 deg; however, the target directionality was not reached. V2V has the clear benefit over an external auditory signal in that more control of the signal's sound, directionality, and amplitude could be maintained inside the following vehicle. It was recommended that further ERS testing not include the external auditory signal component of this research project and that efforts be focused on visual countermeasures.

4. VISUAL WARNING SYSTEM

For many years the research team has been studying light-vehicle rear lighting to help prevent rear-end crashes. The results of that research have been used to aid in the design of ERS for heavy trucks in this project.(6,21,22) Visual warnings have been shown to be effective, assuming the following driver is looking directly at the warning display or has his/her eyes drawn to it. A visual warning can be placed where it is needed and it can be designed so that its meaning is nearly unambiguous. A quick review of previous findings in Phase I, Phase II, and light-vehicle rear lighting research performed by the research team is presented below.

4.1 RELEVANT PREVIOUS RESEARCH

4.1.1 Phase I and Phase II Previous Work

The Phase I and Phase II work performed by other organizations concentrated on three approaches to rear lighting:

- Use of two single-unit high-intensity LED lamps, one on each rear corner of the trailer, tied to brake pedal pressure in terms of brightness,
- Use of a single Traffic Clearing Lamp (TCL); this lamp produced a high-intensity beam that swept in an "M-pattern." This lamp is not unlike an intense flashlight beam that is swept in both the horizontal and the vertical direction, and
- Use of passive, but highly reflective, octagons placed at a uniform width at the back of a trailer.

Phases I and II both investigated the use of auditory warnings and the results suggested that a combination of TCL and sound was effective in reducing or eliminating tailgating. All other on-the-road testing was relatively inconclusive with regard to reducing rear-end crashes. These results suggest that any future FOT should be larger than the 100 h of on-road time used during the Phase II work. The results also suggest that effectiveness may be difficult to assess. Phases I and II were a good start and those studies provided preliminary results that were very useful for the development of Phase III.

4.1.2 Light-vehicle Rear Lighting Previous Work

The research team's work has been limited to light-vehicle research with regard to rear lighting; however, results have been quite conclusive. First, it should be mentioned that the research was a pioneer with regard to TCLs and the use of rear radar, not to mention equations and programming for determining when the rear warning-lights should be activated.(21,22) Early in the work, the research team tested 17 different lighting devices and configurations, including high-output incandescent lamps and strobes of various kinds. In these tests, the TCL was found to have the greatest attention-getting capability and the greatest off-axis (peripheral) detection capability of any device tested. Further results showed that when non-dispersive lenses of clear, red, and amber were used, the TCL retained its status as the most attention-getting. (Note that a dispersive lens is one that spreads light in various directions, such as a typical automotive tail-lamp. A non-dispersive lens is like a tinted pane of glass, it does not spread the beam to any noticeable extent.) If a flashlight beam is placed behind a non-dispersive lens, the beam can still be focused in a narrow area, such as on a wall. With regard to the TCL, it is important to use a non-dispersive lens to obtain its attention-getting effectiveness. With regard to other approaches, a high-output alternating pair of incandescent lamps with pulse-kick startup competed well, but was not quite as effective as the TCL. Studies showed that the optimum flash frequency for the alternating pair was 4.0 Hz. At higher frequencies, the distinct flashes began to fuse, resulting in lower ratings. This fusing was a result of the relatively slow onset and extinguishing times of incandescent lamps. During this previous work, the TCL was considered the first choice and the Improved Alternating Pair (IAP) was the second choice. These two were carried forward for further experimentation using the Virginia Smart Road and full-scale implementation.

It should be mentioned that the TCL and the IAP were also prone to discomfort-glare and created as much or more glare than other lighting approaches tested.(21,22) Discomfort-glare and attention-getting appear to be correlated. It is difficult to conceive of a lighting system that would gain attention without also producing some level of discomfort-glare. Later work on the Smart Road using a surrogate vehicle demonstrated a reduction in braking response time for both the TCL and the IAP.(22) For drivers who were distracted by an in-vehicle task, the brake response time was reduced by 300 ms (0.3 s) for the IAP and by 440 ms (0.44 s) for the TCL. These findings were for drivers who had not been exposed previously to the rear warning-lights and were surprised by it. However, additional results showed that there was little difference for drivers previously exposed. These results suggested average shorter stopping distances of 20 to 29 ft (6.10 to 8.84 m) at 45 mi/h (72.4 km/h). Note that centrally located doors were positioned above the license plate which kept the lamps hidden so that drivers would not become curious prior to their surprise event. For the second exposure, the doors were left open, since the element of surprise was no longer a factor. These tests demonstrated for the first time that rear warning-lights could reduce stopping distances if properly designed. This was an important finding and would likely also occur for appropriate rear warning-lights used on heavy trucks. Considering that rear-end crashes are quite prevalent, it seems likely that fleet implementation would result in a substantial reduction of crashes.

Later work by the research team used data from the 100-Car Naturalistic Driving Study.(10) The 100-Car Study was performed to determine how drivers were actually using their vehicles and why (in a technical sense) crashes occur. Unobtrusive instrumentation was used. In all, 10 rear-end crashes occurred over the duration of the study. Some of the relevant findings were as follows:

- Drivers having long eyes-off-road glances were most likely to have crashes (including rear-end crashes). This result underscores the importance of eye-drawing capability for rear warning-lights.
- Lead-vehicle deceleration of 0.4 g followed by a 5-second timeout would “capture” 90 percent of all rear-end crashes. This finding provided solid information for the design of open-loop activation, which is explained below.
- Earlier recommendations stood up when checked against the 100-Car data.

In general, the findings from the 100-Car data support the earlier findings in all respects, including the design of open-loop activation methods. By way of further explanation, activation methods should be defined. There are two known methods: open-loop and closed-loop.

- An open-loop activation sub-system is one which uses only lead-vehicle parameters to activate the rear lighting. Parameters used could include deceleration level, anti-lock braking system (ABS) activation, and time-out following these parameters reaching the activation levels.

- A closed-loop activation sub-system is one which uses both lead-vehicle parameters as well as measurements related to the following vehicle; for example, closing rate and closing distance. Ordinarily, such a system would include radar or laser measurement at the rear bumper of the lead vehicle (aimed toward the rear). This system would provide the parameters needed for more precise information to compute whether or not there is an instantaneous likelihood of a rear-end collision.

Work performed by the research team in 2003 had worked out strategies and equations for both open-loop and closed-loop activation of rear warning-lights.(21) It is likely that closed-loop activation would result in greater accuracy of activation; that is, more accurate detection of the risk of collisions and fewer false alarms (defined as activations for cases where rear-end collisions are not likely to occur). However, costs would be higher for closed-loop activation in that the measurement system at the rear bumper must be present and computational hardware and software must be used.

Work performed by the research team in 2005 used instrumentation developed in the earlier tests.(23) The TCL and the IAP were installed separately in a sedan and driven on public roadways, using an open-loop activation subroutine. Results suggested that both systems were feasible but, when turning corners after a sharp deceleration, the rear lighting should be extinguished. If not, a new following driver might be confused by the enhanced lighting. This does not seem to apply to heavy trucks because sharp turns only occur at very slow speeds. The work, in general, demonstrated the feasibility of implementing the system as well as using it in real-world traffic. The final work performed during this period involved initial development of a field test program for light vehicles. This work described how such a test could be developed and implemented, and what the vehicle configuration should include.(24)

The most recent work carried out by the research team involved conversion of the TCL and IAP to LED technology.(6) The main question to be answered was whether or not modern LED lighting could be substituted for either the TCL or the IAP while achieving comparable results in terms of attention-getting and eye drawing. To obtain an answer, a variety of light-vehicle and heavy-vehicle lighting units were measured for light output and for beam-width. The results showed clearly that one heavy-vehicle unit had the highest on-axis output, but also had a very narrow beam-width (figure 49, table 6). Other computations showed that if units were ganged they could compete successfully with incandescent units in terms of on-axis light output. In addition, the narrow beam-width would be useful in directing the light backward without high output in adjacent lanes—a desirable feature.

Figure 49. Grouped image. Heavy-vehicle LED unit providing the highest on-axis output with narrow beam-width.

Table 6. Results of the Laboratory Tests of the LED Lighting[6]

Lamp Description	On-axis Output Measurement at 8m (lux)	On-axis Equivalent Source Output (cd)	Half Output Total Horizontal Beam-width (deg)	Number of Active LEDs	Approximate On-axis Output per LED (cd/LED)	Current Draw at 13.5V (milliamps)	Power Consumed at 13.5V (watts)
Round 4" Diameter Stop lamp Type: anythingtruck. com 440RHW	4.11	263	7	40	6.58	271	3.66

These results were used to develop a display board for testing (figure 50). This display board used a photographic appliqué over a metal backing. At distances beyond 60 ft (18.29 m), it was quite difficult to tell that the display board was not an actual vehicle.

Figure 50. Photo. Display board used for outdoor testing of an LED lighting system.(6)

Testing with the display board showed that flashing all rear lighting simultaneously resulted in high attention-getting ratings and good eye-drawing capability. Other results showed that the median optimum frequency of flash was 5.0 Hz for simultaneous flash of all lamps, which is slightly higher than the IAP optimum frequency. The reason for the slightly higher frequency was believed to be the sharp onset and extinguishing characteristics of the LED units, as compared with earlier incandescent results. This optimum frequency is also well below brain alpha rhythms (9.0 to 12.0 Hz) that has been shown to trigger seizures in epilepsy sufferers.(25)

In an experiment investigating eye-drawing capability in which drivers were purposely distracted by a navigation task, normal brake-level lighting (baseline condition) did not exhibit any eye-drawing capability, whereas the simultaneous flashing of all rear lights at increased brightness resulted in a 56 percent look-up percentage among the drivers on first (uninformed) presentation. These results were for bright daylight with the sun shining on the display.

In yet another experiment, the best LED configuration was compared with both the incandescent and LED versions of the TCL. The results showed that the best LED configuration was substantially superior to either type of TCL. These results indicated that future work should be directed toward use of the best LED configuration; that is, the one that simultaneously flashes all rear lighting at an increased brightness.

4.1.3 Lessons Learned from Previous Work

Previous work suggested that for heavy trucks, lighting similar to that developed for light vehicles should be used; namely, multiple high-output LED units that flash simultaneously at a

5-Hz frequency. It was determined by the research team that these experiments did not need to be repeated for heavy trucks. The results also suggested that the round units found to have the highest output (table 6) do not need to be modified. However, because of their narrow beam-width it would be necessary to properly aim the lights so that the following-driver's eyes would be within the main beam. This means that the units needed to be aimed appropriately, particularly vertically, as shown in figure 51. Preliminary analyses were performed in which vertical aim was adjusted according to potential height locations on the back of the trailer and horizontal aim was adjusted according to potential following-vehicle positions (table 7). These eye heights were necessary to account for because following-driver eye height varies as a function of seated stature and type of vehicle.

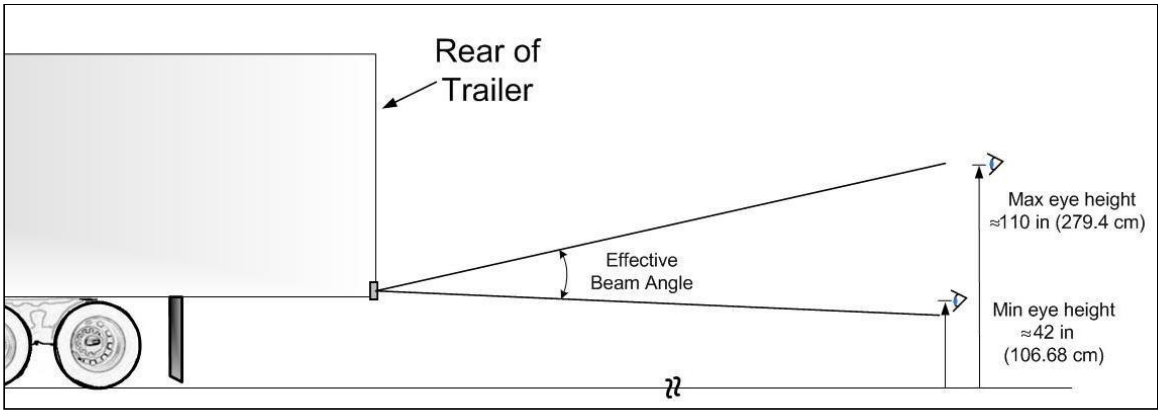

Figure 51. Diagram. Initial concept of LED unit aiming to accommodate various eye heights (figure not to scale).

Table 7. Preliminary Analysis of Vertical and Horizontal Aim of LED Units Using 6° Beam-width

Position on Trailer	Approximate Height Above Roadway	Vertical Aim Angle	Horizontal Aim Angle
Main bumper	45 in (114.3 cm)	2.64 deg upward	2.5 deg inward
ICC bumper (Sides)	22.5 in (57.15 cm)	3.75 deg upward	2.5 deg inward
ICC bumper (Center)	22.5 in (57.15 cm)	3.75 deg upward	0.0 deg inward
Lower unit on door	56 in (142.24 cm)	1.33 deg upward	2.5 deg inward
Middle unit on door	97 in (246.38 cm)	1.45 deg downward	2.5 deg inward
Top unit on door	134 in (340.36 cm)	3.88 deg downward	2.5 deg inward

4.2 STATIC EXPERIMENTATION

4.2.1 Purpose & Objectives

The purpose of static testing (parked vehicle with participants not driving) was to determine how well various configurations of rear lighting positioned on the rear of a heavy-truck trailer would provide improved eye-drawing capabilities as well as improved attention-getting and discomfort-glare performance. The different groups of rear lighting that will be referred to for the remainder of this report are further described as follows:

- **Rear-lighting configurations**: This group consists of both the normal brake light configuration pre-installed on the manufactured trailer as well as newly designed warning-light configurations selected for the particular experiment in question.
- **Rear warning-light configurations**: This group consists only of newly designed warning-light configurations selected for the particular experiment in question.

Static testing was used first to down-select rear warning-light configurations prior to dynamic testing performed on the Virginia Smart Road. Two static experiments were performed in total. Each experiment and the results obtained are discussed below.

4.2.2 Experiment 1

4.2.2.1 Method

Study Design: A total of 84 naïve drivers (no previous exposure to the rear-lighting configurations) were used. Half of the participants were males and half were females. Candidate participants were screened over the phone with a verbal questionnaire to determine whether they were licensed drivers, were of the appropriate age, and whether they had any health concerns that might exclude them from participating. Approval for participant experimentation was approved by the research team's Institutional Review Board's (IRB) Human Assurances Committee. The age of participants ranged between 20 and 62 years old (mean of 41.4). Counterbalancing of two conditions was performed (i.e., gender and lighting configuration). Data were collected during the day from 9:00 a.m. Eastern Standard Time (EST) to 5:30 p.m. EST. Time of day was not considered in the counterbalancing; however, participants were randomly assigned to the available time slots in order to avoid potential sunlight angle bias.

Both performance and opinion data were gathered during this experiment. The main aspect of the performance testing was determining the eye-drawing capability of each rear-lighting configuration. The number of occurrences of eye drawing (participants looking up) and the time to redirect their gaze to the forward roadway were measured and served as the main dependent measures in this experiment. An uninformed event detection paradigm method (administered before drivers were informed about the true purpose of the study) was used for each experiment that was designed during previous research.[(6)] This method had the purpose of assessing the eye-drawing capability of each rear-lighting configuration (rear-lighting configurations for these uninformed trials were treated as a between-subjects factor). In total, six rear-lighting configurations were tested using all of the 84 participants (14 participants per rear-lighting configuration). The use of this between-subjects design was necessary because after each participant was exposed to the surprise event (uninformed event) re-exposure would not provide the same effect.

Subjective rating scales were also administered to a portion of the participants. Twenty-four of the 84 participants filled out attention-getting and discomfort-glare rating scales at multiple light-vehicle positions behind the experimental CUT. The reason for using these unequal numbers was that the use of 24 participants was found to be sufficient to test a group of six different rear-lighting configurations using a totally within-subject design. The use of 84 participants was used to obtain sufficient statistical power for the between-subjects design portion of the experiment (14 per condition). The experimental design is depicted in figure 52.

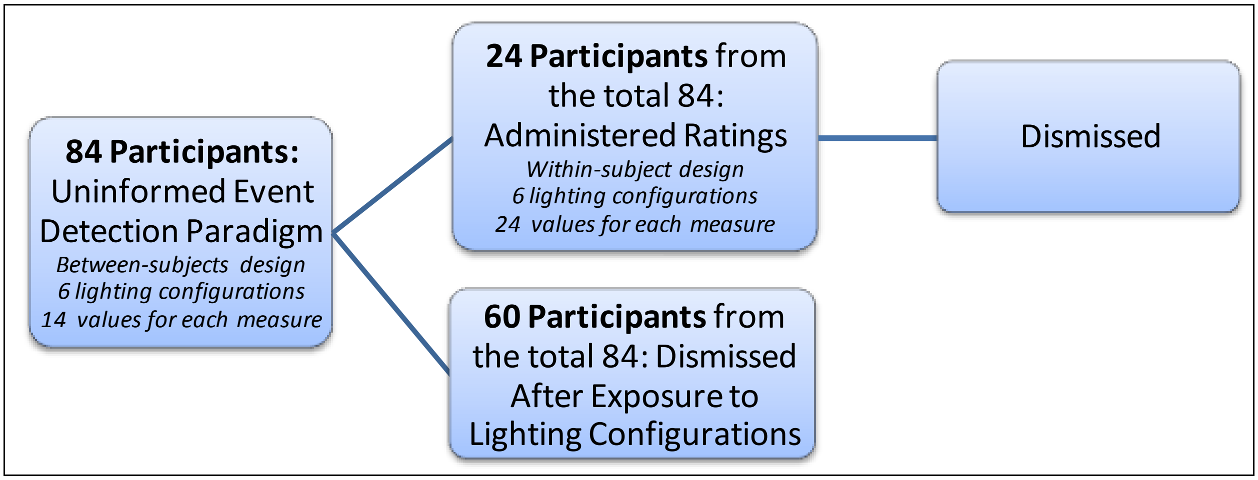

Figure 52. Diagram. Study design for the Experiment 1 uninformed event detection paradigm and administered ratings.

Apparatus: Six rear-lighting configurations installed on the rear of a 53-ft (16.15-m) trailer connected to a tractor were used during static testing (five rear warning-light configurations, one normal brake-light configuration). All testing performed through this project was performed using this heavy truck and trailer combination and will be referred to as the experimental CUT for the remainder of this report. All five rear warning-light configurations were made up of numerous high-output LED units selected from previous research (figure 49).[6] Previous light-vehicle rear signaling research has shown that by ganging LED units together, eye-drawing performance is greatly improved.[6] Therefore, three of the five rear warning-light configurations contained LED units that were ganged close together on the main bumper.

Each high-output LED unit was aimed appropriately, both vertically and horizontally, according to the location on the back of the experimental CUT (table 7). While vertical aiming was extremely important, horizontal aiming was also considered. Horizontal aiming included turning the units located near the sides of the trailer inward slightly (2.5 deg), so that drivers in the adjacent lane would not be subjected to high-output warnings. Because of the narrow output beam-width of the units, it was possible to minimize adjacent lane output while concentrating energy directly behind the trailer where it would be needed for rear-end collision mitigation. The baseline rear-lighting configuration was made up of two normal LED units already installed on the trailer. Detailed specifications on all rear-lighting configurations used in static testing can be found in appendix C. All rear-lighting configurations are shown and labeled in figure 53. Rear-lighting configuration descriptions and figure labels are summarized as follows:

- *Main Bumper* (A): Twelve high-output LED units ganged and positioned on the rear main bumper.
- *Cargo Box* (B): Six high-output LED units positioned on the rear of the cargo box.
- *ICC Bumper* (C): Five high-output LED units positioned on the Interstate Commerce Commission (ICC) bumper.
- *Main Bumper/Cargo Box* (D): Twelve high-output LED units ganged and positioned on the rear main bumper and six LED units positioned on the rear of the cargo box.

- *Main Bumper/ICC Bumper* (E): Twelve high-output LED units ganged and positioned on the rear main bumper and five LED units positioned on the ICC bumper.
- *Baseline* (F): Two LED-unit brake lights pre-installed by trailer manufacturer (baseline condition).

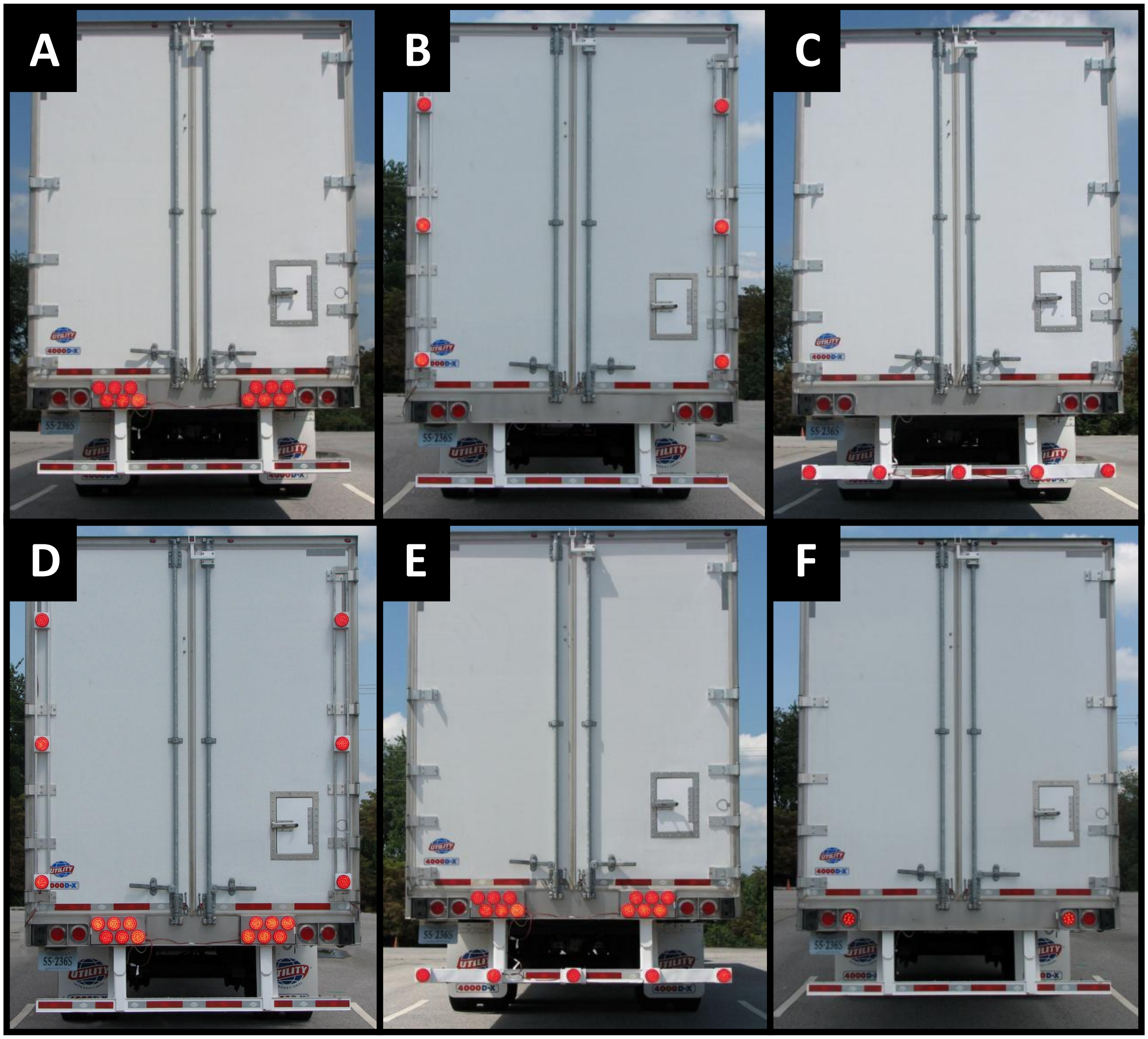

Figure 53. Grouped image. Rear-lighting configurations used during preliminary static testing.

During the uninformed event detection portion of the experiment, participants sat in the driver seat of a late model sedan (light vehicle) positioned 100 ft (30.48 m) directly behind the experimental CUT (figure 54). Participants were instructed by the experimenter (sitting in the passenger seat) to follow along and complete in-vehicle navigation system tasks. These tasks were intended to distract each participant’s gaze away from the forward roadway. Similar to earlier research, the navigation system display and controls were located at a horizontal angle of approximately 30 deg to the right of the on-axis forward glance position and at a vertical downward angle of approximately18 deg (subject to error from variation in participant seat position) (figure 55).[(6)]

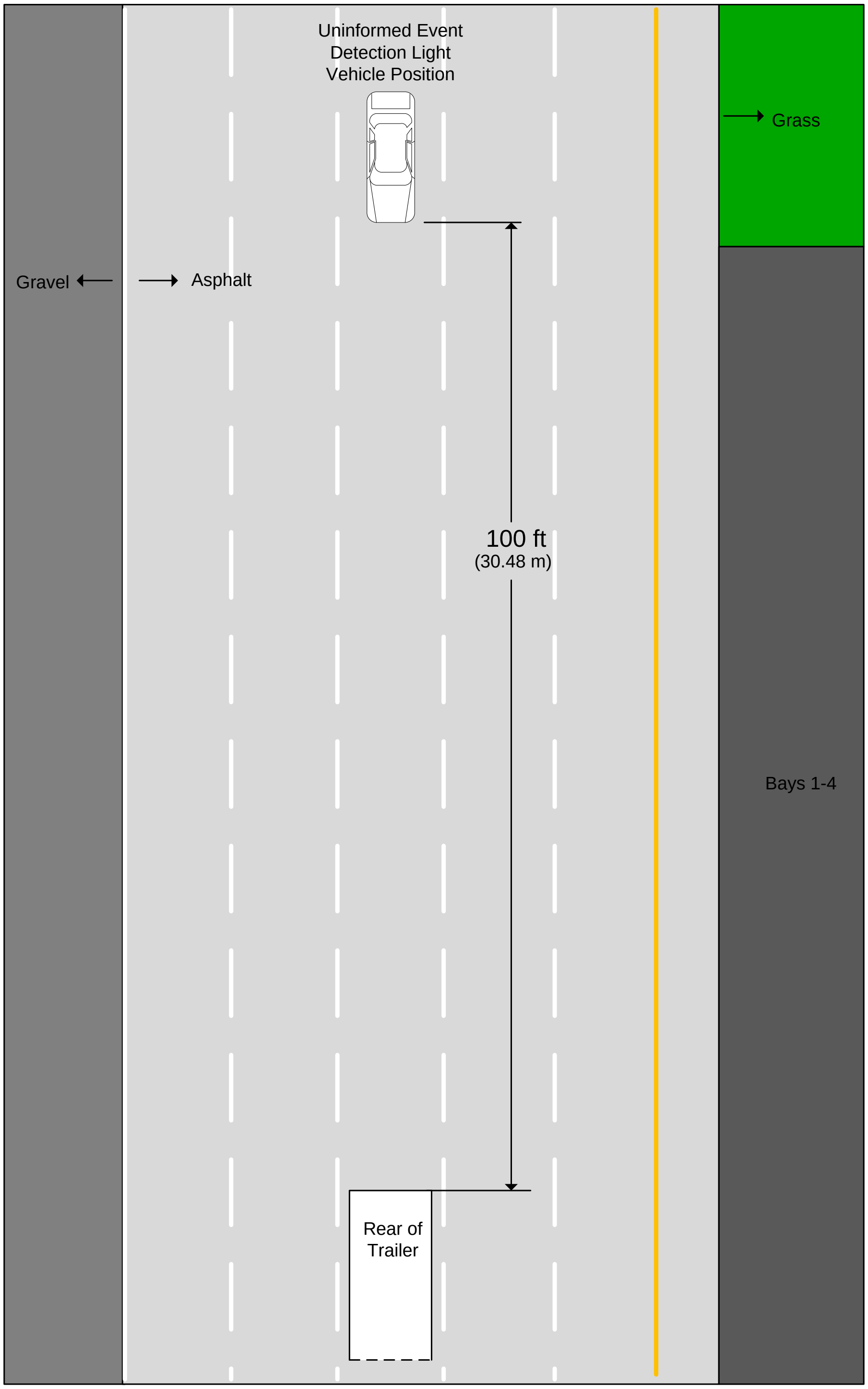

Figure 54. Diagram. Overhead diagram of light-vehicle and experimental-CUT positions for the uninformed event detection trials.

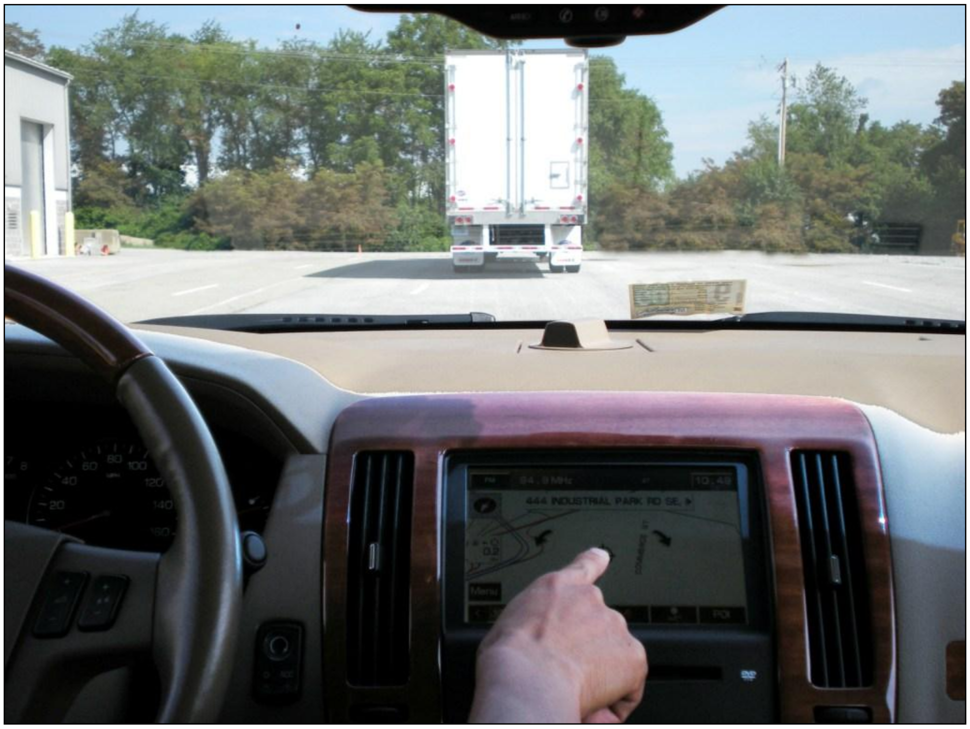

Figure 55. Photo. Navigation system display location for the uninformed event detection.

Rear-lighting activation was controlled by the lead experimenter in the passenger seat of the light vehicle. A small button, hidden from the view of the driver, was used to activate the rear-lighting configurations through a wireless signal sent from the light-vehicle's Data Acquisition System (DAS) and received by a wireless antenna under the trailer. Upon activation of each rear warning-light configuration, lights would flash simultaneously at a 5-Hz frequency for a period of 5 s. Upon activation of the *Baseline* configuration, steady brake lighting (no simultaneous flashing) was initiated for a period of 5 s. The time period of 5 s was chosen based on rear-lighting activation algorithms developed in previous light-vehicle rear signaling research.[21] These algorithms, which will be discussed later in the section on activation sub-system testing, show that a crash is likely to occur if action is not taken within 5 s of rear-lighting activation. Four camera views were recorded in the light vehicle by the DAS. Views recorded included the driver's face, forward view, an over-the-shoulder view, and brake pedal view (figure 56).

Figure 56. Screenshot. Screenshot from video recorded inside the light vehicle.

Upon completion of the uninformed event detection trials, 24 of the 84 participants filled out attention-getting rating scales (an 8-point ordinal scale) and discomfort-glare rating scales (modified DeBoer 9-point scale) at multiple light-vehicle positions behind the experimental CUT (figure 57 and figure 58, respectively). Participants provided their ratings verbally and the experimenter wrote them down. Participants were also permitted to provide half-value ratings (such as 5.5). Light-vehicle positions used during the rating scale portion will be discussed in more detail in the procedures section.

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 57. Screenshot. Attention-getting rating scale.

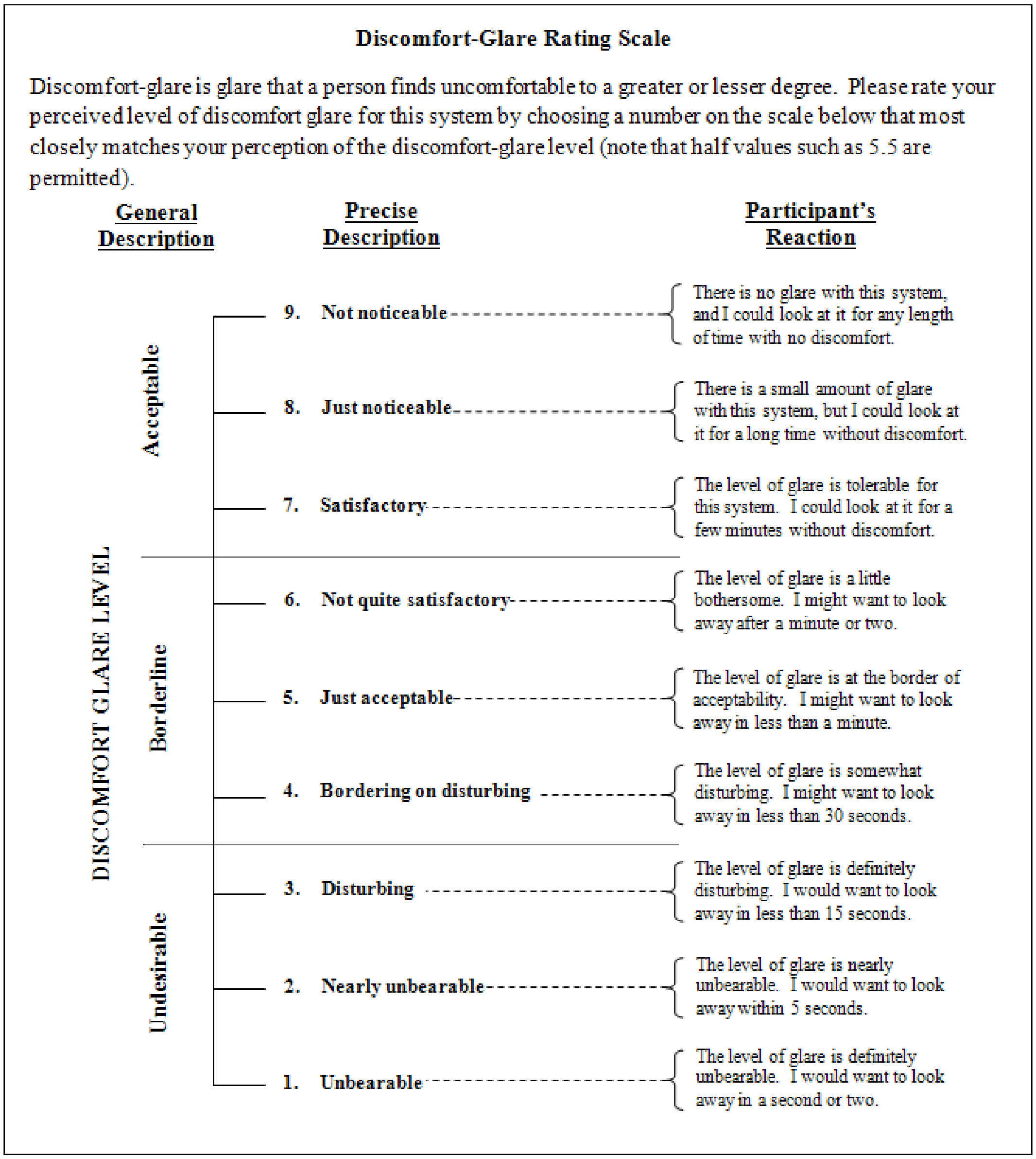

Figure 58. Screenshot. Discomfort-glare rating scale.

Procedure: Upon arrival, each participant read and signed an initial informed consent form information sheet. After addressing all of the participant's questions, both the participant and the experimenter signed the form. Next, participants were asked to show a valid driver's license, and a brief informal hearing test and three vision tests were administered. The informal hearing test consisted of the experimenter reading four statements aloud and instructing each participant to correctly repeat back what he/she heard. The first vision test was a Snellen test to ensure that vision acuity was within the legal driving limit (corrected to 20/40). Immediately following, the Ishihara Color Vision test was also administered.[26] The experimenter recorded each participant's ability to detect color, but it was not part of the eligibility criteria. Of the 84, 10 were found to have at least some level of color blindness. Of these 10, 3 participants were found to look-up at rear-lighting configurations. The final vision test administered was the Useful Field of View (UFOV) test which was a computer-administered and computer-scored test of functional vision and visual attention. This test has been shown in previous research to be a good predictor of driving performance.[27] It was administered in approximately 15 minutes and consisted of three subtests which assessed the speed of visual processing under increasingly complex task demands. As with the ability to detect color, the results of the UFOV test had no effect on eligibility for participation. Complete data for the UFOV test were obtained for all 84 participants. Of the 84 participants, 81 scored in the very-low-risk category and 3 scored in the low-risk category. No participants were dismissed due to ineligibility (all participants had sufficient vision and/or hearing). All vision and hearing protocols can be found in appendix D.

After the screening session was complete, each participant was escorted to an asphalt test-pad area at the research facility. Each participant was asked to sit in the driver seat of a light vehicle that was positioned 100 ft (30.48 m) behind the experimental CUT in the same lane (see figure 54). Although participants were aware that the experimental CUT was parked in front of the light vehicle, they were not aware that it was in any way associated with the in-vehicle navigation display tasks to be performed. As mentioned previously, participants were instructed by the experimenter to complete several in-vehicle navigation system tasks. There were three tasks performed which were intended to distract each participant's gaze away from the forward roadway and, while participants were involved in the task, the assigned rear-lighting configuration was activated. Each of these tasks is further described below in the order that they were administered:

- *Exposure 1*: Light activation triggered while receiving experimenter instruction on use of the in-vehicle navigation system display (observing only; low level of visual, cognitive, and manual loading).
- *Exposure 2*: Light activation triggered while selecting among available menu items on the navigation system display (participant interaction; medium level of visual, cognitive, and manual loading).
- *Exposure 3*: Light activation triggered during text entry on the navigation system display (participant interaction; high level of visual, cognitive, and manual loading).

As previously mentioned, this uninformed event detection paradigm was successfully executed in previous light-vehicle rear signaling research.[6] Participants were not driving during these navigation system tasks, and therefore had no need to look forward. However, the hypothesis behind this method was that effective lighting configurations would still draw visual attention to the forward view.

Upon completion of the navigation system tasks, participants were asked a series of debriefing questions, told the true purpose of the research, and then returned to the main building at the research facility to review the formal debriefing form and sign the investigative project informed consent form. These forms included an apology for not explaining the true purpose of the study in the initial informed consent form information sheet, and requested permission to include their data in the analyses. Twenty-four of the 84 participants were then invited to participate in a rear-lighting configuration ratings session by reviewing and signing the subjective-ratings informed consent form. All 24 participants invited did agree to participate. Each of these participants was again escorted back to the asphalt pad study area and returned to the light-vehicle's driver seat. Participants were told they would not be driving the vehicle during tasks; however, they would be asked to reposition the vehicle when necessary between tests, under in-vehicle experimenter guidance. As mentioned previously, the two ratings scales that participants used to rate each rear-lighting configuration were attention-getting and discomfort-glare (figure 57 and figure 58, respectively). Participants rated each rear-lighting configuration 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 another looking 30 deg off-axis to the right while focusing on an orange cone). Participants rated the level of discomfort-glare of each rear-lighting configuration 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 rating provided while positioned in the same lane was given while looking directly ahead at the lighting. However, the discomfort-glare rating provided while positioned in the adjacent lane was given while looking directly ahead in the lane (not focusing directly on the lighting). The vehicle positions for the rating scale portion of this experiment are depicted in figure 59.

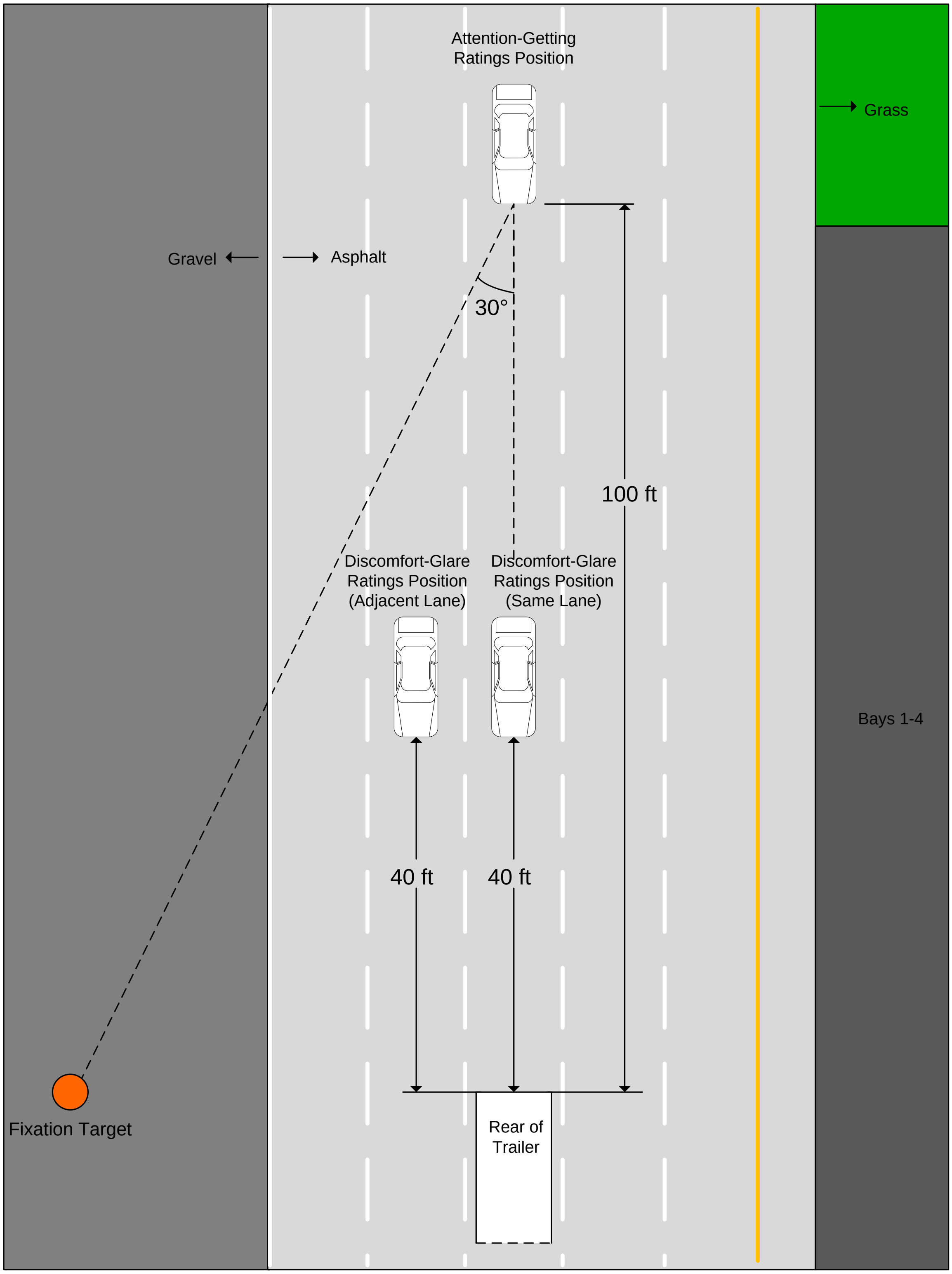

Figure 59. Diagram. Overhead diagram of light-vehicle positions for the ratings portion of the experiment.

After completion of all ratings for each rear-lighting configuration, participants were returned to the main building at the research facility, compensated, and thanked for their time.

4.2.2.2 Results

Uninformed Event Detection Results: The uninformed event detection portion of this experiment had the purpose of determining how well six rear-lighting configurations would provide improved eye-drawing capabilities. The total number of eye-drawing events (i.e., participants looking up after rear lighting was initiated—*Look-ups*) and non-eyedrawing events (i.e., participants not looking up after rear lighting was initiated—*Non-look-ups*) was tabulated. Also collected was the duration between the signal initiation and the participant's look-up response (*Time To Look-up*). The number of *Look-ups* and *Non-look-ups* are shown in table 8 as a function of the rear-lighting configuration. The table shows that four of the six rear-lighting configurations resulted in look-ups.

Table 8. Number of *Look-ups* and *Non-look-ups* in the Uninformed Event Detection Portion Across All Exposures of Experiment 1

Lighting Configuration	Look-ups	Non-look-ups	Total Events
ICC Bumper	0	42	42
Cargo Box	0	42	42
Baseline (Normal Brake Lights)	*2*	40	42
Main Bumper/Cargo Box	*4*	38	42
Main Bumper	*8*	34	42
Main Bumper/ ICC Bumper	*13*	29	42
Total	**27**	**225**	**252**

As previously mentioned, all rear-lighting configurations were displayed for a total of 5 s after initiation. If the participant did not look up, a value of 5 s was assigned on the assumption that this would be the minimum time in which the participant might have looked up. There were two occasions when a participant looked up after a rear-lighting configuration had already been extinguished (after 5 s) and in these situations a value of 5 s was assigned.

The first analysis performed using *Time To Look-up* as the primary variable of interest was across all three exposures (i.e., low demand, moderate demand, and high demand). A two-way Analysis of Variance (ANOVA) was performed with rear-lighting configuration as a between-subjects variable with six levels, and exposure as a within-subject variable with three levels. Main effects were found for both rear-lighting configuration and exposure. The main effect of rear-lighting configuration was significant at $F(5,78) = 3.81$, $p < 0.0038$. The main effect of exposure was significant at $F(2,156) = 11.65$, $p < 0.0001$. The interaction of these two variables was also found to be significant at $F(10,156) = 2.92$, $p < 0.0022$. The interaction is plotted in figure 60. Although the results show significant main effects for both lighting configuration and exposure, the interaction provides insight into what is actually causing a difference in *Time To Look-up* for this analysis. As is seen in the figure, *Exposure 1* shows much lower mean values for *Time To Look-up* in three of the six lighting configuration categories. By further slicing the interaction and holding exposure level constant, *Exposure 1* is shown to be significant at $F(5,78)$

= 12.67, $p < 0.0001$. *Exposure 2* and *Exposure 3* were not significant; $F(5,78) = 2.06$, $p = 0.0739$ and $F(5,78) = 0.84$, $p = 0.526$, respectively. These results indicate that *Exposure 1* should be of primary focus for remaining analyses and suggest that as the cognitive demand increased with each exposure, the possibility of perceptual narrowing may have occurred which mimics previous research results.[6] It is also important to note that *Exposure 1* was the only event which was truly unanticipated across all participants.

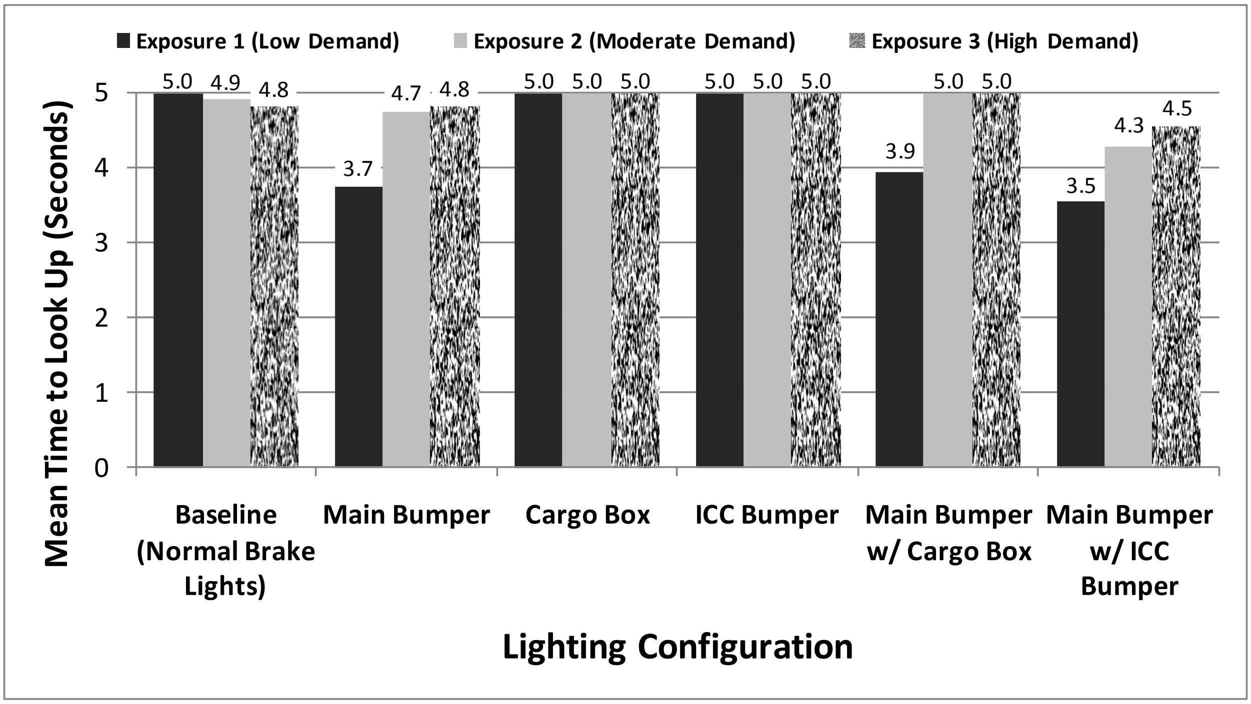

Figure 60. Bar graph. Mean *Time To Look-up* as a function of lighting configuration and exposure for static Experiment 1.

The next analysis performed using *Time To Look-up* as the variable of interest was on *Exposure 1* only (the only situation that was unanticipated across all participants). A one-way between-subjects ANOVA was performed. Results showed significance with $F(5,78) = 4.47$, $p < 0.0012$. A Duncan's multiple range test was also performed to determine where significant differences occurred between rear-lighting configurations. These results are shown in figure 61. In the figure, means with a common letter (i.e., A or B) do not differ significantly at the $\alpha = 0.05$ level. The figure shows that the *Baseline*, *ICC Bumper*, and *Cargo Box* rear-lighting configurations did not cause any *Look-ups* and thus each report a mean *Time To Look-up* of 5 s (the maximum duration of the light exposure). The *Main Bumper*, *Main Bumper/Cargo Box*, and the *Main Bumper/ICC Bumper* rear warning-light configurations were the only ones that resulted in any *Look-ups* and all were significantly better at reducing *Time To Look-up*.

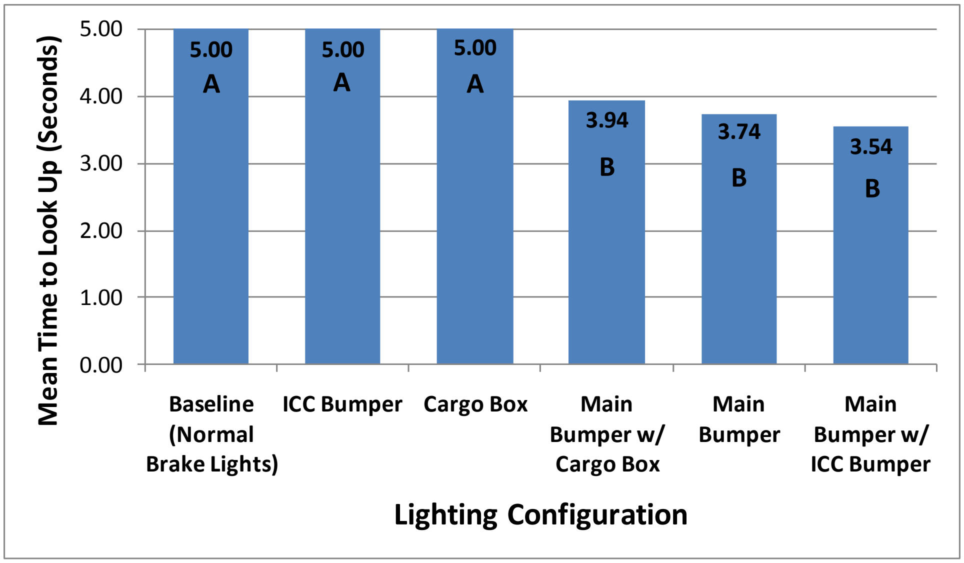

Figure 61. Bar graph. Mean *Time To Look-up* for *Exposure 1* as a function of lighting configuration for static Experiment 1.

In order to further investigate the exposure issue, the percentage of participants who looked up as a function of exposure was calculated and plotted in figure 62. As the figure clearly shows, the percentage of *Look-ups* was much higher for *Exposure 1*. A Chi-square analysis was performed and found to be significant, $\chi 2$ (2) = 15.1822, $p < 0.0005$.

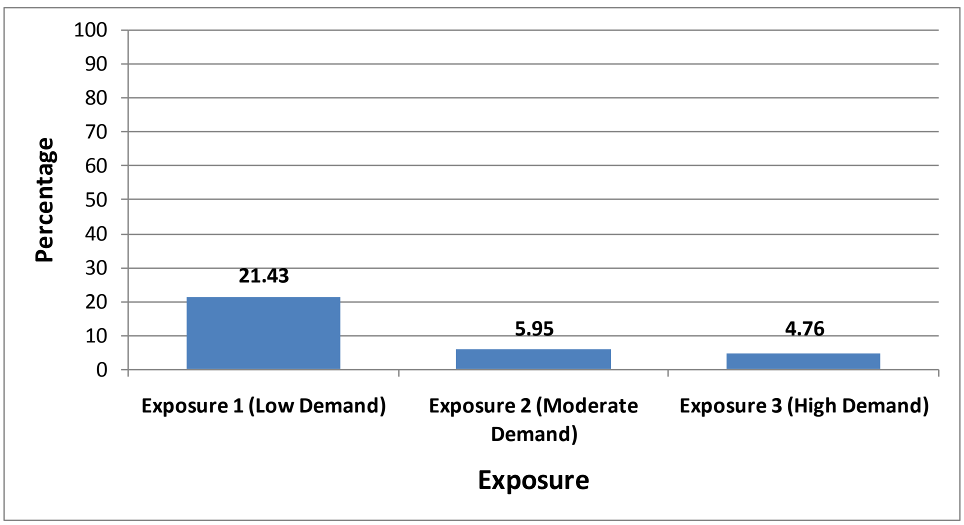

Figure 62. Bar graph. Percentage of participants that looked up as a function of exposure for static Experiment 1.

The percentage of participants who looked up as a function of exposure and rear-lighting configuration is shown in figure 63. Although no statistical tests were performed, it is quite clear that all of the rear warning-light configurations containing the *Main Bumper* ganged-lighting performed the best with the greatest percentage of *Look-ups*. Also, figure 63 shows that *Exposure 1* contained the greatest contribution of *Look-ups*, suggesting once again that during tasks of lower cognitive load, rear warning-lights on trucks may indeed alert drivers to the forward view. These results, in combination with the previous results on *Time To Look-up*, suggest that rear warning-light configurations containing the 12 high-output LED units ganged on the main bumper were the best candidates for moving forward to dynamic testing.

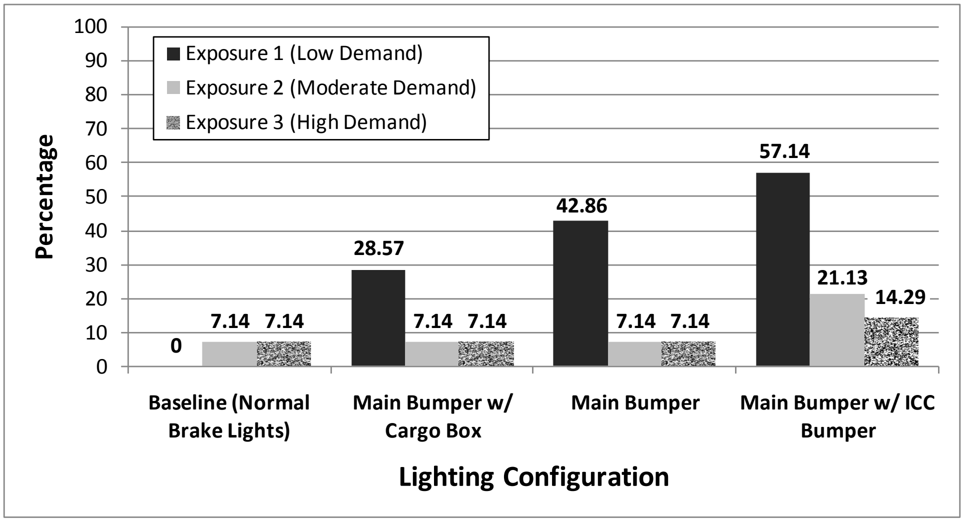

Figure 63. Bar graph. Percentage of participants that looked up as a function of lighting configuration and exposure for static Experiment 1.

The number of participants who looked up for each rear-lighting configuration (regardless of exposure) was analyzed using a Chi-square test and found to be significant, χ^2 (5) = 23.1935, $p <$ 0.0003. However, it is important to note that 50 percent of the cells in the Chi-square table had expected counts of less than 5. Also analyzed was the number of affirmative responses to the first of three interview questions asked at the conclusion of the experiment. Nineteen participants (22.62 percent) answered affirmatively to the question “Did you notice anything unusual outside at any time while we were working with this navigation system?” A Chi-square analysis was used to analyze the number of drivers providing “affirmatives” as a function of the six rear-lighting configurations and was found to be significant, χ^2 (5) = 22.06, $p < 0.0005$. Figure 64 shows both the percentage of drivers that reported look-ups as well as the percentage of drivers that actually looked up for each of the six rear-lighting configurations. As the figure shows, there was only a very small difference, indicating that participants who looked up also reported their *Look-ups* with a good level of accuracy.

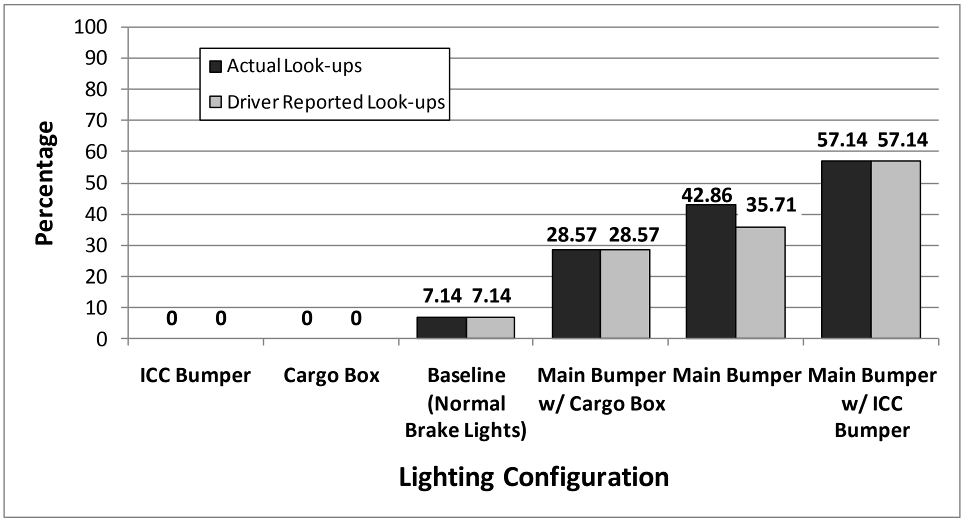

Figure 64. Bar graph. Percentage of participant-reported *Look-ups* and actual *Look-ups* as a function of lighting configuration for static Experiment 1.

The second question asked during the post-experiment interview was "Did it happen more than once?" and 8 of the 19 participants (42.11 percent) answered yes. These eight participants were then asked to provide an answer to the final question, "How many times?" The responses are shown in figure 65 in the form of percentages. As shown in the figure, two of the eight participants (25 percent) recalled the correct amount of "three times" that the rear lighting was activated.

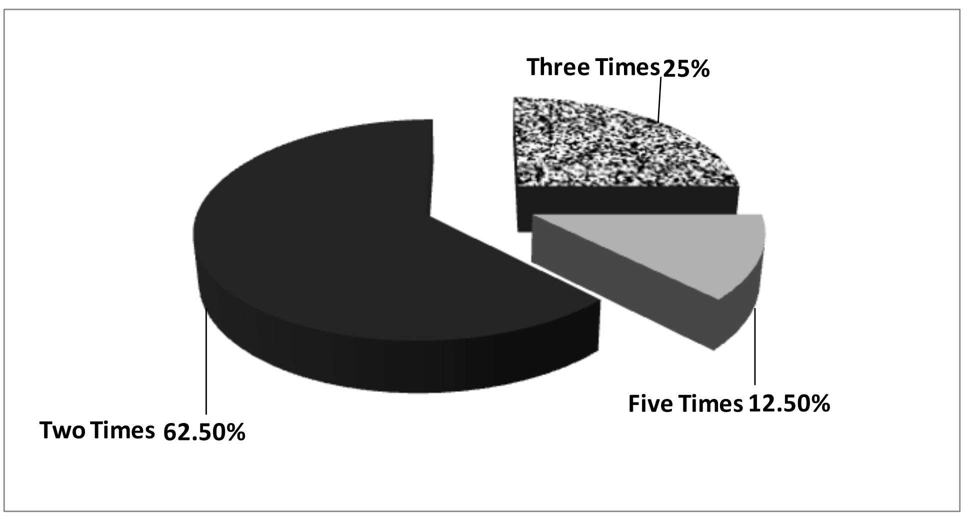

Figure 65. Pie chart. Response percentages to the third question, "How many times did you see the lighting appear?" for static Experiment 1.

Rating Scale Results: As previously mentioned, attention-getting ratings and discomfort-glare ratings were obtained from 24 of the 84 participants. Participants provided an attention-getting rating for each rear-lighting configuration while fixating directly ahead at the lighting, and another while fixating 30 deg off-axis. Participants provided a discomfort-glare rating for each rear-lighting configuration while fixating directly ahead at the lighting, and another while stationary in an adjacent lane and fixating ahead in the lane (looking past the lighting display).

For the attention-getting ratings while fixating directly at the lighting, a one-way within-subject ANOVA was performed and found to be significant, $F(5,115) = 78.52$, $p < 0.0038$. A Tukey's Studentized Range Honestly Significant Difference (HSD) post hoc test was performed and results are shown in figure 66. The attention-getting rating scale (figure 57) contained a scale of 1 to 8 (1 being not at all attention-getting, and 8 being extremely attention-getting). As expected, the three rear warning-light configurations that provided the highest ratings (significantly better than the other three configurations) all had the *Main Bumper* ganged-lighting configuration in common.

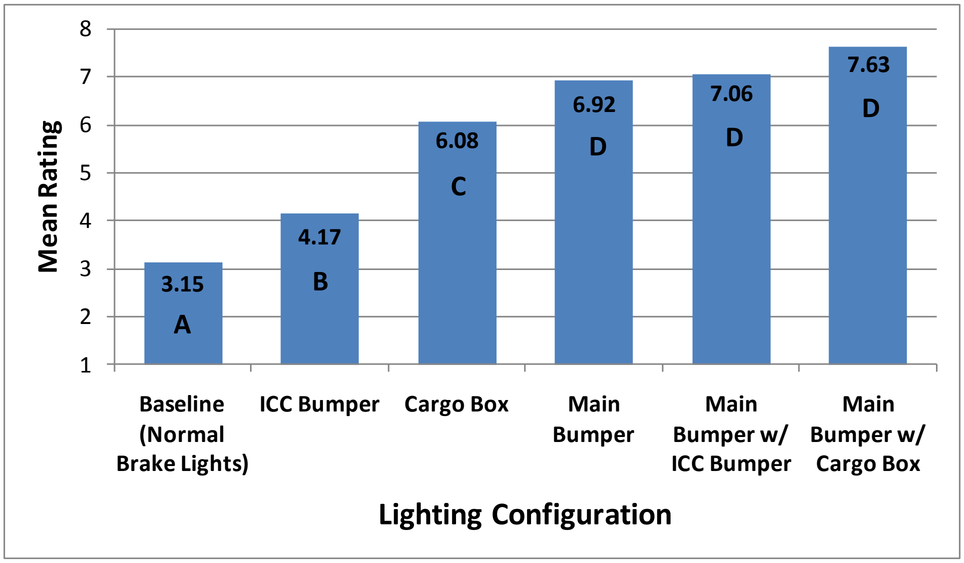

Figure 66. Bar graph. Mean attention-getting ratings of participants fixating at lighting as a function of lighting configuration for static Experiment 1.

For the attention-getting ratings while fixating 30 deg off-axis, a one-way within-subject ANOVA was performed and found to be significant, $F(5,115) = 125.46$, $p < 0.0001$. A Tukey's Studentized Range (HSD) post hoc test was performed and results are shown in figure 67. The figure shows that the highest rated rear warning-light configurations while fixating off-axis were the *Main Bumper/Cargo Box* and the *Main Bumper/ICC Bumper*. The *Main Bumper* lighting configuration was rated a very close second. Similar to the ratings while fixating directly forward at the lighting, the three rear warning-light configurations that provided the highest ratings all had the *Main Bumper* ganged-lighting configuration in common.

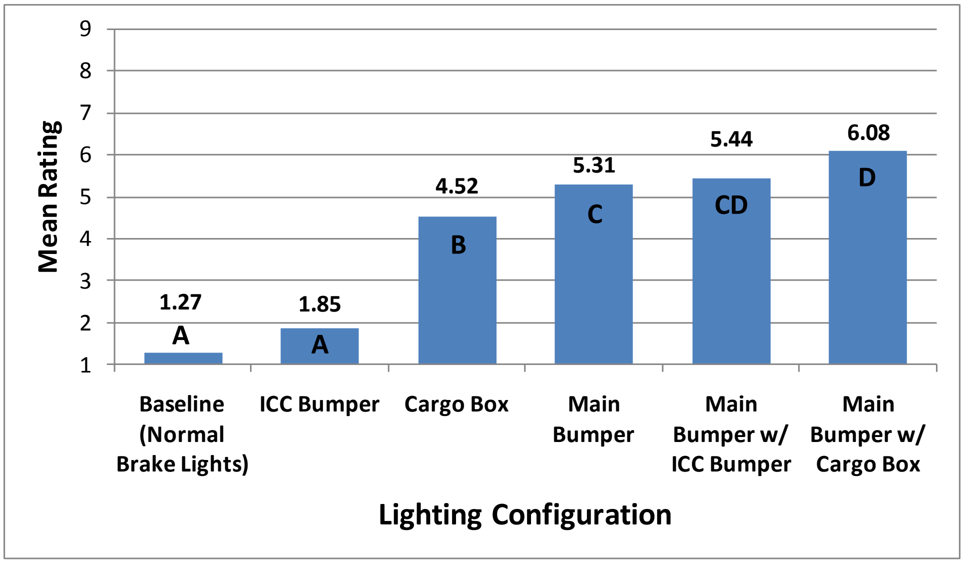

Figure 67. Bar graph. Mean attention-getting ratings of participants fixating 30 deg off-axis as a function of lighting configuration for static Experiment 1.

For the discomfort-glare ratings while fixating directly at the lighting, a one-way within-subject ANOVA was performed and found to be significant, $F(5,115) = 24.92$, $p < 0.0001$. A Tukey's Studentized Range (HSD) post hoc test was performed and results are shown in figure 68. The discomfort-glare rating scale (figure 58) contained a scale of 1 to 9 (1 being unbearable and 9 being not noticeable). The three rear warning-light configurations that provided the higher amount of discomfort-glare all had the main bumper ganged-lighting in common. It is important to note that the mean ratings for each of these rear warning-light configurations were in the middle range for glare.

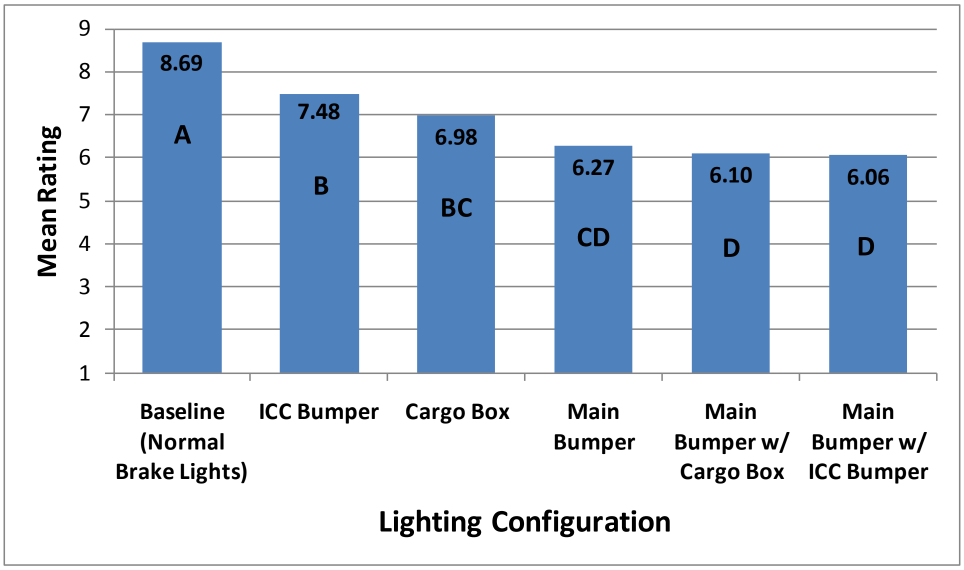

Figure 68. Bar graph. Mean discomfort-glare ratings of participants fixating at lighting as a function of lighting configuration for static Experiment 1.

For the discomfort-glare ratings while stationary in an adjacent lane and fixating ahead in the lane (looking past the lighting display), a one-way within-subject ANOVA was performed and found to be significant, $F(5,115) = 13.65$, $p < 0.0001$. A Tukey's Studentized Range (HSD) post hoc test was performed and results are shown in figure 69. Of the four rear warning-light configurations that provided a higher amount of discomfort-glare, three of them contained the main bumper ganged-lighting configuration (as all or part of the entire configuration). It is important to note that while participants were rating, in the adjacent lane the mean ratings for each of these lighting configurations fell in the low range for glare (indicating above satisfactory levels of glare).

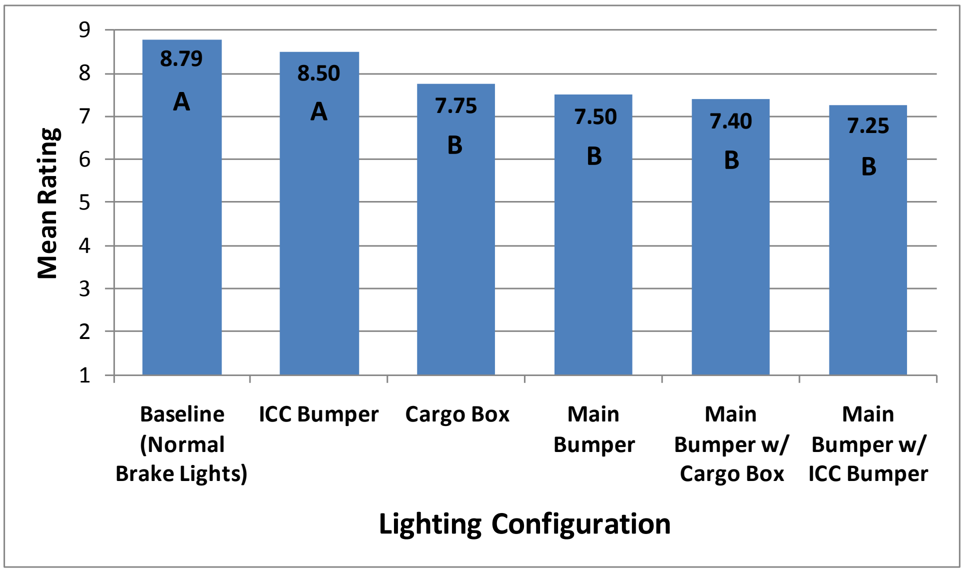

Figure 69. Bar graph. Mean discomfort-glare ratings of participants positioned in adjacent lane fixating forward in the lane (not looking directly at lighting) as a function of lighting configuration for static Experiment 1.

4.2.2.3 Experiment 1 Summary

Uninformed Event Detection: Results indicated that *Exposure 1* data were the most important to focus on as they contained the most look-ups and were the only events which were truly unanticipated across all participants. *Exposure 1* results showed that the *Baseline*, *ICC Bumper*, and C*argo Box* rear-lighting configurations did not cause any participants to look up. The *Main Bumper*, *Main Bumper/Cargo Box*, and *Main Bumper/ICC Bumper* rear warning-light configurations were the only ones that caused any look-ups and all were significantly better at reducing *Time To Look-up*.

The rear warning-light configurations containing the *Main Bumper* ganged-lighting configuration performed the best with the greatest percentage of look-ups. These results in combination with the previous results on *Time To Look-up* suggest that rear warning-light configurations containing the 12 high-output LED units ganged on the main bumper were the best candidates for moving forward to dynamic testing.

The percentages of drivers that reported *Look-ups* and of drivers that actually looked up for each of the six rear-lighting configurations were almost identical. There was only a very small difference, indicating that participants who looked up also reported their *Look-ups* with a good level of accuracy.

Rating Scale Portion: The three rear warning-light configurations that contained the *Main Bumper* ganged-lighting configuration had significantly better attention-getting ratings while the participants were fixating directly ahead at the rear of the trailer. When participants provided attention-getting ratings while fixating 30 deg off-axis, the highest rated rear warning-light configurations were the *Main Bumper/Cargo Box,* and the *Main Bumper/ICC Bumper*. The *Main Bumper* lighting configuration was rated a very close second.

For the discomfort-glare ratings while fixating directly at the lighting, the three rear warning-light configurations that contained the *Main Bumper* ganged-lighting configuration in common once again provided significantly higher ratings. These mean ratings were still in the middle range for glare (not falling in the "undesirable" category). For the discomfort-glare ratings while stationary in an adjacent lane and fixating ahead in the lane (looking past the lighting display), the three rear warning-light configurations with the *Main Bumper* ganged-lighting configuration in common once again had the highest reported ratings. These mean ratings were in the low range for glare (indicating levels of glare that were above satisfactory).

4.2.2.4 Conclusions

All results clearly indicated that the three rear warning-light configurations that contained the *Main Bumper* ganged-lighting configuration performed the best with regard to *Time To Look-up* and ratings performance. These rear warning-light configurations (i.e., *Main Bumper, Main Bumper/Cargo Box,* and *Main Bumper/ICC Bumper*) were determined to be the best candidates to move forward to the dynamic Smart Road tests. This result corresponds to previous research which has also shown that ganging multiple LED units together can improve eye-drawing performance.[(6)] After further consideration, researchers determined that new rear warning-light configurations needed to be developed and tested again in a second experiment to further explore ganging LED units in locations other than the main bumper area. It was determined that one rear warning-light configuration of 12 ganged LED units should be positioned high on each side of the cargo box, with another configuration of 12 ganged LED units positioned on the ICC bumper. The potential benefit of a high-location rear warning-light configuration would be to help in reducing a rear-end collision from the following vehicle immediately behind the trailer as well as multiple other vehicles further behind in the same lane. However, results from static testing showed that the *Main Bumper/ICC Bumper* configuration showed slightly higher (although not statistically significant) eye-drawing capabilities, raising the question as to whether ganged lighting positioned lower would be more beneficial overall. Testing these remaining two ganged rear warning-light configurations in a second static experiment would allow further insight into two areas: determination of whether ganged lighting would also perform well in both high and low locations on the trailer, and determination of the final two most promising concepts to move forward to the dynamic testing on the Smart Road.

4.2.3 Experiment 2

4.2.3.1 Method

Study Design: A total of 28 naïve drivers (no previous exposure to the rear-lighting configurations) participated in an uninformed event detection paradigm with two new rear warning-light configurations. The performance data from these new 28 drivers were then analyzed in comparison to data from Experiment 1. The data to be used from Experiment 1 for the comparison were from participants who received the *Baseline* configuration and the *Main Bumper* configuration. Therefore, the total number of participants to be used in the analysis was 56 (figure 70). Half of the participants were males and half were females. All new candidate participants were screened identically as in Experiment 1 (i.e., over the phone with a verbal questionnaire). Approval for participant experimentation was given by the research team's IRB Human Assurances Committee. The age of all 56 participants ranged between 21 and 63 years old (mean of 40.5). Counterbalancing of two conditions was performed (i.e., gender and lighting configuration). Data were collected during the day from 9:00 a.m. EST to 5:30 p.m. EST. Time of day was not considered in the counterbalancing; however, participants were randomly assigned to the available time slots in order to avoid potential sunlight angle bias.

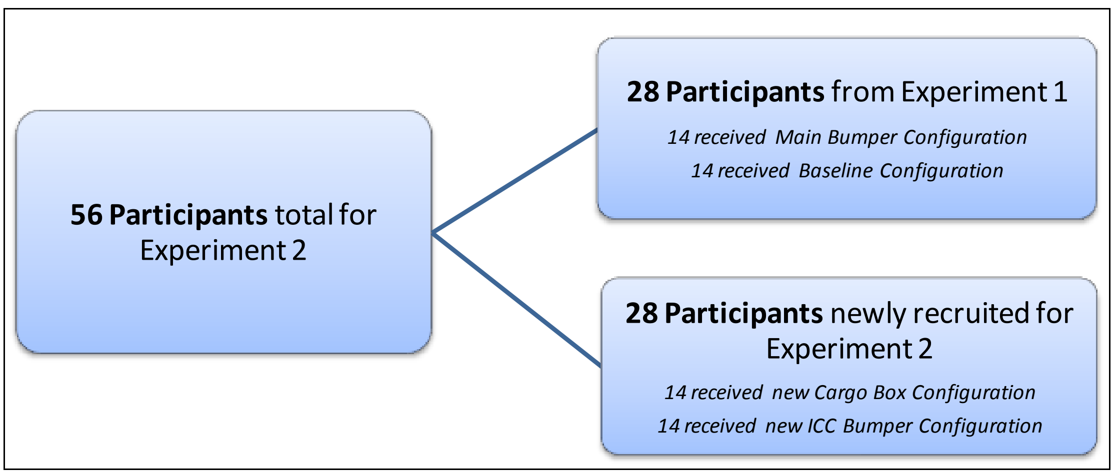

Figure 70. Diagram. Study design for the Experiment 2 uninformed event detection paradigm.

During Experiment 2, only performance data were gathered. The main aspect of the performance testing was determining the eye-drawing capability of each rear-lighting configuration. The number of *Look-ups* and the *Time To Look-up* were measured and served as the main dependent measures. The same uninformed event detection paradigm methodology was used from Experiment 1. In total, two rear warning-light configurations were tested using all 28 newly recruited participants (14 participants per lighting configuration).

Apparatus: Two new rear warning-light configurations installed on the rear of the experimental CUT were used during Experiment 2. Each high-output LED unit was aimed appropriately, both vertically and horizontally, according to the location on the back of the trailer (as was performed in Experiment 1). Detailed specifications on these two new test lighting configurations can be found in appendix C. The two new rear warning-light configurations are shown and labeled in figure 71. Rear warning-light configuration descriptions and labels are summarized as follows:

- *Twelve-light Cargo Box* (A): Twelve high-output LED units ganged and positioned high on the rear of the cargo box.
- *Twelve-light ICC Bumper* (B): Twelve high-output LED units positioned along the ICC bumper.

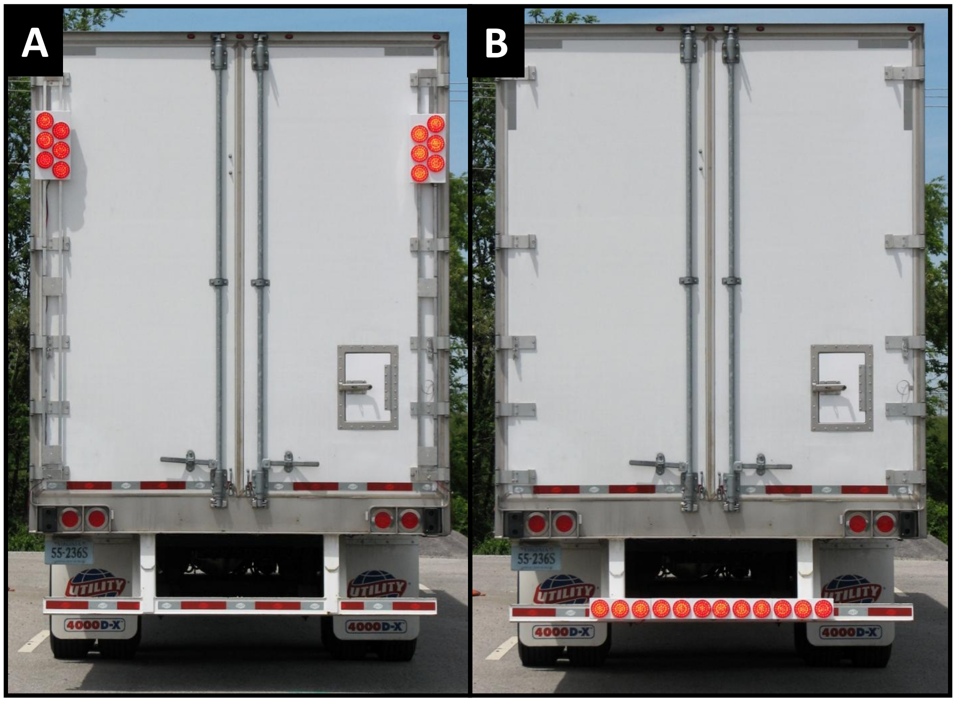

Figure 71. Grouped image. Two new rear warning-light configurations used during Experiment 2 static testing.

All other equipment used for the uninformed event detection portion of Experiment 2 was identical to Experiment 1.

Procedure: Procedures performed in Experiment 2 were identical to Experiment 1 with the exception that no ratings were administered. Of the 56 participants used for this experiment, 6 were found to have at least some level of color blindness. Of these six, no (zero) participants were found to look up at rear-lighting configurations. The final vision test administered was the UFOV test which was a computer-administered and computer-scored test of functional vision and visual attention. As with the ability to detect color, the results of the UFOV test had no effect on eligibility for participation. Complete data for the UFOV test was obtained for all 56 participants. Of the 56 participants, 54 scored in the very-low-risk category and 2 scored in the low-risk category. No participants were dismissed due to ineligibility (i.e., all participants had sufficient vision and/or hearing).

4.2.3.2 Results

Experiment 2 had the purpose of determining how well each new rear warning-light configuration would provide improved eye-drawing capabilities. The frequency of *Look-ups* as well as the *Time To Look-up* was obtained. Because procedures were identical, the two new rear warning-light configurations were compared to the *Baseline* configuration and the *Main Bumper* configuration results from Experiment 1. The numbers of *Look-ups* and *Non-look-ups* are shown in table 9 as a function of rear-lighting configuration. The table shows that both new rear warning-light configurations resulted in look-ups.

Table 9. Number of *Look-ups* and *Non-look-ups* in the Uninformed Event Detection Portion Across All Exposures of Experiment 2

Lighting Configuration	Look-ups	Non-look-ups	Total Events
Baseline *(Normal Brake Lights)*	2	40	42
Twelve-light Cargo Box	3	39	42
Twelve-light ICC Bumper	6	36	42
Main Bumper	8	34	42
Total	**19**	**149**	**168**

All rear-lighting configurations were displayed for a total of 5 s after initiation. If the participant did not look up, a value of 5 s was assigned on the assumption that this would be the minimum time in which the participant might have looked up. There was one occasion when a participant looked up after a rear-lighting configuration had already been extinguished (after 5 s) and in this situation a value of 5 s was assigned. Results in this section for Experiment 2 will be presented in a similar format as the Experiment 1 results section (with the exception that no ratings section will be presented).

The first analysis performed using *Time To Look-up* as the primary variable of interest was across all three exposures. A two-way ANOVA was performed with rear-lighting configuration as a between-subjects variable with four levels, and exposure as a within-subject variable with three levels. A main effect was found for exposure, but not for rear-lighting configuration. The main effect of exposure was significant at $F(2,104) = 7.02$, $p < 0.0014$. For rear-lighting configuration, the effect was not significant at $F(3,52) = 1.38$, $p = 0.2592$. The interaction of these two variables was found to be significant at $F(6,104) = 2.23$, $p < 0.0459$. The interaction is plotted in figure 72. Although the results show a significant main effect for exposure, the interaction provides insight into what is actually causing a difference in *Time To Look-up* for this analysis. As is seen in the figure, *Exposure 1* shows lower mean values for *Time To Look-up* in three of the four rear-lighting configuration categories. By further slicing the interaction and holding exposure level constant, we found that *Exposure 1* was indeed shown to be significant at $F(3,52) = 6.6$, $p < 0.0004$. *Exposure 2* and *Exposure 3* was not significant; $F(3,52) = .41$, $p = 0.7471$ and $F(3,52) = .23$, $p = 0.8771$, respectively. Exactly as was found in the Experiment 1 results, these results indicate that *Exposure 1* should be of primary focus for the remaining analyses and suggest that as the cognitive demand increased with each exposure, the possibility of perceptual narrowing may have occurred.

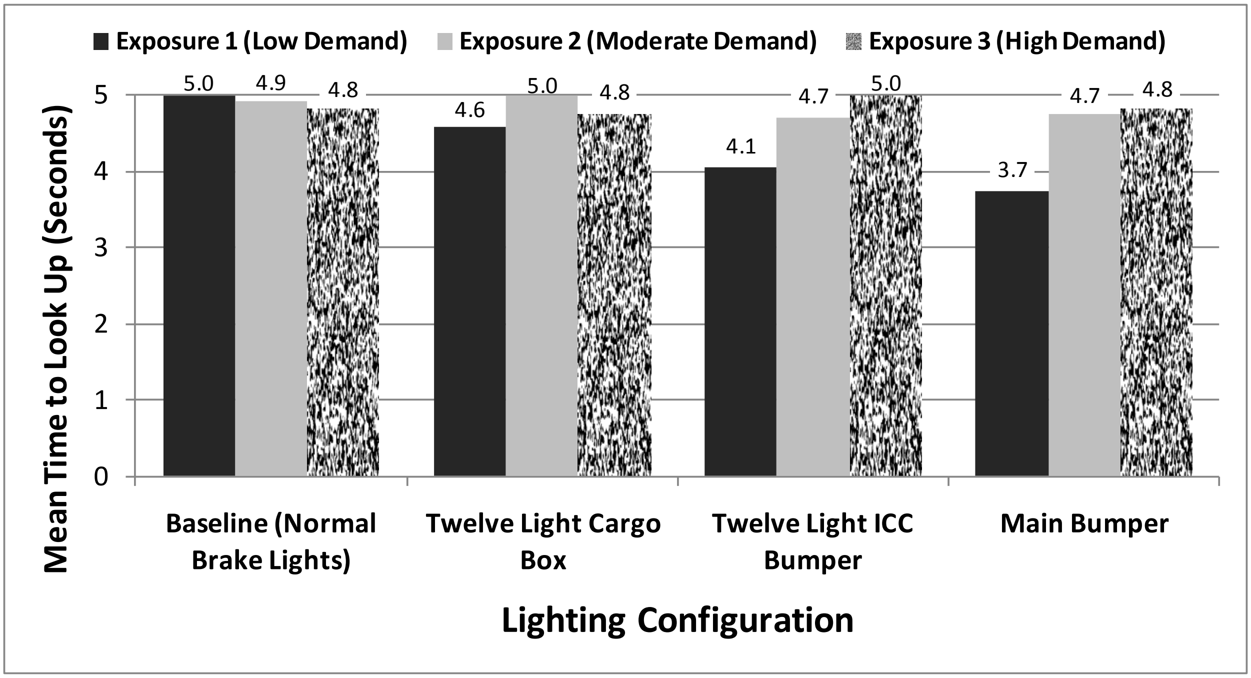

Figure 72. Bar graph. Mean *Time To Look-up* as a function of lighting configuration and exposure for static Experiment 2.

The next analysis performed using duration as the variable of interest was on *Exposure 1* only (the only situation that was unanticipated across all participants). A one-way between-subjects ANOVA was performed. The effect of duration for *Exposure 1* was nearly significant at $F(3,52) = 2.6$, $p < 0.0621$. Although the effect was not significant, a Duncan's multiple range test was performed to determine if significant differences occurred between lighting configurations. These results are shown in figure 73. In the figure, means with a common letter do not differ significantly at the $\alpha = 0.05$ level. The figure shows that the *Baseline* configuration did not cause any participants to look up and, therefore, reports a mean *Time To Look-up* of 5 s (the maximum duration of the light exposure). The *Main Bumper*, the new *Twelve-light ICC Bumper*, and the new *Twelve-light Cargo Box* rear warning-light configurations were the only ones that caused any look-ups. However, the *Main Bumper* was the only countermeasure that had a significantly lower *Time To Look-up* as compared to *Baseline*. The *Twelve-light ICC Bumper* was a close second.

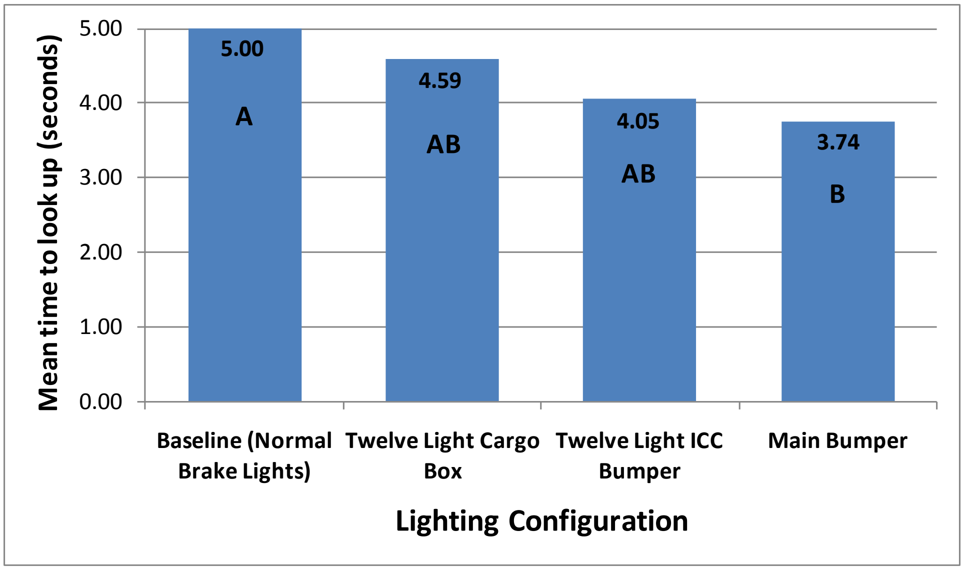

Figure 73. Bar graph. Mean *Time To Look-up* up for *Exposure 1* as a function of lighting configuration for static Experiment 2.

Just as was performed in the Experiment 1 analysis, the percentage of participants who looked up as a function of exposure was calculated and plotted in figure 74. As the figure clearly shows, the percentage of *Look-ups* was much higher for *Exposure 1*. A Chi-square analysis was performed and found to be significant χ^2 (2) = 11.8686, $p < 0.0026$.

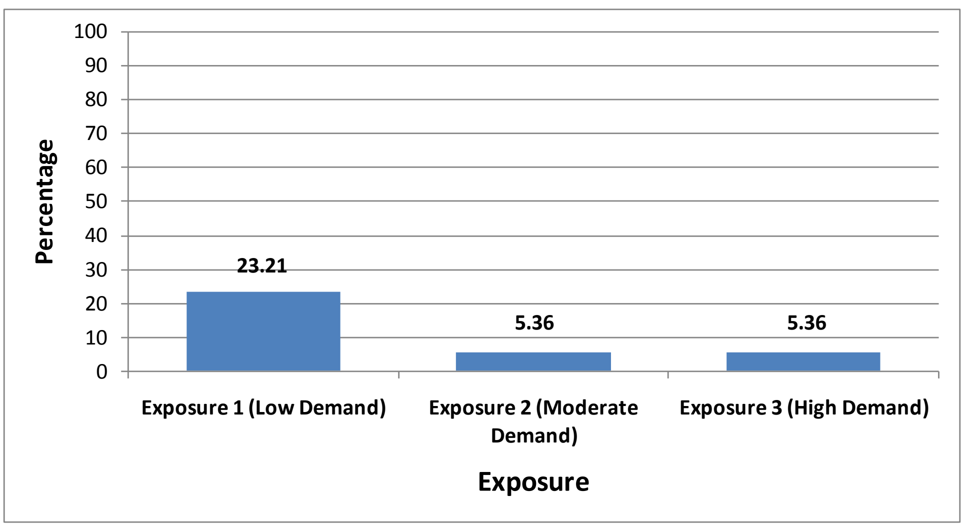

Figure 74. Bar graph. Percentage of participants that looked up as a function of exposure for static Experiment 2.

The percentage of participants who looked up as a function of exposure and rear-lighting configuration is shown in figure 75. No statistical tests were performed; however, it is clear that the rear warning-light configurations (not *Baseline*) performed the best with the greatest percentage of look-ups. These results suggest that rear warning-light configurations containing 12 high-output LED units ganged on trailer locations such as the main bumper, the cargo box, and the ICC bumper may all be potential candidates for moving forward to dynamic testing.

However, the results from *Time To Look-up* suggest that the *Main Bumper* configuration may be the best overall candidate. Also, figure 75 shows that *Exposure 1* contained the greatest contribution of *Look-ups*, suggesting once again that during tasks of lower cognitive load, certain rear warning-light configurations may indeed alert drivers to the forward view.

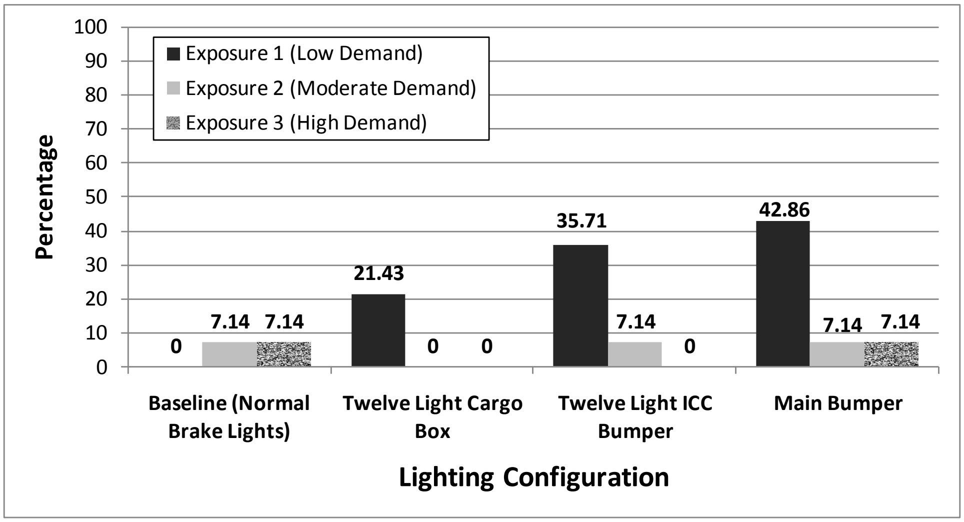

Figure 75. Bar graph. Percentage of participants that looked up as a function of lighting configuration and exposure for static Experiment 2.

The percentage of participants who looked up for each rear-lighting configuration (regardless of exposure) was analyzed using a Chi-square test and found not to be significant, χ^2 (3) = 5.3724, p = 0.1465. Also analyzed was the percentage of affirmative responses to the first of three interview questions asked at the conclusion of the experiment. For the question "Did you notice anything unusual outside at any time while we were working with this navigation system?", 14 participants (25 percent) answered affirmatively. A Chi-square analysis was used to analyze the percentage of drivers providing "affirmatives" as a function of the four lighting configurations and was found not to be significant, χ^2 (3) = 4.1905, p = 0.2416. Figure 76 shows both the percentage of drivers that reported *Look-ups* as well as the percentage of drivers that actually performed *Look-ups* for each of the four rear-lighting configurations. As the figure shows, there was only a very small difference, indicating that participants who looked up also reported their *Look-ups* with a good level of accuracy.

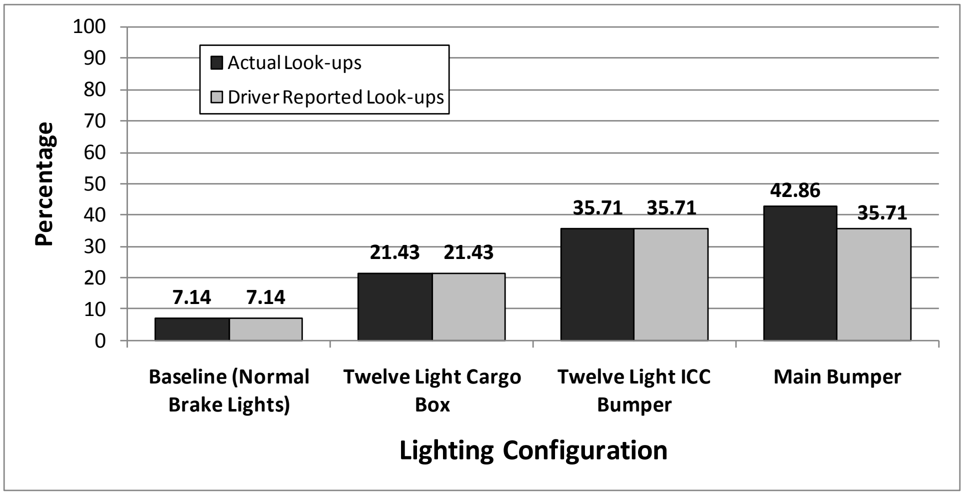

Figure 76. Bar graph. Percentage of participant-reported *Look-ups* and actual *Look-ups* as a function of lighting configuration for static Experiment 2.

The second question asked during the post-experiment interview was "Did it happen more than once?" and 6 of the 14 participants (42.86 percent) answered yes. These six participants were then asked to provide an answer to the final question, "How many times?" The responses are shown in figure 77 in the form of percentages. As shown in the figure, two of the six participants (33 percent) recalled the correct amount of "three times" that the rear lighting was activated.

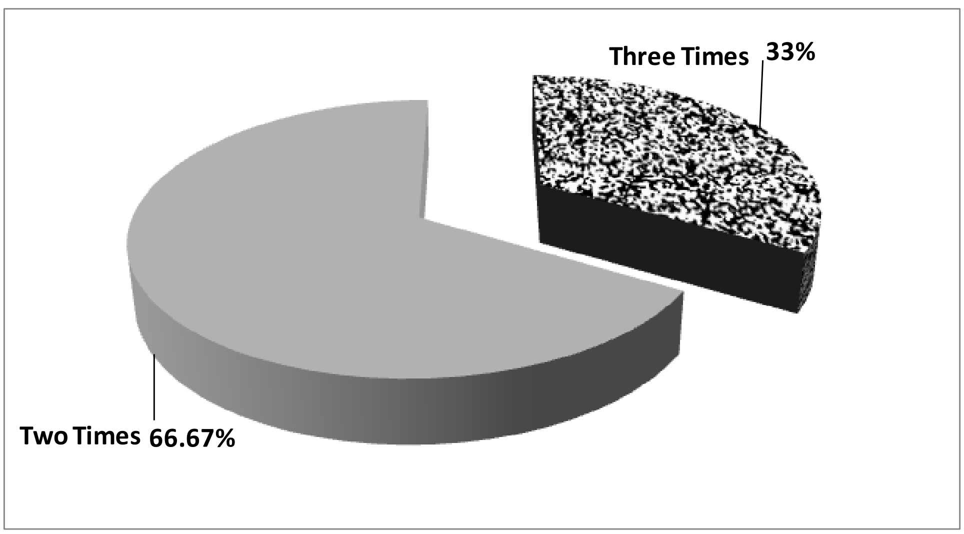

Figure 77. Pie chart. Pie chart of response percentages to the third question, "How many times did you see the lighting appear?" for static Experiment 2.

4.2.3.3 Experiment 2 Summary

As was found in Experiment 1, Experiment 2 results indicated that *Exposure 1* data were the most important to focus on as they contained the most *Look-ups* and represented the only event which was truly unanticipated. The *Main bumper*, *Twelve-light Cargo Box*, and *Twelve-light ICC Bumper* rear warning-light configurations were the only ones that caused any look-ups; however, the *Main Bumper* configuration was significantly better at reducing the *Time To Look-up* than were all others. The *Twelve-light ICC Bumper* was a close second.

The percentage of drivers that reported *Look-ups* and the percentage of drivers that actually performed *Look-ups* for each of the four rear-lighting configurations were almost identical. There was only a very small difference, indicating that participants who looked up also reported their *Look-ups* with a good level of accuracy.

4.2.3.4 Conclusions

Experiment 2 results indicated that the *Main Bumper* rear warning-light configuration performed the best with regard to reduced eye-drawing time (*Time To Look-up*). The other two rear warning-light configurations did result in *Look-ups*, and the *Twelve-light ICC Bumper* lighting configuration performed just behind the *Main Bumper* configuration. This result corresponds to previous research which has also shown that ganging multiple LED units together at bumper height can improve eye-drawing performance.(6) It appears that a reduction in eye-drawing power may result in static situations the further you position the ganged lighting above or below the main bumper of the lead vehicle.

4.2.4 Static Experimentation General Conclusions

Experiment 1 results indicated that rear warning-light configurations containing the *Main Bumper* ganged-lighting performed the best. The two concepts that showed the most promise appeared to be the *Main Bumper* and the *Main Bumper/ICC Bumper*. Experiment 2 results indicated that ganging multiple LED units together in both high and low locations resulted in *Look-ups*. The two concepts that showed the most promise appeared to once again be the *Main Bumper* and the *Twelve-light ICC Bumper*. After further consideration, researchers determined that any further lighting configurations tested should contain ganged lighting. Based on results from both Experiment 1 and Experiment 2, lighting configurations chosen to move forward to the dynamic Virginia Smart Road tests were the *Main Bumper* rear warning-light configuration, and a new hybrid configuration that contained the *Main Bumper* combined with the *Twelve-light ICC Bumper*. This new configuration will be referred to as the *Main Bumper/Twelve-light ICC Bumper* for the remainder of this report. These two rear warning-light configurations would be tested in comparison to *Baseline* in the dynamic Smart Road tests.

4.3 DYNAMIC EXPERIMENTATION

4.3.1 Purpose & Objectives

This project used static testing first to identify the most promising rear warning-light configurations prior to dynamic testing performed on the Virginia Smart Road. The purpose of dynamic testing (moving vehicle with participants driving on the Smart Road) was to investigate the effects of passive conspicuity markings on following distance behavior as well as determine how well a selected group of rear-lighting configurations would provide improved eye-drawing capabilities. Earlier work in Phase II of the heavy-vehicle rear-lighting project included a pair of retro-reflective octagons at the back of a trailer used to test the concept of passive conspicuity. These same exact octagons were used in the current dynamic testing. The purpose of passive conspicuity markings was to provide additional visual cues, making heavy-truck trailers more easily seen and distinguished from the background. Other objective data were also collected, such as acceleration and deceleration behavior of the following vehicle. Subjective data were collected by way of opinion ratings. In total, two dynamic experiments were performed.

Experiment 1 had the objective of investigating improved performance of both passive conspicuity markings and rear-lighting configurations. However, due to methodology constraints, only conspicuity markings were successfully tested. A follow-up experiment (Experiment 2) was designed with a modified method to investigate the performance of the rear-lighting configurations. Each experiment and results obtained will be discussed in their own sections below.

4.3.2 Experiment 1

4.3.2.1 Method

Study Design: As indicated, the primary objectives of this testing were to investigate the effects of conspicuity markings on following distance behavior as well as to assess the eye-drawing capability of rear-lighting configurations positioned on the rear of a trailer. A study was designed to investigate both objectives using a single experimental method. In all, there were four experimental conditions scheduled to be tested: *Baseline* (normal trailer brake-light configuration), *Conspicuity Markings* (set of two retro-reflective octagons), *Main Bumper*, and *Main Bumper/Twelve-light ICC Bumper*. Performance results from *Conspicuity Markings* were to be analyzed in comparison to *Baseline* with the main dependent measure of light-vehicle following distance. The rear warning-lights were to be analyzed in comparison to *Baseline* with the *Time To Look-up* serving as the main dependent measure. Other objective measures for the rear-lighting investigation included the time taken for a participant to release the accelerator pedal after light activation (*Time To Accelerator Release*), and the rate of change in accelerator pedal position after light activation (*Accelerator Position Change Rate*). Further information on how each measure was calculated will be discussed in the results section. An uninformed event detection paradigm methodology similar to the previous static experiments (administered before drivers were informed about the true purpose of the study) was used. This methodology had the purpose of assessing the eye-drawing capability of each lighting configuration (lighting configurations for these uninformed trials were treated as a between-subjects factor).

The experimental paradigm used was for the following-vehicle driver to perform a secondary task while instructed to follow the experimental CUT at a given, demonstrated, following distance of 120 ft (36.58 m). Drivers were shown the distance before data collection began and were instructed to maintain that distance without experimenter coaching. During all conditions, the lead experimental CUT maintained a speed of approximately 25 mi/h (40.23 km/h), but *Baseline* brake lighting was activated at various points along the route (brake lighting activated but the experimental CUT did not decelerate). These points were pre-selected, and the brake lights and rear warning-light configurations on the lead vehicle would be activated both when the following driver looked away from the forward view to attend to the secondary task as well as when he/she was looking forward.

A total of 64 naïve drivers (no previous exposure to the lighting configurations) were to be tested. As it turned out, only 48 drivers completed data collection (fulfilling *Baseline*, *Conspicuity Markings*, and *Main Bumper* conditions) before data collection was halted. Upon preliminary analysis of the *Main Bumper* results compared to *Baseline*, it was found that eye-drawing capability could not properly be determined. Researchers concluded that the experimental method used was insufficient as participants could not maintain an accurate following distance near the target of 120 ft (36.58 m). Data collection with the final rear warning-light configuration (*Main Bumper/Twelve-light ICC Bumper*) was halted and researchers revisited the study design for a follow-up experiment (Experiment 2). Further discussion on these analyses and methodological revisions are provided in the results section.

In Experiment 1, half of the 48 participants were males and half were females. Candidate participants were screened over the phone with a verbal questionnaire to determine whether they were licensed drivers, were of the appropriate age, and whether they had any health concerns that might exclude them from participating. Approval for participant experimentation was given by the research team's IRB Human Assurances Committee. The age of participants ranged between 20 and 61 years old (mean of 34.02). Counterbalancing of two conditions was performed (i.e., gender and lighting configuration). Data were collected during the day from 8:30 a.m. to 5:30 p.m. EST. Time of day was not considered in the counterbalancing; however, participants were randomly assigned to the available time slots in order to avoid potential sunlight angle bias.

Subjective rating scales were also administered to 32 of the 48 participants. Attention-getting (figure 57) and discomfort-glare (figure 58) rating scales were administered at multiple light-vehicle positions behind the experimental CUT to those participants who received the rear warning-light configuration and the *Baseline* brake light condition (32 participants in all). Helpfulness and usefulness ratings were administered to the 16 participants that received the rear warning-light configurations (not the *Baseline* condition). These helpfulness and usefulness ratings were administered upon returning to the main building of the research facility at the completion of the study (appendix F).

Apparatus: The *Conspicuity Markings* were installed on the rear of the experimental CUT (figure 78). At pre-selected positions on the Smart Road the following distance of the light vehicle was recorded and compared to the *Baseline* condition.

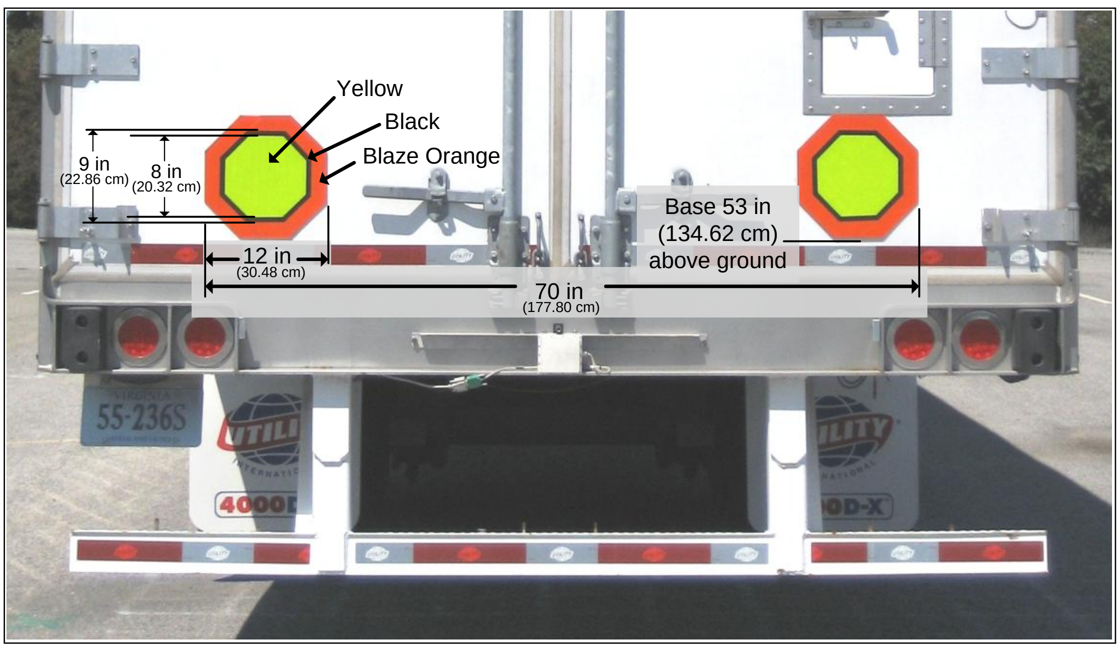

Figure 78. Photo. Photograph of the retro-reflective passive *Conspicuity Markings* positioned on the trailer.

Two rear warning-light configurations and one *Baseline* configuration positioned on the rear of the experimental CUT were scheduled to be used during testing on the Smart Road. However, due to preliminary analyses indicating that the method used was insufficient, one rear warning-light configuration was not tested. The two rear-lighting configurations that were tested are shown and labeled in figure 79. Rear-lighting configuration descriptions and labels are summarized as follows:

- *Baseline* (A): Two LED-unit brake lights pre-installed by trailer manufacturer (baseline condition).
- *Main Bumper* (B): Twelve high-output LED units ganged and positioned on the rear main bumper.

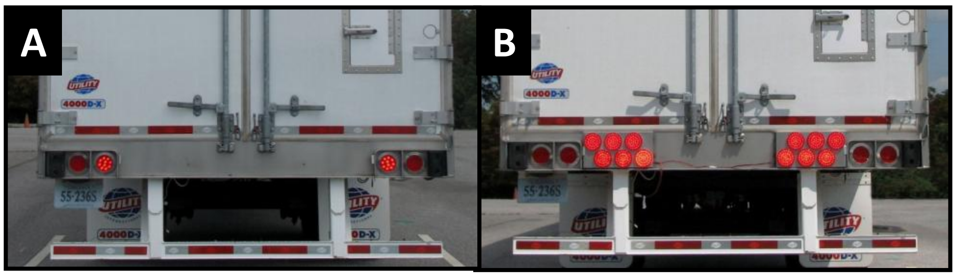

Figure 79. Grouped image. Two rear-lighting configurations used during Experiment 1 dynamic testing.

During the experiment, participants drove a late model sedan directly behind the experimental CUT (figure 80). Participants were instructed by the lead experimenter (sitting in the passenger seat) to follow along and complete in-vehicle tasks using the radio and navigation system. These tasks were intended to distract the participant's gaze away from the forward roadway. The same vehicles were used in the Smart Road study as were used in the previous static experiments.

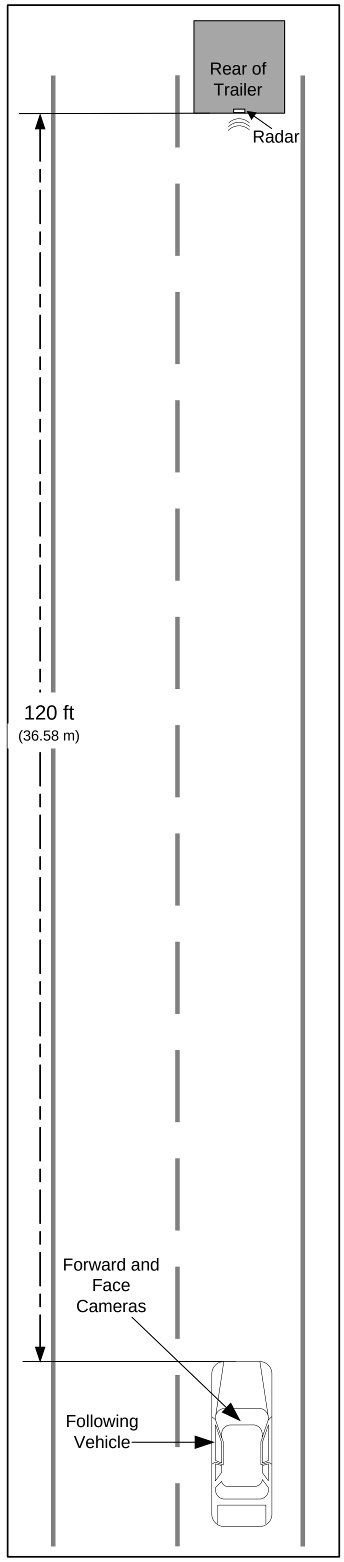

Figure 80. Diagram. Overhead diagram of light-vehicle and experimental-CUT positions for dynamic Experiment 1.

Rear-lighting activation was controlled by the lead experimenter in the passenger seat of the light vehicle. The same procedure was used to activate the rear-lighting configurations as in the previous static experiments (small button, hidden from view of the driver, communicating through a wireless signal). Upon activation of the rear warning-light configuration, lights would flash simultaneously at a 5-Hz frequency for a period of 5 s. Upon activation of the *Baseline* configuration, steady brake lighting (no simultaneous flashing) was initiated for a period of 5 s. Four camera views were recorded in the light vehicle by the DAS, identical to the previous static experiments. A radar unit was installed on the rear of the trailer to provide data on following-vehicle closing rates and distances. Specifications on the radar positioning can be found in appendix E.

Upon completion of the Smart Road data collection, participants filled out attention-getting and discomfort-glare rating scales at multiple light-vehicle positions behind the experimental CUT (see figure 57 and figure 58 for rating scales used). Participants receiving the rear warning-light configurations were also administered helpfulness and usefulness ratings which can be found in appendix F.

Procedure: Upon arrival at the research facility, participants read and signed an initial informed consent form information sheet. After all questions were addressed, both the participant and the lead experimenter signed the form. Next, participants were asked to show a valid driver's license and two brief vision tests were administered. The first vision test was a Snellen test to ensure that vision acuity was within the legal driving limit (corrected to 20/40). Immediately following, the Ishihara Color Vision test was also administered. The experimenter recorded participants' ability to detect color, but it was not part of the eligibility criteria. Of the 48 participants screened for this experiment, 4 were found to have at least some level of color blindness. Of these four, two participants received the conspicuity markings condition, and two received the baseline condition. No participants were dismissed due to ineligibility (i.e., all participants had sufficient vision).

After the screening session was complete, each participant was escorted to the light vehicle parked in front of the research facility. The participant was instructed to adjust the seating position and mirrors to a normal, comfortable, and safe position. As soon as the participant was ready, he/she was instructed to drive the light vehicle onto the Smart Road to the start position (as guided by the experimenter). Although participants were aware that they would be following the experimental CUT during the experiment, they were not aware that rear-lighting configurations or conspicuity markings were the focus of the investigation. Participants were instructed that in-vehicle display tasks were to be performed and the following distances between vehicles would be measured. As was performed in previous static experiments, participants were instructed by the experimenter to complete several in-vehicle secondary driving tasks. During the many secondary driving tasks that participants performed, two were of primary focus as they were intended to distract each participant's gaze away from the forward roadway and, while participants were involved in the task, the assigned rear-lighting configuration was initiated. Each of these tasks is further described below in the order that they were administered:

- *Exposure 1*: Light activation triggered while setting the radio station to an instructed frequency (participant interaction; high level of visual, cognitive, and manual loading).

- *Exposure 2*: Light activation triggered while zooming in closer on the map using the navigation system display (participant interaction; high level of visual, cognitive, and manual loading).

At the start position on the Smart Road, the light vehicle was positioned at the safe distance of 120 ft (36.58 m) directly behind the experimental CUT. While the light vehicle was parked, participants were instructed on the use of the controls and displays. Once the participants were comfortable with use of the controls, each was instructed to follow the experimental CUT at the demonstrated safe distance and to keep that distance at all times (participants were not instructed what the actual distance was in feet, just that it was the target safe distance to maintain). The experimental CUT maintained a speed of approximately 25 mi/h (40.23 km/h) for safety reasons, which also allowed enough time for multiple tasks to be performed during each loop. More details on the dynamic Smart Road testing protocol can be found in appendix G.

Each participant drove a total of three loops around the Smart Road. The first loop consisted of a training loop only and any data collected were excluded from all analyses to follow. The second loop was a data-collection loop in which multiple tasks were performed by each participant. During this loop, there was only one event when both a rear-lighting configuration and a distraction task were initiated simultaneously. This occurred on the uphill portion of the Smart Road. The uphill portion of the Smart Road was used for events because it was much easier for a driver to maintain a certain speed and following distance. Immediately following this event, both vehicles were stopped and the participant was fully debriefed as to the true purpose of the study. The participant then reviewed the debriefing form and the informed consent form before further participation in the experiment. Participants that agreed to continue then returned to driving the vehicle on the Smart Road and proceeded with the third loop. The third loop was very similar to the second loop except that the participant was aware of the true purpose of the study. During the third loop, there was only one event where both a rear-lighting configuration and a distraction task were initiated simultaneously. This also occurred on an uphill portion of the Smart Road. For those participants receiving a rear-lighting configuration upon completion of the third loop, the light vehicle and experimental CUT were returned to their original positions (with the exception that the light vehicle was 20 ft [6.10 m] closer to the rear of the experimental CUT) and attention-getting and discomfort-glare ratings were administered. The same data-collection procedure used during static experimentation for attention-getting and discomfort-glare ratings was used on the Smart Road. Participants rated each rear warning-light configuration 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 another looking 30 deg off-axis to the right while focusing on an orange cone). Participants rated the level of discomfort-glare of each rear warning-light configuration 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 rating provided while positioned in the same lane was given while looking directly ahead at the lighting. However, the discomfort-glare rating provided while positioned in the adjacent lane was given while looking directly ahead in the lane (not focusing directly on the lighting).

After completion of the attention-getting and discomfort-glare ratings, participants were returned to the main building at the research facility. Participants who received a rear warning-light configuration were then asked to complete both helpfulness and usefulness ratings (appendix F).

Upon completion of these ratings, participants were compensated and thanked for their time. Each session lasted approximately one hour and thirty minutes (1.5 h).

4.3.2.2 Results

Conspicuity Markings: As previously mentioned, *Conspicuity Markings* were installed on the rear of the experimental CUT. At pre-selected positions on the Smart Road the following distance of the light vehicle was recorded and compared to *Baseline* (four following distances recorded per loop for a total of eight samples per participant). A two-way between-subjects ANOVA was performed with trailer configuration as the between-subjects variable with two levels (*Baseline* or *Conspicuity Markings*), and Smart Road grade as the within-subject factor with two levels (*Downhill* or *Uphill*). A main effect was found for grade, but not for trailer configuration. The main effect for grade was significant at $F(1,30) = 87.69$, $p < 0.0001$. The main effect for trailer configuration was not significant at $F(1,30) = 0.71$, $p = 0.4049$. The interaction of these two variables was not significant at $F(3,30) = 0.8$, $p = 0.3768$. The mean following-distance results for trailer configuration are shown in figure 81. This figure shows that there was no significant difference in ability to maintain the target following distance of 120 ft (36.58 m). This result suggests that the conspicuity markings did not help participants perform better at the task. This result also indicates that participants had difficulty in perceiving their distance to the lead vehicle and tended to drop very far back. Large following distances such as these may have negatively affected the ability to analyze eye-drawing capability in the rear-lighting configuration analyses to follow.

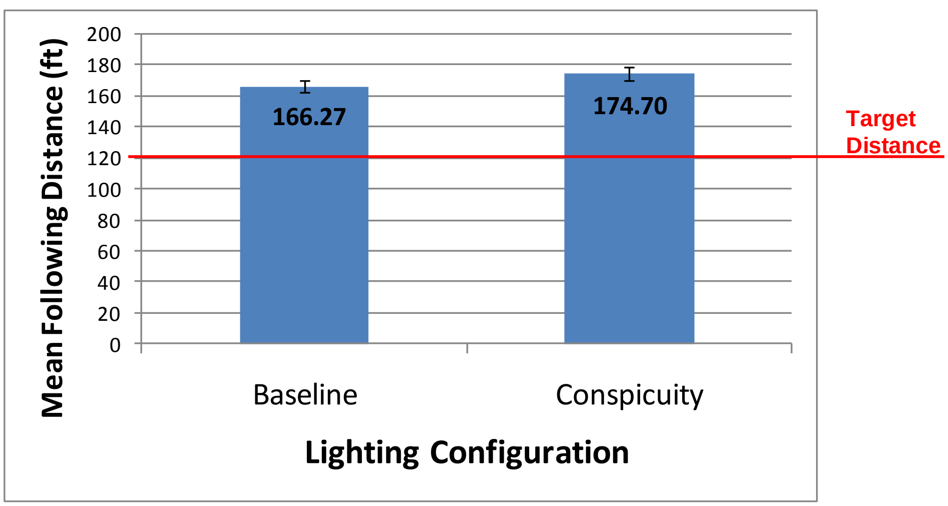

Figure 81. Bar graph. Mean following distance as a function of trailer configuration.

Uninformed Event Detection Paradigm: The uninformed event detection paradigm was used in dynamic testing on the Smart Road. The objective was to determine how well the rear warning-light configurations would provide improved eye-drawing capabilities to that of the *Baseline* configuration. After completion of the data collection for both the *Conspicuity Markings* and *Baseline* conditions, the *Main Bumper* lighting configuration condition was investigated first. Upon analysis of the data, it was found that eye-drawing capability could not properly be determined. Researchers concluded that the method used was insufficient as participants had difficulty in maintaining the target following distance of 120 ft (36.58 m). Data collection using the final rear warning-light configuration (*Main Bumper/Twelve-light ICC Bumper*) was halted and researchers revisited the study design. This section discusses the analyses performed between the *Baseline* and *Main Bumper* lighting configurations which ultimately led to the data collection stoppage.

The amount of time between the initiation of the rear lighting and the participant's look-up response was obtained (*Time To Look-up)*. Any participant who was looking forward when the rear lighting was initiated was removed from all analyses associated with eye-drawing (both objective and subjective). In fact, one participant in the baseline condition and one participant in the experimental condition were looking forward during the initiation of the lighting and, therefore, both were removed from the analyses; thus, leaving the final participant total equal to 15 for the *Baseline* condition and 15 for the *Main Bumper* condition. In contrast to static experimentation, all remaining participants did look up in each lighting exposure across all conditions.

The first analysis performed, using *Time To Look-up* as the primary variable of interest, was across both exposures. A two-way ANOVA was performed with rear-lighting configuration as a between-subjects variable with two levels, and exposure as a within-subject variable with two levels. No main effects or interactions were found to be significant. The main effect of exposure was not significant at $F(1,28) = 0.14$, $p = 0.714$. For rear-lighting configuration, the effect was not significant at $F(1,28) = 1.41$, $p = 0.2452$. The interaction of these two variables was nearly significant at $F(3,28) = 3.76$, $p = 0.0627$.

The second analysis performed was the rate of change in accelerator pedal position (*Accelerator Position Change Rate*) across both exposures. This value was calculated by dividing the amount of change in accelerator position release over time. The time used for this calculation began the instant the participant began releasing the accelerator pedal and ended when the change in accelerator pedal position came to a stop. A two-way ANOVA was performed with lighting configuration as a between-subjects variable with two levels, and exposure as a within-subject variable with two levels. Once again, no main effects or interactions were found to be significant. The main effect of exposure was not significant at $F(1,28) = 0.52$, $p = 0.4785$. For lighting configuration, the effect was not significant at $F(1,28) = 2.27$, $p = 0.1433$. The interaction of these two variables was also not significant at $F(3,28) = 0.07$, $p = 0.789$.

As was previously done during the static experimentation, further analyses were performed using data only from *Exposure 1*. *Exposure 1* was the only event that was unanticipated across all participants and should be of primary focus for remaining analyses. Therefore, the next analysis performed, using *Time To Look-up* as the variable of interest, was on the *Exposure 1* data only. A one-way between-subjects ANOVA was performed. Results found no significance with $F(1,28) = 0.09$, $p = 0.7713$. The mean *Time To Look-up* results are shown in figure 82. The figure shows that, on average, participants receiving the *Main Bumper* configuration took less time to look up to the forward roadway than did participants receiving the *Baseline* configuration (although this was not a statistically significant difference). By further filtering the data, the *Time To Look-up* was calculated for participants that were following at less than 175 ft (53.34 m) and results are shown in figure 83. Although no statistical analysis was performed, it appears that a trend may exist that as participants approached the target distance of 120 ft (36.58 m), the mean *Time To*

Look-up comparison between the *Main Bumper* and *Baseline* conditions may approach significance.

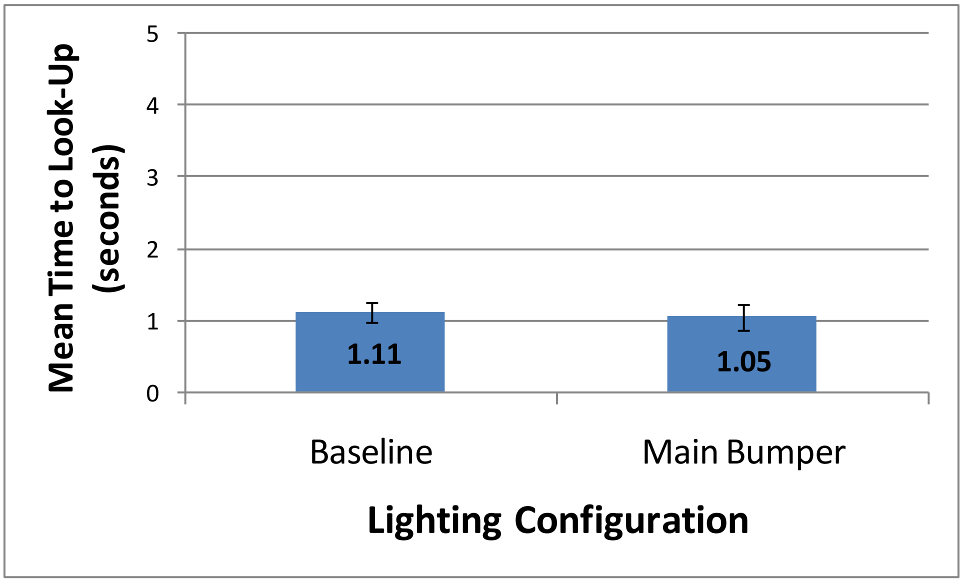

Figure 82. Bar graph. Mean *Time To Look-up* for *Exposure 1* as a function of lighting configuration for dynamic Experiment 1.

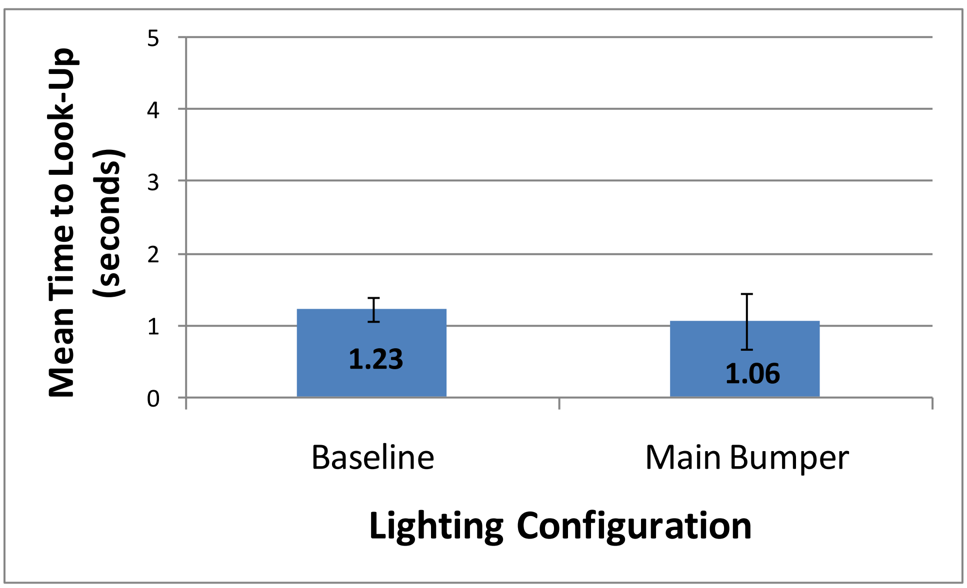

Figure 83. Bar graph. Mean *Time To Look-up* for *Exposure 1* inside 175 ft (53.34 m) as a function of lighting configuration for dynamic Experiment 1.

Another analysis was performed on the time taken for a participant to release the accelerator pedal after eyes returned to the forward roadway (*Time To Accelerator Release*) during *Exposure 1*. A one-way between-subjects ANOVA was performed. Once again no significant effect was found for the rear-lighting configuration, $F(1,20) = 1.55$, $p = 0.227$. The mean *Time To Accelerator Release* results are shown in figure 84. The figure shows that, on average, participants receiving the *Main Bumper* configuration took less time to release the accelerator than did participants receiving the *Baseline* configuration (although the difference was not statistically significant).

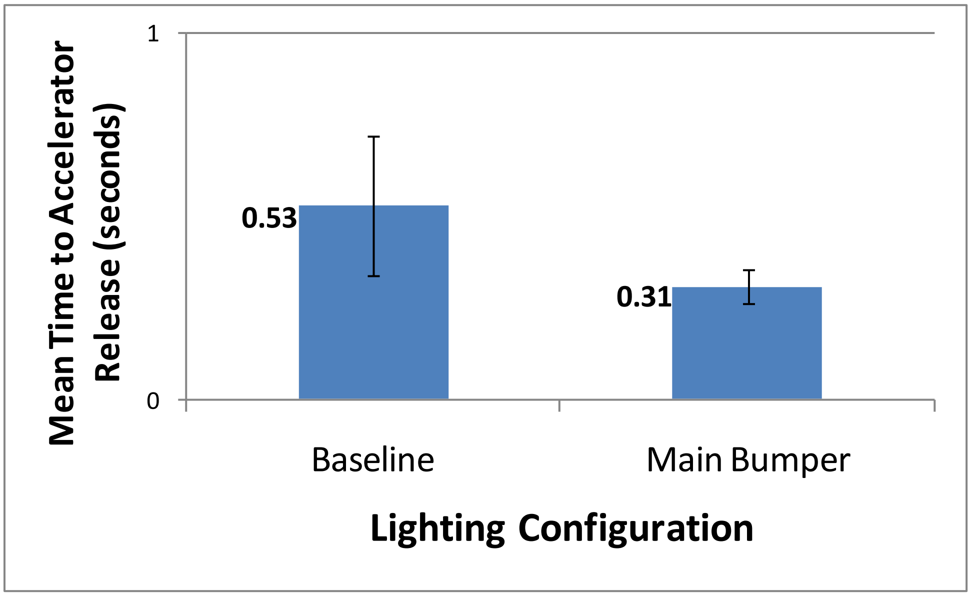

Figure 84. Bar graph. Mean *Time To Accelerator Release* for *Exposure 1* as a function of lighting configuration for dynamic Experiment 1.

Next, an analysis was performed for the *Accelerator Position Change Rate* for *Exposure 1* only. A one-way between-subjects ANOVA was performed. No main effect was found to be significant, $F(1,28) = 0.63$, $p = 0.4324$. The mean *Accelerator Position Change Rate* results are presented in figure 85.

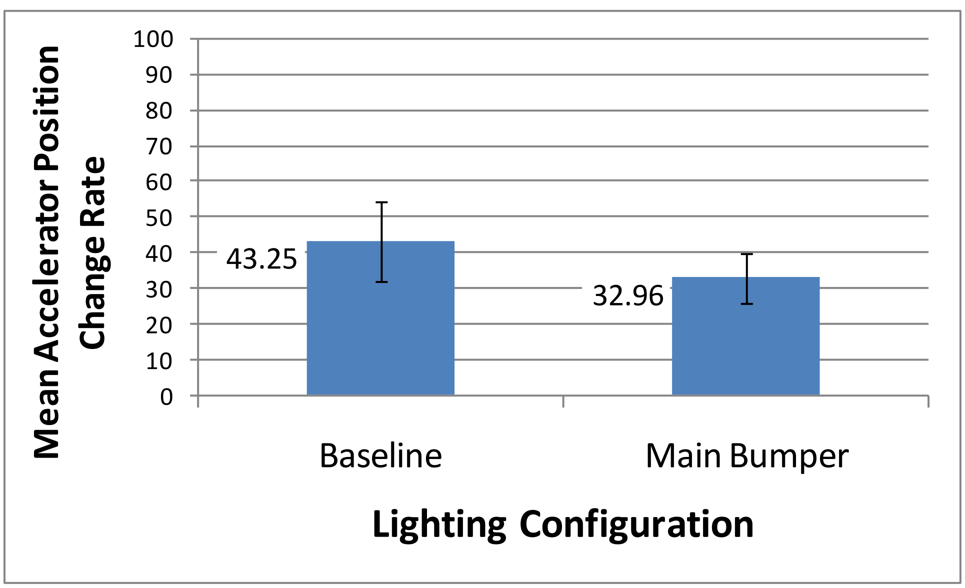

Figure 85. Bar graph. Mean *Accelerator Position Change Rate* for *Exposure 1* as a function of lighting configuration for dynamic Experiment 1.

Ratings: Attention-getting ratings and discomfort-glare ratings were obtained from 32 of the 48 participants for both the *Baseline* condition and the *Main Bumper* condition. For the attention-getting ratings while fixating directly at the lighting, a one-way within-subject ANOVA was performed and found to be significant, $F(1,30) = 12.73$, $p < 0.0012$. The mean ratings for the *Baseline* and *Main Bumper* conditions are shown in figure 86. The attention-getting rating scale (figure 57) contained a scale of 1 to 8 (1 being not at all attention-getting, and 8 being extremely attention-getting). As expected, the *Main Bumper* rear warning-light configuration provided higher ratings (significantly better than *Baseline*).

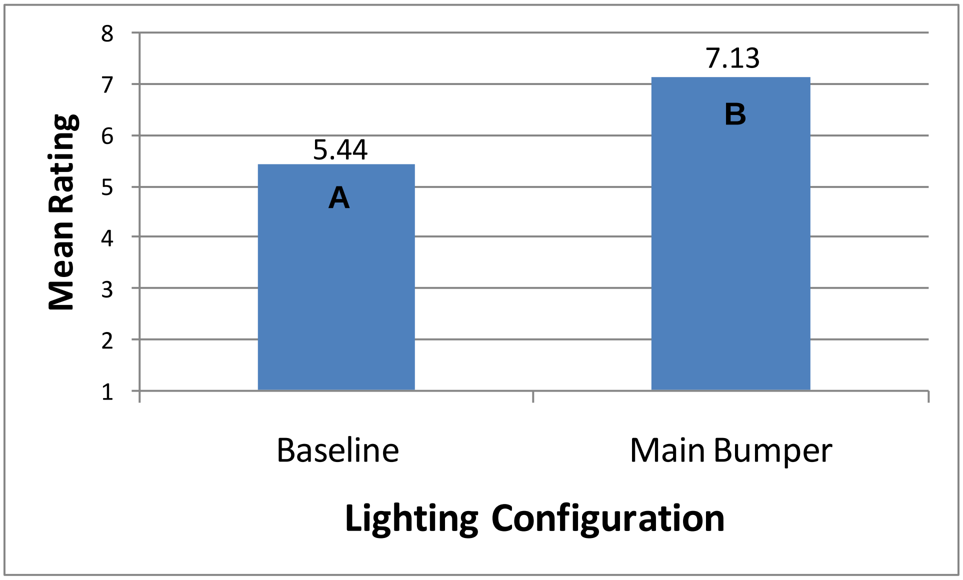

Figure 86. Bar graph. Mean attention-getting ratings of participants fixating at lighting as a function of lighting configuration for dynamic Experiment 1.

For the attention-getting ratings while fixating 30 deg off-axis, a one-way within-subject ANOVA was performed and found to be significant, $F(1,30) = 12.77$, $p < 0.0012$. The mean ratings for the *Baseline* and *Main Bumper* conditions are shown in figure 87. Once again, the *Main Bumper* rear warning-light configuration provided higher ratings.

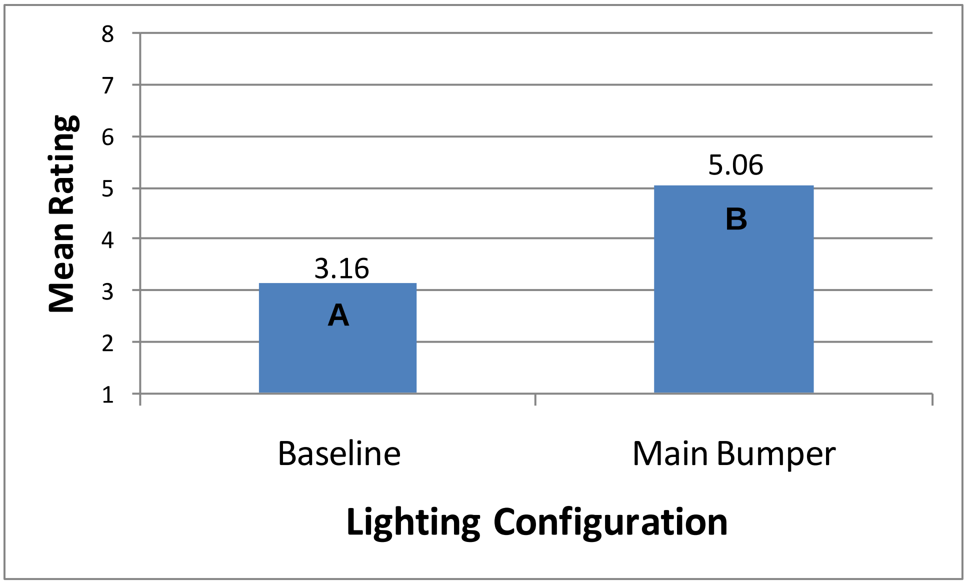

Figure 87. Bar graph. Mean attention-getting ratings of participants fixating 30 deg off-axis as a function of lighting configuration for dynamic Experiment 1.

For the discomfort-glare ratings while fixating directly at the lighting, a one-way within-subject ANOVA was performed and found to be significant, $F(1,30) = 4.54$, $p < 0.0413$. The mean ratings for *Baseline* and *Main Bumper* conditions are shown in figure 88. The discomfort-glare rating scale (figure 58) contained a scale of 1 to 9 (1 being unbearable, and 9 being not noticeable). The *Main Bumper* rear warning-light configuration provided a higher amount of discomfort-glare than did *Baseline*. It is important to note that the mean rating for the *Main Bumper* rear warning-light configuration, although significantly lower than *Baseline*, falls in the middle range for glare.

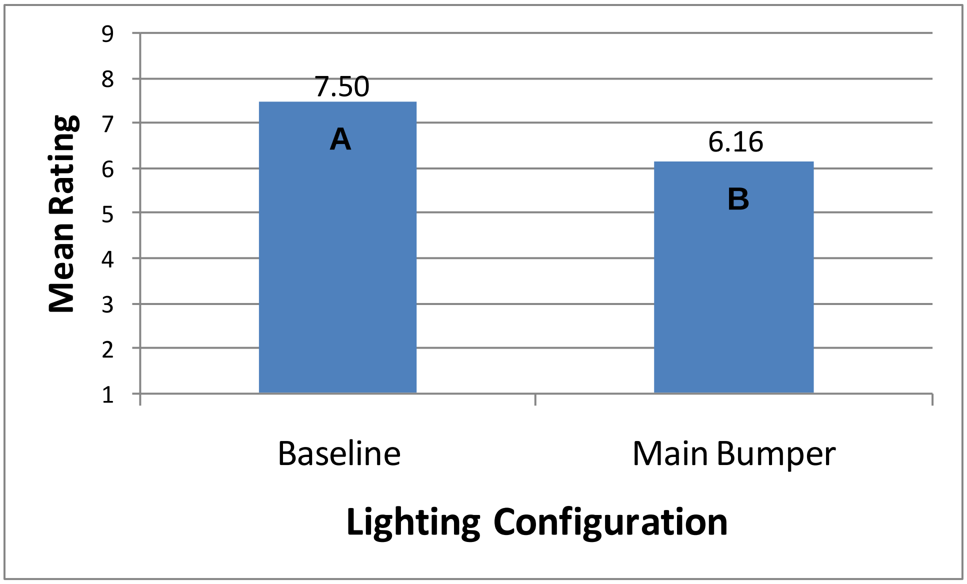

Figure 88. Bar graph. Mean discomfort-glare ratings of participants fixating at lighting as a function of lighting configuration for dynamic Experiment 1.

For the discomfort-glare ratings while stationary in an adjacent lane and fixating ahead in the lane (looking past the lighting display), a one-way within-subject ANOVA was performed and found not to be significant, $F(1,30) = 0.81$, $p = 0.3738$. The mean ratings for *Baseline* and *Main Bumper* conditions are shown in figure 89. It is important to note that while participants were rating in the adjacent lane, the mean ratings for both *Baseline* and *Main Bumper* configurations fell in the low range for glare (indicating above-satisfactory levels of discomfort-glare approaching the not noticeable category).

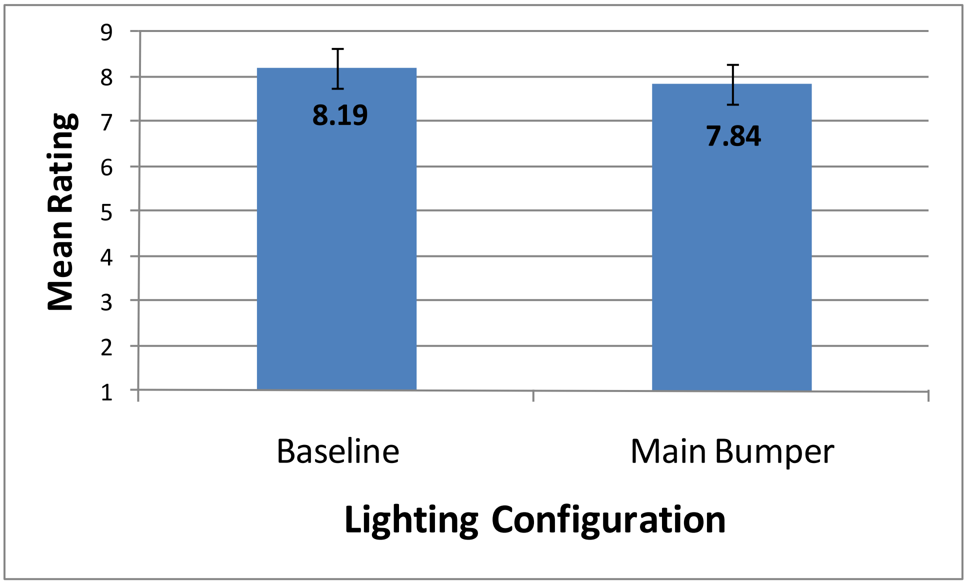

Figure 89. Bar graph. Mean discomfort-glare ratings of participants positioned in adjacent lane fixating forward in the lane (not looking directly at lighting) as a function of lighting configuration for dynamic Experiment 1.

After returning to the building, each participant filled out one helpfulness and one usefulness rating (appendix F). The helpfulness rating posed the question, "How helpful was the system at directing your attention?" The helpfulness rating contained a scale of 1 to 9 (1 being not at all helpful, and 9 being extremely helpful). The mean helpfulness rating was 6.88, with a standard deviation (SD) of 1.78. The usefulness rating posed the question, "How useful would the system be on the roadway?" The usefulness rating contained a scale of 1 to 9 (1 being not at all useful, and 9 being extremely useful). The mean usefulness rating was 7.31 (SD = 1.78). Overall, ratings were found to be very positive.

4.3.2.3 Experiment 1 Summary

Conspicuity Markings: No difference in following-distance behavior was found using the *Conspicuity Markings* as compared to the *Baseline* trailer configuration. This result suggests that the conspicuity markings did not help participants in maintaining their distance from the rear of the lead vehicle.

Uninformed Event Detection Paradigm: Upon completion of the data collection of the *Main Bumper* rear warning-light configuration, analyses showed no differences in *Time To Look-up*, T*ime To Accelerator Release*, or *Accelerator Position Change Rate*. Researchers concluded that the final rear warning-light configuration (*Main Bumper/Twelve-light ICC Bumper*) would not be run until the experimental methodology could be redesigned.

Ratings Scale Portion: The *Main Bumper* rear warning-light configuration had significantly better attention-getting ratings than the *Baseline* condition while the participants were fixating directly ahead at the rear of the trailer, as well as while fixating 30 deg off-axis. For the discomfort-glare ratings while fixating directly at the lighting, the *Main Bumper* provided significantly higher ratings. However, these mean ratings were still in the middle range for glare (not falling in the "undesirable" category). For the discomfort-glare ratings while stationary in an adjacent lane and fixating ahead in the lane (looking past the lighting display), the *Main Bumper* once again had the highest reported ratings. These mean ratings were in the low range for glare (indicating above-satisfactory levels of glare).

4.3.2.4 Conclusions

Conspicuity Markings did not provide a performance benefit in maintaining a demonstrated distance behind the experimental CUT. It was recommended that further ERS testing not include the passive conspicuity markings and that efforts be focused on rear-lighting configurations. The investigation of eye-drawing capability of rear warning-lights could not effectively be measured due to the experimental method used. The methodology was revised by researchers for a follow-up dynamic experiment (Experiment 2). This experiment required the in-vehicle experimenter to coach each participant to maintain a distance much closer to 120 ft (36.58 m) during Smart Road data collection.

4.3.3 Experiment 2

4.3.3.1 Method

Study Design: The primary objective of dynamic testing in Experiment 2 was to assess the eye-drawing capability of rear-lighting configurations on the rear of a trailer. Three experimental conditions were investigated: *Baseline*, *Main Bumper*, and *Main Bumper/Twelve-light ICC Bumper*. Performance results from the two rear warning-light configurations were analyzed in comparison to the *Baseline* condition.

The experimental paradigm was almost identical to the Experiment 1 dynamic testing. The following driver was instructed to perform a secondary task while following the lead experimental CUT at a given, demonstrated, following distance of 120 ft (36.58 m). The only change from Experiment 1 was that the in-vehicle experimenter coached each driver to maintain the approximate target distance of 120 ft (36.58 m) during each loop around the Virginia Smart Road. The lead experimental CUT maintained speed, but the *Baseline* configuration and the rear warning-light configurations were activated at various points along the route. These points were pre-selected, and were activated both when the following driver looked away from the forward view to attend to the secondary task as well as when the driver was looking forward. Rear-lighting configurations for these uninformed trials were treated as a between-subjects factor.

A total of 30 naïve drivers (no previous exposure to the lighting configurations) were tested to investigate trends in rear-lighting performance. Half of the participants were males and the other half were females. Recruitment of participants in Experiment 2 was carried out in the same way as Experiment 1. The age of participants ranged between 20 and 65 years old (mean of 39.27). Counterbalancing of two conditions was performed (i.e., gender and lighting configuration). Data were collected from 8:30 a.m. to 5:00 p.m. EST. Time of day was not considered in the counterbalancing; however, participants were randomly assigned to the available time slots in order to avoid potential sunlight angle bias.

As was performed in Experiment 1, Experiment 2 collected both performance and opinion data. The *Time To Look-up* was measured and served as the main dependent measure. Other objective measures included were *Time To Accelerator Release* and *Accelerator Position Change Rate*. The use of a between-subjects design was necessary because after each participant was exposed to the surprise event (uninformed event) re-exposure would not provide the same effect. Attention-getting, discomfort-glare, helpfulness, and usefulness rating scales were administered exactly the same as in Experiment 1.

Apparatus: Two rear warning-light configurations and one *Baseline* configuration positioned on the rear of the experimental CUT were used during testing on the Smart Road. The three rear-lighting configurations are shown and labeled in figure 90. Rear-lighting configuration descriptions and labels are summarized as follows:

- *Baseline* (A): Two LED-unit brake lights pre-installed by trailer manufacturer (baseline condition).
- *Main Bumper* (B): Twelve high-output LED units ganged and positioned on main bumper.
- *Main Bumper/Twelve-light ICC Bumper* (C): Twelve high-output LED units ganged and positioned on main bumper combined with 12 high-output LED units positioned on the ICC bumper.

Figure 90. Grouped image. Three rear-lighting configurations used during follow-up Experiment 2 dynamic testing.

Procedure: Procedures to be performed in Experiment 2 were identical to Experiment 1 with the exception of following-distance coaching from the in-vehicle experimenter to the driver.

4.3.3.2 Results

Uninformed Event Detection Paradigm: The uninformed event detection paradigm was used in dynamic testing on the Smart Road. The main objective was to determine how well the rear warning-light configurations would provide improved eye-drawing capabilities to that of normal brake lights (Baseline). Participants were coached to maintain a target following distance of 120 ft (36.58 m). Overall, the coaching was successful and a mean following distance of 125.71 ft (38.32 m) was maintained by drivers with an SD of 17.35 ft (5.29 m).

The duration between the initiation of the rear lighting and the participant's look-up response was obtained. Any participant who was looking forward when the rear lighting was initiated was to be removed from all analyses associated with eye drawing (both objective and subjective). In fact, no participants in any condition were looking forward during the initiation of the lighting and, therefore, none were removed from the analyses.

The first analysis performed, using Time To Look-up as the primary variable of interest, was across both exposures. A two-way ANOVA was performed with rear-lighting configuration as a between-subjects variable with three levels, and exposure as a within-subject variable with two levels. No main effects or interactions were found to be significant; however, a trend was found. Rear-lighting configuration demonstrated a trend at $F(2,27) = 2.26$, $p = 0.124$. The main effect of exposure was not significant at $F(2,27) = 0.17$, $p = 0.6859$. The interaction of these two variables was not significant at $F(2,27) = 0.34$, $p = 0.7143$. The mean Time To Look-up results are shown in figure 91. The figure shows that, on average, participants receiving the rear warning-lights took less time to look up to the forward roadway than did participants receiving the Baseline configuration (although this was not a statistically significant difference). The mean Time To Look-up for the Main Bumper (12 total LED units) was considerably lower than the Main Bumper/Twelve-light ICC Bumper (24 total LED units). Although this result was not significant, it was still unexpected as previous results from static experiments would suggest that both values would be closer to one another.

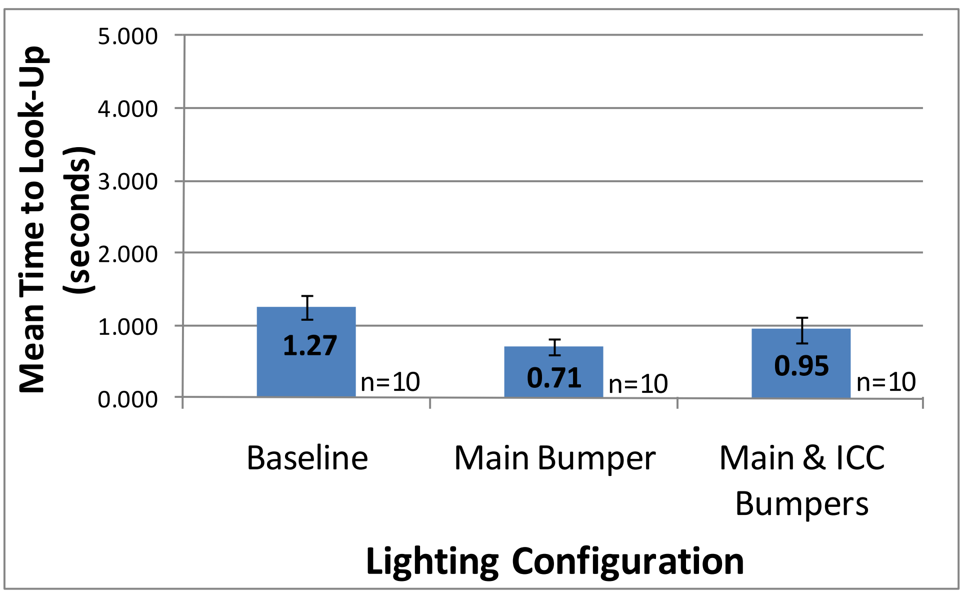

Figure 91. Bar graph. Mean *Time To Look-up* for both lighting exposures as a function of lighting configuration for dynamic Experiment 2.

As was done during all previous rear-lighting experiments in this project (both in static and dynamic tests), an analysis was performed using data from *Exposure 1* only. *Exposure 1* was the only event that was unanticipated across all participants. A one-way between-subjects ANOVA was performed. Although not significant, results demonstrated a trend with $F(2,27) = 1.36$, $p = 0.2732$. The mean *Time To Look-up* results are shown in figure 92. The figure shows that, on average, participants receiving the rear warning-lights (especially the *Main Bumper* lighting configuration) took less time to look up to the forward roadway than did participants receiving the *Baseline* configuration (although this was not a statistically significant difference). The mean *Time To Look-up* for the main bumper configuration was again lower than the main bumper combined with the ICC bumper. This result, in combination with the previous analysis across both exposures, led researchers to further evaluate each participant's data to identify potential outliers that could be affecting the analyses.

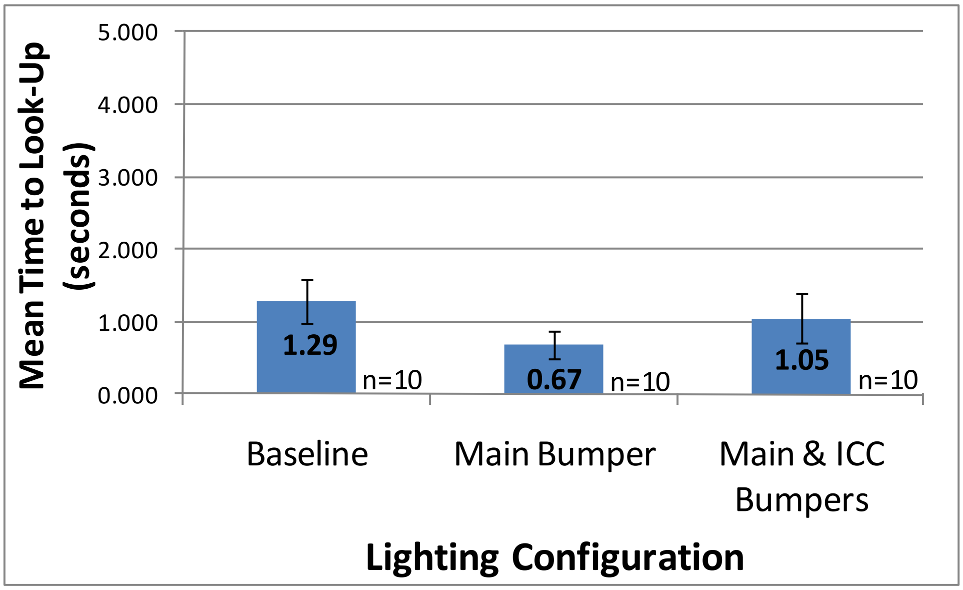

Figure 92. Bar graph. Mean *Time To Look-up* for *Exposure 1* as a function of lighting configuration for dynamic Experiment 2.

Upon further investigation of the *Time to Look-up* values across all exposures, two were identified as outliers. The first outlier was found in one *Baseline* participant's data which contained a *Time to Look-up* value of 3.7 s. This was determined to be a clear outlier and this participant's data were removed from further performance analyses. The second outlier was found within a participant's data in the *Main Bumper/Twelve-light ICC Bumper* condition. This participant's data contained a *Time to Look-up* value of 3.2 s. This was also determined to be an outlier and removed from further performance analyses. All remaining analyses will use data from 28 participants (9 in the *Baseline* condition, 10 in the *Main Bumper* condition, and 9 in the *Main Bumper/Twelve-light ICC Bumper* condition).

The next analysis performed, after the removal of outliers, was across both exposures using *Time To Look-up* as the primary variable of interest. A one-way ANOVA was performed with rear-lighting configuration as a between-subjects variable with three levels. Although not significant, rear-lighting configuration demonstrated a trend at $F(2,25) = 3.06$, $p = 0.0645$. The mean *Time To Look-up* results are shown in figure 93. The figure shows that, on average, participants receiving the rear warning-lights took less time to look-up to the forward roadway than did participants receiving the *Baseline* configuration (although this was not a statistically significant difference). After removing the outliers, the difference between the mean *Time To Look-up* for the *Main Bumper* configuration and the *Main Bumper/Twelve-light ICC Bumper* was much smaller.

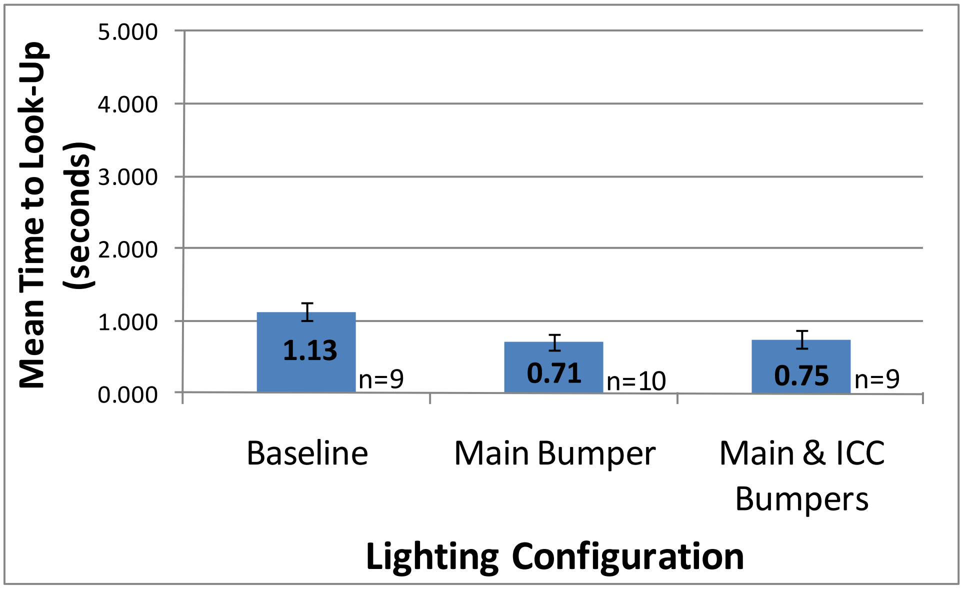

Figure 93. Bar graph. Mean *Time To Look-up* for both lighting exposures as a function of lighting configuration for dynamic Experiment 2.

The next analysis performed was again across both exposures using the *Accelerator Position Change Rate* as the primary variable of interest. A one-way ANOVA was performed with lighting configuration as a between-subjects variable with three levels. Once again, the main effect was not significant; however, a strong trend nearing significance was found. Rear-lighting configuration demonstrated a trend that was nearly significant at $F(2,25) = 2.58$, $p = 0.0958$. The mean *Accelerator Position Change Rate* results are presented in figure 94. The results show that the mean *Accelerator Position Change Rates* were much larger for the rear warning-lights than for the *Baseline* condition.

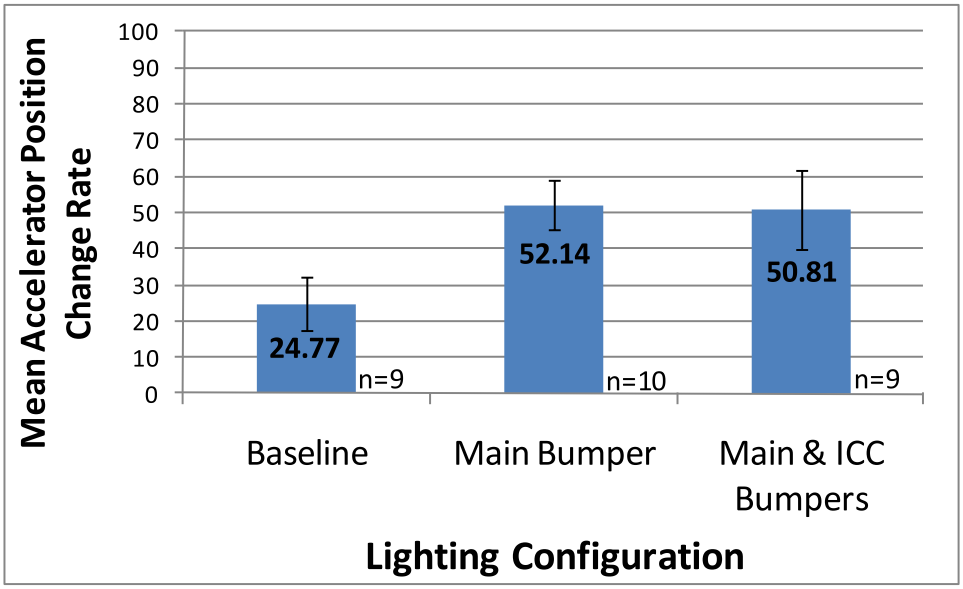

Figure 94. Bar graph. Mean *Accelerator Position Change Rate* for both lighting exposures as a function of lighting configuration for dynamic Experiment 2.

Just as was performed prior to outlier removal, an analysis was performed using data from *Exposure 1* only. A one-way between-subjects ANOVA was performed. The main effect of rear-lighting configuration was not significant, $F(2,25) = 0.95$, $p = 0.4003$. However, the means were in the same direction that was found previously across both exposures. The mean *Time To Look-up* results are shown in figure 95. The figure shows that, on average, participants receiving the rear warning-lights (especially the *Main Bumper*) took less time to look up to the forward roadway than did participants receiving the *Baseline* configuration (although this was not a statistically significant difference).

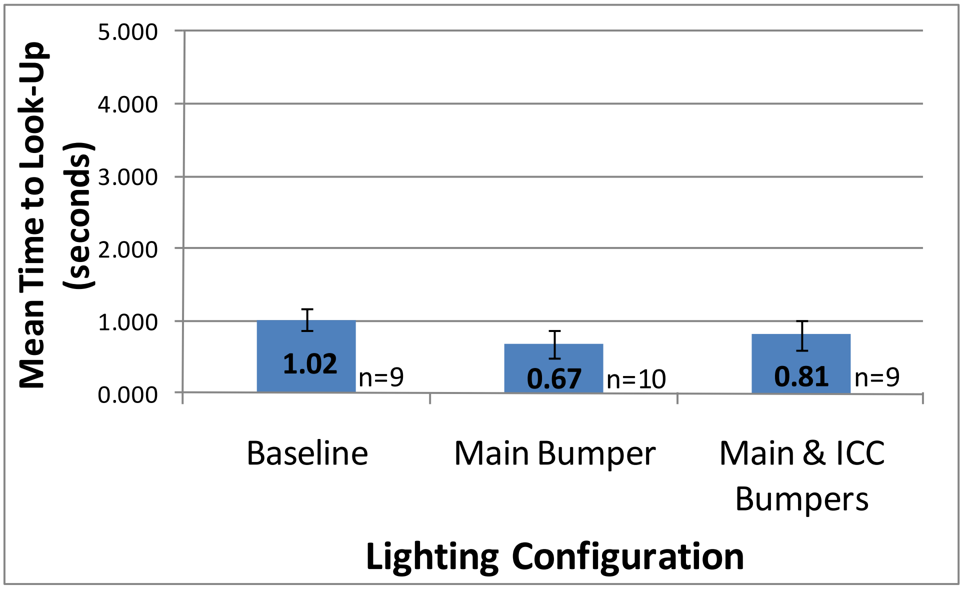

Figure 95. Bar graph. Mean *Time To Look-up* for *Exposure 1* as a function of lighting configuration for dynamic Experiment 2.

Another analysis was performed on *Time To Accelerator Release* during *Exposure 1*. A one-way between-subjects ANOVA was performed. No significant effect was found for rear-lighting configuration; however, results demonstrated a trend at $F(2,21) = 2.02$, $p = 0.1582$. The mean *Time To Accelerator Release* results are shown in figure 96. The figure shows that, on average, participants receiving the rear warning-light configurations took less time to release the accelerator than did participants receiving the *Baseline* configuration (although the difference was not statistically significant).

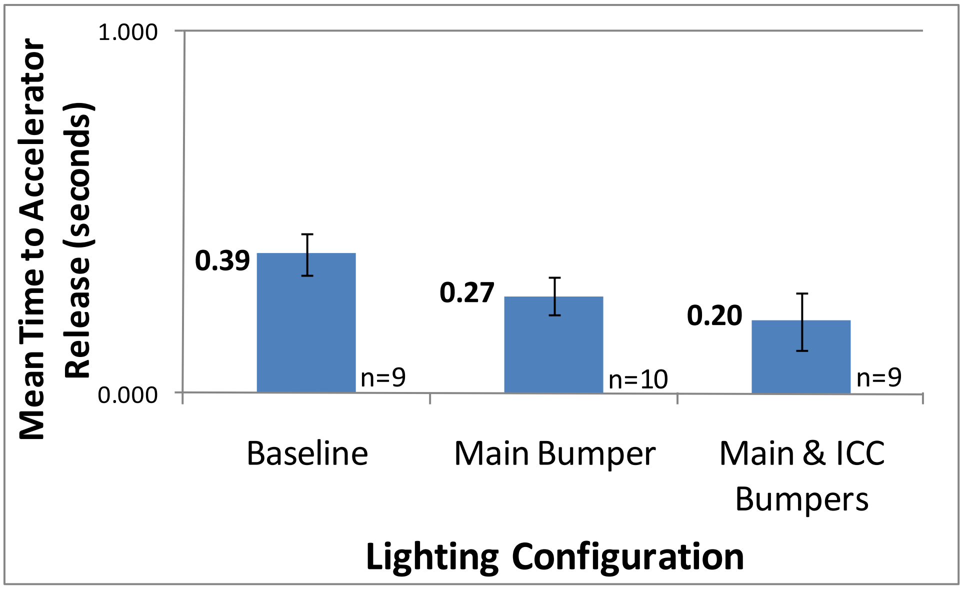

Figure 96. Bar graph. Mean *Time To Accelerator Release* for *Exposure 1* as a function of lighting configuration for dynamic Experiment 2.

Next, an analysis was performed for *Acclerator Position Change Rate* for *Exposure 1* only. A one-way between-subjects ANOVA was performed. No main effect was found to be significant, $F(2,25) = 0.28$, $p = 0.7545$. The mean *Acclerator Position Change Rate* results are presented in figure 97.

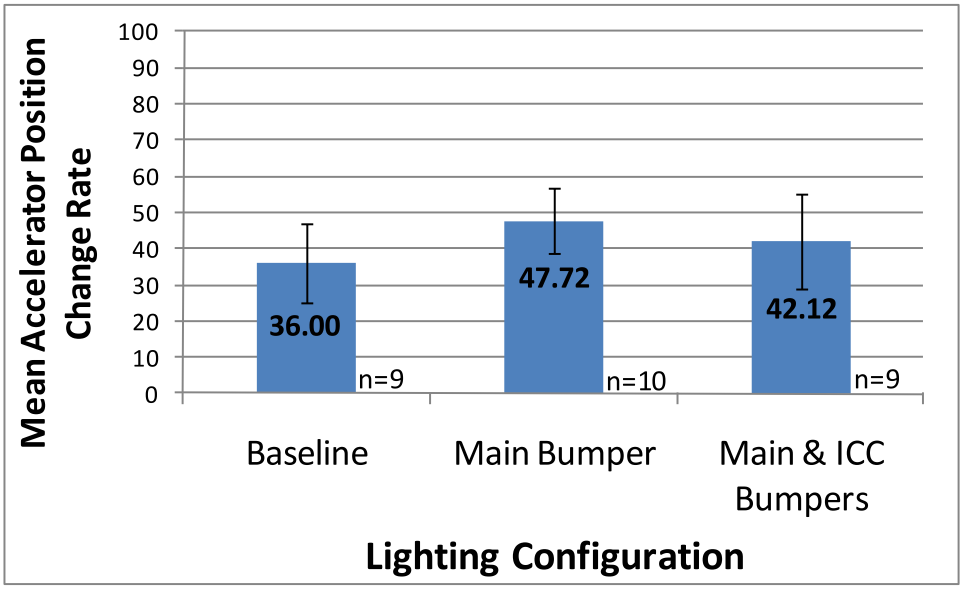

Figure 97. Bar graph. Mean *Accelerator Position Change Rate* for *Exposure 1* as a function of lighting configuration for dynamic Experiment 2.

The number of brake pedal activations immediately following rear-lighting activations was also recorded. Of the nine participants that received the baseline condition (one outlier removed), there were zero brake pedal activations during *Exposure 1* and two during *Exposure 2*. Of the 10 participants that received the *Main Bumper* configuration, there were two brake pedal activations during *Exposure 1* and five during *Exposure 2*. Of the nine participants that received the *Main Bumper/Twelve-light ICC Bumper* configuration (one outlier removed), there were four brake pedal activations during *Exposure 1* and four during *Exposure 2*. Although no statistical analyses were performed, these results indicated that both rear warning-light configurations may have generated a higher perceived urgency than that of the normal brake lights.

Ratings: Attention-getting ratings and discomfort-glare ratings were obtained from all 30 participants. For the attention-getting ratings while fixating directly at the lighting, a one-way within-subject ANOVA was performed and found to be significant, $F(2,27) = 29.13$, $p < 0.0001$. The mean ratings as a function of lighting configuration are shown in figure 98. The attention-getting rating scale (figure 57) contained a scale of 1 to 8 (1 being not at all attention-getting, and 8 being extremely attention-getting). As expected, the rear warning-lights provided higher ratings (significantly better than *Baseline*).

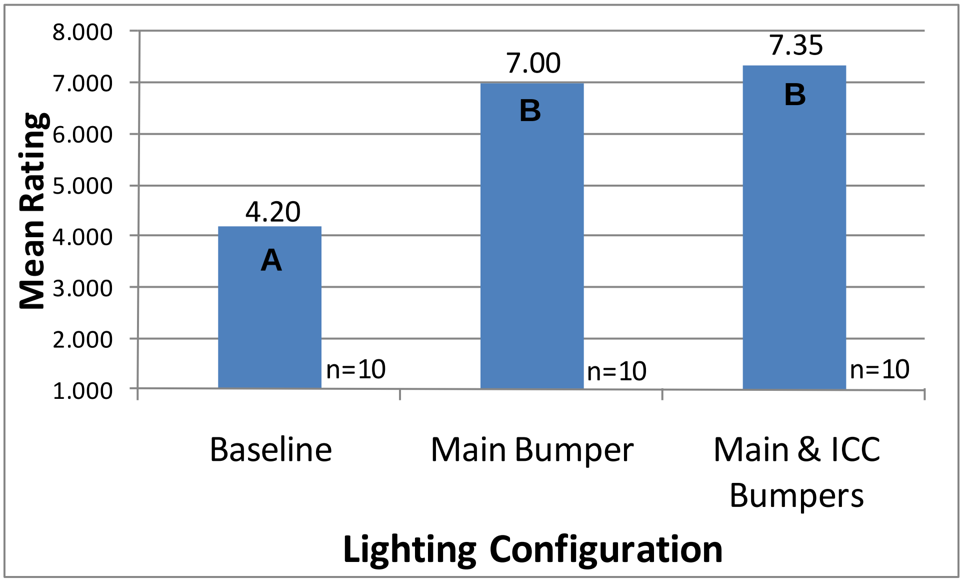

Figure 98. Bar graph. Mean attention-getting ratings of participants fixating at lighting as a function of lighting configuration for dynamic Experiment 2.

For the attention-getting ratings while fixating 30 deg off-axis, a one-way within-subject ANOVA was performed and found to be significant, $F(2,27) = 20.33$, $p < 0.0001$. The mean ratings as a function of lighting configuration are shown in figure 99. Once again, the rear warning-lights provided higher ratings.

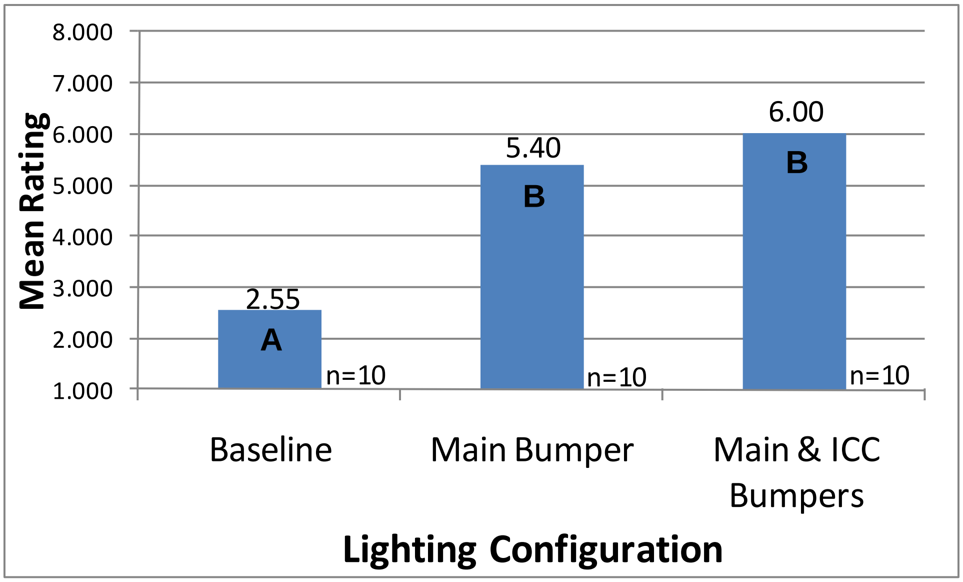

Figure 99. Bar graph. Mean attention-getting ratings of participants fixating 30 deg off-axis as a function of lighting configuration for dynamic Experiment 2.

For the discomfort-glare ratings while fixating directly at the lighting, a one-way within-subject ANOVA was performed and found to be nearly significant, $F(2,27) = 2.87$, $p = 0.0739$. The mean ratings as a function of lighting configuration are shown in figure 100. The discomfort-glare rating scale (figure 58) contained a scale of 1 to 9 (1 being unbearable, and 9 being not noticeable). The *Main Bumper* configuration provided a higher amount of discomfort-glare than did the *Baseline* and the *Main Bumper/Twelve-light ICC Bumper* configurations (although this was not statistically significant). It is important to note that the mean ratings for all lighting configurations fell in the middle range for glare.

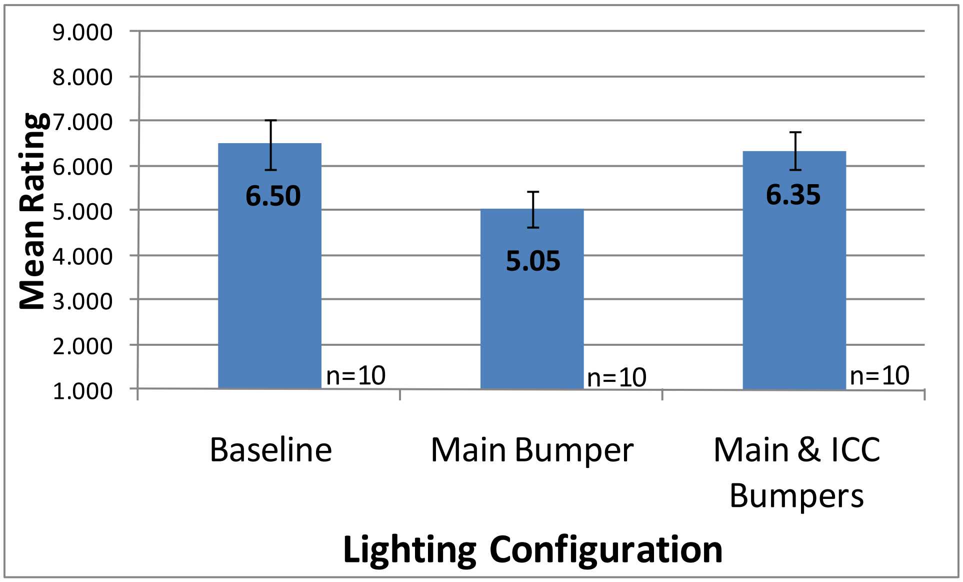

Figure 100. Bar graph. Mean discomfort-glare ratings of participants fixating at lighting as a function of lighting configuration for dynamic Experiment 2.

For the discomfort-glare ratings while stationary in an adjacent lane and fixating ahead in the lane (looking past the lighting display), a one-way within-subject ANOVA was performed and found not to be significant, $F(2,27) = 2.23$, $p = 0.1264$. The mean ratings as a function of lighting configuration are shown in figure 101. It is important to note that while participants were rating in the adjacent lane, the mean ratings for all rear lighting configurations fell in the low range for glare (indicating above-satisfactory levels of discomfort-glare approaching not noticeable).

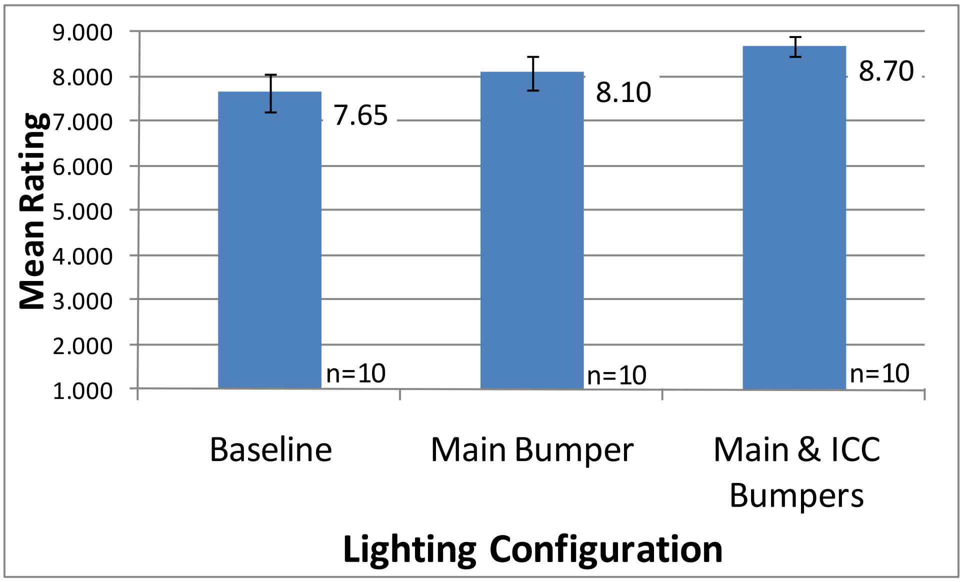

Figure 101. Bar graph. Mean discomfort-glare ratings of participants positioned in adjacent lane fixating forward in the lane (not looking directly at lighting) as a function of lighting configuration for dynamic Experiment 2.

Each participant that received rear warning-light configurations filled out one helpfulness and one usefulness rating (appendix F). The helpfulness rating posed the question, "How helpful was the system at directing your attention?" The helpfulness rating contained a scale of 1 to 9 (1 being not at all helpful, and 9 being extremely helpful). The mean helpfulness ratings for the *Main Bumper* and *Main Bumper/Twelve-light ICC Bumper* configurations were 7.5 (SD = 0.85) and 8.0 (SD = 1.05), respectively. The usefulness rating posed the question, "How useful would the system be on the roadway?" The usefulness rating contained a scale of 1 to 9 (1 being not at all useful, and 9 being extremely useful). The mean usefulness ratings for the *Main Bumper* and *Main Bumper/Twelve-light ICC Bumper* configurations were 7.3 (SD = 1.418) and 8.2 (SD = 1.135), respectively. Overall, helpfulness and usefulness ratings for each rear warning-light configuration were found to be very positive.

4.3.3.3 Experiment 2 Summary

Uninformed Event Detection: Results indicated that a strong trend was found for improved eye-drawing performance for both rear warning-light configurations over that of normal brake lights. This was found across both exposures, as well as for *Exposure 1* alone. A trend was also found for the *Accelerator Position Change Rate* for the rear warning-light configurations across both exposures. This, combined with an overall increase in the number of brake pedal activations for the rear warning-lights, indicated that a higher perceived urgency and/or risk may exist in controlled test-track scenarios.

Rating Scale Portion: The rear warning-light configurations had significantly better attention-getting ratings while the participants were fixating directly ahead and while fixating 30 deg off-axis. For the discomfort-glare ratings while fixating directly at the lighting and positioned in the adjacent lane (looking past the lighting display), no significant differences were found. The helpfulness and usefulness ratings showed that, overall, participants perceived both rear warning-light configurations positively.

4.3.3.4 Conclusions

Experiment 2 found trends that indicated, as expected, both rear warning-light configurations performed better than normal brake lighting at reducing eye-drawing time. No major differences in performance or subjective ratings between the *Main Bumper* configuration and the *Main Bumper/Twelve-light ICC Bumper* configuration were found. Just as results indicated from static tests, both appeared to be prime candidates for real-world data collection.

4.3.4 Dynamic Experimentation General Conclusions

Although the method used in Experiment 1 did not result in useful data for the determination of rear warning-light configuration performance, it was sufficient for determining that passive conspicuity markings did not provide a performance benefit in maintaining a demonstrated distance behind the experimental CUT. For the remainder of this project, it was recommended that efforts be focused on rear-lighting configurations as they have shown the most promise at mitigating rear-end crashes involving heavy trucks. The two rear warning-light configurations both performed well in the second dynamic Virginia Smart Road experiment. However, one rear warning-light configuration did not substantially show improved performance over that of the other. Both appeared to be good candidates for the real-world data collection effort.

5. ACTIVATION SUB-SYSTEM

In order to successfully develop an ERS system for heavy trucks, two major efforts were performed at VTTI. The first development effort consisted of static and dynamic testing involving the investigation of multiple rear-lighting configurations in order to select the most promising candidates with which to move forward in a real-world data collection setting. The second effort (discussed in this section) consisted of researchers and engineers modifying previously designed rear-signaling activation (triggering) algorithms and testing the performance of these on the Virginia Smart Road.

5.1 INTRODUCTION

Determining when to activate and de-activate a rear warning-light system is a critical component of an effective system. If such a system is activated correctly, it should provide the warning only when a rear-end crash is likely to occur and not at any other time. Additionally, it must not miss situations where a rear-end crash is likely to occur. There are four aspects to such a system, as with any other detection system, when applied to rear-end crashes:

- Activation when a crash would otherwise occur (correct detection),
- Non-activation when a crash would otherwise occur (missed detection),
- Activation when a crash would not otherwise occur (false alarm), and
- Non-activation when a crash would not otherwise occur (correct non-detection).

The objective was to maximize the probabilities of occurrence of correct detections and correct non-detections, and minimize the probabilities of occurrence of missed detections and false alarms. While this may seem to be a straightforward situation, closely related to signal detection theory,(8,9) in practice it can be very difficult to achieve. Previously, the research team developed two distinct concepts for activation in light-vehicle rear-signaling research: the open-loop system and the closed-loop system.(6,21) Upon further investigation of these concepts and their application to rear-end crash scenarios involving heavy vehicles, a third concept was developed: the hybrid system. These three concepts will be discussed in further detail in the following section with regard to their potential for heavy-vehicle rear-end crash prevention.

5.2 ACTIVATION SUB-SYSTEM CONCEPTS

5.2.1 Open-loop Activation Sub-system Concept

In an open-loop system, there are no measurements associated with the following vehicle, only lead vehicle parameters are available. Consequently, selection of parameters and appropriate thresholds are critical for optimizing activation of the rear warning-lights. For example, if high decelerations by lead heavy trucks are found to correlate with following-vehicle rear-end crashes, an accelerometer could be mounted on the trailer and used in an algorithm to activate the rear warning-lights. Recent work by the research team proposed an open-loop activation sub-system with three main branches: one associated with deceleration, one associated with ABS triggering, and one associated with accelerator depression.(6) This activation sub-system concept was selected as an appropriate candidate for development and Smart Road testing.

5.2.2 Hybrid Activation Sub-system Concept

One of the major shortcomings of open-loop systems is the standing lead-vehicle problem. In both the light-vehicle and heavy-vehicle configurations, it is assumed that deceleration of substantial magnitude precedes standing on the pavement. However, there certainly are situations in which decelerations may not reach threshold, but the vehicle stands on pavement and gets struck from behind. There is a trade-off in using a standing-vehicle signal. On the one hand, if such a signal is used it should reduce the number of rear-end crashes in which the lead vehicle is standing or moving very slowly on the pavement. On the other hand, there is extreme annoyance for the driver of the following vehicle because the rear warning-lights continue to flash brightly even after the following vehicle has stopped, creating discomfort glare for the following driver.

A hybrid system would extinguish the rear warning-lights after the following vehicle reaches a standstill or the same very low velocity as the lead vehicle. Doing so requires the use of another sensor, namely, an ultrasonic sensor system similar to those used for sensing objects during backing. If a similar device can be developed for use with an open-loop system, then rear warning-lights can be extinguished when there is a vehicle or object directly behind that is also standing or moving slowly. The great advantage of such a system is that it would cover the case of being struck while standing, even after the timeout interval has passed, or when activation has not occurred. Such a system is actually a "hybrid" system (that is, neither strictly open-loop nor closed-loop), because it does in fact use distance between the lead and the following vehicle. However, it does so only at close intervals, such as 25 ft (7.6 m) or less, and at very slow speeds or standing. It is worth mentioning that ultrasonic sensors are not capable of replacing radar or laser systems at longer distances. Ultrasonic systems are therefore not suitable for full closed-loop systems.

It is important to understand that a hybrid system would need to have a sensor on the trailer that indicates when the trailer is standing still or moving slowly. If the trailer is equipped with wheel speed sensors associated with the ABS, one or both of them can be tapped and the signal conditioned for use in a hybrid activation sub-system. If the trailer does not have wheel speed sensors, some type of wheel sensing would have to be added to determine if the trailer is at or near zero velocity. Another concern of a hybrid system is that the associated cost may be much higher than for an open-loop system (approaching the cost of a more expensive, yet more accurate, closed-loop system). This concern, combined with the potentially poor performance of ultrasonic sensors at distances of 25 ft (7.6 m), ultimately led researchers to exclude the hybrid activation sub-system concept as a candidate for development and Smart Road testing.

5.2.3 Closed-loop Activation Sub-system Concept

Closed-loop activation includes the measurement of closing rate (velocity) and closing distance to the following vehicle, along with lead-vehicle velocity and deceleration, regardless of speed and distance between vehicles. To obtain the closing rate and closing distance, a radar or laser system is ordinarily used. Thereafter, computations are used to determine whether a vehicle approaching from the rear represents a crash threat. A closed-loop system, although of higher cost, was found to be an ideal candidate for development and Smart Road testing.

5.3 ACTIVATION SUB-SYSTEM DEVELOPMENT

Both the open-loop activation sub-system and the closed-loop activation sub-system were chosen to be developed and tested in a dynamic setting on the Smart Road. Each activation sub-system is discussed in more detail in their respective sections below.

5.3.1 Open-loop Activation Sub-system Development

As mentioned previously, an open-loop system has only lead-vehicle parameters available. Consequently, selection of parameters and appropriate thresholds are critical to optimizing activation of rear warning-lights. The three main branches proposed in recent work for an open-loop activation sub-system were used as the basis for this project's open-loop system development: one associated with deceleration, one associated with ABS triggering, and one associated with accelerator depression (figure 102).[6]

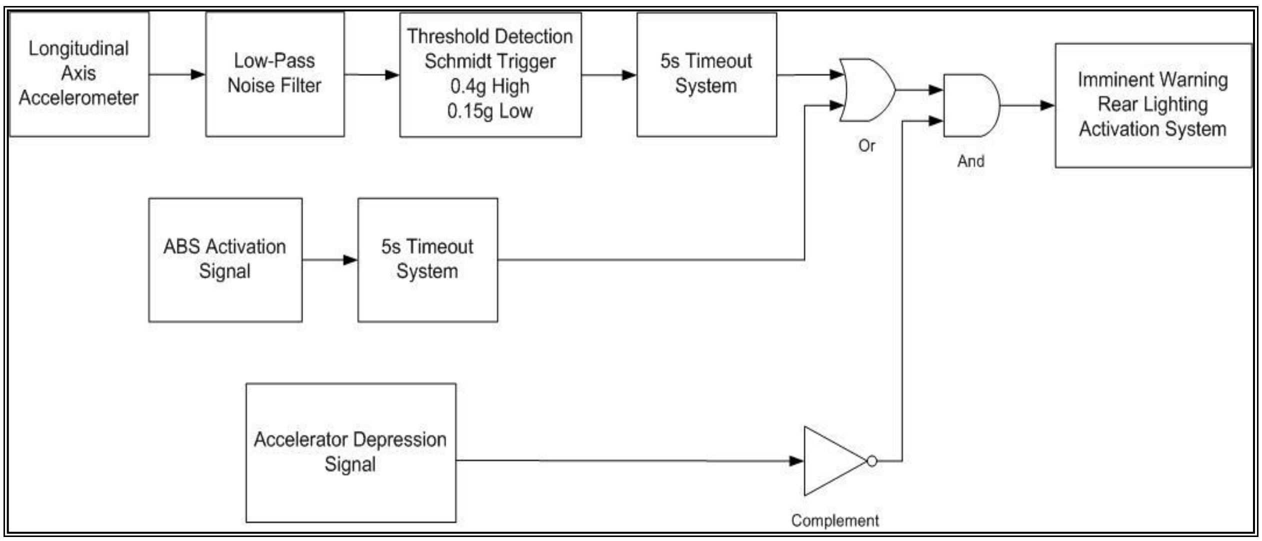

Figure 102. Diagram. Block diagram of an open-loop triggering logic for the enhanced rear lighting for a light-vehicle application.[7]

Each main branch will be explained as well as any modifications made to better correspond with heavy-vehicle rear-end crash scenarios. With regard to the accelerometer, it was used to determine when the vehicle was undergoing a high level of deceleration. The threshold used was 0.4 *g*, as shown in the diagram. To correct for potential noisy accelerometer signals (which can cause thresholds to be exceeded even though a vehicle has not actually reached a 0.4 *g* threshold), a low-pass filter was used between the accelerometer and the threshold detector. A deceleration of 0.4 *g* was selected based on previous research.[10,21]

A vehicle undergoing 0.4 *g* of deceleration or more will come to a stop relatively quickly. For that reason, a timeout feature was added. This feature continued the activation of the rear warning-lights for a period of 5 s after the vehicle fell below 0.15 *g* in deceleration. This feature was intended to continue the rear warning-lights while the vehicle was 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 high deceleration or it may occur without high deceleration. Therefore, using this activation supplements particularly those cases where the deceleration threshold for activation has not been reached. An example is lack of adhesion on ice or snow. When using ABS it is similarly desirable to use a timeout, because ABS activation is usually short in duration.

Finally, deactivation based on accelerator use (figure 102) was not included for use with the heavy-vehicle open-loop activation sub-system. The deactivation based on accelerator use was used in the light-vehicle research to avoid the problem of having the light-vehicle warning lights continue after a sharp turn. This was not likely to transfer well to heavy trucks because heavy trucks generally do not make sharp turns. Any sharp, fast turn would be likely to have severe consequences, probably resulting in rollover. Heavy truck deceleration was measured at the tractor by using an accelerometer mounted near the DAS. In addition, ABS activation was detected at the tractor and at the trailer by tapping a signal from the ABS control module at each location. These two signals were used to appropriately make the decision as to when the rear lighting was to be activated.

To summarize, the open-loop activation sub-system developed contained the following capabilities:

- Accepted power from the tractor and conditioned it as necessary.
- Included an accelerometer to determine when the trailer was decelerating at a rapid rate.
- Included an input from the ABS-equipped tractor and ABS-equipped trailer indicating when ABS was active.
- Contained the logic to determine the onset of emergency lighting activation.
- Contained timeout logic to determine ending time of emergency lighting activation.
- Produced a 5-Hz rectangular wave, and generated a power signal sufficient to power the rear warning-lights.

Figure 103 shows the major elements of the heavy-vehicle open-loop activation sub-system. This system can also be used for straight trucks. Two real time inputs were used: sensed deceleration level and activation of ABS.

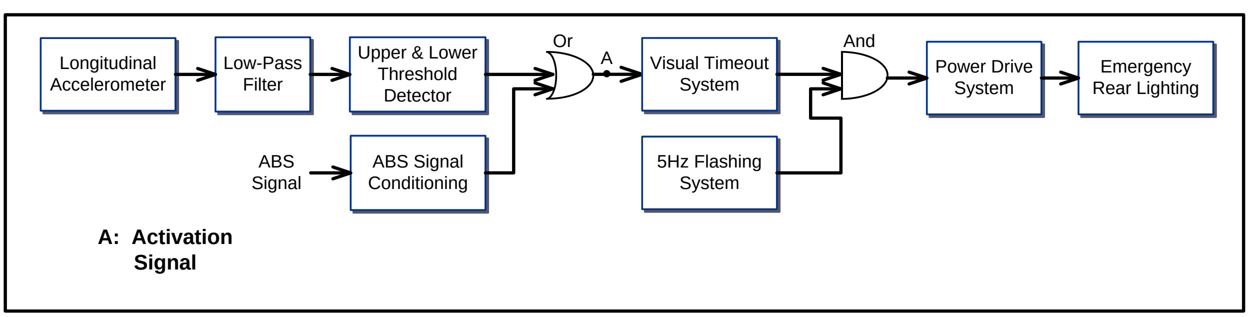

Figure 103. Diagram. Block diagram of the open-loop activation sub-system for use on a heavy vehicle.

5.3.2 Closed-loop Activation Sub-system Development

As previously mentioned, a closed-loop activation sub-system includes the measurement of closing rate (velocity) and closing distance to the following vehicle, along with lead-vehicle velocity and deceleration, regardless of speed and distance between vehicles. To obtain the closing rate and closing distance, radar was used. Computations were used to determine whether a vehicle approaching from the rear represented a crash threat. The radar used was designed to work for moving-vehicle applications. Radar systems used in vehicle applications generally are not designed to work when the vehicle is standing on the pavement. For these initial closed-loop activation sub-system tests, it was determined that using this radar system was a good first step in order to determine if this type of radar would be sufficient. Approximately 50 percent of rear-end crashes involving heavy trucks occur when the lead vehicle is stopped; therefore, radar that is specifically designed for both a moving lead vehicle and a stopped lead vehicle would be ideal.

There were two approaches identified toward developing the heavy-vehicle closed-loop activation sub-system. Both of these approaches were based on different assumptions as to the heavy vehicle's behavior. For the current report, Approach 1 was ultimately used for development and testing. However, each approach will be discussed below.

5.3.2.1 Closed-loop Activation Sub-system Approach 1

The simpler approach makes the assumption that the lead vehicle (heavy vehicle) is traveling at a constant speed or is standing still.(21) In that case, the equations become greatly simplified, as follows:

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

$$t_0 = t_{pr} - \frac{v_r}{gc_F} \qquad \text{(Eq. 2)}$$

In these equations:

- R_{min} is the minimum initial separation without a collision, measured between the lead vehicle rear bumper and the following vehicle front bumper (ft).
- c_F is the deceleration capability of the following vehicle in *g*'s during braking (positive for deceleration; dimensionless).
- v_r is the initial closing rate between vehicles; negative for following-vehicle closing on the lead vehicle (ft/s).
- g is the acceleration due to gravity (32.2 ft/s^2 or 9.81 m/s^2).
- t_{pr} is the perception-reaction time of the following driver (s).
- t_0 is the time to touch between the rear bumper of the lead vehicle and the front bumper of the following vehicle (s).

In these equations it is assumed that the closing rate v_r is negative; that is, the following vehicle is closing in on the lead vehicle. If the following vehicle is not closing in on the lead vehicle, then there is no instantaneous likelihood of a rear-end collision. Of course, this could change in future measurements.

To better understand the equations above and the definition of terms, refer to figure 104. This figure is taken directly from previous research by Wierwille, Lee, and DeHart.(21) The explanation from that document (p. 116) is as follows:

> "Consider the [figure] which shows the relative movements of the following vehicle and the lead vehicle for the specific case in which the lead vehicle is at a constant-slower velocity equal to v_{Li}. The vehicles are initially separated by R_{min}, the minimum distance for which there will be no collision. During the perception-reaction time of the following driver, the following vehicle moves a distance of d_{Fp}. The lead vehicle travels a corresponding distance d_{Lp}. Once braking begins, the following vehicle travels a distance d_{Fb}, while the lead vehicle continues to travel at constant velocity for a corresponding distance d_{Lb}. For minimum separation, both vehicles have the same forward velocity at the instant they touch. Thereafter the following vehicle once again falls behind due to continued deceleration, but there is no collision."

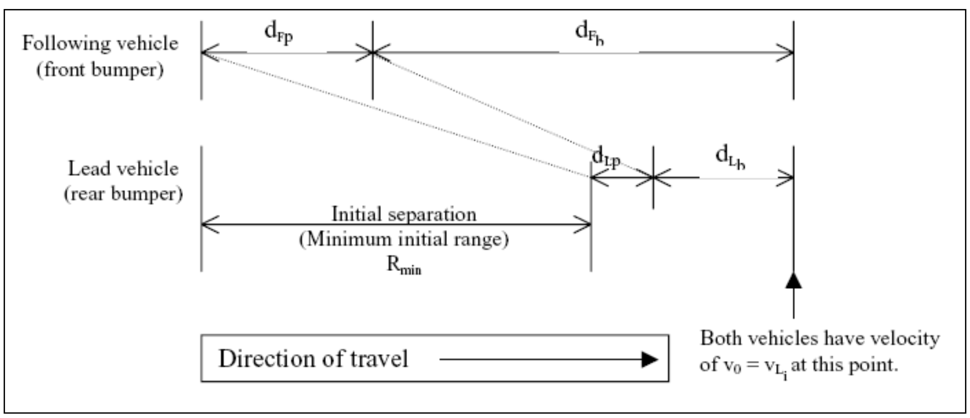

Figure 104. Diagram. Depiction of the limit condition for a constant velocity lead vehicle.(21)

Calculation of R_{min} is needed to determine whether the measured range obtained from the radar is greater than R_{min}, or less than or equal to R_{min}. If greater than R_{min}, there is no momentary threat of a rear-end collision. If less than or equal to R_{min}, there is a threat of a rear-end collision and the warning system should be activated. Note that the velocity of the lead vehicle does not enter these equations, except indirectly, through v_r. This represents a great simplification.

Typical parameter values for assumed perception-reaction time are t_{pr} = 1.5 s.(28) For following-vehicle deceleration, typical values range from 0.5 to 0.75 *g*.(29) The fact that different vehicles are capable of different deceleration values presented a dilemma. If a value of 0.5 *g* is used, the warning may be initiated too early for higher performance vehicles, whereas if a value of 0.75 *g* is used, the warning may be initiated too late for lower performance vehicles. Faced with this dilemma, researchers chose a value of 0.5 *g*, which would allow all vehicles to stop in time. High performance vehicles would then have some additional "cushion." Another issue not addressed in the previous algorithm work was the need for the addition of a *Time To Look-up* variable. Although a value of 1.5 s has been provided for perception-reaction time, the time it takes for a driver involved in a distracting task to have his/her eyes drawn to the rear warning-lights must be included (and can be added to the perception-reaction time variable t_{pr}). During dynamic testing it was found that, on average, it took drivers approximately 1.5 s to look up after lighting was activated. Therefore, for the purpose of closed loop testing the t_{pr} value was increased to 3.0 s.

5.3.2.2 Closed-loop Activation Sub-system Approach 2

The second approach is to include the acceleration and deceleration capabilities of the lead vehicle in the equations. Five cases have been previously identified, as follows:[(21)]

- *Condition 1*: The lead vehicle is standing on the pavement (it 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 then stands on the pavement.
- *Condition 5*: The lead vehicle is slowly accelerating.

The first two conditions are covered by the equations already presented in Approach 1. The latter three are not covered, except indirectly, because of the updating of the radar information. The equations for the latter three become somewhat complicated. It was determined that due to the latter three conditions' complexity, and for safety reasons, initial algorithm testing on the Smart Road should use Approach 1 only (focusing only on *Conditions 1* and *2*). The equations and the logic for selection have already been worked out in previous research[(21)] and these are provided in appendix H, including modifications made for use with heavy trucks.

5.4 ACTIVATION SUB-SYSTEM TESTING

Both the open-loop activation sub-system and closed-loop activation sub-system were tested on the Smart Road. Testing scenarios and results found for each system are discussed in more detail in their respective sections below.

5.4.1 Open-loop Activation Sub-system Testing

5.4.1.1 Method

Study Design: All testing performed was done with researchers and engineers (i.e., no naïve participants). As previously mentioned, an open-loop system requires no measurements associated with the following vehicle. Only lead-vehicle parameters are available. The two lead-vehicle parameters tested were deceleration (measured by an accelerometer), and ABS activation (activation of either the tractor or trailer ABS). The main aspect of the open-loop activation sub-system testing was determining the system detection performance of a rear-end crash threat and thus activating the rear warning-lights. The system was tested under various driving scenarios on the Smart Road. A signal detection theory experimental design was used.[(8,9)] Four categories for open-loop activation performance were defined: 1) correct detection, 2) missed detection, 3) false alarms, and 4) correct non-detection. The main dependent variable (DV) was light activation (*Yes* or *No*). The main independent variables (IV) were braking level and ABS signal type. The different levels of each IV are shown below:

- Braking Level
  - *Low-level* (< 0.4 *g*)
  - *High-level* ($\geq$ 0.4 *g*)
- ABS Signal Type
  - *Tractor ABS*
  - *Trailer ABS*

The experimental CUT was driven five loops around the Smart Road. During each loop, each condition above was initiated four times, thus equaling a total of 20 samples per condition.

Apparatus: Light activation logic was calculated by a DAS installed in the tractor. An accelerometer was used to measure the level of braking. Due to safety reasons, actual scenarios involving the activation of the *Tractor ABS* and *Trailer ABS* were not performed. However, this signal was reproduced manually by an experimenter button plugged directly into the DAS.

Although actual scenarios involving the activation of ABS were not performed, engineers were still able to identify the tractor and trailer ABS signals and develop the open-loop activation sub-system to work in a real-world application. According to the Code of Federal Regulations (CFR), title 49, section 393.55, each truck tractor manufactured on or after March 1, 1997 shall be equipped with an ABS that meets the requirements of Federal Motor Vehicle Safety Standard (FMVSS) No. 121 (49 CFR 571.121, S5.1.6.1 (b)).[30] Also, each air braked commercial motor vehicle other than a truck tractor, manufactured on or after March 1, 1998 shall be equipped with an ABS that meets requirements of FMVSS No. 121 (CFR 571.121 S5.2.3 for semitrailers, converter dollies and full trailers).[30]

Therefore, tractors built after the above date will most likely contain a signal on the vehicle network which can be used for driving the open-loop activation sub-system. Trailers built after the above associated date will have an ABS; however, they may or may not provide this signal to the truck network upon connection. In situations when a trailer does not provide this signal to the truck, the signal will have to be retrieved from the trailer modulator control. Researchers and engineers retrieved the tractor ABS signal from the vehicle network, and retrieved the trailer ABS signal from the modulator control.

Procedure: As previously mentioned, five loops were driven on the Virginia Smart Road in an experimental CUT. Each loop was approximately 2.2 mi (3.54 km). During the first half of the loop (downhill portion) both braking levels and both ABS signals were initiated twice. Once again during the second half of the loop (uphill portion), both braking levels and both ABS signals were initiated twice.

5.4.1.2 Results

As mentioned previously, a signal detection theory experimental design was used.[8,9] Table 10 shows the parameters of this detection paradigm.

Table 10. Detection Paradigm Parameters for Open-loop Activation Sub-system Testing

Light Activation	Threat (High-level Braking)	No Threat (Low-level Braking)
Yes	Hit (Correct Detection)	False Alarm
No	Miss (Missed Detection)	Correct Rejection (Correct Non-detection)

The objective is to maximize the probabilities of occurrence of correct detections and correct non-detections, and minimize the probabilities of occurrence of false alarms and missed detections.

Braking Level: As mentioned previously, there were 10 loops driven around the Smart Road, with both braking level conditions tested twice per loop (20 samples per braking condition). Table 11 shows the results for the braking level conditions. Results indicated that all threats were correctly detected and 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) = 20/20 = 1.0. The estimated probability of the system correctly rejecting *Low-level* braking and not activating the lights was 100 percent, P(cr) = 20/20 = 1.0.

Table 11. Detection Results from Brake Level Testing for the Open-loop Activation Sub-system

Light Activation	Threat	No Threat
Yes	20	0
No	0	20

ABS Signal Type: Similarly to the braking level testing, there were 10 loops driven around the Smart Road, with both ABS Signal Types tested twice per loop (40 total samples of potential ABS detections). Table 12 shows the results for ABS signal types. Results indicated that all threats were correctly identified and 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 ABS signal and activating the lights was 100 percent, a P(hit) = 40/40 = 1.0. Although there were no possibilities of correct rejections in the ABS signal testing, results still indicated that the open-loop activation sub-system performed well.

Table 12. Detection Results from ABS Signal Type Testing for the Open-loop Activation Sub-system

Light Activation	Threat	No Threat
Yes	40	0
No	0	NA

5.4.1.3 Open-loop Activation Sub-system Testing Summary

Results showed that, as programmed, rear warning-lights were initiated whenever braking levels were greater than or equal to 0.4 *g* of deceleration. The timeout feature also performed correctly, keeping the lights initiated for a period of 5 s after the tractor-trailer fell below 0.15 *g*. The rear warning-lights were also initiated whenever an ABS signal was received. The timeout feature for the ABS signal was also found to work successfully in each situation.

5.4.2 Closed-loop Activation Sub-system Testing

5.4.2.1 Method

Study Design: All testing performed was done with researchers and engineers (i.e., no naïve participants). The main aspect of the closed-loop activation sub-system testing was determining the prototype algorithm performance under various rear-end crash scenarios. A signal detection theory experimental design was used.[8,9] Four occurrences of detection were categorized: 1) correct detections, 2) missed detections, 3) false alarms, and 4) correct non-detections. The main DV was light activation (*Yes* or *No*). The main IVs were closing speed, light-vehicle approach, and algorithm condition. The different levels of each IV are shown below:

- Closing 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
  - *Same Lane*
  - *Left Lane*
  - *Right Lane*
  - *Left to Same Merge at 75 ft, 100 ft* and *125 ft* (22.86 m, 30.48 m, and 38.81 m)
  - *Right to Same Merge at 75 ft, 100 ft* and *125 ft* (22.86 m, 30.48 m, and 38.81 m)
- Algorithm Condition
  - *Condition 1* = Experimental CUT standing on the pavement (zero velocity)
  - *Condition 2* = Experimental CUT moving at a constant forward speed of 25 mi/h (40.23 km/h)

All IVs were counterbalanced equally. Each scenario was performed four times. However, it is important to note that the light-vehicle approaches for *Left to Right Merge at 75 ft* and *Right to Left Merge at 75 ft* were not performed at a closing speed of *25 mi/h* due to safety reasons. For algorithm *Condition 1*, there was a total of 100 light-vehicle approaches performed (76 rear-end crash approaches and 24 adjacent lane approaches). For algorithm *Condition 2* there was also a total of 100 light-vehicle approaches performed (76 rear-end crash approaches and 24 adjacent lane approaches). The experimental CUT was standing on the pavement for both algorithm *Conditions 1* and *2*; however, during *Condition 2* the algorithm was provided a lead-vehicle speed value of 25 mi/h (40.23 km/h). This portion of the testing was performed in this way due to the fact that *Condition 1* and *Condition 2* are calculated almost identically, and to maintain a safer testing environment on the Smart Road.

Apparatus: The main bumper lighting configuration and radar were installed on the rear of an experimental CUT trailer. Light activation logic was calculated by a DAS installed in the tractor.

This DAS was also responsible for recording the rear-end crash scenario data. Rear-end crash scenarios were executed on a long, flat portion of the Smart Road. The approaching light vehicle was a full-size sedan (figure 105).

Figure 105. Photo. Light vehicle used was a full-size sedan.

Procedure: Multiple rear-end crash scenarios as well as adjacent-lane passing scenarios were performed at multiple light-vehicle approach speeds. One researcher sat in the driver seat of the approaching light vehicle and another researcher sat in the passenger seat to manually collect data on light activations. The approaching light vehicle began accelerating at a distance of 400 ft (121.92 m) back from the rear of the trailer and reached each specified speed by at least 300 ft (91.44 m). Figure 106 shows an overhead diagram of the multiple scenarios performed. Scenarios are described below the figure corresponding to each labeled vehicle in the diagram.

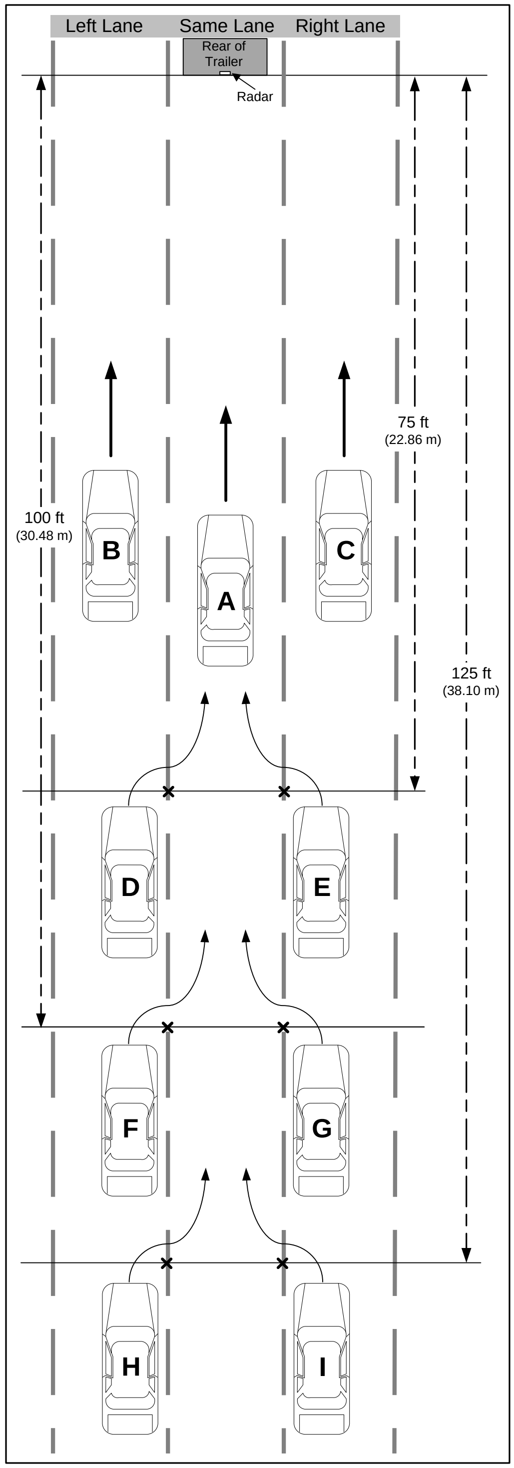

Figure 106. Diagram. Rear-end collision and adjacent-lane passing scenarios performed in closed-loop activation sub-system testing.

- **Scenario A (threat)**: Light vehicle approached the rear of the trailer in the *Same Lane* four times at each closing speed (*5 mi/h*, *15 mi/h*, and *25 mi/h*). This process was performed for algorithm *Condition 1* and algorithm *Condition 2* (24 approaches in total).

- **Scenario B (no threat)**: Light vehicle approached the rear of the trailer in the *Left Lane* four times at each closing speed (*5 mi/h*, *15 mi/h*, and *25 mi/h*). This process was performed for algorithm *Condition 1* and algorithm *Condition 2* (24 approaches in total).
- **Scenario C (no threat)**: Light vehicle approached the rear of the trailer in the *Right Lane* four times at each closing speed (*5 mi/h*, *15 mi/h*, and *25 mi/h*). This process was performed for algorithm *Condition 1* and algorithm *Condition 2* (24 approaches in total).
- **Scenario D (threat)**: Light vehicle approached the rear of the trailer in the *Left Lane* and merged into the *Same Lane* at a distance of 75 ft (22.86 m). This was done four times for each closing speed of *5 mi/h* and *15 mi/h*. This process was performed for algorithm *Condition 1* and algorithm *Condition 2* (16 approaches in total).
- **Scenario E (threat)**: Light vehicle approached the rear of the trailer in the *Right Lane* and merged into the *Same Lane* at a distance of 75 ft (22.86 m). This was done four times for each closing speed of *5 mi/h* and *15 mi/h*. This process was performed for algorithm *Condition 1* and algorithm *Condition 2* (16 approaches in total).
- **Scenario F (threat)**: Light vehicle approached the rear of the trailer in the *Left Lane* and merged into the *Same Lane* at a distance of 100 ft (30.48 m). This was done four times for each closing speed (*5 mi/h*, *15 mi/h*, and *25 mi/h*). This process was performed for algorithm *Condition 1* and algorithm *Condition 2* (24 approaches in total).
- **Scenario G (threat)**: Light vehicle approached the rear of the trailer in the *Right Lane* and merged into the *Same Lane* at a distance of 100 ft (30.48 m). This was done four times for each closing speed (*5 mi/h*, *15 mi/h*, and *25 mi/h*). This process was performed for algorithm *Condition 1* and algorithm *Condition 2* (24 approaches in total).
- **Scenario H (threat)**: Light vehicle approached the rear of the trailer in the *Left Lane* and merged into the *Same Lane* at a distance of 125 ft (38.81 m). This was done four times for each closing speed (*5 mi/h*, *15 mi/h*, and *25 mi/h*). This process was performed for algorithm *Condition 1* and algorithm *Condition 2* (24 approaches in total).
- **Scenario I (threat)**: Light vehicle approached the rear of the trailer in the *Right Lane* and merged into the *Same Lane* at a distance of 125 ft (38.81 m). This was done four times for each closing speed (*5 mi/h*, *15 mi/h*, and *25 mi/h*). This process was performed for algorithm *Condition 1* and algorithm *Condition 2* (24 approaches in total).

5.4.2.2 Results

As previously mentioned, a signal detection theory experimental design was used.[8,9] Table 13 shows the parameters of this detection paradigm.

Table 13. Detection Paradigm Parameters for Closed-loop Activation Sub-system Testing

Light Activation	Threat	No Threat
Yes	Hit (Correct Detection)	False Alarm
No	Miss (Missed Detection)	Correct Rejection (Correct Non-detection)

The objective is to maximize the probabilities of occurrence of correct detections and correct non-detections, and minimize the probabilities of occurrence of false alarms and missed detections.

Algorithm Condition 1: There were 100 light-vehicle approach scenarios performed for algorithm *Condition 1* (76 rear-end crash approaches and 24 adjacent lane approaches). Results indicated that all threats were correctly detected (table 14). There were, however, four occurrences of false alarms, all of which occurred during *Left Lane* light-vehicle approaches. Therefore, the estimated probability of the system correctly detecting a rear-end crash threat and activating the lights was 100 percent, P(hit) = 76/76 = 1.0. The estimated probability of the system correctly rejecting a non-rear-end crash threat and not activating the lights was 83.33 percent, P(cr) = 20/24 = 0.833.

Table 14. Detection Results from Algorithm *Condition 1* Testing

Light Activation	Threat	No Threat
Yes	76	4
No	0	20

Algorithm Condition 2: There were 100 light-vehicle approach scenarios performed for algorithm *Condition 2* (76 rear-end crash approaches and 24 adjacent lane approaches). Results indicated that all threats were correctly detected (table 15). There was, however, one occurrence of a false alarm which also occurred during one *Left Lane* light-vehicle approach. Therefore, the estimated probability of the system correctly detecting a rear-end crash threat and activating the lights was 100 percent, P(hit) = 76/76 = 1.0. The estimated probability of the system correctly rejecting a non-rear-end crash threat and not activating the lights was 95.83 percent, P(cr) = 23/24 = 0.958.

Table 15. Detection Results from Algorithm *Condition 2* Testing

Light Activation	Threat	No Threat
Yes	76	1
No	0	23

5.4.2.3 Closed-loop Activation Sub-system Testing Summary

Overall, results indicated that both algorithm conditions performed well at rear-end crash detection and rear warning-light activation. There were five false alarms found leading researchers to further investigate the video and radar data collected. Upon further investigation, it was found that during almost all of the light-vehicle approaches, there were large amounts of radar clutter in the left adjacent lane and surrounding area. This clutter (or multiple false targets being tracked) was increasing the risk of false triggering.

Researchers decided to measure a sample of radar returns in a follow-up test session. The goal was to characterize the accuracy of the radar y-axis return values using a stationary vehicle in the left adjacent lane and in the right adjacent lane. The light vehicle was positioned 12.19 m (40 ft) back from the trailer five separate times in the left lane and five separate times in the right lane. The center of the light vehicle was positioned 2 m (6.56 ft) over from the center of the radar on each side. At each location for each time the light vehicle was positioned, a y-axis radar return value was recorded. Figure 107 shows an overhead diagram of the vehicle positions used.

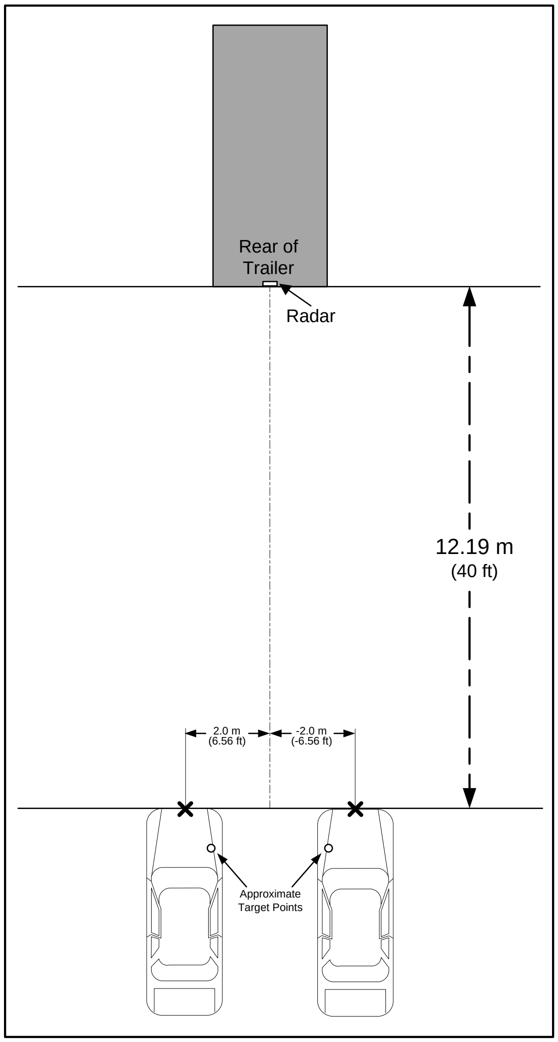

Figure 107. Diagram. Left lane and right lane stationary vehicle positions used in y-axis radar value testing.

Table 16 shows the values found for both the left lane and right lane y-axis radar return values. Results showed that the left lane values contained greater variability due to the radar clutter. The y-axis values from the right lane were much more accurate and precise. The radar used a phased array to detect objects, and once an object is detected a scattering technique is administered (multiple points targeted on an object) to determine an overall central target point. Therefore y-axis values should be less than 2 m (6.56 ft) in this testing situation for the vehicle as the central target point should fall between 1 m (3.28 ft) and 2 m (6.56 ft) due to scattering.

As previously mentioned, the radar used was not designed for stationary vehicles. It was recommended that the propensity of these false triggers be addressed prior to activation sub-system testing in the real-world data collection effort.

Table 16. Right Lane and Left Lane Y-axis Radar Values

Left Lane Y-axis Values (meters)	Right Lane Y-axis Values (meters)
1.28	-1.44
2.3	-1.34
3.4	-1.47
2.36	-1.28
1.63	-1.31
Mean = 2.19	**Mean = -1.37**
Standard Deviation = 0.81	**Standard Deviation = 0.08**

5.4.3 Activation Sub-system Discussion

Overall, both the open-loop and closed-loop activation sub-systems performed well in initial testing. The open-loop system warning-lights were initiated whenever braking levels were greater than or equal to 0.4 *g* of deceleration and when the system received an ABS activation signal. This system shows promise as a potential rear-end crash countermeasure that is relatively inexpensive. However, as previously discussed, an open-loop system is based on lead-vehicle parameters only and, therefore, has its limitations. This system may reduce some rear-end crashes, but not all.

The closed-loop activation sub-system performed well with a very small amount of false alarms. The false alarms that occurred, however, were determined to be due to radar issues and not the closed-loop algorithms. The propensity for these false triggers was to be addressed prior to activation sub-system testing in the real-world data collection effort. The closed-loop activation sub-system has the potential of being an ERS system that could reduce the risk of the majority of rear-end crash situations involving heavy trucks and it was suggested that this system be further tested in the Real-world Data Collection phase of this project. It was also recommended that all five closed-loop algorithm conditions be included for testing in the Real-world Data Collection phase.

6. REAL-WORLD DATA COLLECTION

6.1 ERS SYSTEM DEVELOPMENT

In the analysis of countermeasures effort, multiple visual warning signals were developed and tested in both static and dynamic experiments. Nine different rear-lighting configurations were investigated as well as a set of passive *Conspicuity Markings*. Static tests were helpful in down-selecting rear warning-light configurations based on better eye-drawing and attention-getting performance. The three rear-lighting configurations that moved forward to dynamic tests on the Virginia Smart Road were *Baseline* (normal brake lights), *Main Bumper*, and *Main Bumper/Twelve-light ICC Bumper* (as previously shown in figure 90, labeled as A, B, and C, respectively). There were two key findings from the dynamic tests: (1) both rear warning-light configurations performed equally better than normal trailer brake lighting, and (2) the *Conspicuity Markings* did not provide a performance benefit in maintaining a demonstrated distance behind the tractor trailer. It was recommended that further ERS testing not include the passive *Conspicuity Markings* and that efforts be focused on rear warning-light configurations. Both final rear warning-light configurations appeared to be potential candidates for the real-world data collection effort.

Because both rear warning-light configurations performed equally well in the analysis of countermeasures effort, researchers identified two options for moving forward to the real-world data collection. The first option consisted of testing both the *Main Bumper* and the *Main Bumper/Twelve-light ICC* rear warning-light configurations along with the *Baseline* configuration (normal brake lights). This procedure would allow for a comparison of the configurations in an operational context; however, it would result in a reduction of on-road data collection hours per rear warning-light configuration (less data for analyses), thus reducing the power of the analysis. The second option employed engineering judgment to determine the most promising rear warning-light configuration based on its potential success in future design implementation (i.e., cost of overall system, trailer structural constraints, etc.). This would allow for more data collection hours for that specific rear warning-light configuration and improve the power of the analysis for comparing its abilities against the baseline configuration.

6.1.1 Rear Warning-light Configuration Selection

While both final rear warning-light configurations appeared to be potential candidates for the real-world data collection effort, the research team recommended that one configuration be selected to move forward based on the potential success of future design implementation (i.e., cost of overall system, trailer structural constraints, etc.). Researchers recommended that the *Main Bumper* configuration be selected to move forward to real-world data collection. This recommendation was supported by the project's Contracting Officer's Technical Representative (COTR) from FMCSA.

6.1.1.1 Anticipated Cost of Overall System

The recommended rear warning-light configuration contained a total of 12 LED units. This configuration contained half the amount of lights as the competing rear warning-light configuration. This resulted in a substantial reduction in the quantity of LED units and would reduce the cost of a final ERS system for any future FOT or potentially manufactured system.

6.1.1.2 LED and Radar Antenna Positioning

The recommended rear warning-light configuration was positioned on the main bumper in close proximity to the radar antenna used for the closed-loop activation sub-system. These similar positions provided an easier to implement, future stand-alone system for trailer manufacturers and aftermarket applications. The competing rear warning-light configuration contained an additional 12 LED units in a separate location which would make a future ERS system much more difficult to implement.

6.1.1.3 ICC Bumper Design Problems

The competing rear warning-light configuration required LED units to be mounted on the ICC bumper of a trailer. An ICC bumper has the purpose of preventing vehicles colliding with the rear of a trailer from traveling underneath and fatally injuring the driver and passengers (trailer underride). This safety device is made for this purpose only and, due to the varying sizes, shapes, and their overall structural designs, makes it difficult to secure LED units properly and consistently. For these reasons, it was recommended that the ICC bumper lighting not be included in the real-world data collection effort.

6.1.2 Activation Sub-system Selection

In order to successfully develop an ERS system for heavy trucks, an effort was performed which consisted of researchers and engineers utilizing and modifying activation (triggering) algorithms and testing the performance of these on the Smart Road. Both an open-loop activation sub-system and a closed-loop activation sub-system were tested in potential rear-end crash scenarios and non-rear-end crash scenarios. Both systems performed well. In the end, the research team recommended that the closed-loop system be the final candidate to move forward to the real-world data collection effort. This system was determined to have greater potential for mitigating rear-end crashes involving heavy trucks over that of the simpler open-loop system. A closed-loop activation sub-system includes the measurement of closing rate (velocity) and closing distance to the following vehicle, along with lead-vehicle velocity and deceleration, regardless of speed and distance between vehicles (usually obtained through radar).

During the closed-loop activation sub-system testing, 5 of the 48 non-rear-end collision scenarios (no threat of a rear-end collision) resulted in false alarms. After further analysis, it was determined that these false alarms were due to the radar and not the algorithm performance. Researchers concluded that the closed-loop activation sub-system algorithms performed well. However, the current radar implementation produced clutter (identifying false objects) in the left adjacent lane and surrounding area, which increased the risk of false triggering. In order to reduce the propensity for these false triggers, an effort was undertaken to modify the radar firmware to specifically work in heavy-truck rear-end collision scenarios. This required that the radar work both when a heavy truck was stationary on the road and when in motion. The research team worked with the radar manufacturer to make necessary modifications to the radar firmware to allow it to operate more effectively while the lead vehicle was stationary.

There have been five algorithm conditions previously identified for the current closed-loop activation sub-system. The five algorithm conditions are briefly described below:

- *Condition 1*: The lead vehicle is standing on the pavement (it 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 then stands on the pavement.
- *Condition 5*: The lead vehicle is slowly accelerating.

Condition 1 and *Condition 2* were tested previously in the analysis of countermeasures effort. During these tests, *Condition 1* did not require the experimental CUT to be in motion, making it an ideal candidate for preliminary testing. *Condition 2*, by definition, required that the experimental CUT be in motion; however, during *Condition 2* the experimental CUT remained stationary and the algorithm was provided a fake lead-vehicle speed value of 25 mi/h (40.23 km/h). The testing of *Condition 2* in this way was performed because both conditions were calculated almost identically. Also, preliminary tests with the experimental CUT stationary maintained a safer testing environment on the Smart Road. Because results indicated that the closed-loop activation sub-system performed well, the next step needed was to test the remaining conditions that required the experimental CUT to be in motion. Two experiments were performed on the Smart Road. Experiment 1 was performed with the original radar firmware, and Experiment 2 was performed with the newly modified radar firmware.

6.1.2.1 Closed-loop Activation Sub-system Experiment 1

Method:

Study Design: Conditions 2-5 were tested on the Smart Road with the experimental CUT in motion using a similar methodology to the the previous static tests. All testing performed was done with researchers and engineers (i.e., no naïve participants). The main aspect of this testing was determining the activation sub-system performance under various rear-end crash scenarios. A signal detection theory experimental design was used.[8,9] Four occurrences of detection were categorized: correct detections, missed detections, false alarms, and correct non-detections. The main DV was light activation (yes or no). The main IVs were light-vehicle approach and algorithm condition. The different levels of each IV are shown below:

- Light-vehicle Approach (closing speed of approximately 15 mi/h [24.14 km/h])
  - *Same Lane*
  - *Left Lane*
  - *Right Lane*
  - *Left to Same Merge at 100 ft* (30.48 m)
  - *Right to Same Merge at 100 ft* (30.48 m)
- Algorithm Condition
  - *Condition 2* – Experimental CUT moving at a constant forward speed of 25 mi/h (40.23 km/h)
  - *Condition 3* –Experimental CUT slowly decelerating from 35 mi/h (56.33 km/h) to 25 mi/h (40.23 km/h)
  - *Condition 4* – Experimental CUT decelerates to a stop and then stands on the pavement

- *Condition 5* – Experimental CUT slowly accelerates from 25 mi/h (40.23 km/h) to 35 mi/h (56.33 km/h)

All IVs were counterbalanced equally. Each scenario was performed four times. For each algorithm condition, there were 20 light-vehicle approaches performed (12 rear-end crash approaches and 8 adjacent lane approaches).

Apparatus: The main bumper lighting configuration and radar were installed on the rear of a tractor trailer. Light activation logic was calculated by a DAS installed in the tractor. This DAS was also responsible for recording the rear-end crash scenario data. The approaching light vehicle was a full-size sedan (figure 105).

Procedure: Multiple rear-end crash scenarios as well as adjacent-lane passing scenarios were performed. One researcher sat in the driver's seat of the approaching light vehicle and another researcher sat in the passenger seat to manually collect data on light activations. Figure 108 shows an overhead diagram of the multiple scenarios performed. Scenarios are described below the figure corresponding to each labeled vehicle in the diagram.

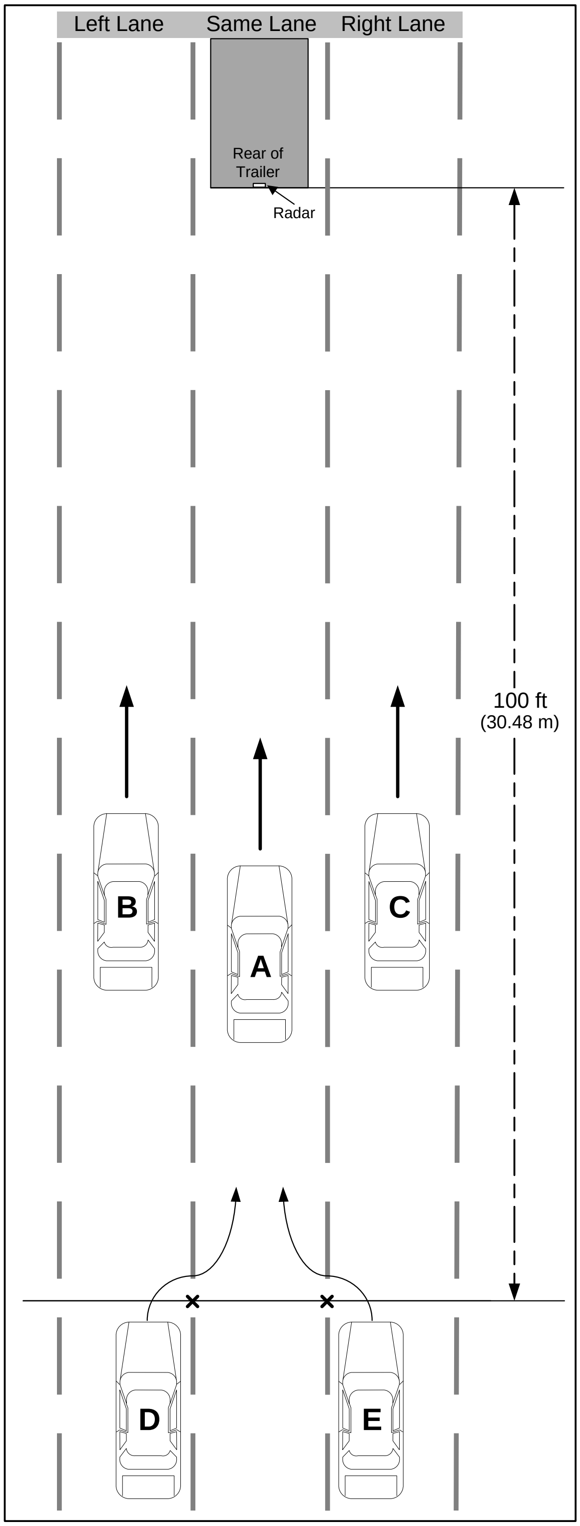

Figure 108. Diagram. Rear-end collision and adjacent-lane passing scenarios performed in closed-loop activation sub-system testing.

- **Scenario A (threat)**: Light vehicle approached the rear of the trailer in the *Same Lane* four times at a closing speed of 15 mi/h (24.14 km/h). This was performed for algorithm *Conditions* 2-5 (16 approaches in all).
- **Scenario B (no threat)**: Light vehicle approached the rear of the trailer in the *Left Lane* four times at a closing speed of 15 mi/h (24.14 km/h). This was performed for algorithm *Conditions 2-5* (16 approaches in all).
- **Scenario C (no threat)**: Light vehicle approached the rear of the trailer in the *Right Lane* four times at a closing speed of 15 mi/h (24.14 km/h). This was performed for algorithm *Conditions 2-5* (16 approaches in all).
- **Scenario D (threat)**: Light vehicle approached the rear of the trailer in the *Left Lane* and merged into the *Same Lane* at a distance of approximately 100 ft (30.48 m). This was done four times at a closing speed of 15 mi/h (24.14 km/h). This was performed for algorithm *Conditions 2-5* (16 approaches in all).
- **Scenario E (threat)**: Light vehicle approached the rear of the trailer in the *Right Lane* and merged into the *Same Lane* at a distance of approximately 100 ft (30.48 m). This was done four times at a closing speed of 15 mi/h (24.14 km/h). This was performed for algorithm *Conditions 2-5* (16 approaches in all).

Experiment 1 Results: As previously mentioned, a signal detection theory experimental design was used.[8,9] Table 13 shows the parameters of this detection paradigm.

Algorithm Condition 2 Results: There were 20 light-vehicle approach scenarios performed for *Condition 2* (12 rear-end crash approaches and 8 adjacent lane approaches). Results indicated that all threats were correctly detected and all non-threats were correctly rejected (table 17). Therefore, the estimated probability of the system correctly detecting a rear-end crash threat and activating the lights was 100 percent, P(hit) = 12/12 = 1.0. The estimated probability of the system correctly rejecting a non-rear-end crash threat and not activating the lights was 100 percent, P(cr) = 8/8 = 1.0.

Table 17. Detection Results from Algorithm *Condition 2* Testing

Light Activation	Threat	No Threat
Yes	12	0
No	0	8

Algorithm Condition 3 Results: There were 20 light-vehicle approach scenarios performed for algorithm *Condition 3* (12 rear-end crash approaches and 8 adjacent lane approaches). Results indicated that all threats were correctly detected (table 18). There were, however, three false alarms (two which occurred during *Left Lane* approaches and one which occurred during a *Right Lane* approach). Therefore, the estimated probability of the system correctly detecting a rear-end crash threat and activating the lights was 100 percent, P(hit) = 12/12 = 1.0. The estimated probability of the system correctly rejecting a non-rear-end crash threat and not activating the lights was 62.50 percent, P(cr) = 5/8 = 0.625.

Table 18. Detection Results from Algorithm *Condition 3* Testing

Light Activation	Threat	No Threat
Yes	12	3
No	0	5

<u>Algorithm Condition 4 Results</u>: There were 20 light-vehicle approach scenarios performed for algorithm *Condition 4* (12 rear-end crash approaches and 8 adjacent lane approaches). Results indicated that all threats were correctly detected (table 19). There were, however, three false alarms, all of which occurred during *Left Lane* approaches. Therefore, the estimated probability of the system correctly detecting a rear-end crash threat and activating the lights was 100 percent, P(hit) = 12/12 = 1.0. The estimated probability of the system correctly rejecting a non-rear-end crash threat and not activating the lights was 62.50 percent, P(cr) = 5/8 = 0.625.

Table 19. Detection Results from Algorithm *Condition 4* Testing

Light Activation	Threat	No Threat
Yes	12	3
No	0	5

<u>Algorithm Condition 5 Results</u>: There were 20 light-vehicle approach scenarios performed for algorithm *Condition 5* (12 rear-end crash approaches and 8 adjacent lane approaches). Results indicated that all threats were correctly detected and all non-threats were correctly rejected (table 20). Therefore, the estimated probability of the system correctly detecting a rear-end crash threat and activating the lights was 100 percent, P(hit) = 12/12 = 1.0. The estimated probability of the system correctly rejecting a non-rear-end crash threat and not activating the lights was 100 percent, P(cr) = 8/8 = 1.0.

Table 20. Detection Results from Algorithm *Condition 5* Testing

Light Activation	Threat	No Threat
Yes	12	0
No	0	8

Closed-loop Activation Sub-system Experiment 1 Summary: Overall, results indicated that algorithm *Conditions 2-5* performed well at rear-end crash detection and rear warning-light activation. There were a total of six false alarms found during *Conditions 3* and *4*. The majority of these false alarms occurred during *Left Lane* approaches, leading researchers to conclude that radar clutter (multiple false targets being tracked) was still occurring in the left lane. Also, these false alarms occurred when the lead vehicle was slowing down. These results confirmed the false alarms found in closed-loop activation sub-system testing. To address these false alarms, an updated radar system was designed to work both in static and dynamic situations to increase closed-loop activation sub-system accuracy. The radar manufacturer was contracted by the research team to modify current radar firmware to specifically work for the heavy-vehicle closed-loop activation sub-system. The new radar firmware was implemented and tested using the same methodology in a follow-on study (Experiment 2).

6.1.2.2 Closed-loop Activation Sub-system Experiment 2

Method:

Study Design: Because the modified radar firmware had not yet been tested, all closed-loop activation sub-system conditions (1-5) were tested on the Smart Road in this experiment. *Condition 1* was tested with the experimental CUT stationary, and *Conditions 2-5* were tested with the experimental CUT in motion using the same method performed in Experiment 1. Therefore, the study design performed in Experiment 2 was identical to Experiment 1 with the exception that *Condition 1* was also tested.

Apparatus: All equipment and vehicles used in Experiment 2 were identical to Experiment 1 with the exception of the newly modified radar.

Procedure: Procedures performed in Experiment 2 were identical to Experiment 1.

Experiment 2 Results: Results obtained are presented identically to Experiment 1 with the exception of the addition of *Condition 1* tests.

Algorithm Condition 1 Results: There were 20 light-vehicle approach scenarios performed for algorithm *Condition 1* (12 rear-end crash approaches and 8 adjacent lane approaches). Results indicated that all threats were correctly detected and all non-threats were correctly rejected (table 21). Therefore, the estimated probability of the system correctly detecting a rear-end crash threat and activating the lights is 100 percent, P(hit) = 12/12 = 1.0. The estimated probability of the system correctly rejecting a non-rear-end crash threat and not activating the lights was 100 percent, P(cr) = 8/8 = 1.0.

Table 21. Detection Results from Algorithm *Condition 1* Testing

Light Activation	Threat	No Threat
Yes	12	0
No	0	8

Algorithm Condition 2 Results: There were 20 light-vehicle approach scenarios performed for algorithm *Condition 2* (12 rear-end crash approaches and 8 adjacent lane approaches). Results indicated that all threats were correctly detected (table 22). There was, however, one false alarm (which occurred during a *Right Lane* approach). Therefore, the estimated probability of the system correctly detecting a rear-end crash threat and activating the lights was 100 percent, P(hit) = 12/12 = 1.0. The estimated probability of the system correctly rejecting a non-rear-end crash threat and not activating the lights was 87.5 percent, P(cr) = 7/8 = 0.875.

Table 22. Detection Results from Algorithm *Condition 2* Testing

Light Activation	Threat	No Threat
Yes	12	1
No	0	7

Algorithm Condition 3 Results: There were 20 light-vehicle approach scenarios performed for algorithm *Condition 3* (12 rear-end crash approaches and 8 adjacent lane approaches). Results indicated that all threats were correctly detected (table 23). There was, however, one false alarm (which occurred during a *Right Lane* approach). Therefore, the estimated probability of the system correctly detecting a rear-end crash threat and activating the lights was 100 percent, P(hit) = 12/12 = 1.0. The estimated probability of the system correctly rejecting a non-rear-end crash threat and not activating the lights was 87.5 percent, P(cr) = 7/8 = 0.875.

Table 23. Detection Results from Algorithm *Condition 3* Testing

Light Activation	Threat	No Threat
Yes	12	1
No	0	7

Algorithm Condition 4 Results: There were 20 light-vehicle approach scenarios performed for algorithm *Condition 4* (12 rear-end crash approaches and 8 adjacent lane approaches). Results indicated that all threats were correctly detected and all non-threats were correctly rejected (table 24). Therefore, the estimated probability of the system correctly detecting a rear-end crash threat and activating the lights was 100 percent, P(hit) = 12/12 = 1.0. The estimated probability of the system correctly rejecting a non-rear-end crash threat and not activating the lights was 100 percent, P(cr) = 8/8 = 1.0.

Table 24. Detection Results from Algorithm *Condition 4* Testing

Light Activation	Threat	No Threat
Yes	12	0
No	0	8

Algorithm Condition 5 Results: There were 20 light-vehicle approach scenarios performed for algorithm *Condition 5* (12 rear-end crash approaches and 8 adjacent lane approaches). Results indicated that all threats were correctly detected and all non-threats were correctly rejected (table 25). Therefore, the estimated probability of the system correctly detecting a rear-end crash threat and activating the lights was 100 percent, P(hit) = 12/12 = 1.0. The estimated probability of the system correctly rejecting a non-rear-end crash threat and not activating the lights was 100 percent, P(cr) = 8/8 = 1.0.

Table 25. Detection Results from Algorithm *Condition 5* Testing

Light Activation	Threat	No Threat
Yes	12	0
No	0	8

Closed-loop Activation Sub-system Experiment 2 Summary: Overall, results indicated that algorithm *Conditions 1-5* performed well at rear-end crash detection with the new radar firmware. There were a total of two false alarms found during *Conditions 2* and *3*. These false alarms occurred during *Right Lane* approaches.

6.1.2.3 Activation Sub-system Selection Conclusions

The newly modified radar firmware results in Experiment 2 showed an improvement over the original firmware tested in Experiment 1. There was a reduction in false alarms from six (Experiment 1) to two (Experiment 2). These results led researchers to determine that the closed-loop activation sub-system was ready for follow-on testing on public roadways.

6.2 REAL-WORLD DATA COLLECTION TESTING

The final dynamic evaluation of the ERS system was conducted on public roadways in order to observe and measure the reaction of the driving public. There were three main areas of investigation during this task. The first area of investigation was in regard to the presence or absence of following-vehicle unintended consequences during warning-light activation. Unintended consequences were determined through a combination of video and sensor data collected from the DAS and compared to typical baseline braking events. For example, an unintended consequence in this situation might include a following-vehicle driver dangerously swerving after the activation of the heavy truck rear warning-lights. The second area of investigation was the performance of the closed-loop activation sub-system in a real-world environment. The closed-loop activation sub-system performance was also determined through a combination of video and sensor data collected from the DAS. A signal detection theory[8,9] experimental design was used to evaluate the closed-loop activation sub-system performance. The third and final area of investigation was the eye-drawing capability of the rear warning-lights. Video data were the primary source of information used to investigate eye-drawing capability. Results from previous rear-signaling work with light vehicles indicated that the yield of data for following-driver direction of glance on public roads was relatively small, approximately 9 percent of all activations.[6] This assessment was for the case in which a lead-vehicle passenger-seat experimenter was looking for the following driver (via video) to look away from the forward view, at which time the experimenter triggered the warning lights. Although the eye-drawing capability of the final warning-light configuration had already been established, both in static and dynamic tests, assessing eye-drawing in the real-world data collection effort was still attempted.

6.2.1 Method

6.2.1.1 Study Design

This study took place on the public roadways of southwest Virginia. The following-vehicle driver's behavior was observed on multiple road types and in many driving scenarios. Because this was an observational study, no drivers were recruited to participate. Rather, the experimental CUT joined other vehicles in the available traffic stream and observed vehicle-following situations. Approval for this observational study was given by the research team's IRB Human Assurances Committee. Data were collected during the day from 8:00 a.m. to 6:00 p.m. EST.

As previously mentioned, there were three areas of investigation in this study: (1) following-vehicle unintended consequences, (2) closed-loop activation sub-system performance, and (3) eye-drawing capability. Each area will be discussed in further detail in their respective sections below.

Following-vehicle Unintended Consequences: The presence or absence of following-vehicle unintended consequences during manual warning-light activation was investigated. Manual rear-lighting activations were limited to driving scenarios that were deemed safe by the lead experimenter (low to moderate traffic densities) and when the lead vehicle (experimental CUT) was traveling at a constant forward speed. Unintended consequences investigated when the experimental CUT was decelerating or stationary were performed during the closed-loop activation sub-system investigation and will be discussed in that particular section later in this report. It was determined that these two scenarios were potentially more dangerous and it was necessary to initially determine if unintended consequences were indeed a problem before continuing forward with other areas of investigation. Researchers decided that these two scenarios would occur during the closed-loop activation sub-system testing portion, and following-vehicle unintended consequences could be observed then.

Unintended consequences were determined through a combination of video and sensor data collected from the DAS and compared to typical baseline braking events. There were two categories of interest for investigation with regard to roadway type. The first roadway type investigated was a *Single-lane Roadway* (one lane in each direction). In this category, a following vehicle had no lane option other than following directly behind the experimental heavy truck in the same lane. The second roadway type investigated was a *Multi-lane Roadway* (at least two lanes available in the same direction of travel and one or more lanes in the opposite direction). In this category, a following vehicle had the option to follow the experimental CUT in the same lane or in an adjacent lane (to the left or the right, depending on the experimental heavy truck's lane position). The main DV was the presence or absence of an unintended consequence (*Yes* or *No*). The main IVs and the different levels of each for the *Single-lane Roadway* category are shown in table 26. The main IVs and the different levels of each for the *Multi-lane Roadway* category are shown in table 27.

Table 26. *Single-lane Roadway* Category IVs and Levels

IV Name	IV Levels
Rear Lighting	Warning-light Configuration (*Main Bumper*), Normal Brake Lights (*Baseline*)
Following-vehicle Distance	Close Distance of d < 100 ft (30.48 m) Far Distance of 100 ft (30.48 m) $\leq d$ < 175 ft (53.34 m)

Table 27. *Multi-lane Roadway* Category IVs and Levels

IV Name	IV Levels
Rear Lighting	Warning-light Configuration (*Main Bumper*), Normal Brake Lights (*Baseline*)
Following-vehicle Distance	Close Distance of d < 100 ft (30.48 m) Far Distance of 100 ft (30.48 m) $\leq d$ < 175 ft (53.34 m)
Following-vehicle Lane Position	*Same*, *Right*, *Left*

A goal of 16 events for each condition was set to obtain sufficient statistical power for the between-subjects design. Therefore, a total collection of 64 events was attempted for the single-lane roadway category, and 192 for the multi-lane roadway category.

Closed-loop Activation Sub-system: The second area of investigation was the performance of the closed-loop activation sub-system in a real-world environment. A signal detection theory experimental design(8,9) was used to evaluate the closed-loop activation sub-system performance. During pilot tests, it was determined that there were three categories of roadway type in need of investigation. 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., rural and town roads with traffic lights, consisting of both single-lane and multi-lane roadways. This third roadway type was categorized as *Other*. Further details regarding each of the three roadway types on which the activation sub-system was 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 roadway, 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 aspect of this testing was determining the activation sub-system performance on each roadway type under normal public roadway driving conditions. Four occurrences of detection were categorized: correct detections, missed detections, false alarms, and correct non-detections. The main DV was light activation (*Yes* or *No*). The main IV was following-vehicle lane position (*Same*, *Right*, *Left*).

Eye-drawing Capability: The third area of investigation was the eye-drawing capability of the *Main Bumper* rear warning-lights. Although the eye-drawing capability of the final warning-light configuration had already been established, both in static and dynamic tests, assessing eye-drawing in the real-world data collection effort was still attempted. The experimental paradigm used was for the experimenter to monitor following-vehicle drivers' head position and eye gaze in real time by way of rearward-mounted cameras installed on the trailer of the experimental CUT. When a following-vehicle driver glanced away from the forward roadway, the experimenter would activate a rear-lighting configuration. The primary objective was to assess the eye-drawing capability of the rear warning-light configuration (*Main Bumper*) in comparison to normal brake lights (*Baseline*). The time taken for a participant to redirect his/her gaze originating away from the forward roadway back to the forward roadway was measured and served as the main dependent measure (*Time To Look-up*). The use of a between-subjects design was used.

6.2.1.2 Apparatus

Two rear-lighting configurations positioned on the rear of the experimental CUT were used during real-world testing (one rear warning-light configuration, one baseline brake-light configuration). The first lighting configuration was made up of normal trailer brakelights (*Baseline*) and the rear warning-light configuration was made up of 12 high-output LED units (*Main Bumper*) (as shown in figure 79 labeled as A and B respectively).

Because all three areas of investigation relied heavily on video data, a majority of the development effort in this task was dedicated to camera selection, camera lens selection, and camera positioning on the rear of the trailer. A total of six different types of cameras were tested, as well as a total of 12 lenses. In the end, a single camera type was found to provide the best resolution and was the appropriate size for trailer installation. The camera type selected was a high-resolution color module camera designed for indoor use. It was determined that a total of four camera views would be needed to collect the necessary views for real-world data collection. Four different lenses were selected, each with a different focal length, to maximize the head position and eye-gaze identification of following-vehicle drivers. Further specifications on the camera type and lenses are provided in appendix I. A single camera housing to be mounted on the rear of the trailer was built to hold these four cameras. The camera housing was built to be as small and inconspicuous as possible. A brief study was performed to determine the final position of the camera housing. This camera housing was initially positioned at the bottom center of the trailer (figure 109) and the sufficiency of the camera angles and image quality was determined by researchers as a sedan approached. The sedan started at a distance of 150 ft (45.72 m) directly behind the trailer and approached at a speed of 5 mi/h (8.05 km/h) until it reached the rear of the trailer. After this, the camera housing was incrementally moved upward on the trailer by 24 in (60.96 cm) and the process was repeated until a total of five camera housing positions were tested (figure 110). This entire process was performed once in sunny conditions and once in overcast conditions. Results indicated that the best location for the camera housing was at the bottom center of the trailer for both sunny and overcast conditions.

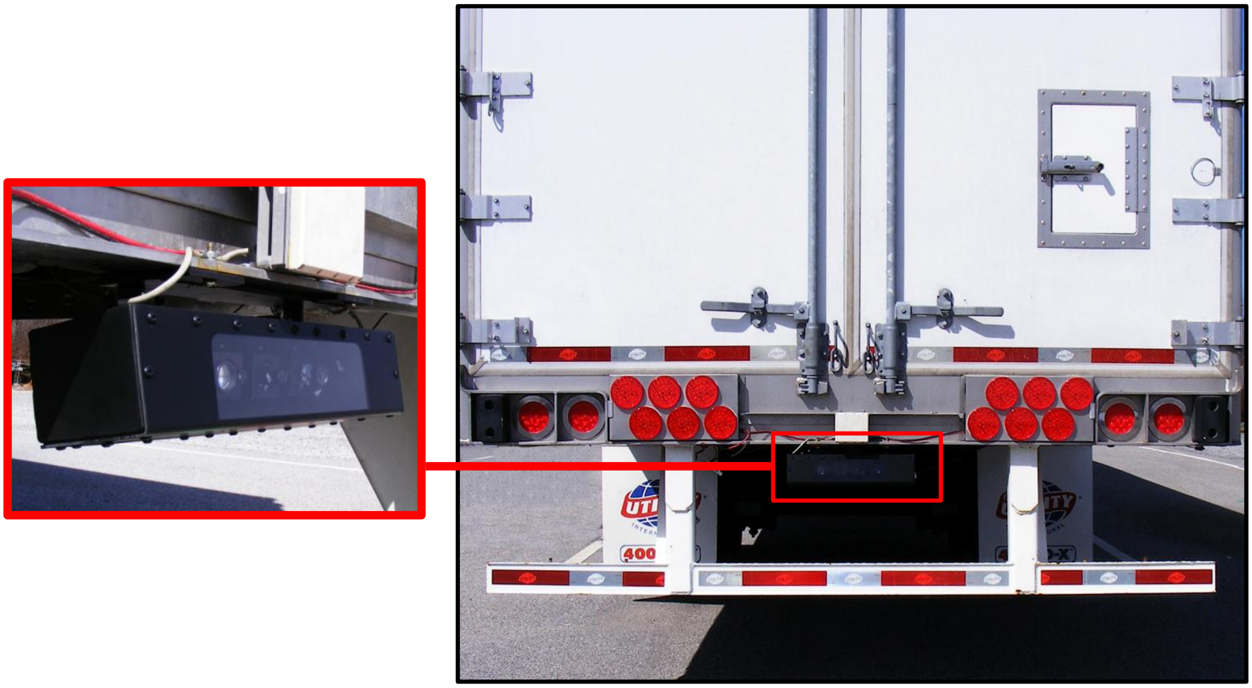

Figure 109. Grouped image. Camera housing appearance and initial position during testing.

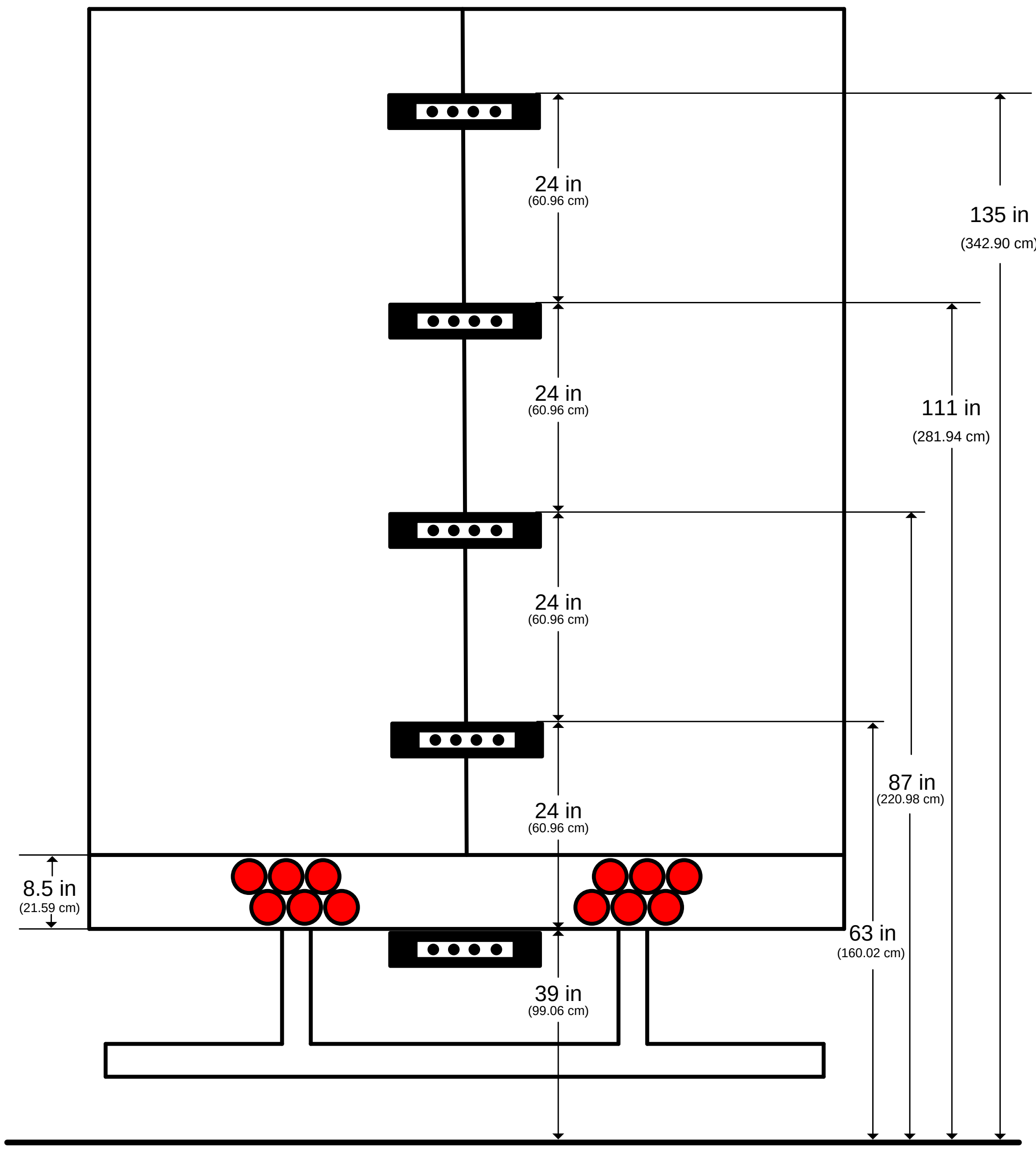

Figure 110. Diagram. Camera housing positions used during testing.

Rear-lighting activation was controlled by the experimenter in the truck sleeper berth (figure 111). A small button was used to activate the rear lighting for the various following-vehicle scenarios. Upon activation of the rear warning-light configuration, lights would flash simultaneously at a 5-Hz frequency for a period of 5 s. Upon activation of the baseline configuration, steady brake lighting (no simultaneous flashing) was initiated for a period of 5 s. Four camera views were used for determining following-vehicle lane position and following-vehicle driver head position and eye-gaze. These four video views were recorded in a single video view (figure 112). A rear-mounted radar system was used for determining following-vehicle distances and for collecting following-vehicle closing rate information. Specifications on radar positioning can be found in appendix E. The closed-loop activation sub-system algorithms used can be found in appendix H.

Figure 111. Photo. Experimenter data collection system positioned in experimental CUT sleeper berth.

Figure 112. Screenshot. Experimenter display during an example following-vehicle scenario.

6.2.1.3 Procedure

The experimental CUT joined other vehicles in the available traffic stream on multiple roadway types and observed vehicle-following situations. Two experimenters were located in the experimental CUT: one to drive the experimental heavy truck, and the second to manually trigger the two rear-lighting configurations. Moreover, manual activations of rear lighting were not tied to actual experimental heavy-truck decelerations; this allowed the eye-drawing power of the rear lighting to be captured without the risk of hard-braking events. As previously mentioned, there were three areas of investigation in this study: following-vehicle unintended consequences, closed-loop activation sub-system performance, and eye-drawing capability. Each area will be discussed in further detail in their respective procedure sections below.

Following-vehicle Unintended Consequences: The two primary road types used for the following-vehicle unintended consequences investigation were *Single-lane Roadways* and *Multi-lane Roadways*. The experimental CUT, with the experimenter positioned in the sleeper berth, joined the traffic stream on each of the roadway types. Rear warning-lights or baseline brake lights were activated when following vehicles were positioned in one of the previously defined lane positions and associated following distances. To review, the following-vehicle lane positions were *Same*, *Right*, and *Left*. The two following-vehicle distances (d) were *Close* ($d <$ 100 ft [30.48 m]) and *Far* (100 ft [30.48 m] $\leq d <$ 175 ft [53.34 m]). A data reduction effort was performed on each activation event. Further details on the reduction and analysis performed for following-vehicle unintended consequences are presented in the associated results section to follow.

Closed-loop Activation Sub-system: The closed-loop activation sub-system was tested on public roadways using a signal detection theory experimental method.(8,9) Three primary road types were used for testing in this investigation (*Interstate Highway*, *State Highway*, and *Other*). The experimental heavy truck joined the traffic stream on multiple roadway types with the closed-loop activation sub-system 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. Further details on the reduction and analysis performed for following-vehicle unintended consequences are presented in the associated results section to follow.

Eye-drawing Capability: Eye-drawing capability of the *Main Bumper* rear warning-light system was investigated on public roadways using a similar methodology as was used in static and dynamic tests. Using multiple rearward camera views, the experimenter monitored the following-vehicle drivers' head position and eye-gaze in the same lane directly behind the experimental heavy truck. When a following-vehicle driver glanced away from the forward roadway, the lead experimenter would activate one of the rear-lighting configurations (*Main Bumper* or *Baseline*) depending on the assigned condition. Video data for each event were later reduced in order to determine the *Time To Look-up*. The mean *Time To Look-up* values were compared between those drivers that received the rear warning-lights, and those drivers that received the normal brake lights (*Baseline*).

6.2.2 Results

Results for each main area of investigation are presented in their own respective sections below. First, results from the following-vehicle unintended consequences investigation will be presented. This will be followed by results from the closed-loop activation sub-system investigation and results from the eye-drawing capability investigation.

6.2.2.1 Following-vehicle Unintended Consequences

The presence or absence of following-vehicle unintended consequences during rear-lighting activation was investigated. After unintended consequences were identified, data were compared to typical *Baseline* brake-lighting events. There were two categories of interest for investigation with regard to roadway type. The first roadway type investigated was a *Single-lane Roadway*, while the second roadway type investigated was a *Multi-lane Roadway*.

Single-lane Roadway Type: As previously mentioned, the main DV was the presence or absence of an unintended consequence (*Yes* or *No*). The main IVs and the sub-levels of each were presented in table 26 (rear lighting and following-vehicle distance). For an event to be considered an unintended consequence in the *Single-lane Roadway* category, the following vehicle had to be positioned in the same lane directly behind the heavy truck as well as fall into at least one of the categories below:

- Following vehicle accelerated within 5 s after rear-lighting activation.
- Following vehicle swerved inside lane within 5 s after rear-lighting activation.
- Following vehicle performed lane deviation within 5 s after rear-lighting activation.
- Following vehicle performed heavy deceleration (brake lockup) within 5 s after rear-lighting activation.
- Any combination of above four statements.

Acceleration was determined by calculating the closing rate of the following vehicle during the 5 s prior to light activation and comparing it to the 5 s immediately following light activation. If the difference between values was greater than or equal to 5 ft/s (1.52 m/s), then the event was labeled as an acceleration. The value of 5 ft/s (1.52 m/s) is the equivalent of 3.41 mi/h (5.49 km/h). Also, if the following vehicle was not closing on the experimental CUT for the 5 s prior to light activation, but was found to be closing on the experimental CUT for the 5 s immediately following light activation, the event was labeled as an acceleration (even if the difference between closing rate values was less than 5 ft/s (1.52 m/s).

It is important to note that following-vehicle normal deceleration behavior was not considered an unintended consequence during the *Single-lane Roadway* category. It was determined that light to moderate following-vehicle deceleration would be considered normal behavior during actual lead-vehicle braking and/or rear warning-light activity in a real-world driving environment.

The number of following-vehicle unintended consequences found for following vehicles positioned at the *Close* distance (d < 100 ft [30.48 m]) is shown in table 28. Results show that five unintended consequences were found for the *Baseline* condition and no unintended consequences were found for the *Main Bumper* rear warning-light condition. The five unintended consequences that did occur in the *Baseline* condition were all labeled as accelerations. The number of unintended consequences for each rear-lighting configuration was analyzed using a Fisher's Exact Test and found to be significant (p = 0.0434).

Table 28. Total Number of Unintended Consequences that Occurred at the *Close* Distance for the *Single-lane Roadway* Category

Rear Lighting	No	Yes	Total
Normal Brake Lights (*Baseline*)	11	5	16
Rear Warning-lights (*Main Bumper*)	16	0	16

The number of following-vehicle unintended consequences found for following vehicles positioned at the *Far* distance (100 ft [30.48 m] $\leq d <$ 175 ft [53.34 m]) is shown in table 29. Results show that one unintended consequence was found for the *Baseline* condition and no unintended consequences were found for the *Main Bumper* condition. The one unintended consequence that did occur in the *Baseline* condition was labeled as an acceleration. The number of unintended consequences for each rear-lighting configuration was analyzed using a Fisher Exact test and was not significant, (p = 1.0).

Table 29. Total Number of Unintended Consequences that Occurred at the *Far* Distance for the *Single-lane Roadway* Category

Rear Lighting	No	Yes	Total
Normal Brake Lights (*Baseline*)	15	1	16
Rear Warning-lights (*Main Bumper*)	16	0	16

Multi-lane Roadway Type: Identical to the *Single-lane Roadway* category, the DV for the *Multi-lane Roadway* category was the presence or absence of an unintended consequence (*Yes* or *No*). The main IVs and the sub-levels of each were presented in table 27 (rear lighting, following-vehicle distance, and following-vehicle lane position). For an event to be considered an unintended consequence in the *Multi-lane Roadway* category, the following vehicle had to fall into at least one of the categories below:

- Following-vehicle positioned in *Same* lane
    - Following vehicle accelerated within 5 s after rear-lighting activation,
    - Following vehicle swerved inside lane within 5 s after rear-lighting activation,
    - Following vehicle performed lane deviation within 5 s after rear-lighting activation,
    - Following vehicle initiated lane change within 1-5 s of rear-lighting activation (if vehicle initiated lane change between 0-1 s after rear-lighting activation, maneuver was considered predetermined by the following-vehicle driver),
    - Following vehicle performed heavy deceleration (brake lockup) within 5 s after rear-lighting activation, and/or
    - Any combination of above five statements.
- Following-vehicle positioned in *Right* lane
    - Following vehicle accelerated within 5 s after rear-lighting activation,

    - Following vehicle swerved inside lane within 5 s after rear-lighting activation,
    - Following vehicle performed lane deviation within 5 s after rear-lighting activation,
    - Following vehicle initiated lane change within 1-5 s of rear-lighting activation (if vehicle initiated lane change between 0-1 s after rear-lighting activation, maneuver was considered predetermined by the following-vehicle driver),
    - Following vehicle decelerated within 5 s after rear-lighting activation,
    - Following vehicle performed heavy deceleration (brake lockup) within 5 s after rear-lighting activation, and/or
    - Any combination of above six statements.
- Following-vehicle positioned in *Left* lane
    - Following vehicle accelerated within 5 s after rear-lighting activation,
    - Following vehicle swerved inside lane within 5 s after rear-lighting activation,
    - Following vehicle performed lane deviation within 5 s after rear-lighting activation,
    - Following vehicle initiated lane change within 1-5 s of rear-lighting activation (if vehicle initiated lane change between 0-1 s after rear-lighting activation, maneuver was considered predetermined by the following-vehicle driver),
    - Following vehicle decelerated within 5 s after rear-lighting activation,
    - Following vehicle performed heavy deceleration (brake lockup) within 5 s after rear-lighting activation, and/or
    - Any combination of above six statements.

Accelerations and decelerations were determined by calculating the mean closing rate of the following vehicle during the 5 s prior to light activation, and comparing it to the 5 s immediately following light activation. If the difference between values was greater than or equal to 5 ft/s (1.52 m/s), then the event was labeled as an acceleration or deceleration. The value of 5 ft/s (1.52 m/s) is the equivalent to 3.41 mi/h (5.49 km/h). Also, if the following vehicle was not closing on the experimental CUT for the 5 s prior to light activation, but was found to be closing on the experimental CUT for the 5 s immediately following light activation, the event was labeled as an acceleration (even if the difference between mean closing rate values was less than 5 ft/s (1.52 m/s). If the following vehicle was closing on the experimental CUT for the 5 s prior to light activation, but was not found to be closing on the experimental CUT for the 5 s immediately following light activation, the event was labeled as a deceleration (even if the difference between mean closing rate values was less than 5 ft/s (1.52 m/s).

It is important to note that following-vehicle normal deceleration behavior was not considered an unintended consequence during scenarios involving the following-vehicle positioned in the *Same* lane. It was determined that light to moderate following-vehicle deceleration while positioned in the *Same* lane would be considered normal behavior during actual lead-vehicle braking and/or rear warning-light activation in a real-world driving environment.

The number of following-vehicle unintended consequences found for the following vehicles positioned in the *Same* lane at the *Close* distance (d < 100 ft [30.48 m]) is shown in table 30. Results show that no unintended consequences were found for the *Baseline* or *Main Bumper* configurations. Because no unintended consequences were found, a Fisher's Exact Test was unnecessary.

Table 30. Total Number of Unintended Consequences that Occurred for Following Vehicles Positioned in the *Same* Lane at the *Close* Distance for the *Multi-lane Roadway* Category

Rear Lighting	No	Yes	Total
Normal Brake Lights (*Baseline*)	16	0	16
Rear Warning-lights (*Main Bumper*)	16	0	16

The number of following-vehicle unintended consequences found for the following vehicles positioned in the *Same* lane at the *Far* distance (100 ft [30.48 m] $\leq d <$ 175 ft [53.34 m]) is shown in table 31. Results show that no unintended consequences were found for the *Baseline* or *Main Bumper* configurations. Because no unintended consequences were found, a Fisher's Exact Test was unnecessary.

Table 31. Total Number of Unintended Consequences that Occurred for Following Vehicles Positioned in the *Same* Lane at the *Far* Distance for the *Multi-lane Roadway* Category

Rear Lighting	No	Yes	Total
Normal Brake Lights (*Baseline*)	14	0	14
Rear Warning-lights (*Main Bumper*)	16	0	16

The number of following-vehicle unintended consequences found for the following vehicles positioned in the *Right* lane at the *Close* distance ($d <$ 100 ft [30.48 m]) is shown in table 32. Results show that three unintended consequences were found for the *Baseline* configuration and six unintended consequences were found for the *Main Bumper* configuration. Of the three unintended consequences that occurred for the *Baseline* configuration, one was labeled as an acceleration and the other two were labeled as decelerations. Of the six unintended consequences that occurred in the *Main Bumper* configuration, one was labeled as an acceleration and the other five were labeled as decelerations. The number of unintended consequences for each rear-lighting configuration was analyzed using a Fisher Exact test and was not significant, (p = 0.4331).

Table 32. Total Number of Unintended Consequences that Occurred for Following Vehicles Positioned in the *Right* Lane at the *Close* Distance for the *Multi-lane Roadway Category*

Rear Lighting	No	Yes	Total
Normal Brake Lights (*Baseline*)	13	3	16
Rear Warning-lights (*Main Bumper*)	10	6	16

The number of following-vehicle unintended consequences found for the following vehicles positioned in the *Right* lane at the *Far* distance (100 ft [30.48 m] $\leq d <$ 175 ft [53.34 m]) is shown in table 33. Results show that two unintended consequences were found for the *Baseline* configuration and four unintended consequences were found for the *Main Bumper* configuration. Of the two unintended consequences that occurred for the *Baseline* configuration, one was labeled as an acceleration and the other as a deceleration. Of the four unintended consequences that occurred for the *Main Bumper* configuration, two were labeled as accelerations and the other two were labeled as decelerations. The number of unintended consequences for each rear-lighting configuration was analyzed using a Fisher Exact test and was not significant, (p = 0.6539).

Table 33. Total Number of Unintended Consequences that Occurred for Following Vehicles Positioned in the *Right* Lane at the *Far* Distance for the *Multi-lane Roadway* Category

Rear Lighting	No	Yes	Total
Normal Brake Lights (*Baseline*)	14	2	16
Rear Warning-lights (*Main Bumper*)	12	4	16

The number of following-vehicle unintended consequences found for the following vehicles positioned in the *Left* lane at the *Close* distance (d < 100 ft [30.48 m]) is shown in table 34. Results show that three unintended consequences were found for the *Baseline* configuration and six unintended consequences were found for the *Main Bumper* configuration. All three unintended consequences that occurred for the *Baseline* configuration were labeled as decelerations. Of the six unintended consequences that occurred for the *Main Bumper* configuration, one was labeled as an acceleration and the other five were labeled as decelerations. The number of unintended consequences for each rear-lighting configuration was analyzed using a Fisher Exact test and was not significant, (p = 0.4331).

Table 34. Total Number of Unintended Consequences that Occurred for Following Vehicles Positioned in the *Left* Lane at the *Close* Distance for the *Multi-lane Roadway* Category

Rear Lighting	No	Yes	Total
Normal Brake Lights (*Baseline*)	13	3	16
Rear Warning-lights (*Main Bumper*)	10	6	16

The number of following-vehicle unintended consequences found for the following vehicles positioned in the *Left* lane at the *Far* distance (100 ft [30.48 m] ≤ d < 175 ft [53.34 m]) is shown in table 35. Results show that two unintended consequences were found for the *Baseline* configuration and one unintended consequence was found for the *Main Bumper* configuration. Of the two unintended consequences that occurred for the *Baseline* configuration, one was labeled as an acceleration and the other as a deceleration. The only unintended consequence that occurred for the *Main Bumper* configuration was labeled as a deceleration. The number of unintended consequences for each rear-lighting configuration was analyzed using a Fisher Exact test and was not significant, (p = 1.0).

Table 35. Total Number of Unintended Consequences that Occurred for Following Vehicles Positioned in the *Left* Lane at the *Far* Distance for the *Multi-lane Roadway* Category

Rear Lighting	No	Yes	Total
Normal Brake Lights (*Baseline*)	14	2	16
Rear Warning-lights (*Main Bumper*)	15	1	16

6.2.2.2 Closed-loop Activation Sub-system

The closed-loop activation sub-system was tested on three different roadway types. The first roadway type on which the activation sub-system was tested was an *Interstate Highway* (Interstate 81). The second roadway type on which the activation sub-system was tested was a *State Highway* (Virginia Highway 460). The third roadway type on which the activation sub-system was tested included all *Other* lower-speed roadways (i.e., rural and town roads) with traffic lights consisting of both single-lane and multi-lane roadways.

As previously mentioned, a signal detection theory experimental design was used to evaluate the closed-loop activation sub-system performance.[8,9] Four occurrences of detection were categorized: correct detections, missed detections, false alarms, and correct non-detections. The main DV was light activation (*Yes* or *No*). The main IVs were roadway type (*Interstate Highway*, *State Highway*, *Other*) and following-vehicle lane position (*Same*, *Right*, *Left*). Results are presented below by roadway type.

Interstate Highway: Overall, there were 172 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 (hovering). 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 within 150 ft (45.72 m) of the rear of the experimental CUT.

For the *Same* lane following-vehicle condition, there were a total of 17 events captured (3 rear-end crash threats and 14 non-threats). Results indicated that all threats were correctly detected, 11 non-threats were correctly rejected, and 3 false alarms occurred (table 36). Therefore, the estimated probability of the system correctly detecting a rear-end crash threat and activating the lights was 100 percent, P(hit) = 3/3 = 1.0. The estimated probability of the system correctly rejecting a non-rear-end crash threat and not activating the lights was 78.57 percent, P(cr) = 11/14 = 0.786.

Table 36. Detection Results from *Interstate Highway Same* Lane Testing

Light Activation	Threat	No Threat
Yes	3	3
No	0	11

For the *Right* lane following-vehicle condition, there were a total of four events captured (zero rear-end crash threats and four non-threats). Results indicated that all four non-threats were correctly rejected, and zero false alarms occurred (table 37). Therefore, the estimated probability of the system correctly rejecting a non-rear-end crash threat and not activating the lights was 100 percent, P(cr) = 4/4 = 1.0.

Table 37. Detection Results from *Interstate Highway Right* Lane Testing

Light Activation	Threat	No Threat
Yes	0	0
No	0	4

For the *Left* lane following-vehicle condition, there were a total of 151 events captured (0 rear-end crash threats and 151 non-threats). Results indicated that all 151 non-threats were correctly rejected, and 0 false alarms occurred (table 38). Therefore, the estimated probability of the system correctly rejecting a non-rear-end crash threat and not activating the lights was 100 percent, P(cr) = 151/151 = 1.0.

Table 38. Detection Results from *Interstate Highway Left* Lane Testing

Light Activation	Threat	No Threat
Yes	0	0
No	0	151

State Highway: Overall, there were 93 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 to the *Interstate Highway* portion of this data collection effort. Each event consisted of at least the primary vehicle within 150 ft (45.72 m) of the rear of the experimental CUT.

For the *Same* lane following-vehicle condition, there were a total of 11 events captured (4 rear-end crash threats and 7 non-threats). Results indicated that all threats were correctly detected, six non-threats were correctly rejected, and one false alarm occurred (table 39). Therefore, the estimated probability of the system correctly detecting a rear-end crash threat and activating the lights was 100 percent, P(hit) = 4/4 = 1.0. The estimated probability of the system correctly rejecting a non-rear-end crash threat and not activating the lights was 85.71 percent, P(cr) = 6/7 = 0.857.

Table 39. Detection Results from *State Highway Same* Lane Testing

Light Activation	Threat	No Threat
Yes	4	1
No	0	6

For the *Right* lane following-vehicle condition, there were a total of 34 events captured (0 rear-end crash threats and 34 non-threats). Results indicated that 31 non-threats were correctly rejected, and 3 false alarms occurred (table 40). Therefore, the estimated probability of the system correctly rejecting a non-rear-end crash threat and not activating the lights was 91.18 percent, P(cr) = 31/34 = 0.912.

Table 40. Detection Results from *State Highway Right* Lane Testing

Light Activation	Threat	No Threat
Yes	0	3
No	0	31

For the *Left* lane following-vehicle condition, there were a total of 48 events captured (0 rear-end crash threats and 48 non-threats). Results indicated that 46 non-threats were correctly rejected, and 2 false alarms occurred (table 41). Therefore, the estimated probability of the system correctly rejecting a non-rear-end crash threat and not activating the lights was 95.83 percent, P(cr) = 46/48 = 0.958.

Table 41. Detection Results from *State Highway Left* Lane Testing

Light Activation	Threat	No Threat
Yes	0	2
No	0	46

Other: Overall, there were 175 events captured during the *Other* roadway type 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 to the two previous sections (*Interstate Highway* and *State Highway*). Each event consisted of at least the primary vehicle within 150 ft (45.72 m) of the rear of the heavy truck.

For the *Same* lane following-vehicle condition, there were a total of 67 events captured (42 rear-end crash threats and 25 non-threats). Results indicated that all threats were correctly detected, 18 non-threats were correctly rejected, and 7 false alarms occurred (table 42). Therefore, the estimated probability of the system correctly detecting a rear-end crash threat and activating the lights was 100 percent, P(hit) = 42/42 = 1.0. The estimated probability of the system correctly rejecting a non-rear-end crash threat and not activating the lights was 72 percent, P(cr) = 18/25 = 0.72.

Table 42. Detection Results from *Other Same* Lane Testing

Light Activation	Threat	No Threat
Yes	42	7
No	0	18

For the *Right* lane following-vehicle condition, there were a total of 33 events captured (0 rear-end crash threats and 33 non-threats). Results indicated that 20 non-threats were correctly rejected, and 13 false alarms occurred (table 43). Therefore, the estimated probability of the system correctly rejecting a non-rear-end crash threat and not activating the lights was 60.6 percent, P(cr) = 20/33 = 0.606.

Table 43. Detection Results from *Other Right* Lane Testing

Light Activation	Threat	No Threat
Yes	0	13
No	0	20

For the *Left* lane following-vehicle condition, there were a total of 75 events captured (0 rear-end crash threats and 75 non-threats). Results indicated that 44 non-threats were correctly rejected, and 31 false alarms occurred (table 44). Therefore, the estimated probability of the system correctly rejecting a non-rear-end crash threat and not activating the lights was 58.67 percent, P(cr) = 44/75 = 0.587.

Table 44. Detection Results from *Other Left* Lane Testing

Light Activation	Threat	No Threat
Yes	0	31
No	0	44

6.2.2.3 Eye-drawing Capability

The third area of investigation was the eye-drawing capability of the *Main Bumper* rear warning-light configuration in comparison to *Baseline*. The time taken for a participant to redirect his/her gaze from an area away from the forward roadway back to the forward roadway was measured and served as the main dependent measure (*Time To Look-up*). This section discusses the analyses performed between the *Baseline* and *Main Bumper* lighting configuration conditions.

The first analysis performed used duration (*Time To Look-up*) as the primary variable of interest. A one-way between-subjects ANOVA was performed. Although not significant, results demonstrated a positive trend with $F(1,46) = 2.26$, $p = 0.1392$. The mean *Time To Look-up* results are shown in figure 113. The figure shows that, on average, participants receiving the *Main Bumper* took less *Time To Look-up* to the forward roadway than did participants receiving the *Baseline* configuration (although this was not a statistically significant difference, this may have resulted from insufficient statistical power). The mean *Time To Look-up* values did show an observed practical difference and benefit. Converting the mean *Time To Look-up* values (0.579 s for main bumper and 0.7 s for baseline brake lights) to distance traveled at 55 mi/h equates to 46.72 ft and 56.47 ft, respectively (at 88.51 km/h equates to 14.24 m and 17.21 m, respectively). Therefore, drivers, on average, were traveling approximately 10 ft (3.05 m) further without looking at the roadway when exposed to the *Baseline* brake light condition as compared to the *Main Bumper* rear warning-light configuration. According to the results found from the GES analysis, of the crashes for which attempted crash avoidance maneuvers were known, the driver of the striking vehicle attempted a braking maneuver in 70.7 percent of SUT rear-end crashes and 61.6 percent of CUT rear-end crashes. The additional 10 ft (3.05 m) afforded by the main bumper rear warning-light configuration may reduce the occurrence (or crash severity) of rear-end crashes by providing additional time and distance needed for the following-vehicle to get stopped.

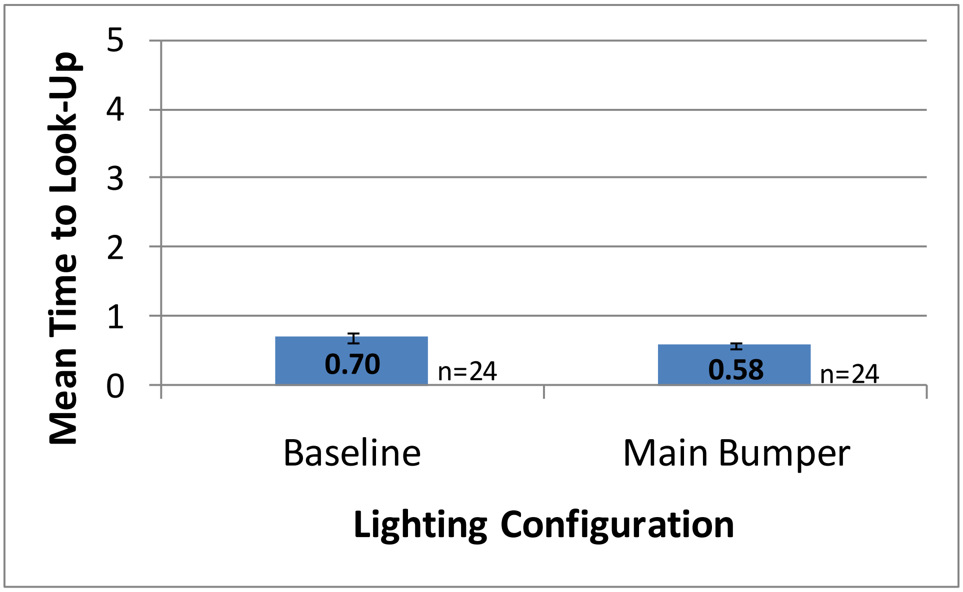

Figure 113. Bar graph. Mean *Time To Look-up* as a function of lighting configuration.

6.2.3 Summary

6.2.3.1 Following-vehicle Unintended Consequences

The occurrence of following-vehicle unintended consequences during both *Baseline* and *Main Bumper* activation was minor. The only statistically significant difference found indicated a higher occurrence of unintended consequences for *Baseline*, all of which were minor accelerations. Upon further investigation of these specific unintended consequences, it was found that two of the five occurred on *State Highway* entrance ramps. This indicated that acceleration may still be acceptable in this scenario as long as the vehicle maintains a safe distance behind the experimental CUT. It is also important to note that during *Baseline* and *Main Bumper* activations the experimental CUT was not actually braking, which may have led following-vehicle drivers to perceive their approach behavior as safe.

Of the unintended consequences that did occur across all roadway categories, all were labeled as decelerations and accelerations (for example: no swerves, lane deviations, or lane changes were found). Table 45 below summarizes the frequency and type of unintended consequences found collapsed across the following-vehicle distance variable (*Close* and *Far* combined). Overall, the results indicate that the *Main Bumper* rear warning-lights did not result in an increase of unintended consequences over that of *Baseline* during the real-world data collection effort.

Table 45. Frequency and Type of Unintended Consequences found Collapsed across Following-vehicle Distance

Roadway Category	Rear-lighting Condition	Following-vehicle Lane	No. of Events	No. of Unintended Consequences	Unintended Consequence Type
Single-lane	*Baseline*	*Same*	32	6	6 Accelerations
Single-lane	*Main Bumper*	*Same*	32	0	N/A
Multi-lane	*Baseline*	*Same*	30	0	N/A
Multi-lane	*Main Bumper*	*Same*	32	0	N/A
Multi-lane	*Baseline*	*Right*	32	5	2 Decelerations, 3 Accelerations
Multi-lane	*Main Bumper*	*Right*	32	10	7 Decelerations, 3 Accelerations
Multi-lane	*Baseline*	*Left*	32	5	4 Decelerations, 1 Acceleration
Multi-lane	*Main Bumper*	*Left*	32	7	6 Decelerations, 1 Acceleration

6.2.3.2 Closed-loop Activation Sub-system

Results indicated that the closed-loop activation sub-system performed well at rear-end crash detection and rear warning-light activation. In all three roadway types, the closed-loop activation sub-system performed with a 100-percent correct detection rate (zero missed detections) indicating excellent performance in rear-end collision-threat scenarios. For the *Interstate Highway* and *State Highway* roadway conditions, the closed-loop activation sub-system had a low false alarm rate in non-rear-end collision-threat scenarios. For the *Other* roadway category, the closed-loop activation sub-system false alarm rate increased substantially, specifically during following-vehicle adjacent lane approaches. This increase in the false alarm rate led researchers to investigate the video and radar data collected for each scenario more closely. Upon further investigation, it was found that a majority of the false alarms occurred when there was more than one following vehicle within 200 ft (60.96 m) of the rear of the heavy truck (46 of the 51 false alarms). This indicated that primary target identification by the newly modified radar firmware may still need refinement at lower speeds in high following-vehicle density scenarios before implementation and data collection in an FOT. Table 46 below contains a summary of the probabilities found for correct detections and correct rejections collapsed across lane position for each roadway type investigated.

Table 46. 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	3/3 = 100%	166/169 = 98.22%
State Highway	4/4 = 100%	83/89 = 93.26%
Other	42/42 = 100%	82/133=61.65%

Following-vehicle unintended consequences were also observed during *Main Bumper* rear warning-light activations in two scenarios that were not observed prior. These scenarios were when the experimental CUT was decelerating, and when the experimental CUT was stationary. During each of these scenarios, an objective measure was not used during data reduction and analysis as the following-vehicle closing rates would be affected by experimental CUT behavior. Using video only, researchers did not observe any following-vehicle unintended consequences in these scenarios. This result was consistent with the previous results found during the following-vehicle unintended consequences investigation.

6.2.3.3 Eye-drawing Capability

Results indicated that a strong trend was found for improved eye-drawing performance of the rear warning-light configuration over that of normal brake lights. This indicated that the *Main Bumper* had improved eye-drawing capability over that of normal brake lights on public roadways during the real-world data collection effort.

6.3 REAL-WORLD DATA COLLECTION GENERAL CONCLUSIONS

An ERS system designed to mitigate rear-end collisions where a heavy truck is struck from behind by another vehicle was developed and tested on the public roadways of southwest Virginia. The main objective of the real-world data collection of the ERS system was to observe and measure the reaction of the driving public. The primary components of this ERS system consisted of a *Main Bumper* rear warning-light configuration and a radar-based closed-loop activation sub-system. Three main areas of investigation were performed during this real-world data collection effort. The first area of investigation was in regard to the presence or absence of following-vehicle unintended consequences during warning-light activation. The second area of investigation was the performance of the closed-loop activation sub-system. The third and final area of investigation was the eye-drawing capability of the rear warning-lights.

Overall, the *Main Bumper* rear warning-light configuration was not found to contribute to a larger number of unintended consequences over that of the *Baseline* brake light condition. The unintended consequences that did occur during rear warning-light activations were light-to-moderate decelerations and accelerations, all of which occurred in adjacent lanes. There were no other following-vehicle unintended consequences found, such as heavy braking (brake lock-ups), swerving, lane deviations, or lane changes. This result indicated that although the *Main Bumper* rear warning-light configuration could be seen from adjacent lanes, warning-light activation did not contribute to unsafe following-vehicle driver reactions/behaviors as compared to the *Baseline* brake lighting.

During the real-world data collection, the closed-loop activation sub-system was tested while joining the normal traffic stream on multiple different roadway types. The roadway types were categorized into the following:

- *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 roadway, 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]).

Results found that during all events and across all roadway types the closed-loop activation sub-system correctly detected all rear-end crash threats (100-percent detection rate). This was a positive result which indicated that the most safety-critical component of the closed-loop activation sub-system (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 sub-system performed well on the *Interstate Highway* and *State Highway* roadways (P(cr) = 98.22 percent [1.78 percent false alarm rate] and P(cr) = 93.26 percent [6.74 percent false alarm rate], respectively). During the *Other* roadway category, the performance of the closed-loop activation sub-system resulted in a reduction in the estimated probability of correct rejections and therefore an increase in false alarm rates as compared to the previous roadway types (P(cr) = 61.65 percent resulting in a false alarm rate of 38.35 percent). As previously mentioned, this reduction in the estimated probability of a correct rejection (increase in false alarm rate) occurred due to radar object-tracking issues found during lower speeds with more than one following vehicle behind the experimental heavy truck. Since the completion of the current data collection effort, the research team has worked with the radar and firmware manufacturer to identify potential solutions for modifying/refining the radar firmware to help reduce the propensity for these false alarms. The radar/firmware manufacturers have expressed confidence in their ability to refine the radar firmware to more accurately track following vehicles at low speeds in high-traffic-density scenarios prior to data collection in an FOT of an ERS system.

Eye-drawing capability was the final area of investigation performed in the real-world data collection effort. Results from previous rear-signaling work with light vehicles indicated that the yield of data for following-driver direction of glance on public roads was relatively small, approximately 9 percent of all activations.[(6)] This previous assessment was for the case in which a lead-vehicle passenger-seat experimenter was looking for the following driver (via video) to look away from the forward view, at which time the experimenter triggered the warning lights. Although the eye-drawing capability of the final warning-light configuration had already been established, both in static and dynamic tests, assessing this configuration's eye-drawing capability was still attempted in the real-world data collection effort. Taking what was learned from the previous work, the research team was able to develop a rearward camera system that performed well. The camera system allowed the experimenter to successfully identify head position and eye-gaze up to maximum of 115 ft (35.05 m) behind the experimental heavy truck in ideal conditions. The yield of data for following-vehicle driver direction of glance for the current real-world data collection effort was approximately 48 percent (48 usable events out of 100 attempts). A total of 48 events were captured, 24 events for the *Baseline* brake light condition and 24 events for the *Main Bumper* rear warning-light condition. Results found were similar to static and dynamic testing in that a reduction in *Time To Look-up* was found for the *Main Bumper* (although not statistically significant). The mean *Time To Look-up* values did show an observed practical difference and benefit. Converting the mean *Time To Look-up* values (0.579 s for main bumper and 0.7 s for baseline brake lights) to distance traveled at 55 mi/h equates to 46.72 ft and 56.47 ft, respectively (at 88.51 km/h equates to 14.24 m and 17.21 m, respectively). Therefore, drivers, on average, were traveling approximately 10 ft (30.5 m) further without looking at the roadway when exposed to the *Baseline* brake light condition as compared to the *Main Bumper* rear warning-light configuration. According to the results found from the GES analysis performed, of the crashes for which attempted crash avoidance maneuvers were known, the driver of the striking vehicle attempted a braking maneuver in 70.7 percent of SUT rear-end crashes and 61.6 percent of CUT rear-end crashes. In CUTs, almost 12 percent of the braking maneuvers were accompanied by a steering maneuver. The additional 10 ft (30.5m) afforded by the main bumper rear warning-light configuration may reduce the occurrence (or crash severity) of rear-end crashes by providing additional time and distance needed for the following-vehicle to get stopped. The consistent reduction in *Time To Look-up* for the *Main Bumper* rear warning-lights over that of the *Baseline* brake lights for all experiments conducted shows that a strong rear warning-light candidate has been selected and is ready for implementation in an FOT.

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, drawing the gazes of following-vehicle drivers back to the forward roadway, which resulted in minor following-vehicle unintended consequences during fair weather and daylight hours. Although the analysis of eye-drawing capability was not statistically significant, because the mean differences in duration were in the same direction as previous eye-drawing capability experiments, there appears to be a strong trend that the rear warning-light system reduces the *Time To Look-up*. A limitation was found during closed-loop activation sub-system testing at lower speeds in high-traffic-density scenarios due to radar target identification problems, thus producing a higher number of false alarms. The propensity of these false alarms should be addressed prior to data collection in an FOT with further radar firmware modifications. Also, the current study's testing included only real-world data collection during daylight hours. Future work may be needed to investigate the potential need for rear warning-light brightness adjustments for lower-light conditions.

7. FIELD OPERATIONAL TEST PLAN

7.1 PRELIMINARY WORK PRIOR TO FOT

The final ERS 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. There were minor following-vehicle unintended consequences recorded during daylight hour testing (i.e., light accelerations and decelerations); however, no difference was found between the ERS and baseline conditions. Prior to data collection in a FOT, the potential need for rear warning-light brightness adjustments for lower-light conditions should be investigated. Additionally, a limitation was found in the closed-loop activation sub-system testing at lower speeds in high-traffic-density scenarios. The radar was not robust in identifying targets at low speeds in high traffic density conditions which resulted in a high number of false alarms in this scenario. This false alarm type should be addressed prior to large-scale real-world data collection efforts. The remainder of this section details the recommended actions to be taken involving ERS system development prior to data collection in an FOT.

7.1.1 Expanded ERS Development

Three ERS system development efforts are needed prior to FOT data collection. The first effort will involve testing the eye-drawing capability and associated discomfort-glare of the current rear warning-light system during nighttime conditions. The second effort will involve 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 sub-system algorithm processing from the vehicle DAS to the radar firmware unit. The third effort will involve the design and modification of the ERS system into a unit designed for simple truck and trailer installation. Each development effort will be discussed in more detail in the sections below.

7.1.1.1 Nighttime Rear Warning-light Testing

Nighttime testing of the FOT rear warning-light configuration should be conducted and include assessing eye-drawing capability and associated perceived discomfort-glare. The purpose of this testing will be to determine if the current brightness of the final rear warning-light configuration while tested in low-light conditions (nighttime) results in similar (or improved) eye-drawing capability, and to determine the level of perceived discomfort-glare. For comparison to Phase III test results, ten participants will be tested using the same procedure used in the dynamic testing performed on the Virginia Smart Road. Data collected during the nighttime testing will be compared to data collected during the daytime testing. If results indicate that eye-drawing capability of the rear warning-light configuration at night is equivalent (or improved), yet discomfort-glare ratings are unacceptable, brightness levels will adjusted and testing repeated. If the nighttime rear warning-light testing determines that brightness adjustments are necessary, an ambient light sensor will be implemented into the ERS system for automatic daytime/nighttime brightness-level switching. Other contributing factors that may affect the eye-drawing capability and perceived discomfort-glare during nighttime testing will be investigated. For example, it is unknown if the current ERS system lighting will interact with the surface of the trailer it is installed on. If reflectivity issues are observed, it may have implications on the selection of trailer types during carrier recruitment.

7.1.1.2 Radar Firmware Refinement

Based on the results from the Phase III real-world data collection, the radar firmware will require refinements to help reduce the frequency of false alarms in lower speed high-traffic-density scenarios. In addition, the current implementation of the ERS system uses a DAS for activation sub-system algorithm processing. During the radar firmware refinement process, a transfer of the activation sub-system algorithm processing from the DAS to the radar firmware unit should occur.

7.1.1.3 Final ERS Unit Development

The current version of the ERS system contains multiple components separately positioned in a variety of locations. These ERS system components include: LED unit housings, a radar antenna, a radar firmware unit, and a DAS for activation sub-system algorithm processing. In addition to these components, there will be multiple data collection components for research purposes separately positioned in a variety of locations. These data collection components will include: a rear-mounted video camera housing, a DAS for recording video camera feeds and vehicle kinematic data, three additional radar antennas (for research purposes) positioned near the front of the truck, and multiple cameras positioned inside the truck cab. (Further details on all components will be discussed in the method section of the FOT plan later in this document.) Currently, each ERS system component and data collection component requires their own wiring harness and mounting specification. A development effort is recommended to combine ERS system components to create a more road-worthy system overall as well as make system installation on different truck and trailer types easier. For example, it is expected that the final ERS system design may include LED unit housings and a radar system housing containing all necessary activation sub-system processing requirements. In this example, only three mounts and three wiring harnesses are required in comparison to the current system's five mounts and five wiring harnesses.

7.2 RESEARCH QUESTIONS

The ERS FOT will address 18 research questions. They are listed and grouped by function below. These research questions contain several key terms that need to be defined. The first is rear-end safety critical event (RESCE). RESCE will include rear-end crashes and near-crash conditions that warrant ERS system activations. The second is unintended consequences by the following-vehicle's driver. Details on the unintended consequences can be found in appendix J.

7.2.1 Activation Sub-system Performance

7.2.1.1 Correct Detection

- What is the probability that the ERS will correctly detect and activate when a RESCE would otherwise occur when an immediately following vehicle approaches a STOPPED lead test vehicle?

- What is the probability that the ERS will correctly detect and activate when a RESCE would otherwise occur when an immediately following vehicle approaches a lead vehicle SLOWLY ACCELERATING?
- What is the probability that the ERS will correctly detect and activate when a RESCE would otherwise occur when an immediately following vehicle approaches a lead vehicle TRAVELING AT CONSTANT FORWARD SPEED?
- What is the probability that the ERS will correctly detect and activate when a RESCE would otherwise occur when an immediately following vehicle approaches a lead vehicle SLOWLY DECELERATING?
- What is the probability that the ERS will correctly detect and activate when a RESCE would otherwise occur when an immediately following vehicle approaches a lead vehicle DECELERATING TO A STOP?

7.2.1.2 Correct Rejection

- What is the probability that the ERS will correctly reject and not activate when an immediately following vehicle approaches a STOPPED lead test vehicle and there is no rear-end crash threat (or following vehicle directly approaching the lead vehicle)?
- What is the probability that the ERS will correctly reject and not activate when an immediately following vehicle approaches a lead vehicle SLOWLY ACCELERATING and there is no rear-end crash threat (or following vehicle directly approaching the lead vehicle)?
- What is the probability that the ERS will correctly reject and not activate when an immediately following vehicle approaches a lead vehicle TRAVELING AT CONSTANT FORWARD SPEED and there is no rear-end crash threat (or following vehicle directly approaching the lead vehicle)?
- What is the probability that the ERS will correctly reject and not activate when an immediately following vehicle approaches a lead vehicle SLOWLY DECELERATING and there is no rear-end crash threat (or following vehicle directly approaching the lead vehicle)?
- What is the probability that the ERS will correctly reject and not activate when an immediately following vehicle approaches a lead vehicle DECELERATING TO A STOP and there is no rear-end crash threat (or following vehicle directly approaching the lead vehicle)?

7.2.2 Following-vehicle Driving Behavior

7.2.2.1 Following-vehicle Acceleration Profiles

- Is there a difference in average following vehicle’s acceleration values when the ERS is present compared to when the ERS is not present when a following vehicle approaches a STOPPED lead vehicle?
- Is there a difference in average following vehicle’s acceleration values when the ERS is present compared to when the ERS is not present when a following vehicle approaches a lead vehicle SLOWLY ACCELERATING?

- Is there a difference in average following vehicle's acceleration values when the ERS is present compared to when the ERS is not present when a following vehicle approaches a lead vehicle TRAVELING AT CONSTANT FORWARD SPEED?
- Is there a difference in average following vehicle's acceleration values when the ERS is present compared to when the ERS is not present when a following vehicle approaches a lead vehicle SLOWLY DECELERATING?
- Is there a difference in average following vehicle's acceleration values when the ERS is present compared to when the ERS is not present when a following vehicle approaches a lead vehicle DECELERATING TO A STOP?
- Overall, is there a difference in average following vehicle's acceleration values between the lead vehicle and the immediately following vehicle when the ERS is present on the lead test vehicle compared to when the ERS is not present?

7.2.2.2 Eye-drawing Capability

- Is there a difference in the *Mean Time to Look Up* (i.e., the mean time for the driver to glance back to the forward roadway after the initiation of the ERS) for the following driver when the ERS is present on the lead test vehicle compared to when the ERS is not present?

7.2.2.3 Unintended Consequences

- Is there a difference in the number of unintended consequences when the ERS is present on the lead test vehicle compared to when the ERS is not present?

7.3 FIELD OPERATIONAL TEST

The purpose of the FOT is to assess the performance of the final Phase III ERS system under operational conditions. This dynamic evaluation will be conducted on public roadways during revenue-producing commercial truck routes. Because this is an observational study, the instrumented heavy trucks will operate on their normal revenue-producing routes and the rear and adjacent traffic stream will be observed for vehicle-following situations. There are two main areas of investigation that should be performed. The first area of investigation is the performance of the ERS activation sub-system which includes both a closed-loop, which triggers the ERS system using velocity and closing distance of the following vehicle, along with lead-vehicle velocity and deceleration, and an open-loop system which triggers the ERS systems using only lead-vehicle's deceleration. A signal detection theory [8, 9] experimental design will be used to evaluate the activation sub-system performance. The second area of investigation will be in regard to following-vehicle driver behavior. The following vehicle driver behavior will be assessed through acceleration data, the ERS's eye-drawing capability, and the occurrences of unintended consequences during warning-light activation. The following sections will describe the design and implementation of a large-scale FOT, intended to evaluate the relative safety benefits and effectiveness of an ERS device to mitigate rear-end crashes.

7.3.1 Method

7.3.1.1 Participants

Carriers: There are several considerations when determining feasible heavy truck carriers for participation in the FOT. These include fleet characteristics (e.g., type and quantity of vehicles), geographic coverage, and sufficient resources available for testing.

There are a variety of commercial fleet vehicles that could be used for this study (table 47), each with varying exposures to rear-end conflicts and unique advantages and challenges for instrumentation. Target-vehicle types should be operated in a manner to: allow for easy tracking of test equipment (e.g., married trailers to power units), have a high exposure to rear-end conflicts (i.e., high average annual mi), and experience mixed traffic densities (i.e., low and high).

Table 47. Candidate Commercial Fleet Vehicle Types

Vehicle	Type	Number of Units in US Truck Inventory[31]	Average Annual Miles Per Vehicle[31]	Advantages	Challenges
Straight Truck	Van	1,322,100	16,579 mi (26,681.31 km)	• Tracking instrumentation • Relatively high traffic density	• Low exposure
Straight Truck	Dump	727,000	9,964 mi (16,035.50 km)	• Tracking instrumentation • Relatively high traffic density	• Potential for instrumentation damage on rear of vehicle • Low exposure
Straight Truck	Flatbed, Stake, or Platform	948,100	9,964 mi (16,035.50 km)	• Tracking instrumentation • Relatively high traffic density	• Low exposure
Trailer	Van	621,500	79,871 mi (128,539.91 km)	• High Exposure	• Difficulty tracking instrumentation • Relatively low density traffic (i.e., highway)
Trailer	Refrigerated Van	120,400	89,219 mi (143,584.06 km)	• Tracking instrumentation • High Exposure • Mixed Traffic Densities	• None related to instrumentation damage, traffic density, or exposure.
Trailer	Tanker	108,900	68,142 mi (109,663.92 km)	• Tracking instrumentation • High Exposure • Mixed Traffic Densities	• None related to instrumentation damage, traffic density, or exposure.
Trailer	Flatbed, Stake, or Platform	193,500	49,488 mi (79,643.22 km)	• Tracking instrumentation	• Potential for instrumentation damage on rear of vehicle
Trailer	Dump	129,200	40,704 mi (65,506.74 km)	• Tracking instrumentation	• Potential for instrumentation damage on rear of vehicle

From table 47, the priority candidate vehicle types for this FOT should be refrigerated van and tanker trailers because of their higher, mixed traffic-density exposures and typical conjoined relationship between the power unit and the trailer. Tanker trailers also have the distinctive requirement of mandatory stops at railroad crossings, creating an interesting scenario for ERS operations.

During the Real-world Data Collection effort, the research team found 49 RESCEs during 400 mi (643.74 km) of data collection. The primary performance variable of interest for the ERS system will be the change in following-vehicle velocity (i.e., acceleration) occurring from the onset of system activation to 3 s after activation of each RESCE. The mean acceleration value and SD were computed for the purpose of performing a power analysis for the FOT plan. From the data that have been collected, we see that the mean acceleration for following-vehicle approaches in the ERS condition was -3.82 (SD = 3.53), while the mean acceleration for the baseline condition was estimated at -2.00 (SD = 2.2). An estimate of the baseline mean and SD was necessary to perform the power analysis. The power analysis for a two-sample t-test that compares an ERS distribution to a Baseline distribution using a minimum power value of 0.8 and a two-sided significance level of 0.05, yielded a sample size of 111 units (each unit equals 400 mi [643.74 km]) to detect a difference between the two means. This will result in a final value of 44,400 mi (71,454.87 km) required. Collecting exactly 44,400 mi (71,454.87 km) would result in an estimate of approximately 5400 RESCEs for analyses. To achieve this quantity of RESCEs, a single experimental truck tested for more than 1 year would be sufficient. However, the research team recommends that 32 test trucks (16 refrigerated vans and 16 tanker trailers) be used for this FOT. The use of 32 trucks provide ample mi traveled to overcome potential sampling issues such as limitations of the power analysis (i.e., estimates of means and SDs), data collection problems (i.e., truck and apparatus downtime), and variability of actual mi traveled by participating vehicles. The recommended 32 trucks should yield an expected 2.5 million mi (4,023,360 km) of data collected. This recommended number of exposure mi collected is comparable to previous US DOT FOT studies (table 48). Of the 32 test trucks, 8 trucks (4 refrigerated vans and 4 tanker trailers) would be included in the FOT as controls. These control trucks would collect data but not include an active ERS. Data from the control trucks would be included in comparative analyses to assess the efficacy of the ERS system.

Table 48. Previous US DOT FOT Experimental Designs.

FOT Name	Experimental Design

Integrated Vehicle-Based Safety Systems (IVBSS)[32]	• 20 participants
	• 10 research vehicles
	• 2 shifts (daytime and nighttime)
	• 10-month exposure/driver
	    ○ 2-month baseline
	    ○ 8-month treatment period
	• Estimate 1.3 million mi (2,092,147.2 km) to be collected based on 79,871 annual mi (128,539.91 annual km) per vehicle from table 47.

The Drowsy Driver Warning System FOT[33]	• 103 participants
	• 46 research vehicles
	• 11-weeks exposure/driver
	    ○ 2-week baseline
	    ○ 9-week treatment period
	• 2.3 million mi (3,701,491.20 km) collected

Drivers: Because this FOT is an observational study, the individual characteristics of drivers are not necessary for this study. Thus, there will be no selection criteria for assigning drivers to the instrumented vehicles. Instead, the participating company will assign drivers to the instrumented vehicles based on normal operational needs. These assigned drivers will be briefed (either in person or through a write-up) on the purpose of the project and the technologies involved. This briefing will make the drivers aware of the instrumentation, how to identify damage to the system, and how to convey this damage information back to the company. They will be instructed that the system will work without intervention from the driver and that the drivers should operate their vehicles as they normally would.

7.3.1.2 Apparatus

In the FOT, it will not be possible to instrument the following-vehicles, because they would contain ordinary public drivers in their own vehicles. Therefore, all data to be analyzed must be gathered at the rear bumper of the experimental vehicle. The FOT will be comparing the performance of two rear-lighting configurations positioned on the rear of the experimental vehicle (one baseline condition without the rear warning-light configuration, one treatment condition with rear warning-light configuration). This section will describe the equipment associated with the brake lights, the ERS system, and the data collection system. Specific details on all lighting configurations can be found in appendix C.

Brake Lights: As required by Federal Motor Vehicle Safety Standard (FMVSS) 108, trailers with widths of 80 in or more (203 cm or more) are required to have permanently mounted stop lamps (i.e., brake lights) on the rear.(34) These brake lights are to activate with the application of the vehicle's service brakes. The operation of the brake lights will not be affected by the ERS system. An example of trailer brake lights can be seen in figure 79 labeled as A.

ERS: The ERS system is a visual warning system that operates independently of the vehicle's existing brake lights. The ERS system primarily consists of a rear warning-light configuration made up of 12 high-output LED units (figure 4) which is activated (or triggered) by the closed-loop or open-loop activation sub-system. The other component of the ERS system is the radar system used to measure and track the locations of adjacent traffic at the rear of the instrumented vehicle (figure 114). This radar unit provides a means to measure range, radial relative speed, and azimuth angle relative to the sensor. The data collected by the units are fed into tracking algorithms that perform target stabilization over time. From the radar data, the following vehicle closing rates can be computed, providing input for the ERS activation algorithms. This component of the ERS system will remain on the instrumented vehicles during the baseline condition to continue to measure and track the locations of adjacent traffic. Detailed specifications on the radar positioning can be found in appendix E.

Figure 114. Photo. Position of ERS' Range Sensing Technology.

DAS: Installed sensors should include a box containing computer equipment for obtaining data from the vehicle network, an accelerometer box for longitudinal and lateral acceleration, range sensing technology that provides information on distance to lead and trailing vehicles, a video-based lane-tracking system that measures lane-keeping behavior, and video recordings to validate any sensor-based findings. The video sub-system provides a continuous visual display of the events and situations that occur in and around the truck and trailer while driving. The video data should be digital, with software-controllable video-compression capability. This feature allows synchronization, simultaneous display, and efficient archiving and retrieval of data. Additional system capabilities include system initialization equipment to automatically control system status, and a Global Positioning System (GPS) to collect information on vehicle position. Each of the sensor subsystems within the instrumented vehicle should be independent with respect to the others, resulting in containment of sensor failures to the single sensor itself.

<u>The Main DAS Unit:</u> The main DAS unit could be mounted under the passenger seat of a day cab truck or within the luggage compartment of a sleeper cab. The DAS should automatically

start when the truck's ignition is turned on. The DAS could have a backup battery that allows it to continue collecting data when the ignition is turned off, if necessary.

Video Cameras: Because the data collection will rely heavily on video data, there should be two separate camera systems used in the FOT. The first is a set of four cameras to capture the general driving context of the instrumented vehicle. Four cameras are suggested to record video of the roadway, including: a view of the forward roadway, a backward-facing view of the left side of the tractor-trailer, a backward-facing view of the right side of the tractor-trailer, and a top-down view of the rear of the trailer.

The second is a specialized camera system consisting of as many as four high-resolution color module cameras, each with a different focal length lens to maximize the viewing of the head position and eye-gaze identification of the following-vehicle driver (figure 112). This specialized camera system should have, a single camera housing mounted on the rear of the (figure 109). The camera housing should be built to be as small and inconspicuous as possible. Further specifications on the camera type and lenses used in in the previous public roadway data collection effort are provided in appendix I. The views from both camera systems should be multiplexed into two video streams that are time-synchronized via a timestamp (frame number).

Global Positioning System (GPS): A GPS device should be mounted on top of the truck to provide data on the truck's location. Data output includes measures of latitude, longitude, altitude, horizontal and vertical velocity, heading, and status/strength of satellite signal acquisition as well as time and date data.

Lane Tracker: The DAS should also include a sensor to measure the lead vehicle's position within the lane relative to the road lane markings. Key capabilities include:

- Distance from center of truck to left and right lane markings (estimated max error < 6 in [15.24 cm], average error < 2 in [5.08 cm]).
- Angular offset between truck centerline and road centerline (estimated max error < 1 degree).
- Approximate road curvature.
- Confidence in reported values for each marking found.
- Marking characteristics, such as dashed versus solid and double versus single.
- Status information, such as in-lane or solid line crossed.

Yaw Rate Sensor: A yaw rate (gyro) sensor should be installed in the main DAS unit to provide a measure of steering instability (i.e., jerky steering movements).

X/Y Accelerometer: Accelerometers should be instrumented in the vehicle for measuring longitudinal (x) and lateral (y) accelerations to verify the ERS algorithm thresholds and system activations.

Vehicle Network: The vehicle network refers to a from-the-factory on-board data collection system. The format of messages and data collected by on-board microprocessors are defined by the Society of Automotive Engineers (SAE). These microprocessors are installed on the vehicle at the truck manufacturing facility and not by the research team. Depending on the truck model, year, and manufacturer, there are several data network protocols or standards that can be used, including those defined by SAE J1708[35], SAE J1939[36] , and SAE J1587[37]. After assessing the data requirements, the final data network standards will be selected. An interface should be developed to access the data and bring it into the DAS data set. A measure of the mi traveled by the vehicle, brake pedal use, cruise control use, and turn signal use are acquired through the vehicle network.

7.3.1.3 Experimental Design

Thirty-two trucks will be used for data collection. Each truck will have a trailer (e.g., refrigerator van or tanker) that will remain permanently coupled over the course of a 12-month data-collection interval. Of the 32 trucks, 24 trucks will collect a four-month baseline data period and an eight-month test condition data period (figure 115). Based on the anticipated 2.5 million mi (4,023,360 km) traveled by the 32 trucks, approximately 800,000 mi (1287475.2 km) will be collected during the baseline period and 1.7 million mi (2,735,884.8 km) collected during the ERS test period. There is also a control test period in figure 115 that will involve a separate set of 8 instrumented trucks. These controls will mirror the operations of the 24 experimental trucks while collecting baseline data throughout the entire 12-month period. The purpose of these controls is to provide a comparison for uncontrolled circumstances such as traffic, weather, and time of year.[38]

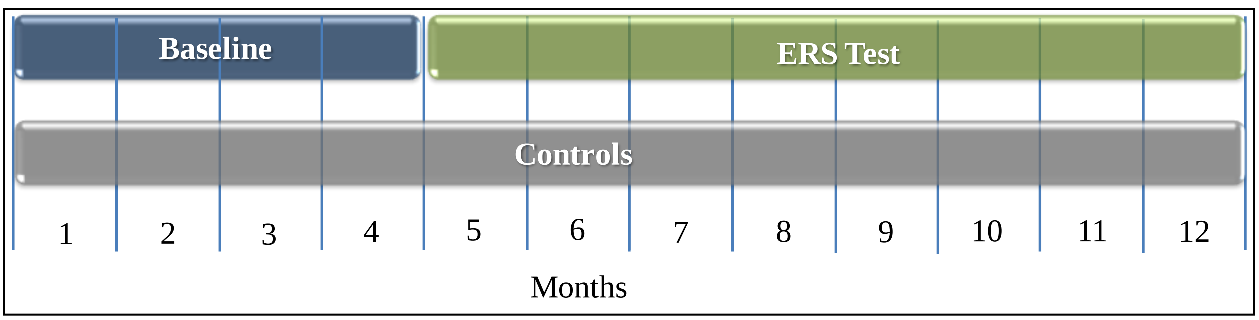

Figure 115. Diagram. Experimental conditions timeline.

As previously noted, there are two main areas of investigation that should be performed in the FOT: (1) ERS activation sub-system performance (both the closed-loop and open-loop systems), and (2) following-vehicle driver behavior (acceleration data, eye-drawing capability, and unintended consequences). The ERS test phase will include the operation of both the closed- and open-loop systems simultaneously. Each area will be discussed in further detail in their respective sections below.

ERS Activation Sub-system:

Closed-loop Activation Sub-system: The first ERS activation sub-system to be tested under real-world conditions is the closed-loop activation sub-system. The closed-loop activation sub-system includes the measurement of closing rate (velocity) and closing distance to the following vehicle, along with lead-vehicle velocity and deceleration, regardless of speed and distance between vehicles (usually obtained through radar) to trigger the ERS system. There are five activation conditions for the closed-loop activation sub-system. A signal detection theory experimental design [8, 9] will be used to evaluate the closed-loop activation sub-system performance. There will be two categories of roadway type to be investigated:

- **Interstate/State Highway**: Multi-lane roadway, speed limit 45-65 mi/h (72.42-104.61 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 aspect of this testing is to determine the activation sub-system performance on each roadway type under normal public roadway driving conditions. Four occurrences of activation will be categorized as either: correct detections, missed detections, false alarms, or correct non-detections (table 10). The performance objective of the closed-loop activation sub-system will be to maximize the probabilities of occurrence of correct detections and correct non-detections, and minimize the probabilities of occurrence of false alarms and missed detections. The main dependent variable will be light activation (*Yes* or *No*). The main independent variable will be following-vehicle lane position (*Same, Left, Right*).

Open-loop Activation Sub-system: The second ERS activation sub-system to be tested under real-world conditions is the open-loop activation sub-system. The open-loop activation sub-system uses only lead-vehicle parameters to trigger the rear warning-lights as an additional activation condition (*Condition 6*). The proposed threshold of 0.4 *g* can be measured directly by an accelerometer or derived by vehicle speed. The ERS system in this FOT will derive this activation threshold using the measured change in the instrumented vehicle's speed. A deceleration of 0.4 *g* was selected based on data taken from a light vehicle equipped with an accelerometer.[21] Later analysis of the 100-Car data demonstrated that such a threshold would have captured 90 percent of rear-end crashes. Therefore, this value was selected as being appropriate.[10]

Open-loop testing performed found that the system performed exactly as designed with a 100-percent detection rate, mostly due to the simplistic overall design of the system. Therefore, a performance evaluation of the open-loop activation sub-system is unnecessary in the FOT. However, the investigation of following-vehicle driver behavior on public roadways has not been investigated and will be examined in the proposed study. Because the closed-loop activation sub-system's algorithm *Condition 4* and the open-loop activation sub-system algorithm will produce overlapping warning-light activations when there is a vehicle immediately following the instrumented vehicle, the following-vehicle unintended consequences (following-vehicle driver behavior) will be examined for the open-loop activations only when there is a vehicle in the adjacent lane. Therefore, the main independent variable will be the following-vehicle's lane position (*Left, Right*).

Following-vehicle Driver Behavior:

Following Vehicle Velocity Data: The following vehicle velocity, as measured by the lead vehicle's rear-facing radar, will be used as a dependent measure to objectively compare the performance of the ERS system when it is present as compared to when it is not present. For each of the identified RESCEs, the change in the following vehicle's velocity from the onset of the ERS system and 3 s after this onset will be derived. It is the change in following vehicle velocity that is of interest to the researchers. It is expected that the ERS system will result in a lower average acceleration after ERS system activation as compared to the baseline condition with no ERS system present.

Eye-drawing Capability: Eye-drawing capability of the rear warning-lights, while activated, will be investigated. With regard to rear-end crashes, the most prevalent contributing factor is that of the following-vehicle driver looking away, either into the vehicle interior or to the outside (but not the forward view).[6,10] Most previous work on prevention of rear-end crashes has been directed toward attention-getting and eye-drawing; that is, trying to get the following-vehicle driver to look forward instead of continuing to look away. The primary objective will be to assess the eye-drawing capability of the rear warning-light configuration in comparison to normal brake lights. Video data from each ERS activation and sampled baseline braking events will be examined to determine if the following vehicle driver is looking away from the forward roadway at the time of ERS activation, and the amount of time it takes for the driver to redirect his/her glance back to the forward roadway. The time taken for a participant to redirect his/her gaze originating away from the forward roadway back to the forward roadway will be measured from video data and serve as the main dependent measure. The use of a between-subjects design will be used.

One limitation in determining following-vehicle driver eye-drawing capability in this study will be in nighttime conditions. It will be very difficult to determine following-vehicle driver head position and gaze using cameras positioned on the rear of a lead vehicle at distances such as these in low-light conditions. Eye-drawing capability in nighttime environments will be investigated during the preliminary work on the Virginia Smart Road as cameras will be installed in the interior of the following vehicle.

Following-vehicle Unintended Consequences: The presence or absence of following-vehicle unintended consequences during the ERS warning-light activation will be investigated. For example, an unintended consequence in this situation might include a following-vehicle driver dangerously swerving after the activation of the heavy truck rear warning-lights. Unintended consequences will be determined through a combination of video and sensor data collected from the DAS and compared to typical baseline unintended consequences. Further details on the determination of unintended consequences can be found in appendix J. There will be two categories of interest for investigation with regard to roadway type. The first roadway type to be investigated is a *Single-lane Roadway* (one lane in each direction). In this category, a following vehicle has no option other than following directly behind the experimental heavy truck in the same lane. The second roadway type to be investigated is a *Multi-lane Roadway* (two lanes in each direction). In this category, a following vehicle has the option to follow the experimental heavy truck in the same lane or in an adjacent lane (to the left or the right depending on the experimental heavy truck's lane position). The main dependent variable (DV) is the presence or absence of an unintended consequence (*Yes* or *No*). The main independent variables (IVs) and the different levels of each for the *Single-lane Roadway* category are shown in table 26. The main independent variables and the different levels of each for the *Multi-lane Roadway* category are shown in table 27.

7.3.1.4 Data Reduction Strategy

There will be five primary data reduction efforts to be performed in the FOT. The first two data reduction efforts will be conducted on the closed-loop and open-loop activation sub-system performance. The third effort will be conducted on the following-vehicle acceleration values. The fourth effort will be conducted on the eye-drawing capability of the ERS rear warning-lights. The fifth effort will be conducted on following-vehicle unintended consequences observed during rear warning-light activations.

There are three main steps involved in the data reduction process. The first step should be to run event-trigger algorithms on all of the data to flag potential events of interest. The second step should be to validate the event triggers by visually inspecting the video data pertaining to them, and the final step should be to record the attributes that pertain to the events. Each of these steps is described in more detail below.

ERS Activation Sub-system Reduction:

Closed-loop Activation Sub-system: The closed-loop activation sub-system reduction process will involve identifying correct detections, missed detections, false alarms, and correct rejections. Events of interest will be found by scanning the data set for rear warning-light activations and approaching-vehicle radar targets during all five closed-loop activation sub-system algorithm conditions. To identify approaching-vehicle radar targets, a target-vehicle distance threshold value ("trigger") of 175 ft (53.34 m) in the same lane, adjacent left lane, and adjacent right lane behind the truck will be used.

Open-loop Activation Sub-system: The open-loop activation sub-system reduction process will involve identifying following-vehicle driver unintended consequences during open-loop rear warning-light activations. Events of interest will be found by scanning the data set for rear warning-light activations associated with heavy braking.

Following-vehicle Driver Behavior Reduction:

Following-vehicle Acceleration Data: The purpose of the following-vehicle acceleration data reduction is to record velocity values at the onset and 3 s after actual rear warning-light activations (test condition), and activations that would have occurred if the lights were present (baseline condition). These events of interest will be found by scanning the data set for programmed triggers meeting these requirements. Only correct detection events will be chosen as valid and used in the analyses.

Eye-drawing Capability: The purpose of the eye-drawing capability reduction is to record the time for a following-vehicle driver who is looking away at the onset of the rear warning-light system activation to redirect his/her glance back to the forward roadway. Video data from each correct detection event (both during the test condition and baseline) will be examined.

Following-vehicle Unintended Consequences: The purpose of the following-vehicle unintended consequence reduction is to determine the presence or absence of unintended consequences during rear lighting activations on both *Single-lane Roadways* and *Multi-lane Roadways.* The same data reduction procedure that was used during Real-world Data Collection will be used in the proposed study. Unintended consequences will be determined through a combination of video and sensor data collected from the DAS and compared to typical baseline braking events. Video data will be used to determine if a following-vehicle performs any swerves, lane deviations, or heavy decelerations (brake lockup). Sensor data will be used to determine other following-vehicle acceleration and deceleration behaviors. When a following vehicle is present in one of the three lanes of interest (*Same*, *Left*, and *Right*), data reductionists will record the target following-vehicle speed at the onset of rear warning-light activations (test condition) and normal brake light activations (baseline condition), as well as record the following-vehicle speed 3 s after activation. An average rate of change in acceleration/deceleration will be calculated for comparisons.

Trigger Validation: For all data reduction efforts described above, the data set will be scanned for potential events of interest and will be flagged with a trigger for review. A 60-second epoch will be created for each trigger; an epoch consists of 30 s prior to the trigger and 30 s after the trigger. The result of the automatic scan will be a data set that includes both valid and invalid triggers.

Valid triggers will be those where present conditions actually occurred and were verifiable in the video and other sensor data (also identified by an analyst); one or more valid triggers may be included. Invalid triggers will be those triggers where sensor readings were spurious due to a transient spike or some other anomaly (false positive). The validity of all triggers will be determined through video review. Triggers determined to be invalid will not be analyzed further.

7.4 EXPECTED FINDINGS

The ERS system has the potential to reduce the number and severity of crashes where a heavy truck has been struck from behind. This FOT is designed to study the efficacy of the ERS system by investigating the activation sub-system performance and following-vehicle driver behavior. Based on the number and type of priority candidate truck types, it is expected that this FOT will result in 2.5 million mi (4,023,360 km) of data collected using 32 trucks.[(31)]

7.4.1 Activation Sub-system Performance

7.4.1.1 Closed-loop Activation Sub-system

An estimated number of events for closed-loop activation sub-system performance testing was calculated based on data collected during Real World Data Collection, the expected mi per vehicle[(31)], and an estimated distribution of mi per roadway type of 80 percent *Interstate/State Highway* to 20 percent *Other* (this estimated distribution will vary based on refrigerator and tanker trailer operational characteristics). If the 32 trucks successfully collect data for one year it is expected that approximately 1.7 million *Interstate/State Highway* roadway events and 1.3 million *Other* roadway events will be collected. (An event here is defined as a following-vehicle approach regardless of lane and ERS system activation).

7.4.1.2 Open-loop Activation Sub-system

An estimated number of events for open-loop activation sub-system performance testing was calculated based on data collected during a recently completed naturalistic truck study performed by the research team[(39)], and the expected mi per vehicle[(31)]. If 32 trucks successfully collect data for one year it is expected that approximately 2000 heavy-braking events will be collected. It is expected that warning-light activations will occur for each heavy-braking event (100 percent detection rate).

7.4.2 Following-vehicle Driver Behavior

7.4.2.1 Following-vehicle Acceleration Profile

An estimated number of events for following-vehicle acceleration value testing was calculated based on data collected during the Real-world Data Collection effort, the expected mi per vehicle(31) (this estimate will vary based on refrigerator and tanker trailer operational characteristics, as well as the actual distribution of mi traveled per roadway type). If 32 trucks successfully collect data for one year it is expected that approximately 300,000 events RESCEs will be collected.

7.4.2.2 Eye-drawing Capability

An estimated number of potential eye-drawing events was calculated based on data collected during the Real-world Data Collection effort, and the expected mi per vehicle(31). A potential eye-drawing event assumes that every following-vehicle driver will be glancing away from the forward roadway during a valid warning-light activation; therefore, all estimates to follow can be considered liberal. Taking what was learned from previous work, the research team was able to develop a rearward camera system that performed well at identifying following-vehicle driver head position and eye-gaze up to a maximum of 115 ft (35.05 m) behind the experimental heavy truck in ideal daytime conditions. The yield of data for following-vehicle driver direction of glance was approximately 48 percent (48 usable events out of 100 attempts). Overall, if 32 trucks collect data for one year it is expected that approximately 25,000 potential eye-drawing events will occur on the *Interstate/State Highway* roadways, 48 percent of which the driver direction of glance may be determinable (12,000). In addition, if 32 trucks collect data for one year it is expected that approximately 42,500 potential eye-drawing events will occur on the *Other* roadways, 48 percent of which the driver direction of glance may be determinable (20,400).

7.4.2.3 Unintended Consequences

During the Real-world Data Collection Effort, the occurrence of following-vehicle unintended consequences during rear warning-light activation and during normal brake light use was minor (no difference found between conditions). Of the unintended consequences that did occur across all roadway categories, all were labeled as decelerations and accelerations (e.g., no swerves, lane deviations, or lane changes were found). It is expected that the rear warning lights will not result in an increase of unintended consequences over that of normal brake lights during the FOT.

7.5 SUMMARY

The Phase III testing demonstrated that, under controlled conditions, the ERS performs properly and effectively draws the attention of the following-vehicle's drivers. The FOT, however, will assess the performance of a road-worthy ERS on heavy trucks driving revenue producing routes under an operational context. The ERS will be exposed to environmental (e.g., temperature, vibration, and debris) and operational (loading and unloading, durability, and maintenance) factors that will test the robustness of the near-production design.

The recommended FOT study approach is summarized in table 49. The recommended number of vehicles is based on results of limited on-road exposure (i.e., 1300 mi [2,092.15 km]) of the ERS during the Real-World Data Collection task of Phase III. Therefore, this number of vehicles should be considered accurate for sufficiently assessing the ERS effectiveness.

Table 49. FOT Design Summary

Parameter	Recommendation
Vehicle Fleets	• Refrigerated Van • Tanker Trailer

Sample Size	• 32 total instrumented vehicles
	  ○ Refrigerated Van
	    ▪ 12 (Test) equipped with ERS and DAS
	    ▪ 4 (Control) equipped with DAS
	  ○ Tanker Trailer
	    ▪ 12 (Test) equipped with ERS and DAS
	    • 4 (Control) equipped with DAS

Duration	• 12 months of data collection
	  ○ Test Vehicles
	    ▪ 8 months for ERS Test
	    ▪ 4 months for Baseline
	  ○ Control Vehicles
	    ▪ 12 months of baseline

ERS configuration	12 High-output LED-unit ganged on the trailer’s main bumper
Vehicle Instrumentation	Triggered Data Collection with DAS, including rear-facing radar and cameras.

8. DISCUSSION

As previously mentioned, the purpose of the Phase III effort was threefold: (1) conduct a General Estimates System (GES) database analysis using the most recent data available to report various break-outs/characterizations of rear-end truck crashes, (2) explore the benefits of the countermeasures developed in Phases I and II, and (3) develop a plan for a large scale Field Operational Test (FOT) to assess countermeasures for rear-end truck crashes.

Generally, the 2006 GES findings were consistent with those from the 2001 GES analysis. There were some minor shifts found as well as other interesting findings that are noteworthy. For example, in the 2006 GES data set, only 36 percent of daytime rear-end crashes occurred on *Interstate Highways*. This marks a sharp reduction since 2001 when 67.3 percent of daytime rear-end crashes occurred on Interstates. Nighttime rear-end crashes that occurred on the Interstate increased from 38.5 percent in the 2001 GES data set to 55 percent in the 2006 GES data set. It is also interesting to note that CUTs strike other CUTs in approximately 27 percent of the CUT rear-end crashes, yet CUTs only strike passenger vehicles in 2.2 percent of passenger vehicle rear-end crashes. This finding suggests that CUT drivers' vehicle-following behavior may differ depending on the type of lead vehicle.

Many different types of ERSs were investigated in Phase III across both the auditory and visual modalities. Narrow beam-width external auditory signals were developed and tested; however, the target beam-width could not be obtained. Visual warning signal development was focused on for the remainder of Phase III. Visual warning signals were developed and tested in both static and dynamic experiments. Nine different rear-lighting configurations were investigated as well as a set of *Conspicuity Markings*. *Conspicuity Markings* did not provide a performance benefit in maintaining a demonstrated distance behind the experimental CUT during closed-track dynamic experimental testing. Two rear warning-light configurations appeared to be good candidates for the real-world data collection effort. However, one configuration was selected to move forward based on the potential success of future design implementation. The final rear warning-light configuration was the *Main Bumper*. In regard to closed-loop and open-loop activation sub-system testing, both systems performed well. The closed-loop system was the recommended candidate to move forward to real-world data collection. This system had the greater potential for mitigating rear-end crashes involving heavy trucks over that of the simpler open-loop system.

During the real-world data collection effort, the ERS system was robust in real-world driving conditions. Results indicated that the system performed well at detecting rear-end crash threats and drawing the gazes of following-vehicle drivers back to the forward roadway, and resulted in minor following-vehicle unintended consequences during fair weather and daylight hours. Radar target identification problems that produced higher number of false alarms were found during closed-loop activation sub-system testing at lower speeds and in high-traffic-density scenarios. The likelihood of these false alarms should be addressed prior to data collection in an FOT with further radar firmware modifications, or other design modifications could be implemented such as non-activation or switching to an open-loop application at low travel speeds. Also, the current study's testing only included real-world data collection during daylight hours. Preliminary work prior to an FOT data collection should investigate the potential need of rear warning-light brightness adjustments for lower-light conditions.

8.1 FUTURE WORK

8.1.1 FOT

Based on the above findings, the research team identified three ERS system development efforts needed prior to data collection in an FOT. The first effort should involve testing the eye-drawing capability and associated discomfort-glare of the current rear warning-light system during nighttime conditions. The second effort should involve refinement of the radar target identification firmware to reduce the propensity of false alarms in lower speed high-traffic-density scenarios, and to transfer the activation sub-system algorithm processing from the vehicle DAS to the radar firmware unit. The third effort should involve the design and modification of the ERS system into a unit designed for simple truck and trailer installation. Upon successful completion of these preliminary development efforts, data collection in an FOT can begin. An FOT plan was designed with two main categories of research questions. The first category should focus on the ERS activation sub-system performance. The second category should focus on following-vehicle driving behavior. Priority candidate vehicle types for this FOT should be refrigerated van and tanker trailers because of their higher, mixed traffic-density exposures and typical conjoined relationship between the power unit and the trailer. The research team recommends that 32 trucks be used for this FOT, each truck type category to be evenly distributed. Based on the average annual mi per priority candidate vehicle, the total number of expected mi of data collection for the duration of one year would be 2.5 million mi (4,023,360 km). It is expected that the execution of the FOT plan will result in a sufficient amount of data for proper determination of the final ERS system efficacy.

8.1.2 Intellidrive/ERS Integration

The research focused on developing and testing rear external signaling countermeasures. While these external signaling countermeasures have shown promise in drawing following-driver's attention back to the forward roadway, further development using V2V communications has an even greater potential for mitigating driver distraction related to rear-end crashes. The purpose of introducing an auditory warning in the ERS project was to supplement the visual stimulus to increase the probability of redirecting the driver's attention and visual glance to the forward view. There were two options identified for implementation of an auditory warning for this scenario. One of these involved generating an auditory warning signal at the lead vehicle and focusing it directly backward (external auditory signal). This sound would then directly warn the driver of the following vehicle. However, this type of system has the disadvantage that other drivers may be needlessly alerted by the external auditory warning if it is transmitted by means of a loudspeaker or similar device. This would occur if the sound was not sufficiently directional. Another potential shortcoming was that the sound level may not be in the correct range of amplitude (volume) for the following driver to hear it. The other option involved the use of V2V communications, in which the lead vehicle would transmit a signal to the following vehicle. In such a case, the following vehicle receives the signal and warns the driver by means of an in-vehicle auditory warning.

The ERS project did not investigate the V2V option. Instead, researchers investigated the feasibility of generating a narrow beam-width external auditory signal. However, the two proposed concepts (i.e., tube design and parabolic reflector) were not able to achieve the narrow beam-width goal of ±5 deg. Because this narrow beam-width could not be obtained, further use of either concept might needlessly alert other drivers in adjacent lanes. Researchers determined that V2V has the clear benefit over an external auditory signal in that more control of the signal's sound, directionality, and amplitude could be maintained inside the following vehicle.

If more advanced exterior auditory signal technology becomes more cost effective for application in commercial vehicle operations, this may be important to revisit. However, V2V may be the more appropriate avenue to pursue in that it has the clear benefit over an external auditory signal in that more control of auditory characteristics can be maintained inside the following vehicle. Also, if auditory warnings are indeed investigated through the V2V application, it would be wise to revisit the performance of visual warnings both inside and outside of the cab.

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APPENDIX A. GES DATABASE ANALYSIS UPDATE 2006: REMAINING ANALYSES

INTRODUCTION

As mentioned previously in this report, the research team completed analyses of rear-end crashes involving trucks using 2006 crash data. The crash data used were collected by NHTSA and compiled in the NASS. NASS is comprised of two systems – the CDS and the GES. Data included in the CDS and the GES have been drawn from select crashes using PARs obtained from police agencies around the country. The reports are selected from randomly chosen areas of the country and include counties and major cities that are statistically representative of the United States as a whole. The PARs from which the GES data are coded are a probability sample of police-reported crashes, and because each crash had a chance of being selected, the national estimates and probable errors associated with the estimates can be calculated.[(12)] The national estimates may differ from the actual values because they are based on a probability sample of crashes, not a true census of crashes in the United States.[(12)] A selection of the GES analyses performed were presented earlier in section 2 of this report. All remaining analyses performed are presented here in this appendix.

OVERALL REAR-END CRASH STATISTICS FOR TRUCKS

Crash Severity of Rear-end Crashes

Table 50 presents the maximum injury severity for rear-end crashes compiled by using the three most common configurations: *Lead Vehicle Stopped*, *Lead Vehicle Traveling Slower*, and *Lead Vehicle Decelerating*. In each of these configurations the lead vehicle refers to the heavy truck. The data do not identify which vehicle sustained the maximum injury. Within those configurations, there were 135 fatalities, 1,603 incapacitating injuries, 2,074 non-incapacitating injuries, and 2,711 possible injuries. The most serious injuries (i.e., non-incapacitating injuries and incapacitating injuries) occurred within the *Lead Vehicle Stopped* configuration, which had 1,621 serious crashes. The *Lead Vehicle Traveling Slower* configuration had 1,304 serious crashes and the *Lead Vehicle Decelerating* configuration had 751 serious crashes.

Table 50. Maximum Injury Severity for Heavy Truck Rear-End Crashes by Rear-End Configuration

Configuration	None	Possible	Non-Incapacitating	Incapacitating	Fatal	Unknown
Stopped - Count	**8,524**	**1,049**	**1,035**	**586**	**54**	**0**
Percent of Severity Column	*50.53%*	*38.70%*	*49.93%*	*36.58%*	*39.71%*	*0.00%*
Percent of All Crashes	*36.26%*	*4.46%*	*4.40%*	*2.49%*	*0.23%*	*0.00%*
Slower - Count	**4,674**	**855**	**617**	**687**	**31**	**114**
Percent of Severity Column	*27.71%*	*31.54%*	*29.74%*	*42.86%*	*23.16%*	*98.19%*
Percent of All Crashes	*19.88%*	*3.64%*	*2.62%*	*2.92%*	*0.13%*	*0.48%*
Decelerating - Count	**3,671**	**807**	**422**	**329**	**50**	**2**
Percent of Severity Column	*21.76%*	*29.76%*	*20.33%*	*20.56%*	*37.13%*	*1.81%*
Percent of All Crashes	*15.61%*	*3.43%*	*1.79%*	*1.40%*	*0.21%*	*0.01%*
Note. All figures rounded to the nearest integer.						

REAR-END CRASH CHARACTERISTICS BY TRUCK BODY TYPE

Analysis of Crash Record for Single-unit Trucks (SUTs)

Roadway Characteristics Where Rear-end Crashes Occur

Figure 116 illustrates the findings for the variable *Roadway Alignment*. *Roadway Alignment* describes whether the roadway was curved, straight, or unknown.[8] Only 4.5 percent of rear-end crashes occurred on curving roadways. The large majority of rear-end crashes, 90.8 percent, occurred when the SUT was traveling along a straight roadway.

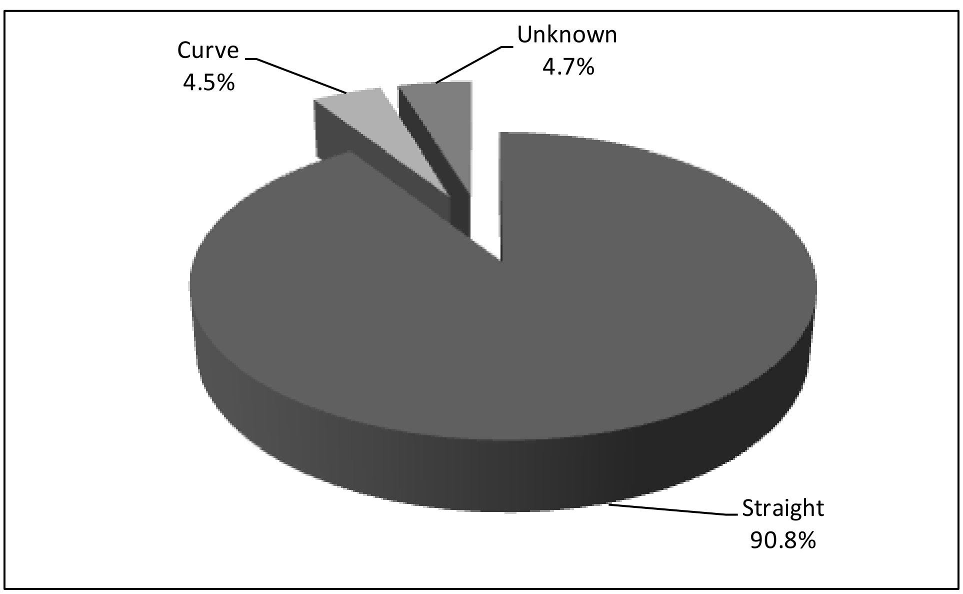

Figure 116. Pie Chart. *Roadway Alignment* for SUT rear-end crashes.

The distribution of the *Speed Limit Ranges* on the roadways where the SUT rear-end crashes occurred is presented in figure 117. Note that these are the posted speed limits and do not reflect the actual speed of the truck. Roadways with *Speed Limit Ranges* of 46-65 mi/h (74.03-88.51 km/h) accounted for 54.6 percent of SUT rear-end crashes. More than 29 percent of the rear-end crashes occurred on roadways with a speed limit of 45 mi/h (72.42 km/h) or less.

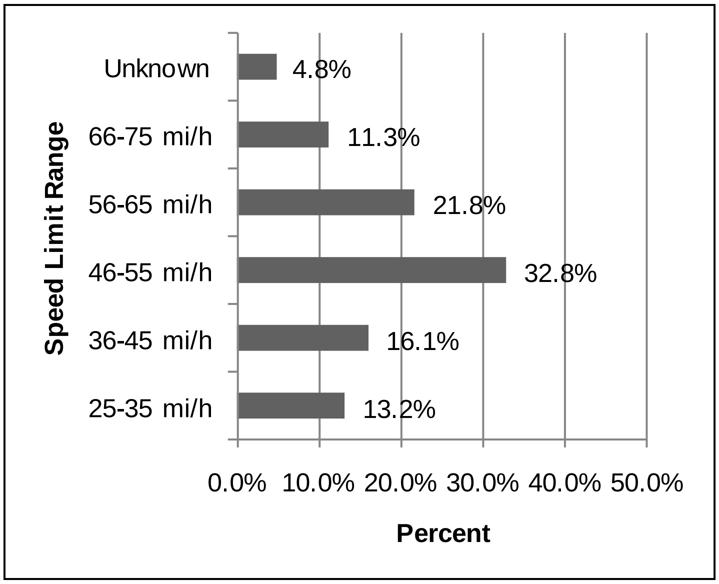

Figure 117. Bar graph. *Speed Limit Range* for SUT rear-end crashes.

Environmental Conditions at Time of Crash

The effects of the environment on SUT rear-end crashes can be explored by examining the GES data coded for atmospheric and lighting conditions. The *Atmospheric Conditions* under which SUT rear-end crashes occurred are presented in figure 118. The vast majority (84.8 percent) of SUT rear-end crashes occurred in good environmental conditions (i.e., *No Adverse Atmospheric Conditions*). Only 15.1 percent of the rear-end crashes occurred with atmospheric adverse conditions (i.e., *Rain*, *Sleet*, *Snow*, or *Fog*).

Similarly, a high proportion of the rear-end crashes (84.5 percent) occurred during *Daylight* conditions, followed by *Dark but Lighted* (9.1 percent) and *Dark* conditions (figure 119). Since 2001, there has been a decrease in the number of rear-end crashes occurring at dawn. More specifically, 8.9 percent of the rear-end crashes in 2001 occurred at dawn, compared to 0.6 percent in 2006.

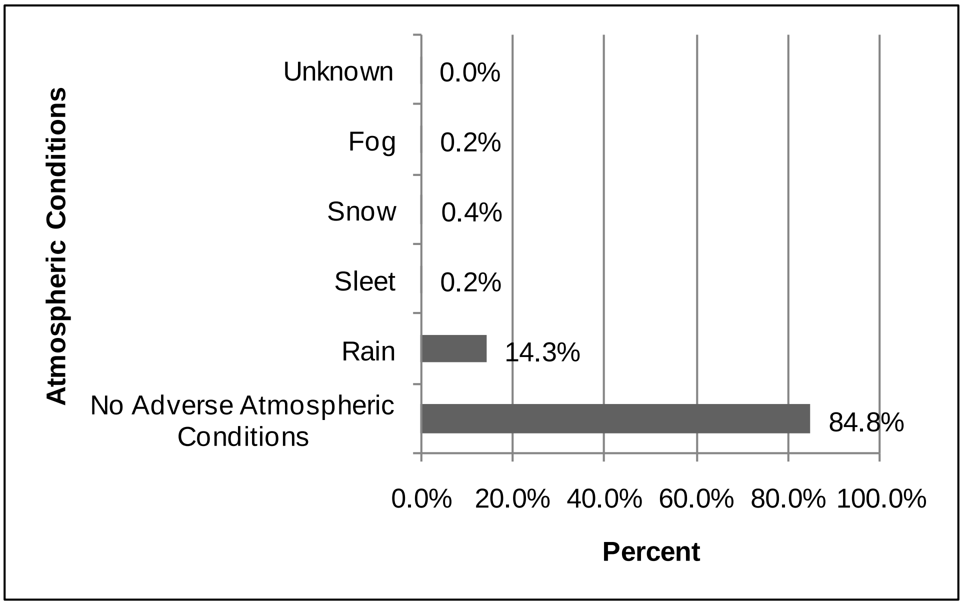

Figure 118. Bar graph. *Atmospheric Conditions* for SUT rear-end crashes.

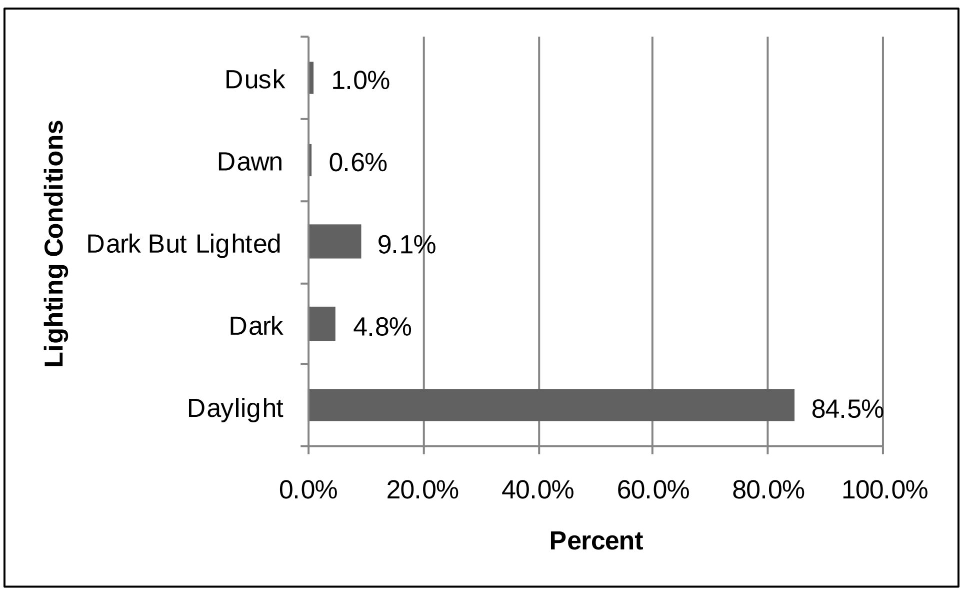

Figure 119. Bar graph. *Lighting conditions* for SUT rear-end crashes.

Maximum Injury Severity for SUT Rear-end Crashes

While table 50 above presented the overall maximum injury severity data for all heavy-truck rear-end crashes, table 51 presents the same information for SUT rear-end crashes. Again, the statistics were consolidated into the three primary crash configurations: *Lead Vehicle Stopped*, *Lead Vehicle Traveling Slower*, and *Lead Vehicle Decelerating*. Also, the data do not identify which vehicle sustained the maximum injury. Within the SUT rear-end crashes there were 53 fatalities, 696 incapacitating injuries, 906 non-incapacitating injuries, and 1,425 possible injuries.

While most of the rear-end crashes occurred in the *Lead Vehicle Stopped* configuration followed by the *Lead Vehicle Traveling Slower* configuration, most of the fatalities occurred in the *Lead Vehicle Decelerating* configuration. The greatest number of serious injuries (i.e., non-incapacitating injuries and incapacitating injuries) occurred in the *Lead Vehicle Traveling Slower* configuration followed closely by the *Lead Vehicle Stopped* configuration. The overall truck statistics found the largest number of serious injuries in the same categories.

Table 51. Maximum Injury Severity for SUT Rear-End Crashes by Rear-End Configuration

Configuration	None	Possible	Non-Incapacitating	Incapacitating	Fatal
Stopped - Count	**5,265**	**518**	**470**	**186**	**7**
Percent of Severity Column	*54.07%*	*36.34%*	*51.81%*	*26.79%*	*12.37%*
Percent of All Crashes	*41.08%*	*4.04%*	*3.66%*	*1.45%*	*0.05%*
Slower - Count	**2,704**	**392**	**274**	**408**	**0**
Percent of Severity Column	*27.77%*	*27.55%*	*30.27%*	*58.61%*	*0.00%*
Percent of All Crashes	*21.09%*	*3.06%*	*2.14%*	*3.18%*	*0.00%*
Decelerating - Count	**1,769**	**515**	**162**	**102**	**46**
Percent of Severity Column	*18.16%*	*36.11%*	*17.92%*	*14.60%*	*87.63%*
Percent of all crashes	*13.80%*	*4.01%*	*1.27%*	*0.79%*	*0.36%*
Note. All figures rounded to the nearest integer.					

Population of Rear-end Crashes Involving CUTs

Roadway Characteristics Where Rear-end Crashes Occur

Figure 120 illustrates the findings for the variable *Roadway Alignment*. Only 6.7 percent of CUT rear-end crashes occurred on curving roadways, while the majority of CUT rear-end crashes (92.5 percent) occurred when the CUT was traveling along a straight roadway.

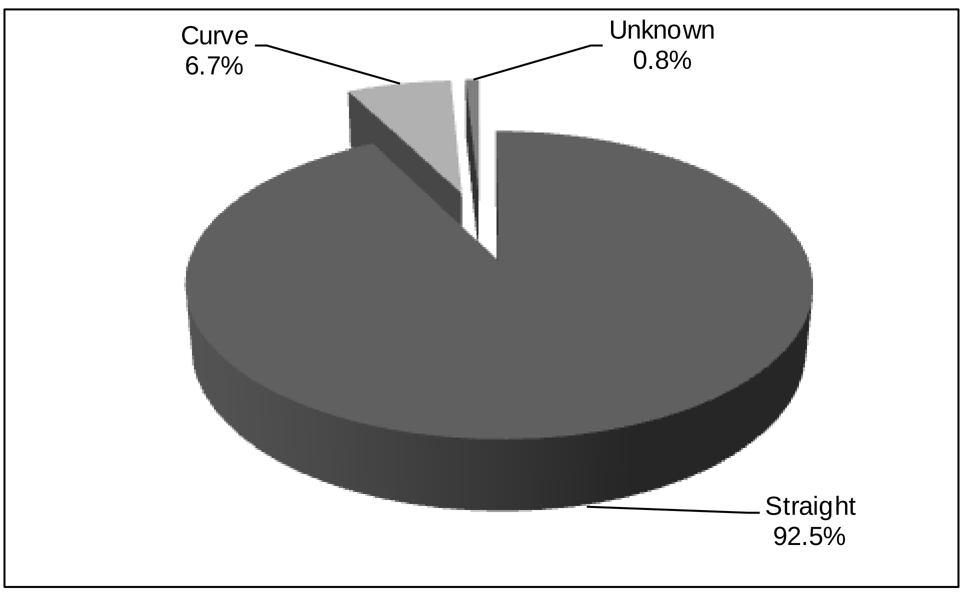

Figure 120. Pie Chart. *Roadway Alignment* for CUT rear-end crashes

The distribution of the *Speed Limit Ranges* where the CUT rear-end crashes occurred is presented in figure 121. Only 31 percent of the CUT rear-end crashes occurred on roadways where the speed limit was 45 mi/h (72.42 km/h) or less. The majority occurred on roadways with speeds greater than or equal to 46 mi/h (74.03 km/h).

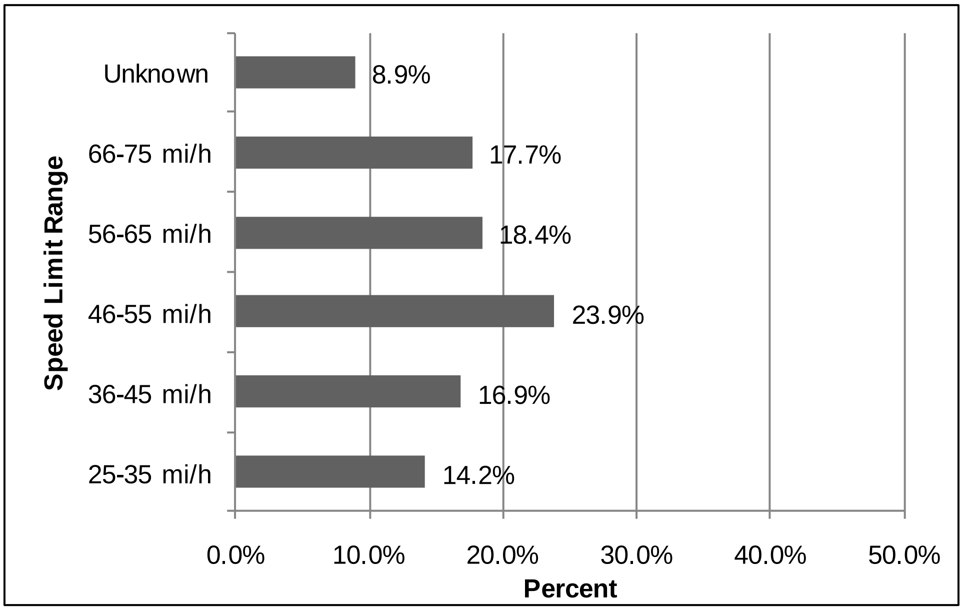

Figure 121. Bar graph. *Speed Limit Range* for CUT rear-end crashes.

Environmental Conditions at Time of Crash

The environmental conditions (i.e., atmospheric and lighting conditions) can be investigated as potential contributing factors associated with rear-end CUT crashes. The *Atmospheric Conditions* under which CUT rear-end crashes occur are presented in figure 122. The environmental conditions were good (i.e., *No Adverse Atmospheric Conditions* in figure 122) for 88.1 percent of these CUT rear-end crashes. Rain was present in 8.2 percent of the CUT rear-end crashes. Figure 123 presents the *Lighting Conditions* at the time of the CUT rear-end crash. The majority of CUT rear-end crashes (74.5 percent) occurred during daylight *Lighting Conditions* while only 21.3 percent of the CUT rear-end crashes occurred during *Dark* or *Dark but Lighted* conditions.

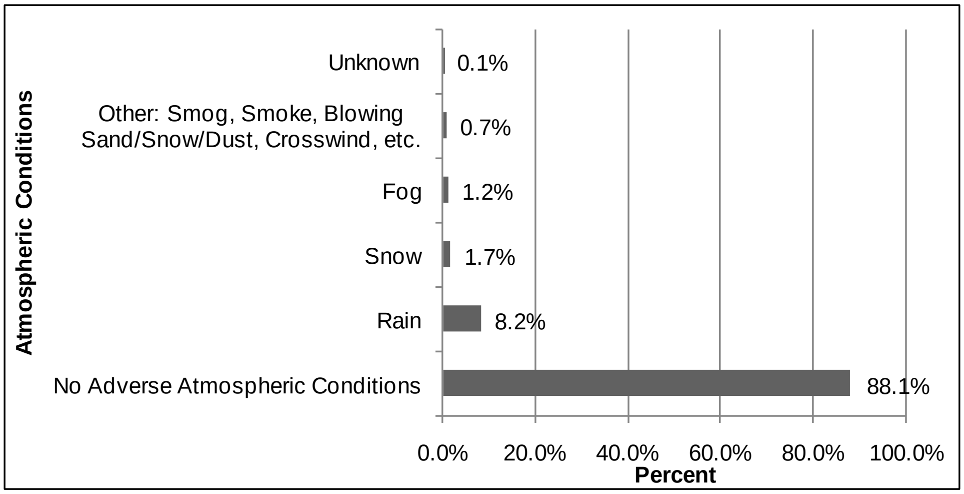

Figure 122. Bar graph. *Atmospheric Conditions* for CUT rear-end crashes.

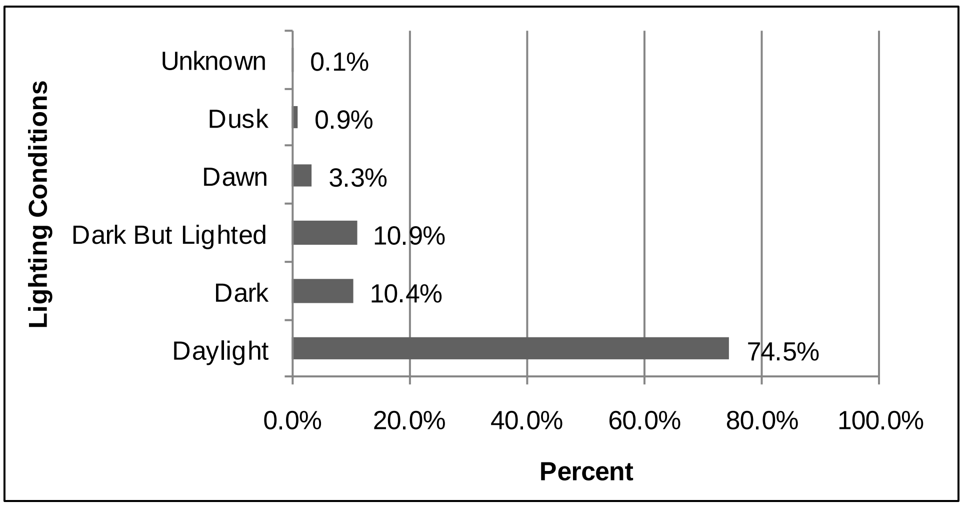

Figure 123. Bar graph. *Lighting Conditions* for CUT rear-end crashes.

Maximum Injury Severity for CUT Rear-end Crashes

While table 50 and table 51 above examined the overall maximum injury severity data for all hevy truck and SUT rear-end crashes, respectively, table 52 inspects the injury severity data for CUT rear-end crashes. Again, the statistics have been consolidated into the three primary crash configurations: *Lead Vehicle Stopped*, *Lead Vehicle Traveling Slower*, and *Lead Vehicle Decelerating*. Also, the data do not identify which vehicle sustained the maximum injury. Within the CUT rear-end crashes; there were 82 fatalities, 907 incapacitating injuries, 1,167 non-incapacitating injuries, and 1,287 possible injuries. Most of the CUT rear-end crashes occurred in the *Lead Vehicle Stopped* configuration followed by *Lead Vehicle Traveling Slower* and *Lead Vehicle Decelerating*. The greatest number of serious injuries (i.e., non-incapacitating injuries and incapacitating injuries) and fatalities occurred in the *Lead Vehicle Stopped* configuration as well.

Table 52. Maximum Injury Severity for CUT Rear-End Crashes by Rear-End Configuration

Configuration	None	Possible	Non-Incapacitating	Incapacitating	Fatal	Unknown
Stopped - Count	**3,114**	**532**	**566**	**400**	**47**	**0**
Percent of Severity Column	*46.49%*	*41.32%*	*48.47%*	*44.10%*	*57.39%*	*0.00%*
Percent of All Crashes	*30.36%*	*5.18%*	*5.52%*	*3.90%*	*0.46%*	*0.00%*
Slower - Count	**1,683**	**463**	**342**	**279**	**31**	**114**
Percent of Severity Column	*25.12%*	*35.96%*	*29.33%*	*30.76%*	*38.15%*	*98.19%*
Percent of All Crashes	*16.41%*	*4.51%*	*3.34%*	*2.72%*	*0.31%*	*1.11%*
Decelerating - Count	**1,902**	**292**	**259**	**228**	**4**	**2**
Percent of Severity Column	*28.39%*	*22.72%*	*22.20%*	*25.13%*	*4.46%*	*1.81%*
Percent of All Crashes	*18.54%*	*2.85%*	*2.53%*	*2.22%*	*0.04%*	*0.02%*
Note. All figures rounded to the nearest integer.						

Actions of the Striking Vehicle Involved in the Crash

Previous sections examined the actions of the struck SUT and CUT drivers during rear-end crashes. This section examines the actions of the striking vehicle in the rear-end crash. The data in this section have been filtered to restrict it to the actions of only the striking vehicle. This is accomplished by using the steps described earlier in the report and by filtering on the following crash category codes, including *Lead Vehicle Stopped*, *Lead Vehicle Traveling Slower*, and *Lead Vehicle Decelerating* (i.e., Codes 20, 24, and 28), to ensure that those rear-end crashes where a vehicle strikes the rear of a truck are included. Additionally, the sample was verified using the variable *Vehicle Role Equals Striking* (i.e., V22, Code 1).

This section presents two concurrent analyses, one for SUTs and one for CUTs, and will examine the maneuvers of the striking vehicle:

- Movement prior to the rear-end crash,
- Travel speed,
- Corrective actions,
- Vehicle stability, and
- Vehicle defects that could have contributed to the rear-end crash.

Each analysis throughout this section will present findings first for the SUT and then for the CUT. Although this analysis will provide insight into rear-end crashes in the heavy truck population, it will not provide causal factor data for the rear-end crashes as the GES database is not sufficiently detailed to allow for such inferences. Instead, this analysis will provide an indication if the driver of the striking vehicle acted improperly. It will also provide an indication of the driver’s level of awareness regarding the following distance between the striking vehicle and heavy truck.

The variable *Movement Prior to the Critical Event* (i.e., V21) can assess if the rear-end crash was the result of a maneuver by the striking vehicle. The results of this analysis are presented in figure 124 and figure 125. In both SUT and CUT rear-end crashes, the majority of rear-end crashes occurred when both vehicles were traveling straight prior to the crash (88.4 percent and 78.2 percent, respectively). For SUTs, the second most common movement was starting in the traffic lane (4.9 percent), while the second most common movement in CUT rear-end crashes was decelerating in the traffic lane (5.3 percent).

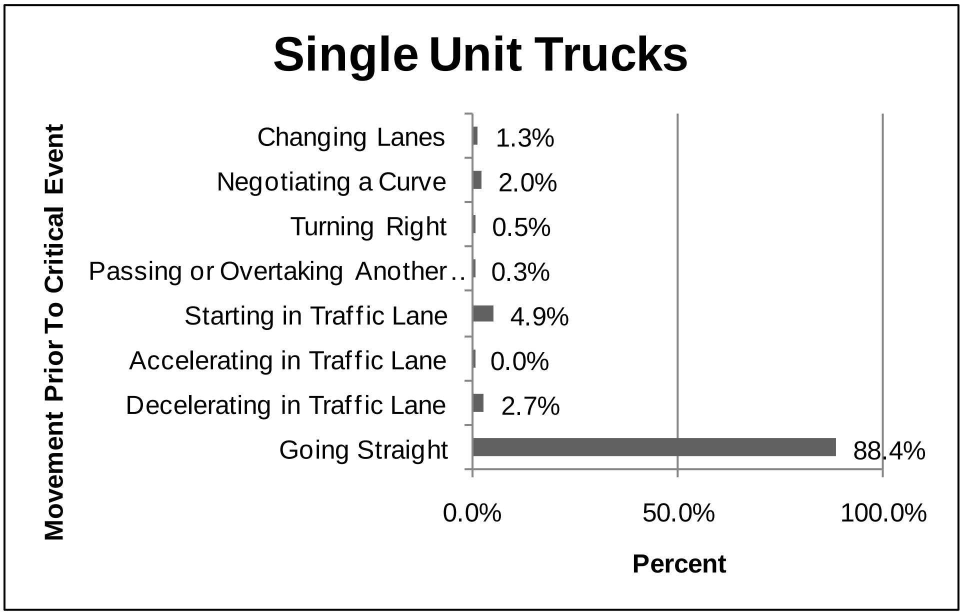

Figure 124. Bar graph. Movements prior to critical event – SUT striking vehicle.

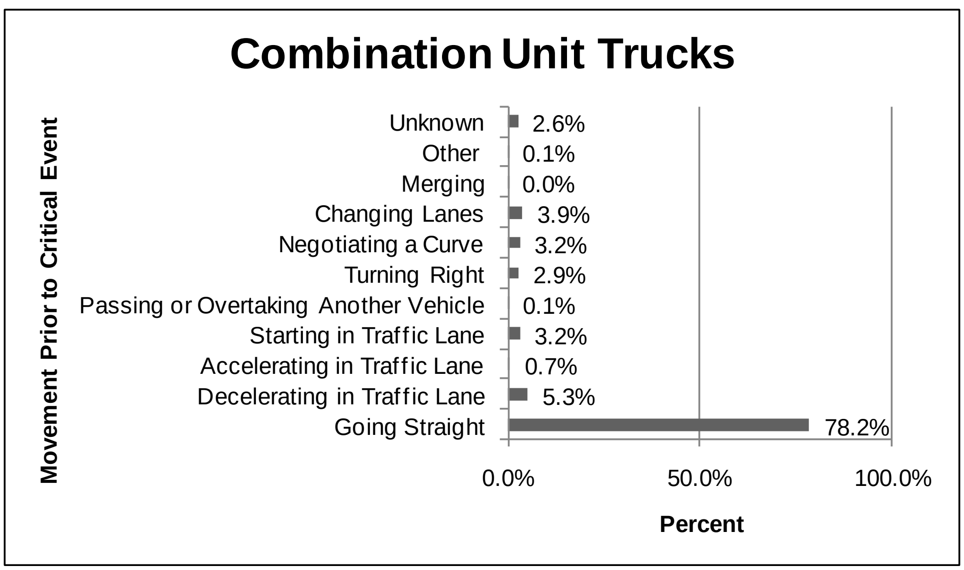

Figure 125. Bar graph. Movements prior to critical event – CUT striking vehicle.

The *Travel Speeds* for vehicles striking SUTs and CUTs are shown in figure 126 and figure 127. The majority of rear-end crashes for both SUTs and CUTs have an unknown *Travel Speed* for the striking vehicle. For SUTs, more than 34 percent of rear-end crashes occurred when the striking vehicle was traveling 5 to 35 mi/h (8.05 to 56.33 km/h). The speed range for the CUT rear-end crashes was more evenly distributed across the *Speed Limit Ranges*; however, it is interesting to note that a greater percentage of rear-end crashes occurred at higher *Travel Speeds* in CUTs than SUTs. CUT rear-end crashes were more likely than SUT rear-end crashes to have occurred when the *Travel Speed* of the striking vehicle was 36 mi/h (57.94 km/h) or greater (21 percent versus 13.6 percent, respectively).

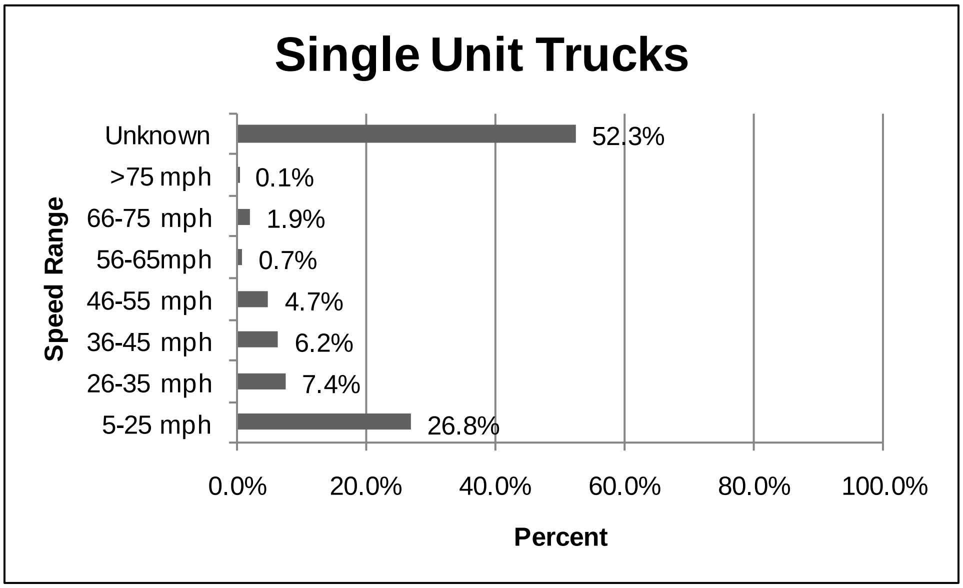

Figure 126. Bar graph. *Travel Speeds* – SUT striking vehicle.

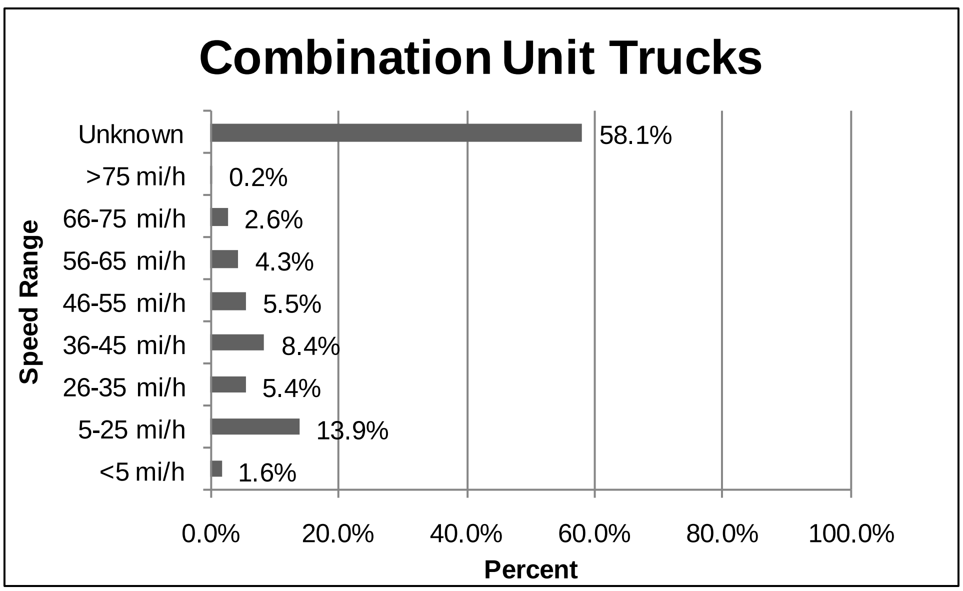

Figure 127. Bar graph. *Travel Speeds* – CUT striking vehicle.

The critical event is that event which made the rear-end crash imminent. Table 53 provides data for the critical event in both SUTs and CUTs. The data confirm that most rear-end crashes occurred when the SUT or CUT was stopped.

Table 53. Critical Event for SUT and CUT Striking Vehicles

Critical Event	SUT Count	SUT Percent	CUT Count	CUT Percent
Disabling Vehicle Failure (e.g., wheel fell off)	0	0	17	0
Excessive Speed	7	0	16	0
From Adjacent Lane (Same Direction) – Over Left Lane Line	11	0	76	1
From Adjacent Lane (Same Direction) – Over Right Lane Line	24	0	76	1
From Crossing Street, Turning into Same Direction	35	0	0	0
From Opposite Direction – Over Lane Line	12	0	4	0
From Parking Lane	34	0	0	0
Minor Vehicle Failure	0	0	6	0
Object in Roadway	4	0	5	0
Other Critical Event	44	0	0	0
Other Loss of Control	0	0	5	0
Other Vehicle Stopped	**5,568**	**43**	**4,319**	**42**
Over the Lane Line on the Left Side of Travel Lane	35	0	127	1
Over the Lane Line on the Right Side of Travel Lane	38	0	124	1
Other Vehicle Traveling in Same Direction while Decelerating	**3,480**	**27**	**3,087**	**30**
Other Vehicle Traveling in Same Direction with Lower Steady Speed	**3,518**	**27**	**2,381**	**23**
Unknown	0	0	10	0
Unknown Travel Direction of Other Motor Vehicle in Lane	0	0	5	0
Note. All figures rounded to the nearest integer.				

Figure 128 and figure 129 present the *Corrective Actions* attempted by the drivers of the striking vehicles in SUT and CUT rear-end crashes, respectively; these were obtained through the *Corrective Action* attempted data element. Only those rear-end crashes where a *Corrective Action* was recorded have been included in this analysis. In 70.7 percent of SUT rear-end crashes and 61.6 percent of CUT rear-end crashes, the driver of the striking vehicle attempted a braking maneuver. In CUTs, almost 12 percent of the braking maneuvers were accompanied by a steering maneuver. CUT rear-end crashes had a higher occurrence of *No Avoidance Maneuver* than SUTs (29.1 percent versus 16 percent, respectively). This was a change from 2001, which found that in 36.5 percent of SUT rear-end crashes there was no avoidance maneuver attempted versus 21.9 percent in CUT rear-end crashes.

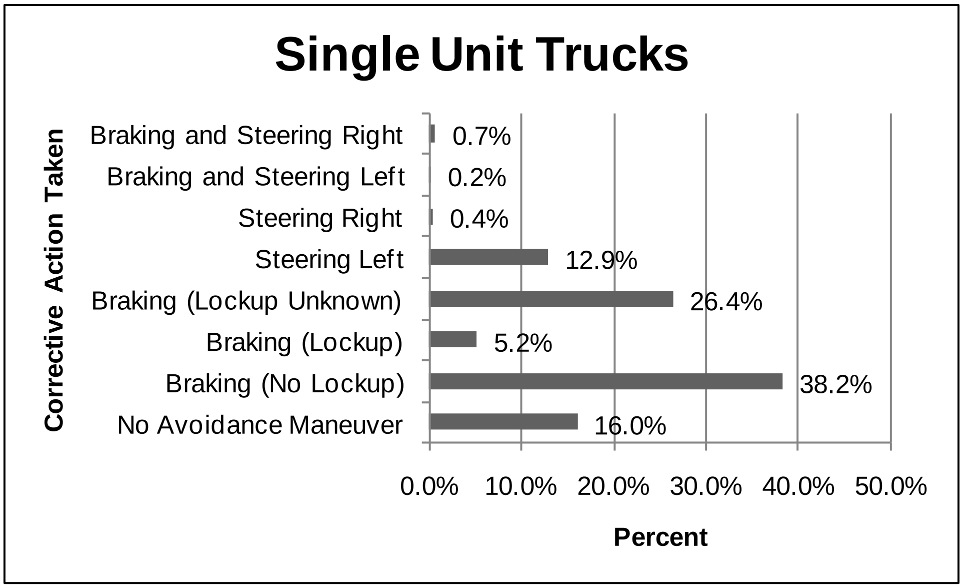

Figure 128. Bar graph. *Corrective Actions* attempted in SUT rear-end crashes – SUT striking vehicle driver.

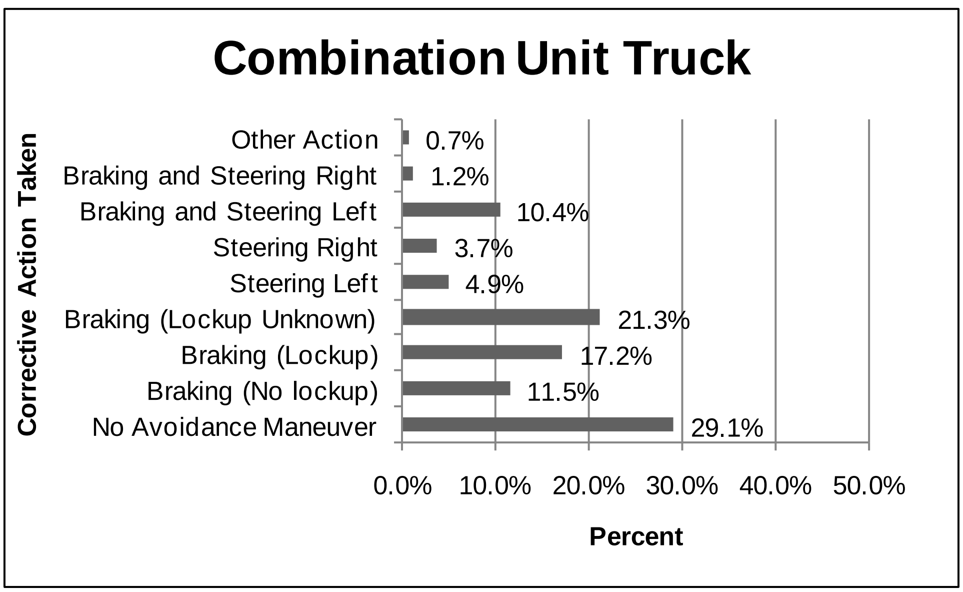

Figure 129. Bar graph. *Corrective Actions* attempted in CUT rear-end crashes – CUT striking vehicle driver.

Figure 130 and figure 131 illustrate the pre-crash vehicle control for both SUT and CUT rear-end crashes. Pre-crash vehicle control refers to whether or not the driver of the striking vehicle was in control of his/her vehicle or if he/she was reacting in a panic. In approximately 90 percent of both SUT and CUT rear-end crashes, the driver of the striking vehicle was tracking, indicating that the driver had control of the vehicle and was not in a panic mode. Tracking includes braking in a controlled manner. Braking and skidding longitudinally accounted for approximately 10 percent of the rear-end crashes for both SUT and CUT rear-end crashes.

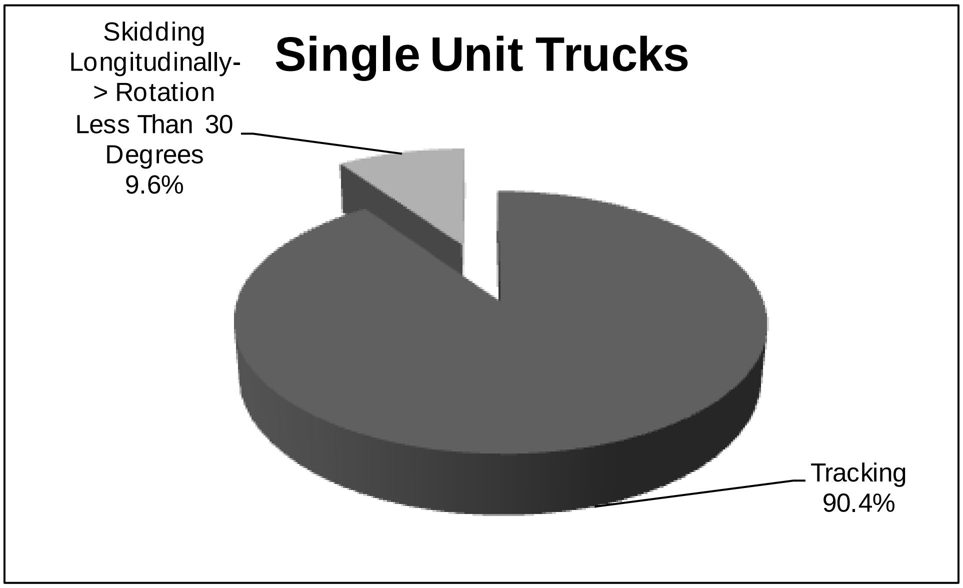

Figure 130. Pie Chart. Pre-rear-end crash vehicle control – SUT striking vehicle.

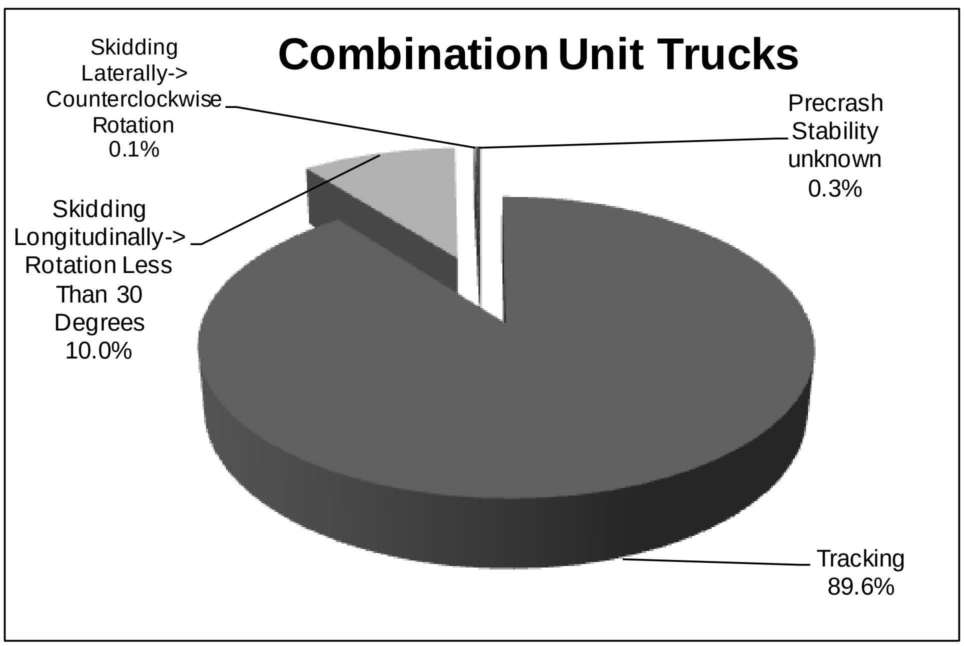

Figure 131. Pie Chart. Pre-rear-end crash vehicle control – CUT striking vehicle.

The data element *Vehicle Contributing Factors* provides information pertaining to any mechanical problems with the striking vehicle that may have contributed to the rear-end crash. As figure 132 and figure 133 illustrate, neither SUT nor CUT rear-end crashes had a vehicle contributing factor as a significant contributor in the crash.

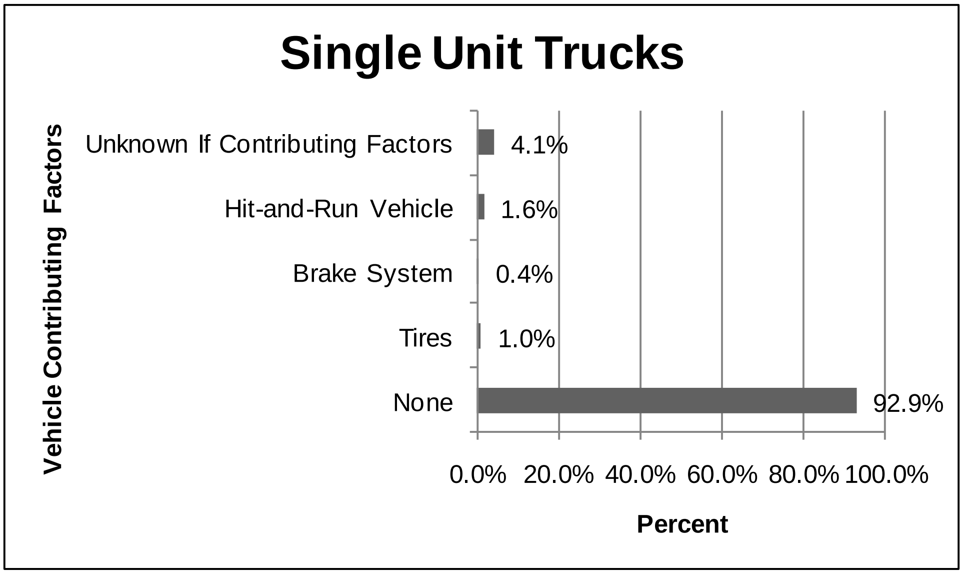

Figure 132. Bar graph. Vehicle contributing factors in rear-end crashes – SUT striking vehicle.

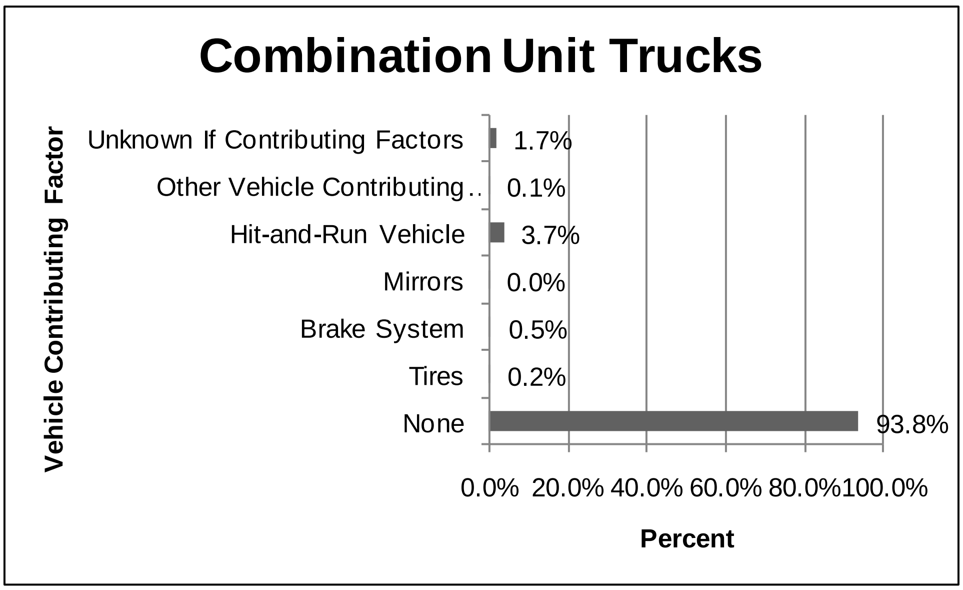

Figure 133. Bar graph. Vehicle contributing factors in rear-end crashes – CUT striking vehicle.

REAR-END CRASHES BY VEHICLE TYPE – PASSENGER VEHICLES VERSUS CUTs

Examining Rear-end Crash Characteristics

Where do Rear-end Crashes Occur?

Figure 134 and figure 135 illustrate the distribution of passenger vehicle and CUT rear-end crashes, respectively, between the IHS and other roadways. A much higher percentage of passenger vehicle rear-end crashes occurred on non-IHS versus IHS (90.2 percent versus 9.8

percent, respectively). CUT rear-end crashes were more evenly divided between non-IHS and IHS (58.1 percent and 41.9 percent, respectively).

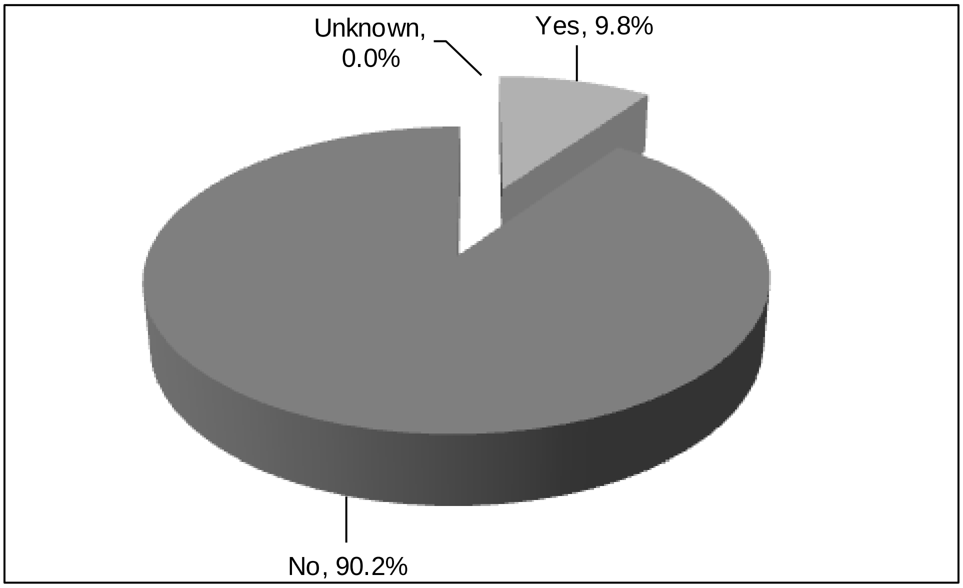

Figure 134. Pie Chart. Passenger vehicle rear-end crashes occurring on *Interstate Highways*.

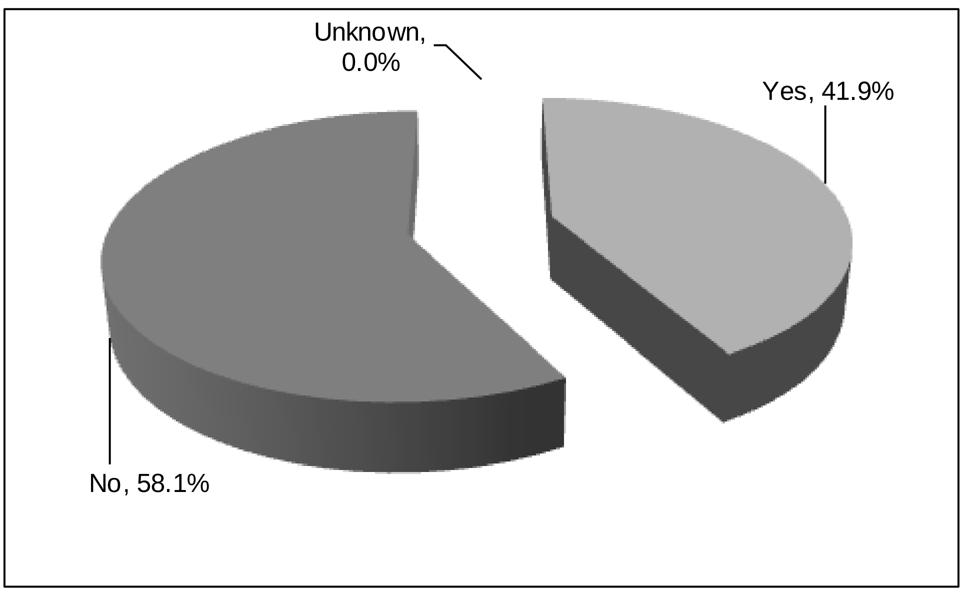

Figure 135. Pie Chart. CUT rear-end crashes occurring on *Interstate Highways*.

Using the data file *Relation to Junction*, one can determine where in the roadway these rear-end crashes occurred. The *Relation to Junction* variable describes where the first event occurred that led to the rear-end crash and is divided into Interchange (e.g., the roadway is separated by an elevation change) and Non-Interchange areas. Data on rear-end crashes based on *Relation to Junction* for passenger vehicles and CUTs are presented in table 54. Non-Interchange area rear-end crashes accounted for 96 percent of passenger vehicle rear-end crashes and 97 percent of CUT rear-end crashes. Figure 136 presents an illustration of Intersection and Non-Intersection areas. The intersection-related area is considered to be the area starting at the entrance to the intersection and extending approximately 150 ft (45.72 m) back from the intersection. Passenger vehicle rear-end crashes were, at a greater percentage, classified as Intersection or Intersection-Related (48 percent) than were CUT rear-end crashes (27 percent). CUT rear-end crashes occurred primarily in non-intersection related areas (i.e., those areas between intersections; 73 percent).

Table 54. *Relation to Junction* for Passenger Vehicle and CUT Rear-End Crashes

Relation to Junction	Passenger Vehicle Count	Passenger Vehicles Percent	CUT Count	CUT Percent
Non-Interchange Area				
Non-Junction	573,780	41	6,031	59
Intersection	50,658	4	146	1
Intersection-Related	615,916	44	2,649	26
Driveway, Alley Access, etc.	44,796	3	544	5
Entrance / Exit Ramp	10,686	1	21	0
Rail Grade Crossing	2,357	0	126	1
On a Bridge	4,925	0	204	2
Crossover Related	819	0	0	0
Other/Unknown, Non-interchange	33,792	2	260	3
Interchange Area		0		0
Non-junction	5,118	0	69	1
Intersection	747	0	0	0
Intersection-Related	5,486	0	0	0
Driveway, Alley Access, etc.	0	0	0	0
Entrance / Exit Ramp	48,660	3	115	1
On a Bridge	385	0	4	0
Other / Unknown, Non-interchange	7,571	1	89	1
Total	1,405,695	100	10,257	100
Note. All figures rounded to the nearest integer.				

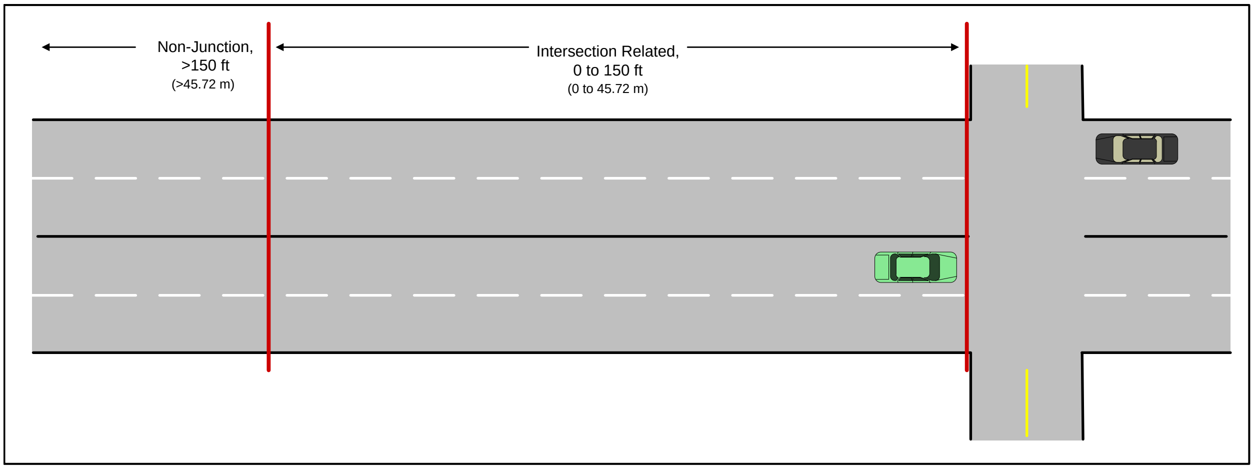

Figure 136. Diagram. Illustration of intersection-related and non-junction areas.

Table 55 provides the data regarding the major types of *Traffic Control Devices* present at passenger vehicle and CUT rear-end crash locations. Table 56 provides a listing of the *Traffic Control Devices*. In the majority of passenger vehicle and CUT rear-end crashes, there were no traffic controls present at the crash (51 percent and 70 percent, respectively). There was a traffic signal present in 33 percent of the passenger vehicle rear-end crashes and 18 percent of the CUT rear-end crashes.

Table 55. Traffic Control Characteristics for Passenger Vehicle and CUT Rear-End Crashes

	Passenger Vehicle Count	Passenger Vehicles Percent	CUT Count	CUT Percent
Description				
No Controls	721,152	51%	7,182	70%
Traffic Signal	463,406	33%	1,868	18%
Stop Sign	60,802	4%	46	0%
Warning Sign	20,607	1%	264	3%
Other / Unknown Signal	55,924	4%	542	5%
Other / Unknown Sign	83,254	6%	345	3%
Total	1,405,146*	100%	10,247**	100%
Note. All figures rounded to the nearest integer.				

* 549 Frequencies Missing in GES Database
**10 Frequencies Missing in GES Database

Table 56. Traffic Control Variables for Passenger Vehicle and CUT Rear-End Crashes

Description	Includes
No Controls	No Controls (00)
Traffic Signal	Traffic Control Signal (On Colors) (01) Flashing Traffic Control Signal or Flashing Beacon (04)
Stop Sign	Stop Sign (21)
Warning Sign	Advisory Speed Sign (40) Warning Sign for Road Conditions (41) Warning Sign for Road Construction (42) Warning Sign for Environment / Traffic (43)
Other / Unknown Sign	Yield Sign (22) School Zone (23) Passive Device (62) Other Sign (28) Unknown Sign (29)
Other / Unknown Signal	Other Traffic Signal (08) Unknown Traffic Signal (09) Active Devices (61) Officer, Crossing Guard (51)

Roadway Characteristics *of Rear-end Crashes*

Table 57 provides a comparison of the *Roadway Alignment* for rear-end crashes involving passenger vehicles and CUTs. In both passenger vehicle and CUT rear-end crashes, at least 90 percent of crashes occurred on roadways having *Straight* alignment profiles.

Table 57. Comparison of *Roadway Alignment* for Passenger Vehicle and CUT Rear-End Crashes

	Passenger Vehicle Count	Passenger Vehicles Percent	Heavy Truck Count	Heavy Trucks Percent
Description				
Straight	1,264,930	90%	9,485	92%
Curve	90,736	6%	686	7%
Unknown	50,029	4%	86	1%
Total	1,405,695	100%	10,257	100%
Note. All figures rounded to the nearest integer.				

The variable *Roadway Profile* describes the vertical alignment of the roadway. When a grade is indicated, the GES database does not differentiate between positive (uphill) and negative (downhill) grades. The *Roadway Profile* for both passenger vehicle and CUT rear-end crashes was level in at least 64 percent of the rear-end crashes (table 58). A greater percentage of CUT rear-end crashes occurred on a grade than did passenger vehicle rear-end crashes (20 percent versus 15 percent, respectively).

Table 58. Comparison of *Roadway Profile* for Passenger Vehicle and CUT Rear-End Crashes

Description	Passenger Vehicle Count	Passenger Vehicle Percent	CUT Count	CUT Percent
Level	910,140	65%	6,566	64%
Grade	209,034	15%	2,049	20%
Hillcrest	13,329	1%	50	0%
Sag	2,291	0%	0	0%
Other / Unknown	270,901	19%	1,592	16%
Total	1,405,695	100%	10,257	100%
Note. All figures rounded to the nearest integer.				

Environmental Conditions at Time of Crash

The *Atmospheric Conditions* under which passenger vehicle and CUT rear-end crashes occurred are presented in figure 137 and figure 138, respectively. More than 85 percent of passenger vehicle rear-end crashes occurred under good conditions (i.e., *No Adverse Atmospheric Conditions*). Only 13.7 percent of passenger vehicle rear-end crashes occurred when there were adverse environmental conditions (i.e., *Rain*, *Sleet*, *Snow*, or *Fog*). These findings were similar for CUT rear-end crashes. More than 88 percent of CUT rear-end crashes occurred under good *Atmospheric Conditions* (i.e., *No Adverse Atmospheric Conditions*) and 11.8 percent occurred under *Adverse Atmospheric Conditions* (figure 138). Rain was the leading adverse weather condition in CUT rear-end crashes (85.7 percent) followed by snow and fog (1.0 percent and 0.3 percent, respectively).

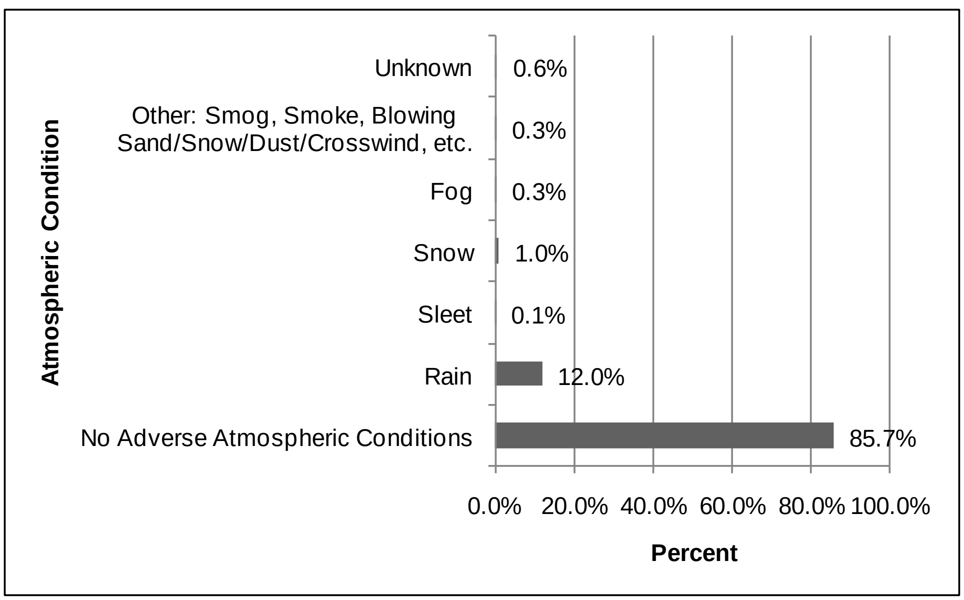

Figure 137. Bar graph. *Atmospheric Conditions* for passenger vehicle rear-end crashes.

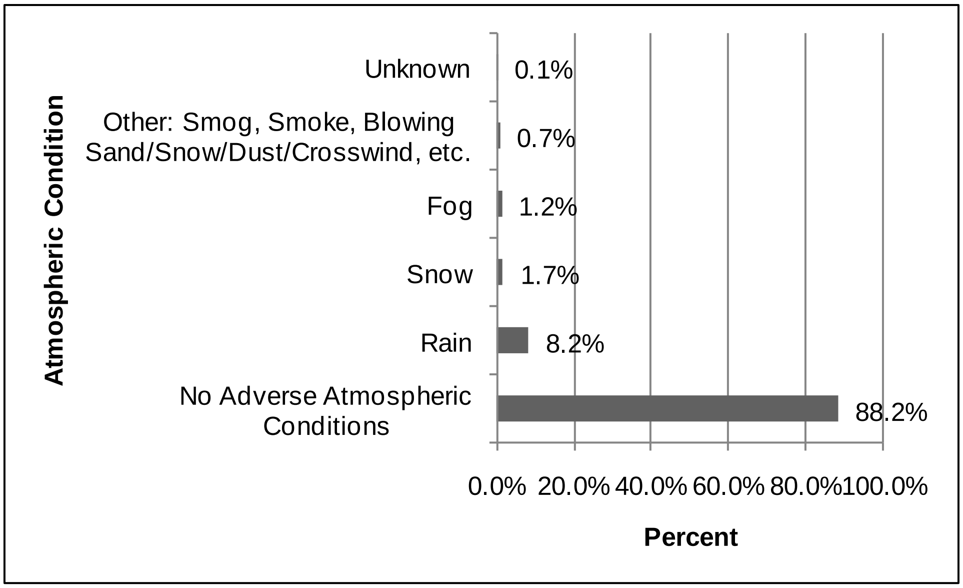

Figure 138. Bar graph. *Atmospheric Conditions* for CUT rear-end crashes.

Maximum Injury Severity for Passenger Vehicle and CUT Rear-end Crashes

Table 59 and table 60 illustrate overall maximum injury severity data for passenger vehicle rear-end crashes and CUT rear-end crashes, respectively. The statistics have been consolidated into three crash configurations: *Lead Vehicle Stopped*, *Lead Vehicle Traveling Slower*, and *Lead Vehicle Decelerating*. The data do not identify which vehicle sustained the maximum injury, it only notes that an injury was sustained. In passenger vehicle rear-end crashes, the *Rear-End Lead Vehicle Stopped* crash configuration resulted in the greatest number of fatalities and serious injuries (i.e., non-incapacitating injuries and incapacitating injuries). In 2001, the primary configuration for passenger vehicle rear-end crashes was also *Rear-End Lead Vehicle Stopped*. However, only 14 fatal passenger-vehicle rear-end crashes occurred in that configuration, while 82.8 percent or 386 fatalities occurred in the *Rear-End Lead Vehicle Traveling Slower* configuration. In 2006, 26 percent of fatalities from passenger vehicle rear-end crashes occurred in the *Rear-End Lead Vehicle Traveling Slower* configuration. Still, this number is high given that *Rear-End Lead Vehicle Traveling Slower* configuration could be attributed to only 9 percent of the passenger vehicle rear-end crashes. For CUTs, the *Rear-End Lead Vehicle Stopped* configuration also resulted in the greatest number of rear-end crash fatalities and serious injuries.

Table 59. Maximum Injury Severity for Passenger Vehicle Rear-End Crashes by Rear-End Configuration

Configuration	None	Possible	Non-Incapacitating	Incapacitating	Fatal	Unknown	Total
Stopped - Count	**616,220**	**188,618**	**39,924**	**14,243**	**461**	**5,662**	**865,127**
Percent of Severity Column	*61.5%*	*63.3%*	*57.1%*	*61.2%*	*49.3%*	*52.9%*	
Percent of All Crashes	*43.8%*	*13.4%*	*2.8%*	*1.0%*	*0.0%*	*0.4%*	
Slower - Count	**84,011**	**25,579**	**9,039**	**2,905**	**243**	**1,264**	**123,042**
Percent of Severity Column	*8.4%*	*8.6%*	*12.9%*	*12.5%*	*26.0%*	*11.8%*	
Percent of All Crashes	*6.0%*	*1.8%*	*0.6%*	*0.2%*	*0.0%*	*0.1%*	
Decelerating - Count	**252,275**	**74,442**	**18,734**	**4,854**	**230**	**3,009**	**353,544**
Percent of Severity Column	*25.2%*	*25.0%*	*26.8%*	*20.8%*	*24.5%*	*28.1%*	
Percent of All Crashes	*17.9%*	*5.3%*	*1.3%*	*0.3%*	*0.0%*	*0.2%*	
Other/Unknown	**50,270**	**9,398**	**2,268**	**1,287**	**2**	**758**	**63,982**
Percent of Severity Column	*5.0%*	*3.2%*	*3.2%*	*5.5%*	*0.2%*	*7.1%*	
Percent of All Crashes	*3.6%*	*0.7%*	*0.2%*	*0.1%*	*0.0%*	*0.1%*	
Total	**1,002,777**	**298,037**	**69,964**	**23,290**	**935**	**10,693**	**1,405,695**
Note. All figures rounded to the nearest integer.							

Table 60. Maximum Injury Severity for CUT Rear-End Crashes by Rear-End Configuration

Configuration	None	Possible	Non-Incapacitating	Incapacitating	Fatal	Unknown	Total
Stopped - Count	**3,114**	**532**	**566**	**400**	**47**	**0**	**4,658**
Percent of Severity Column	*46.5%*	*41.3%*	*48.5%*	*44.1%*	*57.4%*	*0.0%*	
Percent of All Crashes	*24.1%*	*4.1%*	*4.4%*	*3.1%*	*0.4%*	*0.0%*	
Slower - Count	**1,683**	**463**	**342**	**279**	**31**	**114**	**2,912**
Percent of Severity Column	*25.12%*	*35.96%*	*29.33%*	*30.76%*	*38.15%*	*98.19%*	
Percent of All Crashes	*13.03%*	*3.58%*	*2.65%*	*2.16%*	*0.24%*	*0.88%*	
Decelerating - Count	**1,902**	**292**	**259**	**228**	**4**	**2**	**2,687**
Percent of Severity Column	*28.4%*	*22.7%*	*22.2%*	*25.1%*	*4.5%*	*1.8%*	
Percent of All Crashes	*14.7%*	*2.3%*	*2.0%*	*1.8%*	*0.0%*	*0.0%*	
Other/Unknown	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Percent of Severity Column	*0.0%*	*0.0%*	*0.0%*	*0.0%*	*0.0%*	*0.0%*	
Percent of All Crashes	*0.0%*	*0.0%*	*0.0%*	*0.0%*	*0.0%*	*0.0%*	
Total	**6,699**	**1,287**	**1,167**	**907**	**82**	**116**	**10,257**
Note. All figures rounded to the nearest integer.							

Actions of the Striking Vehicle

Violations Charged Against the Striking Vehicle Driver

Figure 139 and Figure 140 illustrate the violations charged against the striking vehicle drivers in both passenger vehicles and CUTs, respectively. In more than 40 percent of both passenger vehicle and CUT rear-end crashes, no violations were charged. Drivers were charged with drugs, alcohol, reckless driving, or hit and runs in only 9.2 percent of passenger-vehicle rear-end crashes and 10.1 percent of heavy-truck rear-end crashes, respectively. Drivers in the striking vehicle were charged with speeding in 9.3 percent of passenger vehicle rear-end crashes and 12.1 percent of CUT rear-end crashes, respectively.

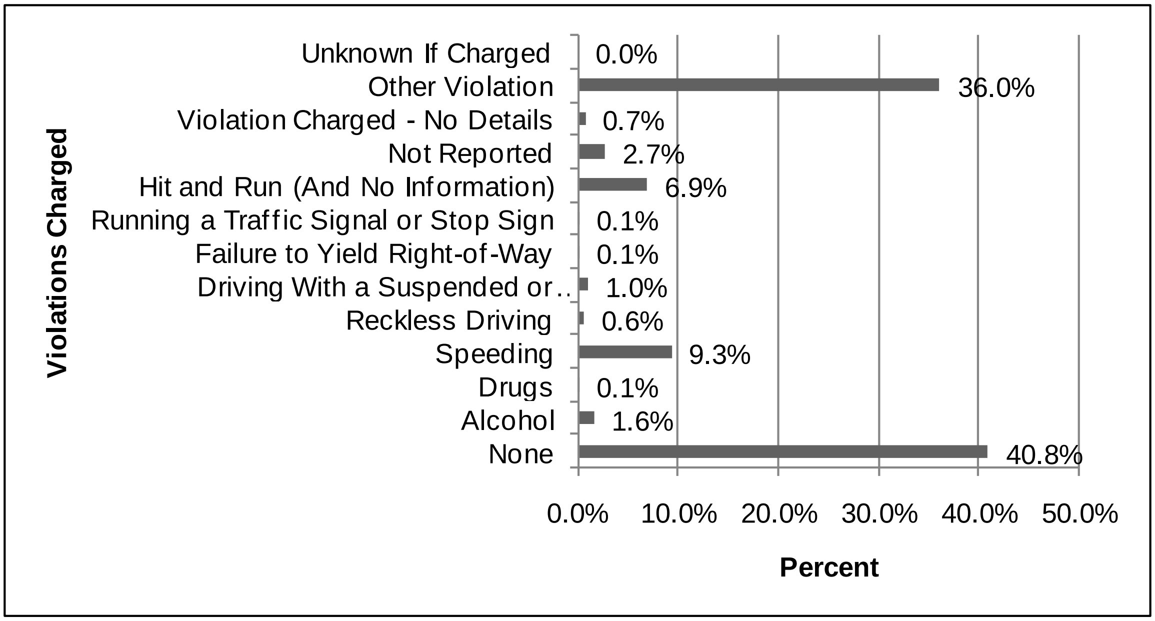

Figure 139. Bar graph. Violations charged to drivers of vehicles striking passenger vehicles in passenger vehicle rear-end crashes.

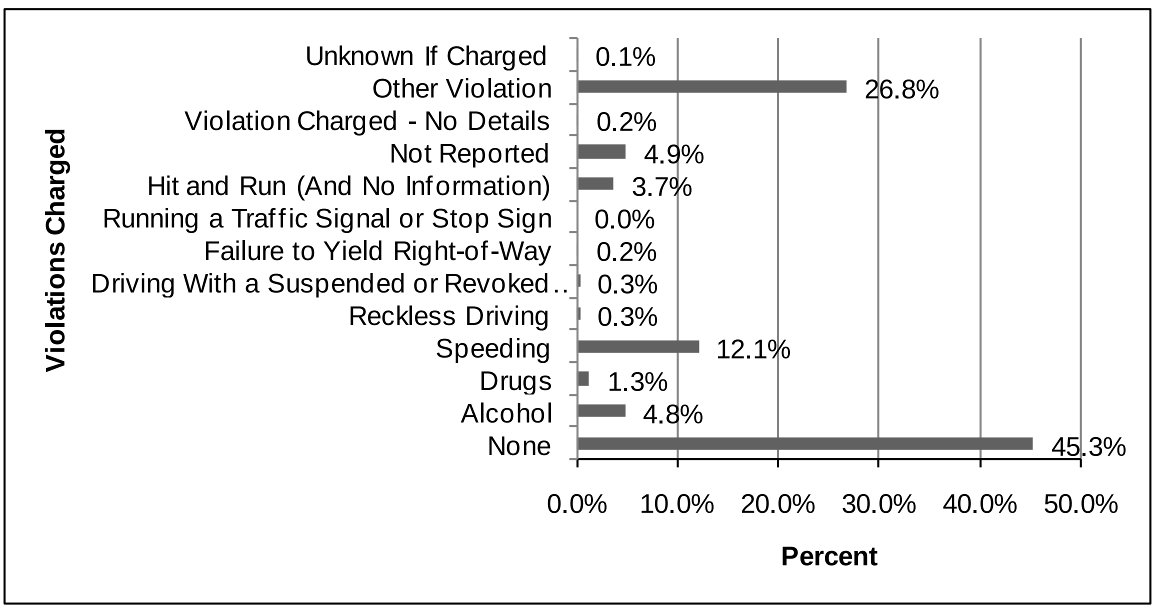

Figure 140. Bar graph. Violations charged to drivers of vehicles striking CUTs in CUT rear-end crashes.

REAR-END CRASHES BY TRAILER NUMBER AND TYPE

This section examines the type of trailer units involved in CUT rear-end crashes. First, an overview of the CUT trailer number and type is explored. Second, a crash data analysis will be conducted. The analyses examine characteristics associated with the roadway, including: *Roadway Type*, *Relation to Junction*, *Traffic Control Devices*, *Roadway Alignment*, *Roadway*

Profile, and *Speed Limit Range*. Additionally, environmental conditions at the time of the rear-end crash are discussed. The section concludes with examinations of the actions of the truck being struck in the rear-end crash and the actions of the striking vehicle.

CUT Trailer Number and Type

The number of trailing units being pulled by power units (tractors) involved in rear-end CUT crashes is illustrated in figure 141. Trucks pulling one trailer unit accounted for 92 percent of the body types involved in CUT rear-end crashes. A much smaller percentage (4 percent) occurred with the tractor pulling no trailer, or "bob tail" configuration. An even smaller percentage (3 percent) of CUT rear-end crashes occurred with trucks pulling two trailer units. As such, the remainder of this section focuses on tractors pulling one trailer.

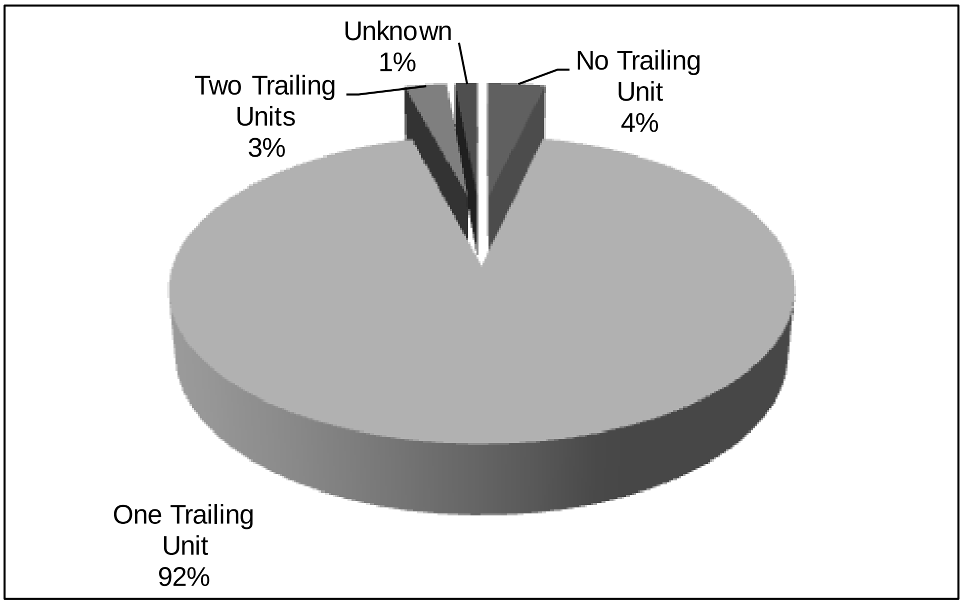

Figure 141. Pie Chart. Number of trailing units pulled by power units (tractors) involved in rear-end CUT crashes.

Trailer Unit Configurations

When examining the trailer unit configurations in CUT rear-end crashes that involved tractors pulling one trailer, the exact trailer type being pulled was unknown in more than 43 percent of the CUT rear-end crashes. Of the known configurations, the most common trailer unit type was the van/enclosed box configuration, which accounted for 32.4 percent of the population of trucks pulling one trailing unit that were involved in CUT rear-end crashes. This was followed by flatbed trailers (12.8 percent), cargo tank trailers (4.8 percent), dump (5.5 percent), auto transporter (0.8 percent), and garbage/refuse (0.1 percent). The remainder of this section will focus on these configurations (figure 142).

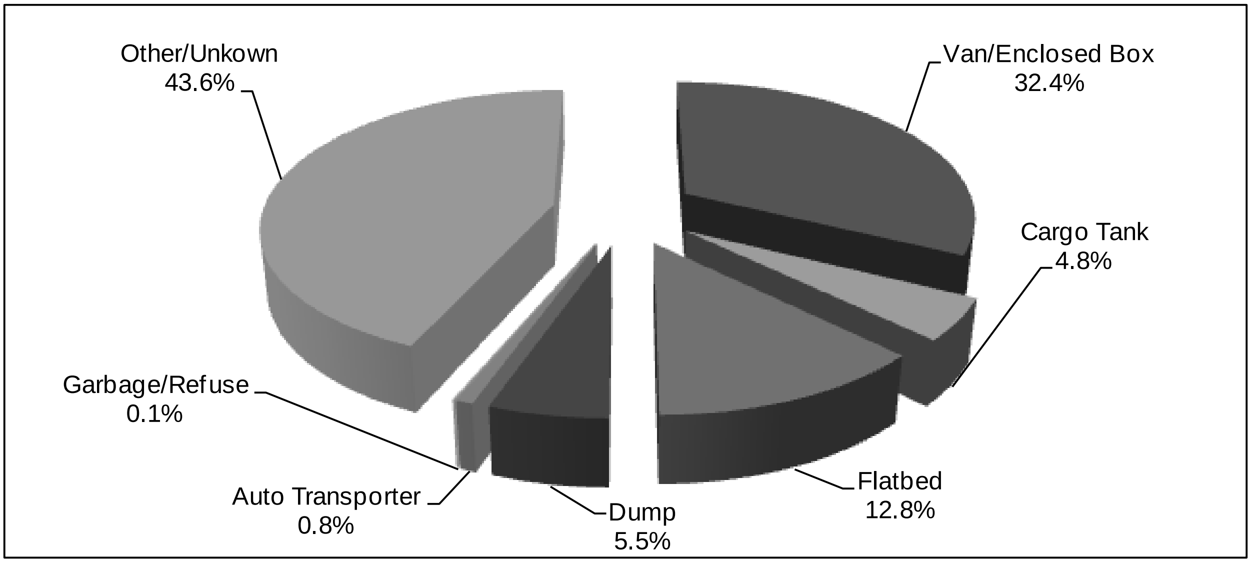

Figure 142. Pie Chart. CUT trailer type distribution in rear-end crashes.

Drawings of typical trailer configurations are provided in figure 143 through figure 148.[3] Note that the configurations of the *Refuse/Garbage* and *Dump* trailers are similar. However, the dump trailer is permitted to pivot along its rear axle point while this feature is not present in the refuse/garbage trailer.

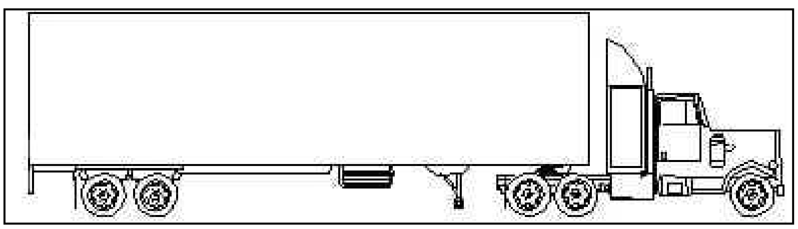

Figure 143. Diagram. Typical Van/Enclosed Box trailer configuration.

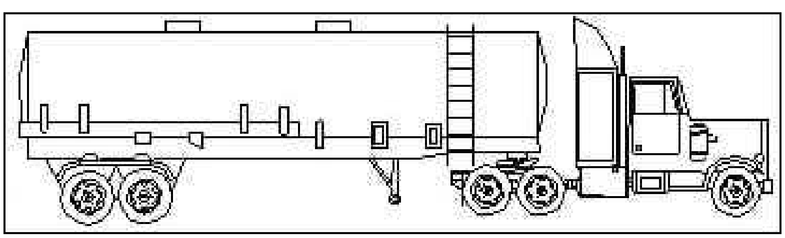

Figure 144. Diagram. Typical Cargo Tank trailer configuration.

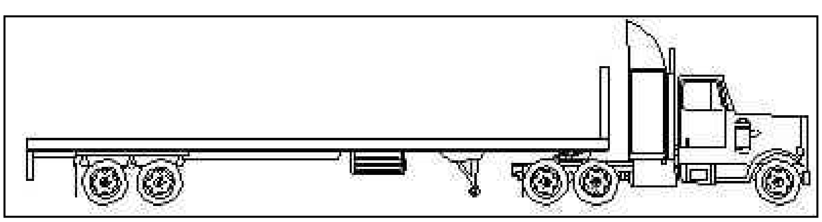

Figure 145. Diagram. Typical Flatbed trailer configuration.

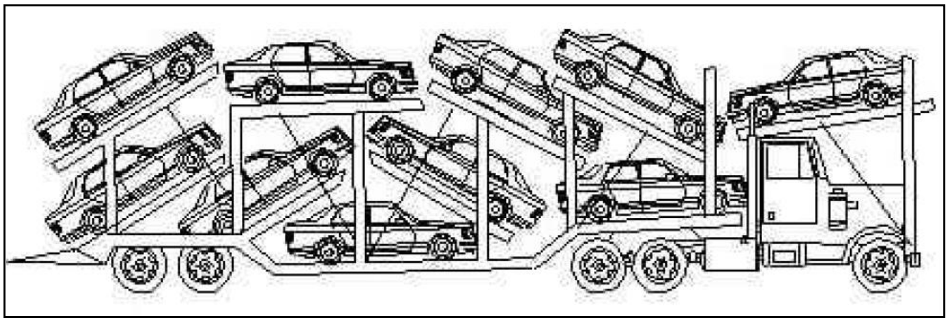

Figure 146. Diagram. Typical Auto Transporter trailer configuration.

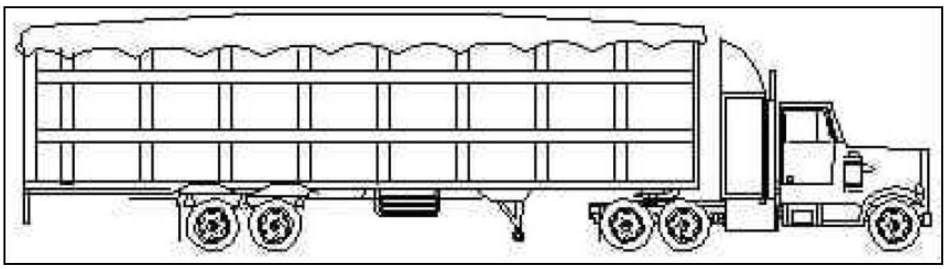

Figure 147. Diagram. Typical Garbage/Refuse trailer configuration.

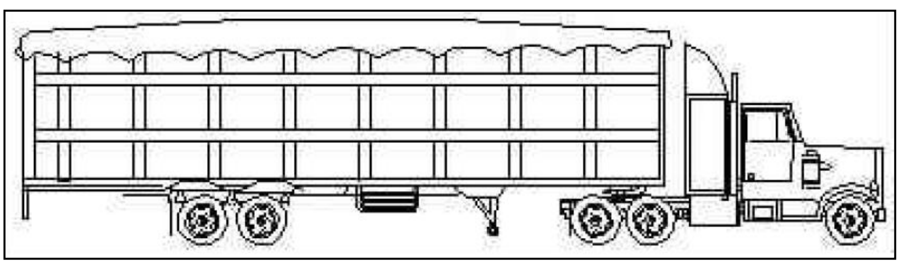

Figure 148. Diagram. Typical Dump trailer configuration.

Crash Data Analysis

The crash data analysis contained in this section focuses on CUT rear-end crashes. Statistics regarding the characteristics of these crashes have been separated into the various trailer types.

Roadway Type – Interstate Highway

Figure 149, figure 150, and figure 151 illustrate the distribution of cargo body types for each of the CUT rear-end crash configurations (i.e., *Rear-End Stopped*, *Rear-End Slower*, and *Rear-End Decelerating*) that occur on the IHS. In each of these configurations, the lead vehicle is the heavy truck. The van/enclosed box cargo body type accounts for more than 45 percent of CUT rear-end crashes for all three crash configurations. The second most common cargo body type was the *Other* classification. These two body types represent 85 percent of the population of trucks involved in CUT rear-end crashes; therefore, it is to be expected that these two body types are involved in the greatest percentage of CUT rear-end crashes.

For *Rear-End Lead Vehicle Stopped* and *Rear-End Lead Vehicle Traveling Slower* crash configurations, the flatbed body type is the next most prevalent (9.3 percent and 12.7 percent, respectively). However, in the *Rear-end Lead Vehicle Decelerating* crash configuration, cargo tanks are more prevalent than flatbeds (7.7 percent versus 2.5 percent, respectively).

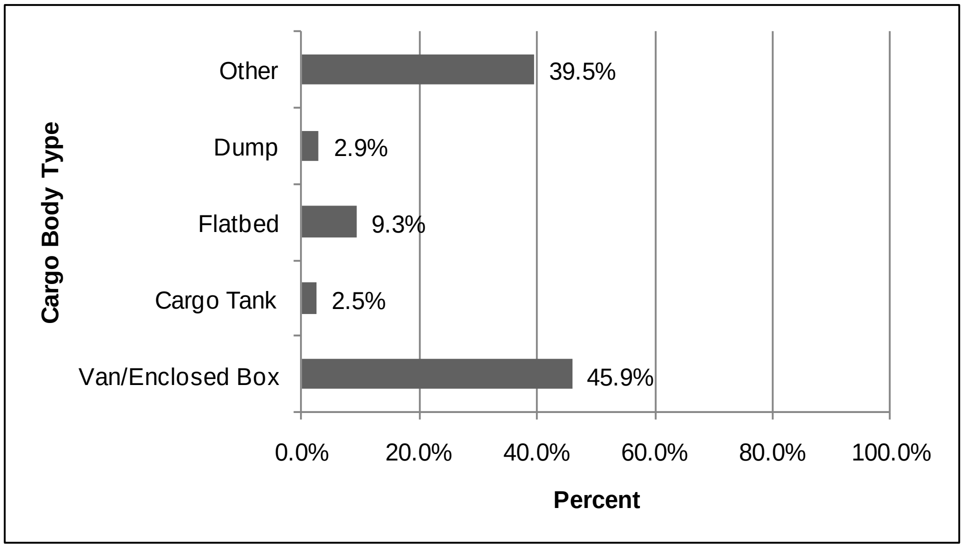

Figure 149. Bar graph. CUT Cargo Body type distribution for *Rear-End Stopped* crash configuration occurring on *Interstate Highways*.

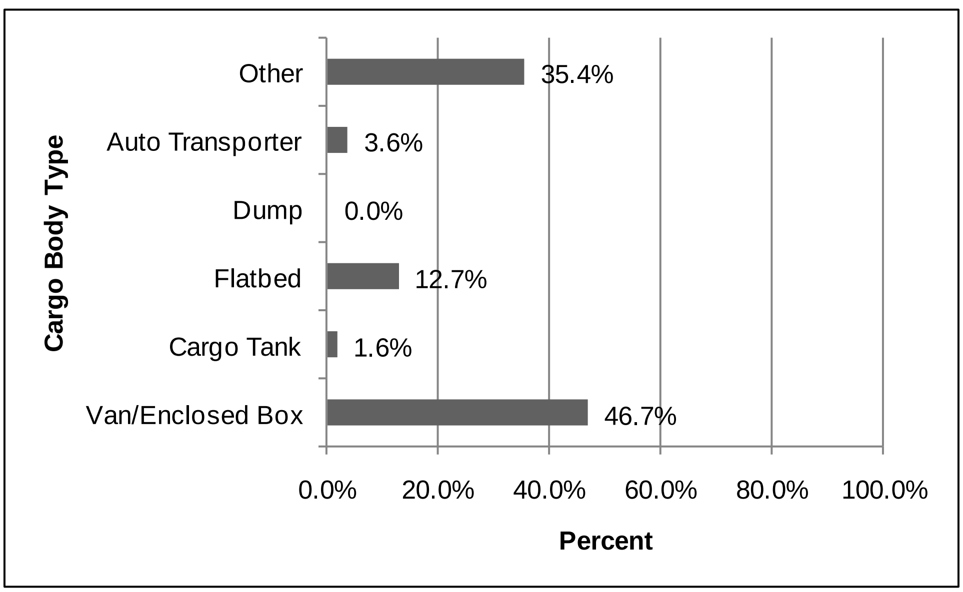

Figure 150. Bar graph. CUT Cargo Body type distribution for *Rear-End Slower* crash configuration occurring on *Interstate Highways*.

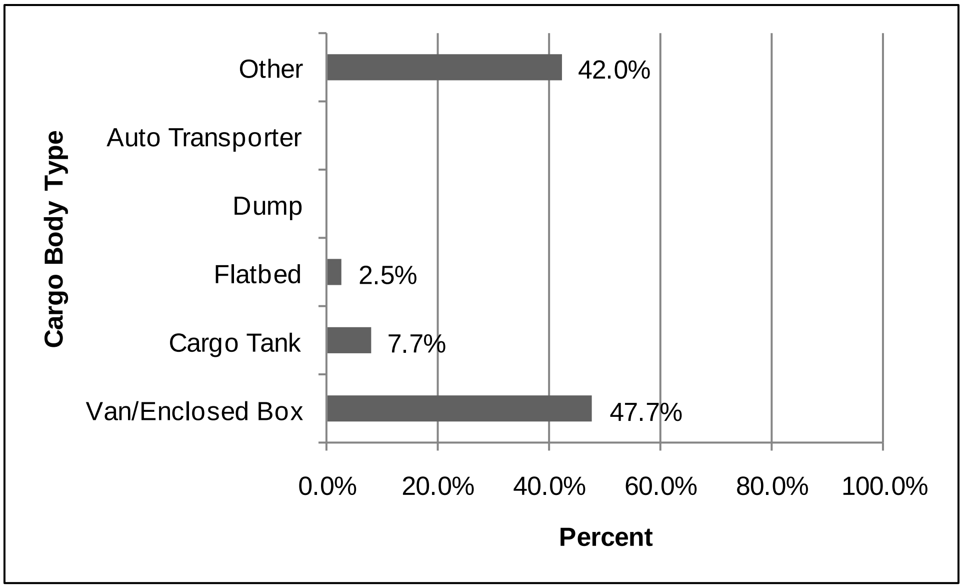

Figure 151. Bar graph. CUT Cargo Body type distribution for *Rear-End Decelerating* crash configuration occurring on *Interstate Highways*.

Relation to Junction

Table 61 to

table 67 illustrate the distribution of cargo body types for each of the CUT rear-end crash configurations (i.e., *Rear-End Stopped*, *Rear-End Slower,* and *Rear-End Decelerating*) that occurred on the IHS. In each of these CUT rear-end crash configurations, the lead vehicle is the heavy truck.

Section 5.2.1 of this report examined *Relation to Junction* configurations for CUT rear-end crashes involving passenger vehicles and heavy trucks. This section further examines the *Relation to Junction* variable for heavy trucks and breaks the distribution of CUT rear-end crashes down by cargo body type configuration. The variable *Relation to Junction* is segregated into *Interchange* and *Non-Interchange* areas. An *Interchange* is a junction of roadway, typically a highway, that uses elevation to allow traffic to move through the junction without directly crossing other traffic flows. A *Non-Interchange* is an area where the roadways are not separated by an elevation change. Because a minimal number of CUT rear-end crashes occur in *Interchange* areas, those rear-end crashes that occurred within areas described as *Interchange* were deleted from the sample.

In all cargo body types, except for auto transporters, a consistent finding was that the primary *Relation to Junction* is *Non-interchange/Non-junction*. CUT rear-end crashes in *Non-junction* areas (i.e., those areas between intersections that are not contained in the other data codes) accounted for 62 percent of the CUT rear-end crashes, while CUT rear-end crashes in *Intersection*-related areas accounted for 26 percent of the crashes.

CUT rear-end crashes involving the van/enclosed box cargo body type occurred 23 percent of the time within an intersection. An additional 6 percent of CUT rear-end crashes with a van/enclosed box cargo body type occurred when the vehicle was in a driveway/alley access area. Only 4 percent of CUT rear-end crashes with a van/enclosed box cargo body type occurred when the truck was stopped on a bridge.

Forty-one percent of the CUT rear-end crashes with a cargo tank-related body type had occurred when the truck was in a stopped position. Of these, 21 percent were intersection or intersection-related crashes, 12 percent occurred in driveway/alley access areas, and 5 percent occurred on a rail grade crossing. Flatbeds were struck 615 times while stopped, 29 percent of which were intersection-related and 4 percent occurred in intersections and driveways/alley access areas. Of the 555 dump truck rear-end crashes, 69 percent occurred when the truck was in a stopped position, including 19 percent which occurred on rail grade crossings. Auto transporter rear-end crashes were intersection-related in 82 percent of the CUT rear-end crashes. Of these, 100 percent occurred when the truck was stopped.

Table 61. *Relation to Junction* – Van/Enclosed Box Body Type by Rear-End Accident Type

Relation to Junction	Stopped	Slower	Decelerating	Unknown	Total
Non-Interchange Area					
Non-Junction	429	895	627	244	2,195
Intersection	0	0	0	0	0
Intersection-Related	573	131	41	0	744
Driveway, Alley Access	15	52	114	0	181
Entrance / Exit Ramp	0	0	0	0	0
Rail Grade Crossing	0	0	0	0	0
On a Bridge	122	17	0	0	139
Crossover-Related	0	0	0	0	0
Other Non-Interchange	0	0	0	0	0
Total	1,138	1,095	781	244	3,258

Table 62. *Relation to Junction* – Cargo Tank Body Type by Rear-End Accident Type

Relation to Junction	Stopped	Slower	Decelerating	Unknown	Total
Non-Interchange Area					
Non-Junction	130	147	121	0	398
Intersection	4	0	0	0	4
Intersection-Related	39	24	3	0	66
Driveway, Alley Access	25	0	0	0	25
Entrance / Exit Ramp	0	0	0	0	0
Rail Grade Crossing	10	0	0	0	10
On a Bridge	0	0	0	0	0
Crossover-Related	0	0	0	0	0
Other Non-Interchange	0	0	0	0	0
Total	208	171	124	0	503

Table 63. *Relation to Junction* – Flatbed Body Type by Rear-End Accident Type

Relation to Junction	Stopped	Slower	Decelerating	Unknown	Total
Non-Interchange Area					
Non-Junction	412	329	83	134	958
Intersection	12	12	0	0	24
Intersection-Related	178	0	118	0	296
Driveway, Alley Access	12	0	0	8	20
Entrance / Exit Ramp	0	0	0	0	0
Rail Grade Crossing	0	0	0	0	0
On a Bridge	0	0	0	0	0
Crossover-Related	0	0	0	0	0
Other Non-Interchange	0	0	0	0	0
Total	615	341	201	142	1299

Table 64. *Relation to Junction* – Dump Body Type by Rear-End Accident Type

Relation to Junction	Stopped	Slower	Decelerating	Unknown	Total
Non-Interchange Area					
Non-Junction	124	88	68	0	280
Intersection	10	0	0	0	10
Intersection-Related	144	0	16	0	160
Driveway, Alley Access	0	0	0	0	0
Entrance / Exit Ramp	0	0	0	0	0
Rail Grade Crossing	105	0	0	0	105
On a Bridge	0	0	0	0	0
Crossover-Related	0	0	0	0	0
Other Non-Interchange	0	0	0	0	0
Total	384	88	84	0	555

Table 65. ***Relation to Junction*** **– Auto Transporter Body Type by Rear-End Accident Type**

Relation to Junction	Stopped	Slower	Decelerating	Unknown	Total
Non-Interchange Area					
Non-Junction	0	0	0	0	0
Intersection	0	0	0	0	0
Intersection-Related	69	0	0	0	69
Driveway, Alley Access	0	0	0	15	15
Entrance / Exit Ramp	0	0	0	0	0
Rail Grade Crossing	0	0	0	0	0
On a Bridge	0	0	0	0	0
Crossover-Related	0	0	0	0	0
Other Non-Interchange	0	0	0	0	0
Total	69	0	0	15	84

Table 66. ***Relation to Junction*** **– Garbage/Refuse Body Type by Rear-End Accident Type**

Relation to Junction	Stopped	Slower	Decelerating	Unknown	Total
Non-Interchange Area					
Non-Junction	0	0	0	8	8
Intersection	0	0	0	0	0
Intersection-Related	0	0	0	0	0
Driveway, Alley Access	0	0	0	0	0
Entrance / Exit Ramp	0	0	0	0	0
Rail Grade Crossing	0	0	0	0	0
On a Bridge	0	0	0	0	0
Crossover-Related	0	0	0	0	0
Other Non-Interchange	0	0	0	0	0
Total	0	0	0	8	8

Table 67. *Relation to Junction* – Other/Unknown Body Type by Rear-End Accident Type

Relation to Junction	Stopped	Slower	Decelerating	Unknown	Total
Non-Interchange Area					
Non-Junction	822	950	601	63	2,435
Intersection	5	90	12	0	107
Intersection-Related	775	32	440	5	1,253
Driveway, Alley Access	311	15	0	0	327
Entrance / Exit Ramp	21	0	0	20	40
Rail Grade Crossing	6	0	5	0	10
On a Bridge	0	0	0	0	0
Crossover-Related	0	0	0	0	0
Other Non-Interchange	0	0	260	0	260
Total	1,939	1,088	1,318	87	4,432

Traffic Control Devices

The *Traffic Control Devices* present at the location of the CUT rear-end crash for each of the body types are listed in table 68 through table 74. Consistent with 2001 data and findings above that indicate that most CUT rear-end crashes do not occur within an intersection, the category *No Traffic Control* made up the largest percentage of *Traffic Control Devices* with 86 percent. Of those CUT rear-end crashes that occurred without a traffic control, the heavy truck was stopped 35 percent of the time, traveling slower 34 percent of the time, or decelerating 24 percent of the time.

Only 5 percent of the CUT rear-end crashes occurred where there was a stop sign, warning sign, or traffic signal. Of the three, warning signs were the most common (3 percent). Regardless of the body type, 100 percent of the CUT rear-end crashes that took place when a traffic signal was present occurred when the truck was stopped. When there was a stop sign present in a CUT rear-end crash, 81 percent of the time the truck was stopped. When a warning sign was present, the truck was stopped in 27 percent of the CUT rear-end crashes and was slowing in 48 percent.

Note that the total number of CUT rear-end crashes included in this section varies from the other sections. The difference corresponds to missing data in the GES database.

Table 68. *Traffic Control Devices* for Van/Enclosed Box Body Type by Rear-End Accident Type

Van/Enclosed Box Body Type Traffic Control Devices	Stopped	Slower	Decelerating	Unknown	Total
No Controls	585	998	779	244	2,606
Other/Unknown	32	16	0	0	48
Stop Sign	5	0	0	0	5
Warning Sign	2	0	10	5	17
Traffic Signals	45	0	0	0	45
Total	669	1014	789	249	2,721

Table 69. *Traffic Control Devices* for Cargo Tank Body Type by Rear-End Accident Type

Cargo Tank Body Type Traffic Control Devices	Stopped	Slower	Decelerating	Unknown	Total
No Controls	153	151	121	0	425
Other/Unknown	10	0	0	0	10
Stop Sign	5	0	0	0	5
Warning Sign	0	0	0	0	0
Traffic Signals	0	0	0	0	0
Total	168	151	121	0	440

Table 70. Traffic Control Devices for Flatbed Body Type by Rear-End Accident Type

Flatbed Body Type Traffic Control Devices	Stopped	Slower	Decelerating	Unknown	Total
No Controls	449	330	154	126	1,059
Other/Unknown	16	3	52	16	87
Stop Sign	0	0	0	0	0
Warning Sign	0	10	0	0	10
Traffic Signals	12	0	0	0	12
Total	477	343	206	142	1,168

Table 71. *Traffic Control Devices* for Dump Body Type by Rear-End Accident Type

Dump Body Type Traffic Control Devices	Stopped	Slower	Decelerating	Unknown	Total
No Controls	170	83	68	0	321
Other/Unknown	105	5	0	0	110
Stop Sign	0	0	0	0	0
Warning Sign	0	0	0	0	0
Traffic Signals	0	0	0	0	0
Total	275	88	68	0	431

Table 72. *Traffic Control Devices* for Auto Transporter Body Type by Rear-End Accident Type

Auto Transporter Body Type Traffic Control Devices	Stopped	Slower	Decelerating	Unknown	Total
No Controls	12	0	0	15	27
Other/Unknown	0	0	0	0	0
Stop Sign	0	0	0	0	0
Warning Sign	0	0	0	0	0
Traffic Signals	0	0	0	0	0
Total	12	0	0	15	27

Table 73. ***Traffic Control Devices*** **for Garbage/Refuse Body Type by Rear-End Accident Type**

Garbage/Refuse Body Type Traffic Control Devices	Stopped	Slower	Decelerating	Unknown	Total
No Controls	45	0	0	7	52
Other/Unknown	0	0	0	0	0
Stop Sign	0	0	0	0	0
Warning Sign	0	0	0	0	0
Traffic Signals	0	0	0	0	0
Total	45	0	0	7	52

Table 74. ***Traffic Control Devices*** **for Other/Unknown Body Type by Rear-End Accident Type**

Other Unknown/Body Type Traffic Control Devices	Stopped	Slower	Decelerating	Unknown	Total
No Controls	1,159	968	665	98	2,890
Other/Unknown	282	0	275	10	567
Stop Sign	27	9	0	0	36
Warning Sign	70	118	54	0	242
Traffic Signals	24	0	0	0	24
Total	1,562	1,095	993	109	3,759

Roadway Alignment by Cargo Body Type by Accident Type Grouping

Table 75 through table 81 illustrate the alignment of the roadway for the CUT rear-end crashes broken down by cargo truck body type. The straight Roadway Alignment accounted for 93 percent of CUT rear-end crashes. Of these CUT rear-end crashes, 42 percent occurred when the heavy truck was stopped, 29 percent occurred when the heavy truck was traveling slower, and 23 percent occurred when the heavy truck was decelerating.

Only 7 percent of CUT rear-end crashes occurred on roadways with curved alignments. When the Roadway Alignment was curved, 48 percent of the CUT rear-end crashes occurred when the heavy truck was stopped and 43 percent occurred when the truck was decelerating. Only 8 percent occurred when the heavy truck was the Lead Vehicle Traveling Slower.

Unknown Roadway Alignments accounted for only 1 percent of the CUT rear-end crashes. Lead Vehicle Stopped and Lead Vehicle Traveling Slower made up approximately 33 percent of the CUT rear-end crashes, while 67 percent of the CUT rear-end crashes occurred when the heavy truck was decelerating in the cases of unknown Roadway Alignments.

Auto transporter rear-end crashes occurred 82 percent of the time when the transporter was stopped on a roadway with straight alignment. The greatest percentage (46 percent) of flatbed rear-end crashes also occurred when the flatbed was stopped on a roadway with straight alignment.

Table 75. *Roadway Alignment* by Van/Enclosed Box Body Type by Rear-End Accident Type

Van/Enclosed Box Body Type *Roadway Alignment* Description	Stopped	Slower	Decelerating	Unknown	Total
Straight	1,151	1,104	743	249	3,247
Curve	13	26	23	0	62
Unknown	16	0	57	0	74
Total	1,181	1,129	823	249	3,382

Table 76. *Roadway Alignment* by Cargo Tank Body Type by Rear-End Accident Type

Cargo Tank Body Type *Roadway Alignment* Description	Stopped	Slower	Decelerating	Unknown	Total
Straight	208	176	119	0	502
Curve	0	0	5	0	5
Unknown	0	0	0	0	0
Total	208	176	124	0	507

Table 77. *Roadway Alignment* by Flatbed Body Type by Rear-End Accident Type

Flatbed Body Type *Roadway Alignment* Description	Stopped	Slower	Decelerating	Unknown	Total
Straight	611	343	226	142	1,323
Curve	16	0	0	0	16
Unknown	0	0	0	0	0
Total	627	343	226	142	1,339

Table 78. *Roadway Alignment* by Dump Body Type by Rear-End Accident Type

Dump Body Type *Roadway Alignment* Description	Stopped	Slower	Decelerating	Unknown	Total
Straight	383	83	84	0	550
Curve	6	5	0	0	10
Unknown	0	0	0	0	0
Total	388	88	84	0	560

Table 79. *Roadway Alignment* by Auto Transporter Body Type by Rear-End Accident Type

Auto Transporter Body Type *Roadway Alignment* Description	Stopped	Slower	Decelerating	Unknown	Total
Straight	69	0	0	15	84
Curve	0	0	0	0	0
Unknown	0	0	0	0	0
Total	69	0	0	15	84

Table 80. *Roadway Alignment* by Garbage/Refuse Box Body Type by Rear-End Accident Type

Garbage/Refuse Box Body Type *Roadway Alignment* Description	Stopped	Slower	Decelerating	Unknown	Total
Straight	0	0	0	6	6
Curve	0	0	0	2	2
Unknown	0	0	0	0	0
Total	0	0	0	8	8

Table 81. *Roadway Alignment* by Other/Unknown Body Type by Rear-End Accident Type

Other/Unknown Body Type *Roadway Alignment* Description	Stopped	Slower	Decelerating	Unknown	Total
Straight	1,653	1,076	1,068	165	3,962
Curve	296	22	266	5	588
Unknown	0	12	0	0	12
Total	1,949	1,110	1,334	170	4,562

Roadway Profiles by Cargo Body Type by Accident Type Grouping

The following tables (table 82 through table 88) present data on *Roadway Profile* by CUT rear-end crash configuration and cargo body type. More than 64 percent of the CUT rear-end crashes occurred on level roads. Of these, 42 percent occurred when the heavy truck was stopped, 25 percent when the truck was traveling slower, and 28 percent when the truck was decelerating. The *Roadway Profile Grade* accounted for 20 percent of the CUT rear-end crashes. When CUT rear-end crashes occurred on a grade, the heavy truck was: traveling slower (38 percent), stopped (30 percent), or decelerating (28 percent). Only 1 percent of CUT rear-end crashes occurred on a hillcrest. Of all the body types, the dump body type had the highest percentage of CUT rear-end crashes that occurred on a grade (42 percent). Ninety-five percent of the dump-involved CUT rear-end crashes that occurred on a grade took place when the dump was in the stopped position.

Table 82. *Roadway Profile* by Van/Enclosed Box Body Type by Accident Type

Van/Enclosed Box Body Type Rear-End Accident Type	Stopped	Slower	Decelerating	Unknown	Total
Description					
Level	809	717	407	142	2,075
Grade	213	308	372	23	915
Hillcrest	9	8	6	0	24
Unknown	149	97	38	85	369
Total	1,181	1,129	823	249	3,382

Table 83. *Roadway Profile* by Cargo Tank Body Type by Accident Type

Cargo Tank Body Type Rear-End Accident Type	Stopped	Slower	Decelerating	Unknown	Total
Description					
Level	131	58	94	0	283
Grade	0	0	11	0	11
Hillcrest	0	5	0	0	5
Unknown	77	112	19	0	208
Total	208	176	124	0	507

Table 84. *Roadway Profile* by Flatbed Body Type by Accident Type

Flatbed Body Type Rear-End Accident Type	Stopped	Slower	Decelerating	Unknown	Total
Description					
Level	480	214	69	105	867
Grade	100	89	116	37	342
Hillcrest	0	0	0	0	0
Unknown	47	40	42	0	129
Total	627	343	226	142	1,339

Table 85. *Roadway Profile* by Dump Body Type by Accident Type

Dump Body Type Rear-End Accident Type	Stopped	Slower	Decelerating	Unknown	Total
Description					
Level	107	70	77	0	255
Grade	220	13	0	0	232
Hillcrest	0	0	0	0	0
Unknown	62	5	7	0	73
Total	388	88	84	0	560

Table 86. *Roadway Profile* by Auto Transporter Body Type by Accident Type

Auto Transporter Body Type Rear-End Accident Type	Stopped	Slower	Decelerating	Unknown	Total
Description					
Level	63	0	0	15	78
Grade	0	0	0	0	0
Hillcrest	0	0	0	0	0
Unknown	6	0	0	0	6
Total	69	0	0	15	84

Table 87. ***Roadway Profile*** **by Garbage/Refuse Body Type by Accident Type**

Garbage/Refuse Body Type Rear-End Accident Type	Stopped	Slower	Decelerating	Unknown	Total
Description					
Level	0	0	0	8	8
Grade	0	0	0	0	0
Hillcrest	0	0	0	0	0
Unknown	0	0	0	0	0
Total	0	0	0	8	8

Table 88. ***Roadway Profile*** **by Other/Unknown Body Type by Accident Type**

Other/Unknown Body Type Rear-End Accident Type	Stopped	Slower	Decelerating	Unknown	Total
Description					
Level	1,209	582	1,198	127	3,116
Grade	77	357	81	30	544
Hillcrest	9	3	9	14	35
Unknown	654	168	45	0	867
Total	1,949	1110	1,334	170	4,562

Speed Limit at Locations of Crash

Table 89 through table 95 present data on *Speed Limit Range* by CUT rear-end crash configuration and cargo body type. The greatest percentage of CUT rear-end crashes (38.0 percent) occurred in the 55-65 mi/h (88.51-104.61 km/h) *Speed Limit Range*. About half as many rear-end crashes (19 percent) occurred within the 40-50 mi/h (64.37-80.47 km/h) range. Of these CUT rear-end crashes in the 40-50 mi/h (64.37-80.47 km/h) speed range, 56 percent occurred when the heavy truck was in a stopped position. Likewise, of the 15 percent of CUT rear-end crashes that occurred in the 25-35 mi/h (40.23-56.33 km/h) range, 77 percent occurred when the vehicle was in the stopped position.

Most stopped CUT rear-end crashes (27 percent) occurred when the *Speed Limit Range* was 25-35 mi/h (40.23-56.33 km/h). The second most frequent speed range was 40-50 mi/h (64.37-80.47 km/h; 25 percent) followed by the 55-65 mi/h range (88.51-104.61 km/h; 23 percent).

When the heavy truck was traveling slower, 49 percent of the CUT rear-end crashes occurred within the 55-65 mi/h (88.51-104.61 km/h) speed range and 31 percent occurred within the over 65 mi/h (104.61 km/h) range.

The majority of CUT rear-end crashes that occurred when the heavy truck was decelerating occurred within the 55-65mi/h range (88.51-104.61 km/h; 52 percent).

With the exception of the dump and flatbed body types, the 55-65 mi/h (88.51-104.61 km/h) *Speed Limit Range* had the greatest percentage of CUT rear-end crashes (45 percent for van/enclosed box body type, 50 percent for cargo tank body type, 54 percent for auto transporter body type, 75 percent for garbage/refuse body type, and 38 percent for other/unknown body type). For the dump body type, 58 percent of the CUT rear-end crashes occurred when the truck was traveling 40-50 mi/h (64.37-80.47 km/h) as compared with 24 percent that occurred when the truck was traveling 55-65 mi/h (88.51-104.61 km/h). The peak speed range for flatbed rear-end crashes was 25-35 mi/h (40.23-56.33 km/h; 34 percent).

Table 89. *Speed Limit Range* by Van/Enclosed Box Body Type by Accident Type Grouping

Van/Enclosed Box Body Type Rear-End Accident Type	Stopped	Slower	Decelerating	Unknown	Total
Description					
No Speed Limit	0	0	0	0	0
5-15 mi/h (8.05-24.14 km/h)	0	0	0	0	0
25-35 mi/h (40.23-56.33 km/h)	108	31	18	21	178
40-50 mi/h (64.37-80.47 km/h)	169	198	218	17	602
55-65 mi/h (88.51-104.61 km/h)	692	417	332	95	1,537
Over 65 mi/h (104.61 km/h)	163	468	244	116	991
Unknown mi/h (km/h)	49	15	11	0	74
Total	1,181	1129	823	249	3,382

Table 90. *Speed Limit Range* by Cargo Tank Body Type by Accident Type Grouping

Cargo Tank Body Type Rear-End Accident Type	Stopped	Slower	Decelerating	Unknown	Total
Description					
No Speed Limit	0	0	0	0	0
5-15 mi/h (8.05-24.14 km/h)	0	0	0	0	0
25-35 mi/h (40.23-56.33 km/h)	115	0	7	0	122
40-50 mi/h (64.37-80.47 km/h)	49	19	0	0	68
55-65 mi/h (88.51-104.61 km/h)	25	133	95	0	252
Over 65 mi/h (104.61 km/h)	19	0	20	0	39
Unknown mi/h (km/h)	0	23	3	0	26
Total	208	176	124	0	507

Table 91. *Speed Limit Range* by Flatbed Body Type by Accident Type Grouping

Flatbed Body Type Rear-End Accident Type	Stopped	Slower	Decelerating	Unknown	Total
Description					
No Speed Limit	0	0	0	0	0
5-15 mi/h (8.05-24.14 km/h)	12	0	23	0	35
25-35 mi/h (40.23-56.33 km/h)	329	55	10	53	448
40-50 mi/h (64.37-80.47 km/h)	154	29	49	61	293
55-65 mi/h (88.51-104.61 km/h)	73	120	38	8	238
Over 65 mi/h (104.61 km/h)	58	137	0	20	215
Unknown mi/h (km/h)	0	2	108	0	110
Total	627	343	226	142	1,339

Table 92. *Speed Limit Range* by Dump Body Type by Accident Type Grouping

Dump Body Type Rear-End Accident Type	Stopped	Slower	Decelerating	Unknown	Total
Description					
No Speed Limit	0	0	0	0	0
5-15 mi/h (8.05-24.14 km/h)	0	0	0	0	0
25-35 mi/h (40.23-56.33 km/h)	13	5	7	0	25
40-50 mi/h (64.37-80.47 km/h)	309	14	0	0	322
55-65 mi/h (88.51-104.61 km/h)	45	13	77	0	135
Over 65 mi/h (104.61 km/h)	19	57	0	0	76
Unknown mi/h (km/h)	2	0	0	0	2
Total	388	88	84	0	560

Table 93. *Speed Limit Range* by Auto Transporter Body Type by Accident Type Grouping

Auto Transporter Body Type Rear-End Accident Type	Stopped	Slower	Decelerating	Unknown	Total
Description					
No Speed Limit	0	0	0	0	0
5-15 mi/h (8.05-24.14 km/h)	0	0	0	0	0
25-35 mi/h (40.23-56.33 km/h)	0	0	0	0	0
40-50 mi/h (64.37-80.47 km/h)	24	0	0	15	39
55-65 mi/h (88.51-104.61 km/h)	45	0	0	0	45
Over 65 mi/h (104.61 km/h)	0	0	0	0	0
Unknown mi/h (km/h)	0	0	0	0	0
Total	69	0	0	15	84

Table 94. *Speed Limit Range* by Garbage/Refuse Body Type by Accident Type Grouping

Garbage/Refuse Body Type Rear-End Accident Type	Stopped	Slower	Decelerating	Unknown	Total
Description					
No Speed Limit	0	0	0	0	0
5-15 mi/h (8.05-24.14 km/h)	0	0	0	0	0
25-35 mi/h (40.23-56.33 km/h)	0	0	0	0	0
40-50 mi/h (64.37-80.47 km/h)	0	0	0	0	0
55-65 mi/h (88.51-104.61 km/h)	0	0	0	6	6
Over 65 mi/h (104.61 km/h)	0	0	0	0	0
Unknown mi/h (km/h)	0	0	0	2	2
Total	0	0	0	8	8

Table 95. *Speed Limit Range* by Other/Unknown Body Type by Accident Type Grouping

Other/Unknown Body Type Rear-End Accident Type	Stopped	Slower	Decelerating	Unknown	Total
Description					
No Speed Limit	278	0	0	0	278
5-15 mi/h (8.05-24.14 km/h)	0	0	0	0	0
25-35 mi/h (40.23-56.33 km/h)	630	70	20	67	787
40-50 mi/h (64.37-80.47 km/h)	420	91	159	3	673
55-65 mi/h (88.51-104.61 km/h)	145	725	803	70	1,742
Over 65 mi/h (104.61 km/h)	358	210	62	20	649
Unknown mi/h (km/h)	118	13	291	11	432
Total	1,949	1,110	1,334	170	4,562

Environmental Conditions at Time of Crash

The environmental conditions under which CUT rear-end crashes occurred are noted in table 96 through table 102. Across body types, 88 percent of the CUT rear-end crashes occurred under no *Adverse Atmospheric Conditions*, 9 percent occurred when it was raining, and 2 percent when it was snowing.

Looking at the *Adverse Atmospheric Conditions*, when it was raining, 45 percent of the CUT rear-end crashes occurred when the heavy truck was decelerating, 23 percent occurred when the truck was stopped, and 23 percent occurred when the heavy truck was traveling slower. When it was snowing, 85 percent of the CUT rear-end crashes occurred when the truck was stopped and 10 percent occurred when it was decelerating. When environmental conditions were foggy, 87 percent of the CUT rear-end crashes occurred when the truck was stopped and 13 percent occurred when the truck was traveling slower.

Table 96. *Atmospheric Conditions* by Van/Enclosed Box Body Type by Accident Type Grouping

Van/Enclosed Box Body Type Rear-End Accident Type	Stopped	Slower	Decelerating	Unknown	Total
Description					
No Adverse Atmospheric Conditions	857	1,008	729	222	2,815
Rain	66	53	89	22	230
Sleet	0	0	0	0	0
Snow	144	3	5	6	157
Fog	95	10	0	0	105
Other: Smog, Smoke, Blowing Sand/Snow/Dust, Crosswind, etc.	20	55	0	0	75
Unknown	0	0	0	0	0
Total	1,181	1,129	823	249	3,382

Table 97. *Atmospheric Conditions* by Cargo Tank Body Type by Accident Type Grouping

Cargo Tank Body Type Rear-End Accident Type	Stopped	Slower	Decelerating	Unknown	Total
Description					
No Adverse Atmospheric Conditions	208	171	115	0	494
Rain	0	5	9	0	13
Sleet	0	0	0	0	0
Snow	0	0	0	0	0
Fog	0	0	0	0	0
Other: Smog, Smoke, Blowing Sand/Snow/Dust, Crosswind, etc.	0	0	0	0	0
Unknown	0	0	0	0	0
Total	208	176	124	0	507

Table 98. *Atmospheric Conditions* by Flatbed Body Type by Accident Type Grouping

Flatbed Body Type Rear-End Accident Type	Stopped	Slower	Decelerating	Unknown	Total
Description					
No Adverse Atmospheric Conditions	551	323	221	123	1,217
Rain	76	16	6	20	117
Sleet	0	0	0	0	0
Snow	0	0	0	0	0
Fog	0	5	0	0	5
Other: Smog, Smoke, Blowing Sand/Snow/Dust, Crosswind, etc.	0	0	0	0	0
Unknown	0	0	0	0	0
Total	627	343	226	142	1,339

Table 99. *Atmospheric Conditions* by Dump Body Type by Accident Type Grouping

Dump Body Type Rear-End Accident Type	Stopped	Slower	Decelerating	Unknown	Total
Description					
No Adverse Atmospheric Conditions	381	82	84	0	547
Rain	5	6	0	0	10
Sleet	0	0	0	0	0
Snow	0	0	0	0	0
Fog	0	0	0	0	0
Other: Smog, Smoke, Blowing Sand/Snow/Dust, Crosswind, etc.	0	0	0	0	0
Unknown	3	0	0	0	3
Total	388	88	84	0	560

Table 100. *Atmospheric Conditions* by Auto Transporter Body Type by Accident Type Grouping

Auto Transporter Body Type Rear-End Accident Type	Stopped	Slower	Decelerating	Unknown	Total
Description					
No Adverse Atmospheric Conditions	69	0	0	5	74
Rain	0	0	0	10	10
Sleet	0	0	0	0	0
Snow	0	0	0	0	0
Fog	0	0	0	0	0
Other: Smog, Smoke, Blowing Sand/Snow/Dust, Crosswind, etc.	0	0	0	0	0
Unknown	0	0	0	0	0
Total	69	0	0	15	84

Table 101. *Atmospheric Conditions* by Garbage/Refuse Body Type by Accident Type Grouping

Garbage/Refuse Body Type Rear-End Accident Type	Stopped	Slower	Decelerating	Unknown	Total
Description					
No Adverse Atmospheric Conditions	0	0	0	2	2
Rain	0	0	0	6	6
Sleet	0	0	0	0	0
Snow	0	0	0	0	0
Fog	0	0	0	0	0
Other: Smog, Smoke, Blowing Sand/Snow/Dust, Crosswind, etc.	0	0	0	0	0
Unknown	0	0	0	0	0
Total	0	0	0	8	8

Table 102. *Atmospheric Conditions* by Other/Unknown Body Type by Accident Type Grouping

Other/Unknown Body Type Rear-End Accident Type	Stopped	Slower	Decelerating	Unknown	Total
Description					
No Adverse Atmospheric Conditions	1,871	984	1,013	146	4,014
Rain	61	125	308	24	518
Sleet	0	0	0	0	0
Snow	6	0	13	0	19
Fog	7	0	0	0	7
Other: Smog, Smoke, Blowing Sand/Snow/Dust, Crosswind, etc.	0	0	0	0	0
Unknown	5	0	0	0	5
Total	1,949	1,110	1,334	170	4,562

Actions of the Truck Being Struck in the Crash

This section examines the *Corrective Action* attempted by the driver of the struck heavy truck. The *Corrective Action* attempted variable describes the actions attempted by the driver of the struck vehicle in response to the impending danger. Using this variable, one can see whether or not the driver of the heavy truck recognized that a rear-end crash was impending and took action to prevent the crash. Table 103 through table 109 present the *Corrective Actions* attempted by truck drivers by cargo body type and rear-end crash configurations. Avoidance maneuvers were coded *No Driver Present* in 8 percent of the CUT rear-end crashes or *Unknown* in 41 percent of crashes. In 47 percent of the CUT rear-end crashes, no avoidance action was attempted by the driver of the truck being struck.

Braking was attempted in 4 percent of the CUT rear-end crashes. A braking maneuver was attempted in 14 percent of the CUT rear-end crashes when the heavy truck was stopped, 77 percent of the CUT rear-end crashes when the heavy truck was traveling slower, and 8 percent of the CUT rear-end crashes when the heavy truck was decelerating. Drivers of other/unknown cargo-body-type trucks most often identified braking maneuvers. Of the identified body types, drivers of van/enclosed box cargo-body-type trucks attempted braking maneuvers in 3 percent of the CUT rear-end crashes.

Steering maneuvers were attempted in 1 percent of the CUT rear-end crashes. Of the total steering maneuvers identified, 93 percent were performed by drivers of flatbed cargo trucks and 97 percent of the time the steering maneuver was combined with the crash configuration lead-vehicle (i.e., the flatbed) decelerating.

Table 103. *Corrective Actions* Attempted by Truck Drivers by Van/Enclosed Box Cargo Body Type and Rear-End Accident Configuration

Rear-End Accident Type	Stopped	Slower	Decelerating	Unknown	Total
Corrective Action Description					
No Driver Present	0	0	320	43	363
No Avoidance Action	844	606	0	153	1,603
Brake	52	20	10	5	87
Steer	0	0	5	0	5
Unknown	285	503	487	48	1323
Total	1,181	1,129	822	249	3,381

Table 104. *Corrective Actions* Attempted by Truck Drivers by Cargo Tank Body Type and Rear-End Accident Type

Rear-End Accident Type	Stopped	Slower	Decelerating	Unknown	Total
Corrective Action Description					
No Driver Present	0	0	32	0	32
No Avoidance Action	193	115	0	0	308
Brake	0	0	5	0	5
Steer	0	0	0	0	0
Unknown	14	61	87	0	162
Total	207	176	124	0	507

Table 105. *Corrective Actions* Attempted by Truck Drivers by Flatbed Cargo Body Type and Rear-End Accident Type

Rear-End Accident Type	Stopped	Slower	Decelerating	Unknown	Total
Corrective Action Description					
No Driver Present	0	0	52	97	149
No Avoidance Action	512	128	0	37	677
Brake	0	0	0	0	0
Steer	0	2	60	0	7
Unknown	115	213	169	8	506
Total	627	343	282	142	1,339

Table 106. *Corrective Actions* Attempted by Truck Drivers by Dump Cargo Body Type and Rear-End Accident Type

Rear-End Accident Type	Stopped	Slower	Decelerating	Unknown	Total
Corrective Action Description					
No Driver Present	0	0	84	0	84
No Avoidance Action	383	13	0	0	396
Brake	0	0	0	0	0
Steer	0	0	0	0	0
Unknown	5	75	0	0	80
Total	388	88	84	0	560

Table 107. *Corrective Actions* Attempted by Truck Drivers by Auto Transporter Cargo Body Type and Rear-End Accident Type

Rear-End Accident Type	Stopped	Slower	Decelerating	Unknown	Total
Corrective Action Description					
No Driver Present	0	0	0	0	0
No Avoidance Action	24	0	0	0	24
Brake	0	0	0	0	0
Steer	0	0	0	0	0
Unknown	45	0	0	15	60
Total	69	0	0	15	84

Table 108. *Corrective Actions* Attempted by Truck Drivers by Garbage Refuse Cargo Body Type and Rear-End Accident Type

Rear-End Accident Type	Stopped	Slower	Decelerating	Unknown	Total
Corrective Action Description					
No Driver Present	0	0	0	0	0
No Avoidance Action	0	0	0	5	5
Brake	0	0	0	0	0
Steer	0	0	0	0	0
Unknown	0	0	0	2	2
Total	0	0	0	7	7

Table 109. *Corrective Actions* Attempted by Truck Drivers by Other/Unknown Cargo Body Type and Rear-End Accident Type

Rear-End Accident Type	Stopped	Slower	Decelerating	Unknown	Total
Corrective Action Description					
No Driver Present	0	0	216	30	246
No Avoidance Action	1,616	218	0	72	1,906
Brake	2	274	14	0	290
Steer	0	0	0	0	0
Unknown	3,31	618	1,104	68	2,121
Total	1,949	1,110	1,334	170	4,563

Actions of the Striking Vehicle in the Crash

The actions of the striking vehicle, the vehicle which impacted the rear of the CUT, can be reconstructed through the use of the data in the crash file. The type of vehicle striking the truck can be determined through the crash record. Figure 152 illustrates the populations of vehicles striking heavy trucks in the rear. Passenger vehicles hit the heavy truck in 43 percent of the CUT rear-end crashes, light trucks accounted for 27 percent of the striking vehicles, and heavy trucks comprised another 27 percent. Buses accounted for 3 percent of the striking vehicle population.

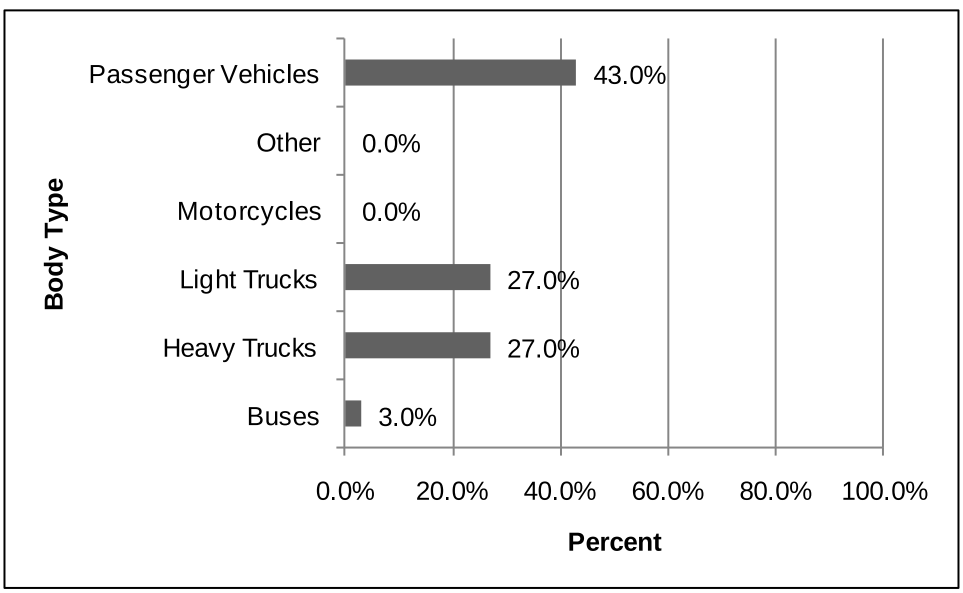

Figure 152. Bar graph. Body type of vehicles striking CUTs in rear-end crashes.

Maneuver Attempted by Striking Vehicle

Figure 153 depicts the movement of the striking vehicles in CUT rear-end crashes. This movement refers to the action immediately preceding the critical event. In 78 percent of the CUT rear-end crashes, the striking vehicle was going straight in the lane of travel. The second most common movement for striking vehicles was decelerating in the traffic lane (5 percent) followed by changing lanes (4 percent).

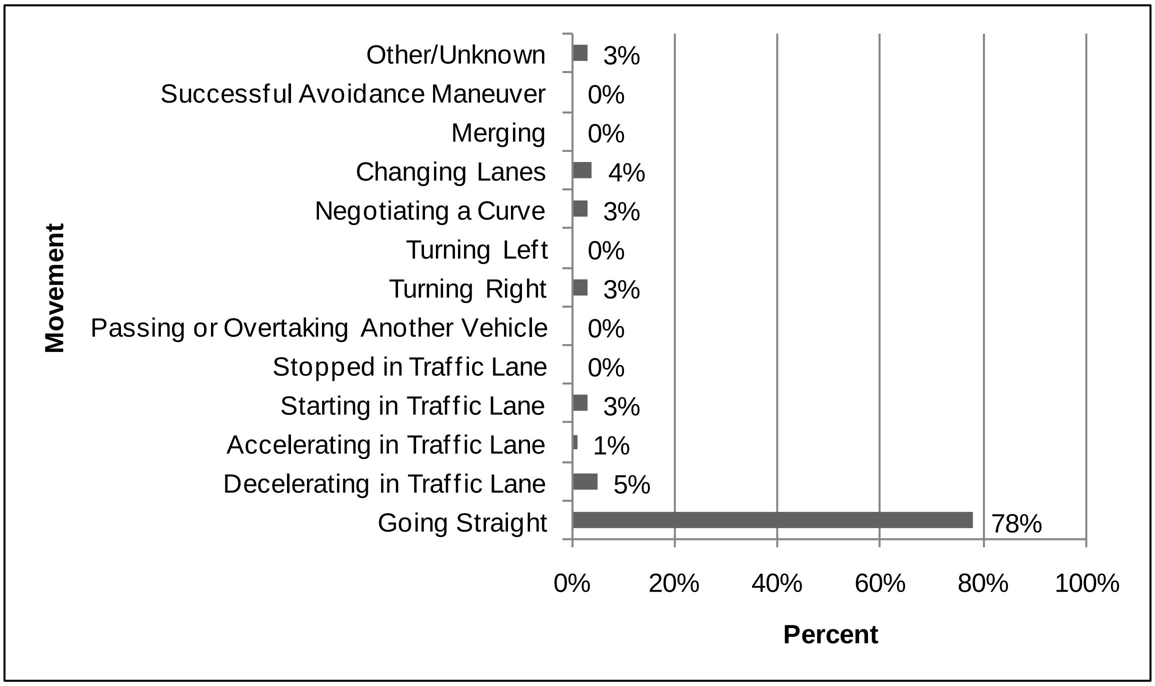

Figure 153. Bar graph. CUT striking vehicle movement prior to critical event for CUT rear-end crashes.

Striking Vehicle Critical Event

The critical event is that event which made the CUT rear-end crash imminent. Table 110 below provides data for the critical event for the striking vehicle. The highlighted rows confirm previously discussed findings and correlate with the CUT rear-end crash configurations that have been used throughout this analysis. The critical event for the striking vehicle in 42 percent of the CUT rear-end crashes was *Other Vehicle Stopped*. In 30 percent of the CUT rear-end crashes the critical event was other vehicle was *Traveling in the Same Direction while Decelerating*. In 24 percent of the CUT rear-end crashes the other vehicle was *Traveling in the Same Direction with Lower Steady Speed*. Combined, these three events accounted for 96 percent of the critical events.

Table 110. CUT Striking Vehicle Critical Event for CUT Rear-End Crashes

Critical Event	Count	Percent
Disabling Vehicle Failure (e.g., wheel fell off)	17	0%
Minor Vehicle Failure	5	0%
Excessive Speed	16	0%
Other cause of control loss	5	0%
Over the Lane Line on Left Side of Travel Lane	127	1%
Over the Lane Line on Right Side of Travel Lane	124	1%
Other Vehicle Stopped	4,122	42%
Traveling In Same Direction With Lower Steady Speed	2,319	24%
Traveling In Same Direction While Decelerating	2,963	30%
Unknown Travel Direction of other Motor Vehicle in Lane	5	0%
From Adjacent Lane (Same Direction) - Over LEFT Lane Line	77	1%
From Adjacent Lane (Same Direction) - Over RIGHT Lane Line	72	1%
From Opposite Direction - Over Left Lane Line	4	0%
Object in Roadway	5	0%
Unknown	10	0%
Total	9,869	100%

Corrective Action Attempted

The *Corrective Action* attempted variable for the striking vehicle provides insight as to whether or not the driver of the striking vehicle recognized that a rear-end crash was imminent and attempted a *Corrective Action*. There is a high percentage of unknown responses (77 percent). Because GES data are drawn from PARs, *Corrective Actions* are only included for those CUT rear-end crashes where police obtained a response from the driver of the striking vehicle and included that data on the report; therefore, the unknown response is common given the design of the GES database.

Braking-related actions were the most commonly indicated actions (11 percent; see figure 154). In 9 percent of the CUT rear-end crashes, no avoidance maneuver was attempted by the driver of the striking vehicle.

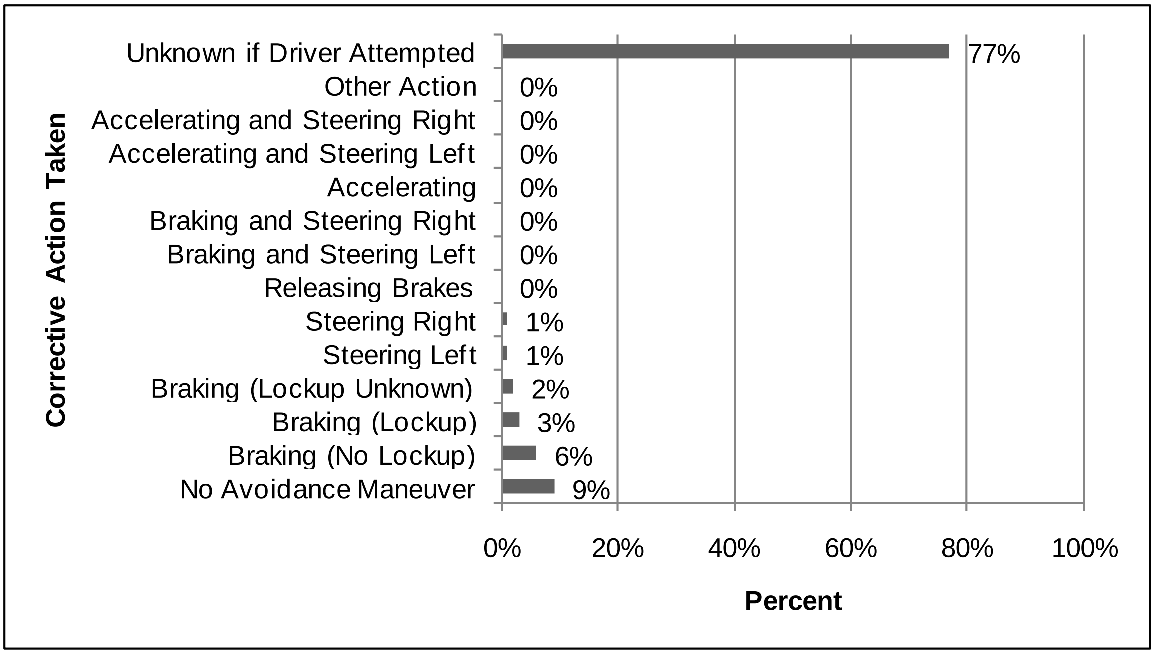

Figure 154. Bar graph. *Corrective Actions* attempted by the CUT striking vehicle drivers in CUT rear-end crashes.

Violations Charged

Figure 155 illustrates the violations charged against the striking vehicle drivers involved in the CUT rear-end crashes. In only 10 percent of the CUT rear-end crashes, drivers were charged with drugs, alcohol, reckless driving, or hit and runs. Drivers of the striking vehicle were charged with speeding in 9 percent of the CUT rear-end crashes.

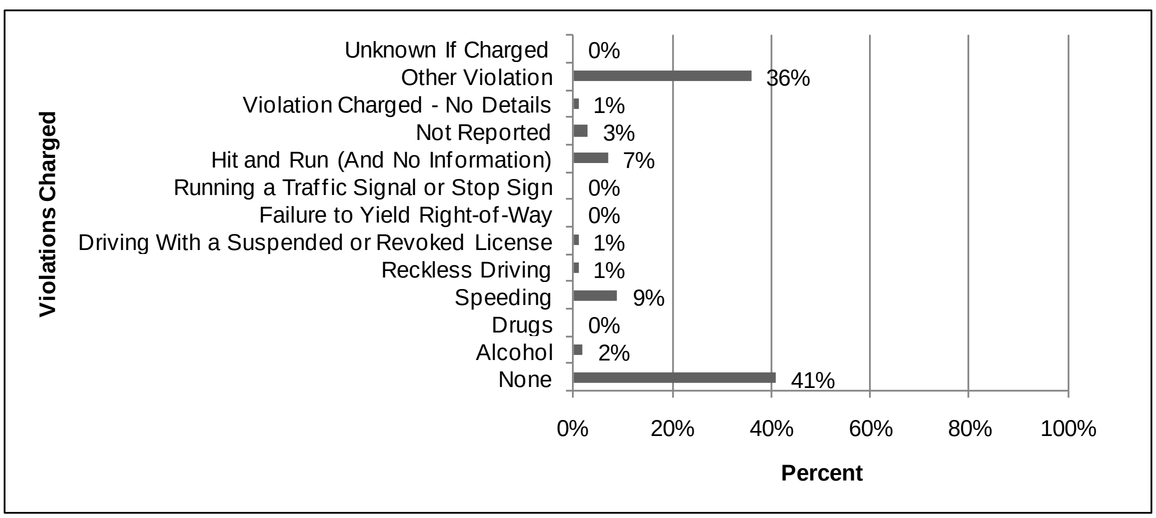

Figure 155. Bar graph. Violations charged against CUT striking vehicle drivers in CUT rear-end crashes.

COMPARISON OF DAYTIME/NIGHTTIME CUT REAR-END CRASHES

This section compares CUT rear-end crashes occurring during daytime conditions and nighttime conditions in good weather. The analyses present data related to the distribution of CUT rear-end crashes occurring during the daytime and nighttime, as well as the basic rear-end crash configurations listed above (i.e., stopped, slower, decelerating) and the population of striking vehicles. Roadway characteristics are also included and feature *Roadway Type, Relation to Junction, Roadway Alignment*, and *Speed Limit Range*. The maximum injury severity in the rear-end crash is also presented. The section concludes with a discussion of the profiles of striking vehicles and their drivers in daytime and nighttime conditions.

Distribution of CUT Rear-end Crashes by Daytime and Nighttime Conditions

The NASS GES datafile was searched to determine the distribution of rear-end crashes where the CUT had been struck and then filtered by the variable *Light Condition*. This variable was chosen because it reflects the actual *Lighting Conditions* at the time of the CUT rear-end crash. Values for the *Light Condition* variable include *Daylight; Dark; Dark, but Lighted; Dawn; Dusk;* and *Unknown*. CUT rear-end crashes coded with *Daylight* were assigned to daytime, while CUT rear-end crashes coded with *Dark; Dark, but Lighted; Dawn; and Dusk* were assigned to nighttime. Figure 156 illustrates the distribution of daytime versus nighttime CUT rear-end crashes.

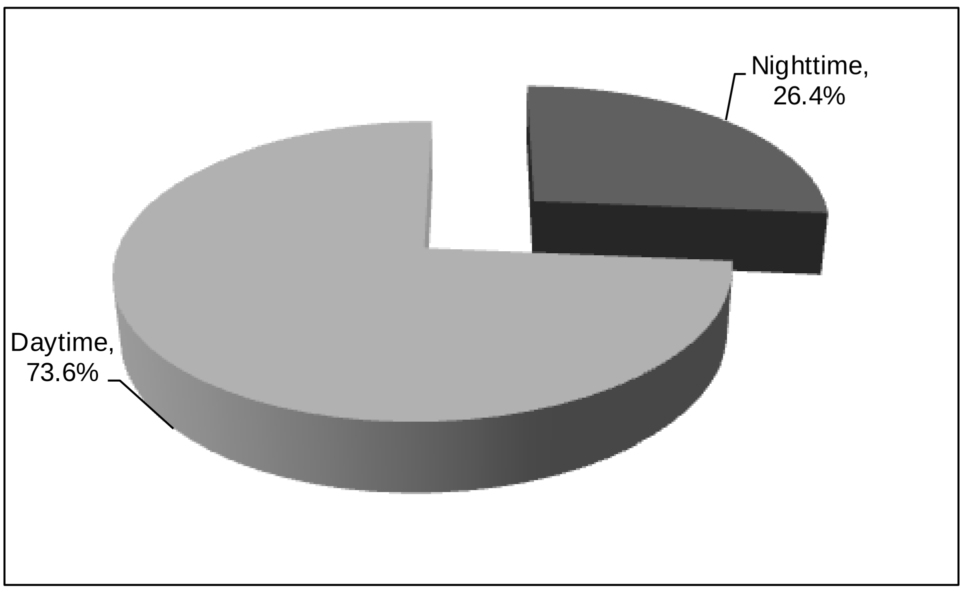

Figure 156. Pie Chart. Daytime/nighttime distribution of CUT rear-end crashes.

Figure 157 presents the CUT rear-end crash configurations for daytime and nighttime rear-end crashes. Consistent with 2001 data, the greatest percentage of daytime crashes occurred when the CUT was in the stopped configuration (49.2 percent). Nighttime crashes occurred predominantly when the CUT was the *Lead Vehicle Traveling Slower* (54 percent).

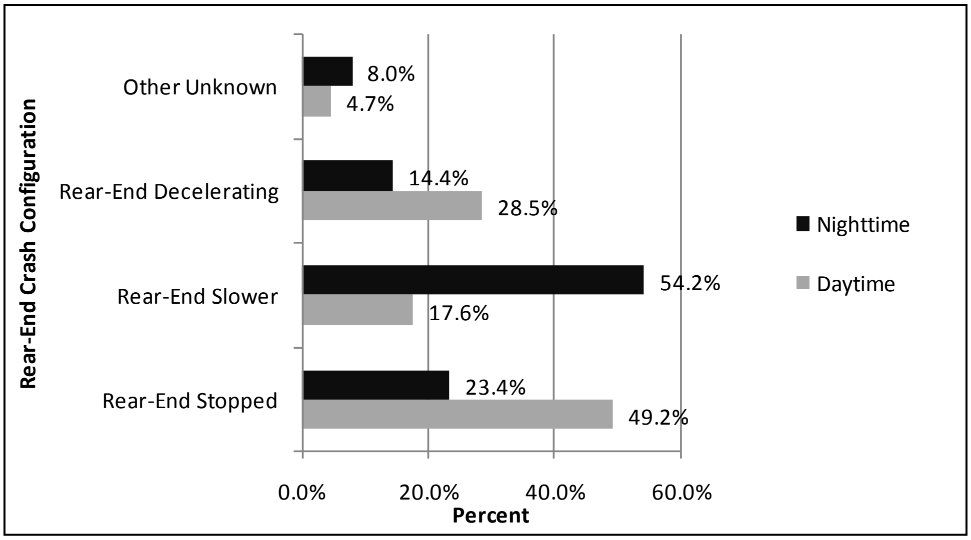

Figure 157. Bar graph. Daytime/nighttime CUT rear-end crash configurations.

Population of Striking Vehicles

During daytime conditions, more than 41 percent of the CUT rear-end crashes were the result of a passenger vehicle striking a CUT (figure 158). Other CUTs (28.5 percent) and light trucks (26.1 percent) were the next most frequent vehicles striking CUTs. Under nighttime conditions, passenger vehicles accounted for more than 46 percent of the CUT rear-end crashes with light trucks and other CUTs making up more than 52 percent of the remaining CUT rear-end crashes.

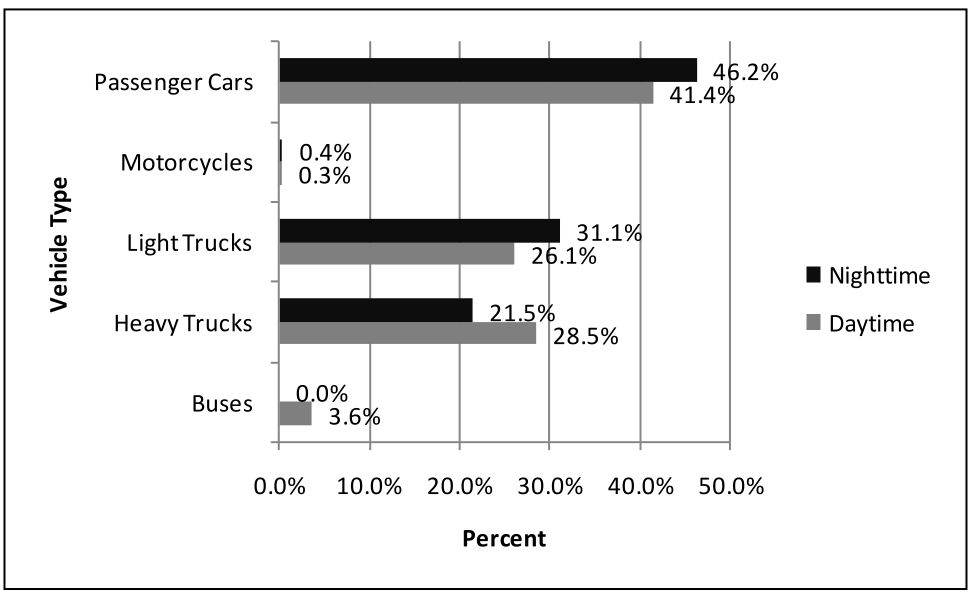

Figure 158. Bar graph. Population of striking vehicles in daytime/nighttime CUT rear-end crashes.

Roadway Characteristics for Daytime/Nighttime Rear-end Crashes

This section will examine the roadway characteristics for daytime and nighttime rear-end crashes. Specifically, using the GES datafile, roadways were examined to determine the following for where the rear-end crashes occurred: whether on an *Interstate Highway*, *Relation to Junction*, *Roadway Alignment*, *Roadway Profile*, and *Speed Limit Range*.

Interstate Highways

The *Interstate Highway* variable indicates whether the incident occurred on the IHS. This information is noted in the form of a binary yes or no answer. Figure 159 and figure 160 present the distribution of daytime and nighttime CUT rear-end crashes occurring on the IHS. Only 36 percent of daytime rear-end crashes occurred on the IHS. This marks a sharp reduction since 2001, when 67.3 percent of daytime CUT rear-end crashes occurred on the IHS. At the same time, there was an increase in the percentage of nighttime rear-end crashes that occurred on the IHS. In 2001, the percentage of CUT rear-end crashes was 38.5 percent, while in 2006 the percentage increased to 55 percent.

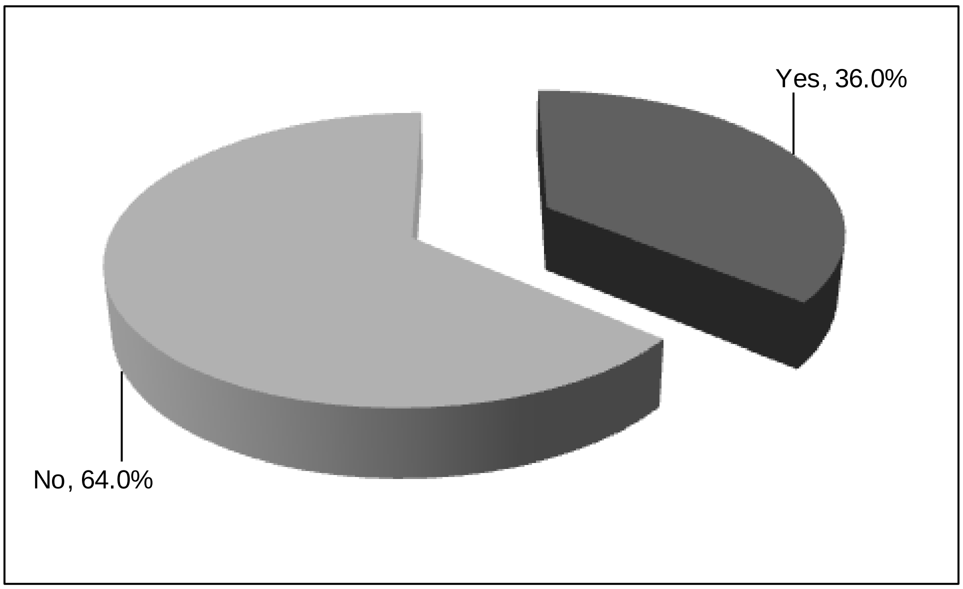

Figure 159. Pie Chart. Distribution of daytime CUT rear-end crashes occurring on *Interstate Highways*.

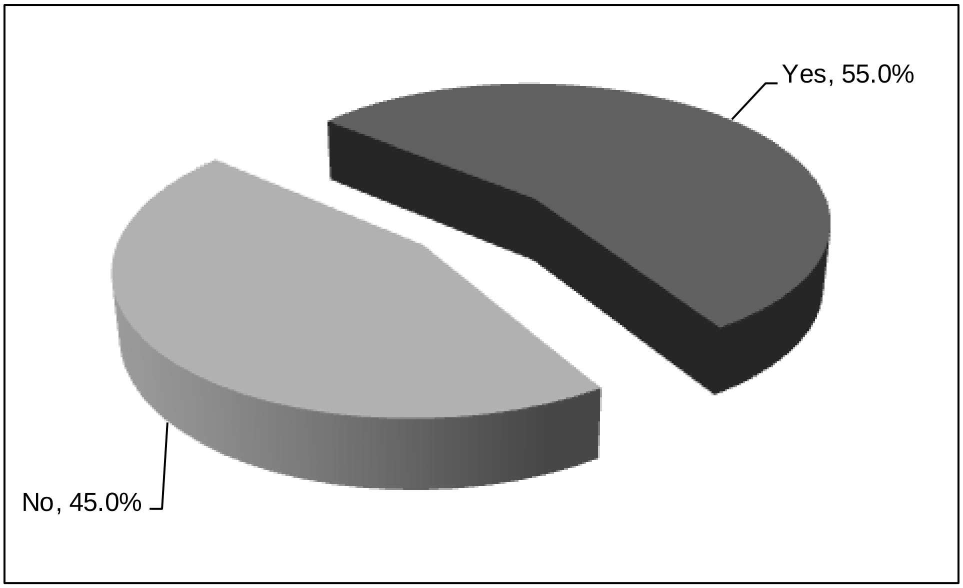

Figure 160. Pie Chart. Distribution of nighttime CUT rear-end crashes occurring on *Interstate Highways*.

Relation to Junction

Using the data file *Relation to Junction*, one can determine where in the roadway these CUT rear-end crashes occurred. This variable describes where the first event occurred that led to the CUT rear-end crash and is divided into *Interchange* (e.g., the roadway is separated by an elevation change) and *Non-Interchange* areas. Data on CUT rear-end crashes with *Relation to Junction* for daytime versus nighttime crashes is presented in figure 161. Of the CUT rear-end crashes occurring at *Non-Interchange/Non-Junction* areas, 54.4 percent occurred during the daytime and 76.2 percent at nighttime. These are areas described as being between intersections and excluded from other categories. *Non-Interchange/Interchange-Related* CUT rear-end crashes (i.e., crashes that occurred on the approach to the intersection) accounted for 27.2 percent of daytime and 17.9 percent of nighttime rear-end crashes. During daytime hours, it is interesting to note that 6.5 percent of CUT rear-end crashes occurred in driveways, alley access areas, etc.

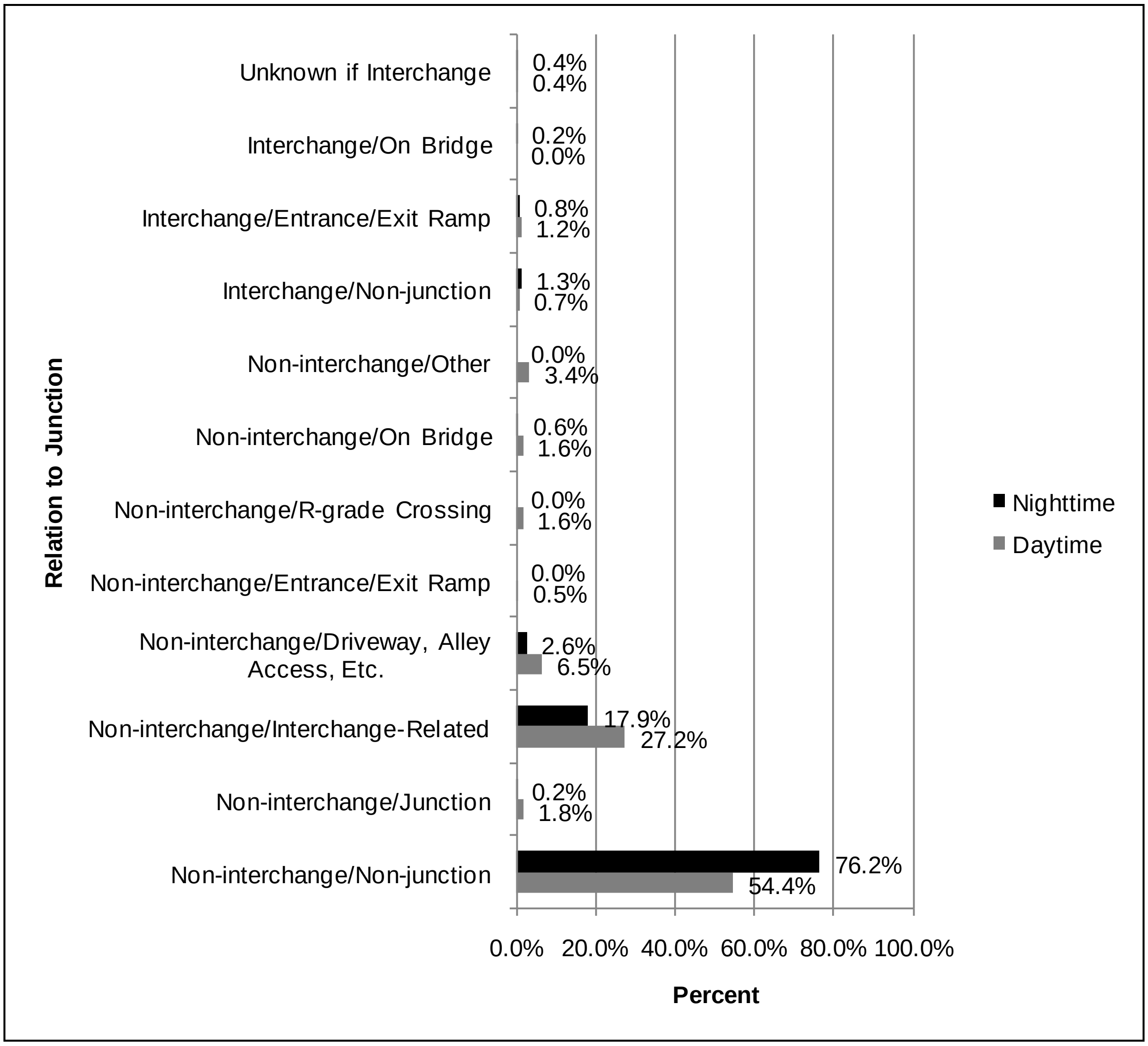

Figure 161. Bar graph. *Relation to Junction* distribution for CUT rear-end crashes occurring during daytime or nighttime hours.

Roadway Alignment and Profile

The *Roadway Alignment* variable indicates the horizontal alignment of the roadway and attribute codes include *Straight, Curve,* and *Unknown*. More than 90 percent of daytime and nighttime CUT rear-end crashes occurred on roadways with straight alignments (figure 162). Daytime CUT rear-end crashes occurred 8 percent of the time on roadways with curved alignment. These percents were greater than in 2001, because fewer 2006 CUT rear-end crashes were assigned the *Unknown* attribute.

The *Roadway Profile* variable indicates the vertical alignment of the roadway. Attribute codes include *Level*, *Grade, Hillcrest, Sag,* and *Unknown*. There was no substantial difference in the distribution of CUT rear-end crashes between daytime and nighttime rear-end crashes (figure 163). This finding was consistent with 2001 findings.

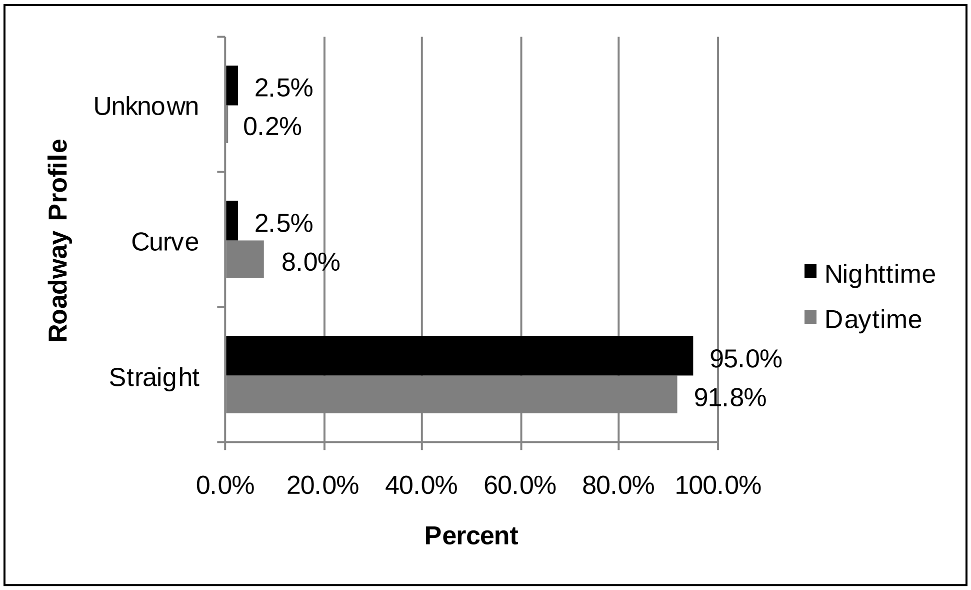

Figure 162. Bar graph. *Roadway Alignment* for CUT rear-end crashes occurring during daytime or nighttime hours.

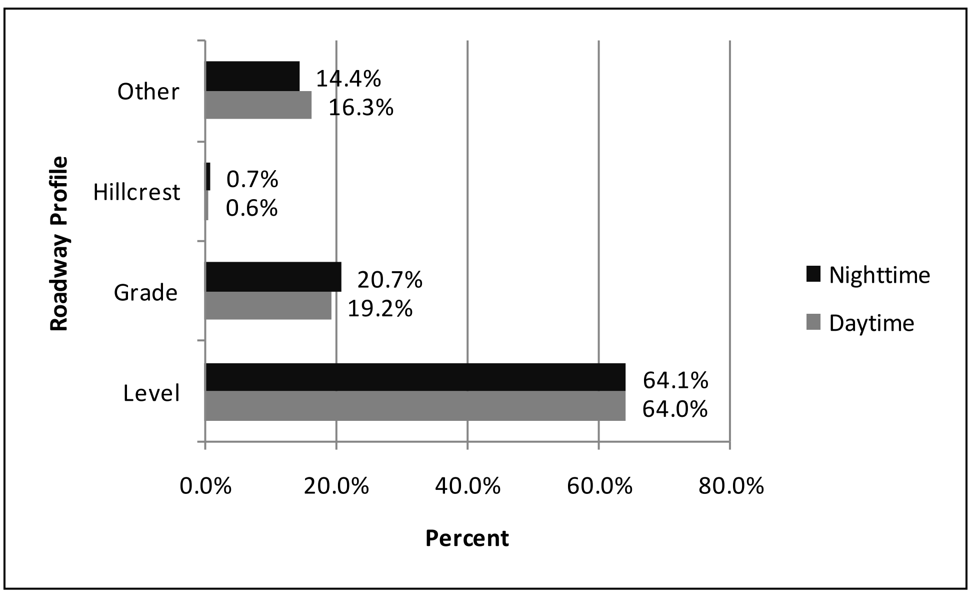

Figure 163. Bar graph. *Roadway Profile* for CUT rear-end crashes occurring during daytime or nighttime hours.

Speed Limit

Figure 164 presents data regarding the *Speed Limit Ranges* on the roadways where the CUT rear-end crashes occurred. Looking at daytime CUT rear-end crashes, 62.3 percent occurred at speeds equal to or less than 55 mi/h (88.51 km/h), speeds which are often associated with non-IHS roads. This finding was supported by the IHS findings. As noted in figure 159, only 36 percent of daytime CUT rear-end crashes occurred on the IHS, where high speeds would be common. Conversely, 52.9 percent of nighttime CUT rear-end crashes occurred at speeds equal to or greater than 55 mi/h (88.51 km/h), speeds more commonly associated with the IHS roadways.

This finding is consistent with the finding that 55 percent of nighttime CUT rear-end crashes were found to occur on *Interstate Highways* (figure 160).

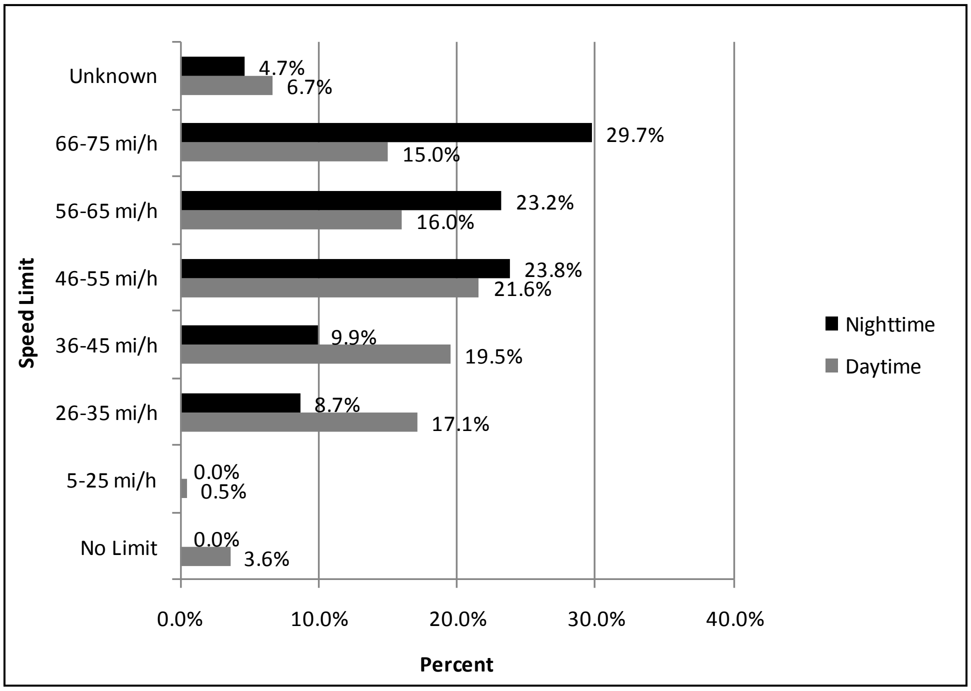

Figure 164. Bar graph. *Speed Limit Ranges* for CUT rear-end crashes occurring during daytime or nighttime hours.

Maximum Injury Severity in Crash

The maximum injury severity indicates the most severe injury of all persons involved in the CUT rear-end crashes. However, it does not distinguish whether the injury was sustained in the striking or struck vehicle. Fatal CUT rear-end crashes occurred mainly at nighttime (figure 165). Of the overall rear-end crashes occurring during nighttime, 4.5 percent resulted in fatalities. Of the overall rear-end crashes occurring during daytime, less than 0.5 percent resulted in fatalities. Additionally, almost 31.3 percent of serious injuries (i.e., non-incapacitating injuries and incapacitating injuries) occurred at nighttime, almost double the percentage of daytime CUT rear-end crashes.

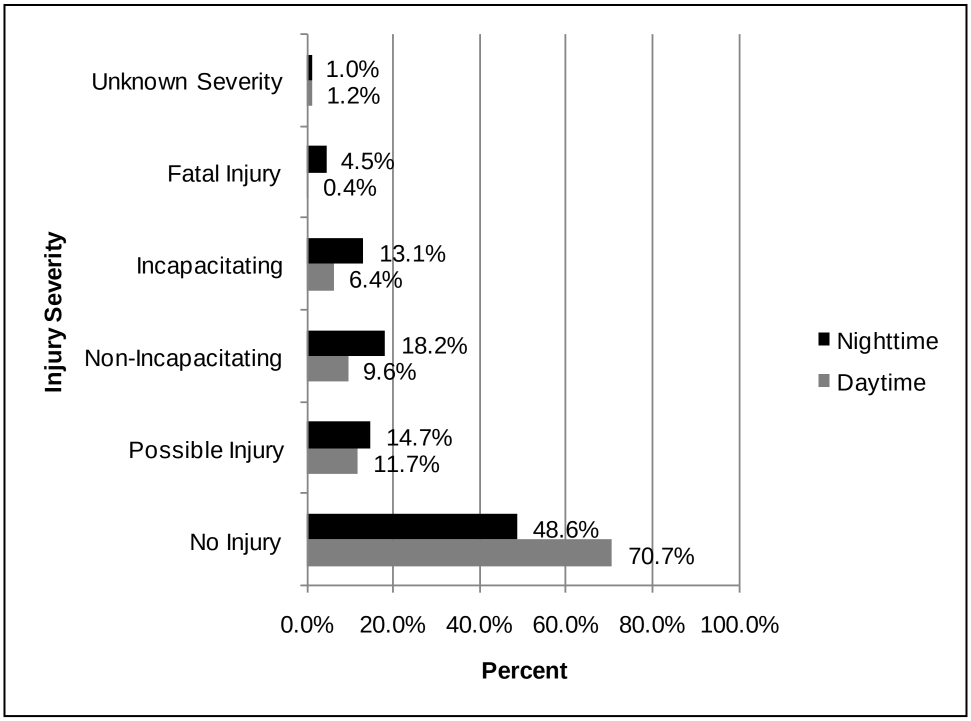

Figure 165. Bar graph. Maximum injury severity for CUT rear-end crashes occurring during daytime or nighttime hours.

Striking Vehicle Profile

This section examines the *Travel Speeds* of the striking vehicles in daytime and nighttime CUT rear-end crashes. Additionally, data regarding the distribution of violations charged to the striking vehicle driver are presented.

Travel Speeds for Striking Vehicles

Figure 166 presents the *Travel Speeds* for the striking vehicles in daytime and nighttime CUT rear-end crashes. The increased injury severity of nighttime CUT rear-end crashes noted above may be the result of the striking vehicle traveling at increased speeds. The striking vehicle was traveling at speeds equal to or greater than 46 mi/h (74.03 km/h) when 57.5 percent of nighttime CUT rear-end crashes occurred. However, a significant percentage (34.6 percent) of CUT rear-end crashes occurred when drivers of striking vehicles were traveling at 26-35 mi/h (41.84-56.33 km/h).

Daytime CUT rear-end crashes occurred most often when the driver of the striking vehicle was traveling 5-25 mi/h (8.05-40.23 km/h; 25.5 percent) or 46-55 mi/h (74.03-88.51 km/h; 23.8 percent). These speed-related findings were consistent with the findings in figure 157 which indicated that the greatest percentage of daytime CUT rear-end crashes occurred when the CUT was in the stopped configuration (49.2 percent), followed by the truck traveling slower (28.5 percent) and decelerating (17.6 percent).

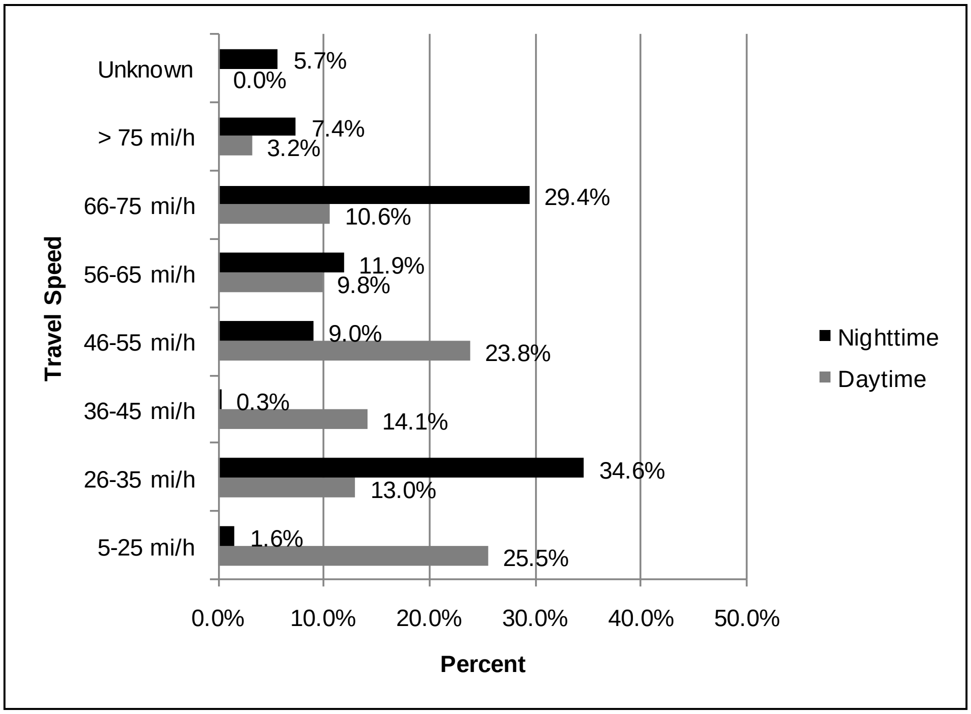

Figure 166. Bar graph. *Travel Speeds* for striking vehicles in CUT rear-end crashes occurring during daytime or nighttime hours.

Violations Charged

Figure 167 provides the distribution of violations charged to the striking vehicle driver. If a driver is charged with multiple violations, the lowest of the attribute codes is recorded. In more than 50 percent of daytime and 45 percent of nighttime CUT rear-end crashes, the driver of the striking vehicle was not charged. The second most commonly noted violation was other violation (25.1 percent of daytime rear-end crashes and 26.8 percent of nighttime rear-end crashes). Alcohol, drugs, reckless driving, and hit and runs accounted for approximately 10 percent of both daytime and nighttime charges in CUT rear-end crashes.

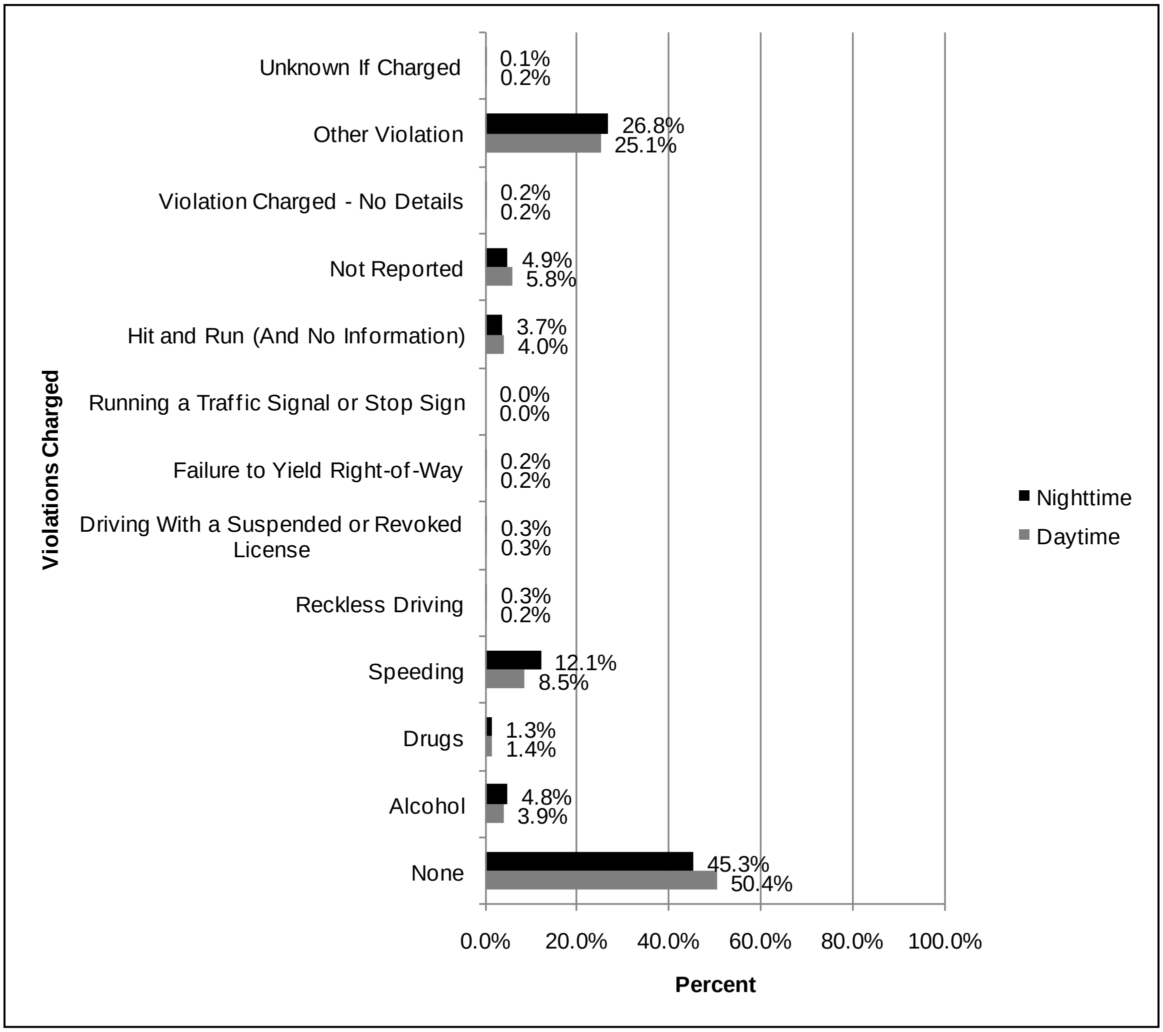

Figure 167. Bar graph. Violations charged against striking vehicle drivers in CUT rear-end crashes occurring during daytime or nighttime hours.

CONCLUSIONS

The purpose of this effort was to analyze the most recent GES data in order to update the various rear-end crash break-outs/characterizations. In doing so, the research team examined the 2006 rear-end crash data in order to obtain insight into:

- The overall truck statistics and overall heavy truck rear-end crash statistics;
- Rear-end crash statistics by truck body type;
- The differences and similarities between passenger vehicle and heavy truck rear-end crashes;
- Rear-end crash characteristics based on truck trailer unit configurations; and
- Daytime and nighttime heavy truck rear-end crash conditions.

Key findings in each of these areas are reviewed below (including data presented in the main body of the final report as well as appendix A).

Overall Truck Statistics

In 2006, there were 10,584,000 total vehicles involved in all vehicle crashes. *Passenger Cars,* as defined by NHTSA, totalled 5,864,000 of the vehicles involved in all vehicle crashes. *Light Trucks* (including SUVs, minivans, and pick-up trucks) accounted for 4,156,000 of the vehicles involved in all vehicle crashes. *Heavy Trucks*, including both CUTs and SUTs, comprised 385,000 of the vehicles involved in all vehicle crashes. Of all the heavy truck crashes:

- Step vans accounted for 1,142 crashes or 0.3 percent;
- Medium/heavy truck-based motor homes accounted for 3,540 crashes or 0.9 percent;
- SUTs accounted for 136,737 crashes or 35.5 percent; and,
- Truck-tractors (cab only, or any trailing units) accounted for 176,108 crashes or 45.7 percent.

In 2006, there were 8,819,007 registered heavy trucks. There were 6,649,337 SUTs and 2,169,670 CUTs. The total number of heavy trucks involved in rear-end crashes was 23,508. SUTs and CUTs together comprised 98.6 percent of the rear-end crashes that involved heavy trucks. SUTs were involved in 12,818 rear-end crashes and CUTs were involved in 10,257 rear-end crashes.

Overall Rear-end Crash Statistics for Trucks

This section examined the methodology used to determine the rear-end crash statistics used within this report. The analyses focused on rear-end crashes with primary focus on the variable *Accident Type*. This variable allowed for the identification of crashes based on category, configuration, and specific crash type. The three most common rear-end crash configurations were *Lead Vehicle Stopped*, *Lead Vehicle Traveling Slower*, and *Lead Vehicle Decelerating*. In each of these configurations the lead vehicle (i.e., the vehicle being struck) is the heavy truck. Of the 23,508 heavy truck rear-end crashes:

- The configuration *Rear-end Stopped* resulted in 11,249 rear-end crashes. This is 47.9 percent of the rear-end crash population for heavy trucks.
- The configuration *Rear-end Traveling Slower* resulted in 6,978 rear-end crashes. This is 29.7 percent of the rear-end crash population.
- The configuration *Rear-end Decelerating* resulted in 5,282 rear-end crashes. This is 22.5 percent of the rear-end crash population.

When looking at the crash severity of rear-end crashes within those three configurations, there were 135 fatalities, 1,603 incapacitating injuries, 2,074 non-incapacitating injuries, and 2,711 possible injuries. The most serious injuries (i.e., non-incapacitating injuries and incapacitating injuries) occurred within the *Lead-vehicle Stopped* configuration, which had 1,621 serious rear-end crashes. The laws of physics may provide an explanation for the larger proportion of serious injuries for *Lead Vehicle Stopped* configuration. Kinetic energy, which is derived from the mass and speed of the vehicles, is directly proportional to the speed differential between the lead and striking vehicles. Since the kinetic energy involved in the rear-end crash varies as the square of the vehicle's velocity, a small increase in the speed will lead to large increases in injury risk.[(21)]

Rear-end Crash Characteristics by Truck Body Type

This section examined rear-end crash characteristics based on heavy-truck body type. Two separate analyses were presented, one for SUTs and one for CUTs, which explore rear-end crash location, roadway, environment, and lighting characteristics, and actions of the struck heavy truck. Actions of the truck include the truck's movement prior to the critical event and *Corrective Action* attempted by the driver of the heavy truck. Maximum injury severity data were also included. The section concluded with two concurrent analyses, one for SUTs and one for CUTs, which presented data regarding the striking vehicle's maneuvers.

The review of the 2006 data for SUTs found the following:

- The *Rear-end Stopped* crash configuration accounted for 50 percent of rear-end SUT crashes. The *Rear-end Slower* and *Rear-end Decelerating* configurations accounted for a combined 50 percent of the SUT rear-end crashes.
- SUT rear-end crashes occurred predominantly (85.3 percent) on non-IHS roads.
- SUT rear-end crashes occurred 55.5 percent of the time at *Non-interchange/Non-junction* areas while 27.7 percent were *Non-interchange – Intersection-related*. Only 3 percent of the rear-end crashes occurred within the intersection.
- *Not Physically Divided Trafficways* accounted for 46.1 percent of SUT rear-end crashes versus 37.2 percent which occurred on *Divided Highways*.
- The percentage of SUT rear-end crashes that occurred on all 2-lane through 5-lane and unknown roadways for 2006 was 91.1 percent.
- The large majority, 90.8 percent, of rear-end crashes occurred when the SUT was traveling along a straight roadway.
- The majority, 54.6 percent, of SUT rear-end crashes occurred on roadways with a *Speed Limit Range* of 46-65 mi/h (74.03-104.61 km/h).
- Approximately 84 percent of the SUT rear-end crashes occurred in good environmental conditions (i.e., *No Adverse Atmospheric Conditions*) and during daylight conditions.
- The highest percentage, 44.1 percent, of the rear-end crashes occurred when the SUT was stopped in a traffic lane, followed by instances when the SUT was traveling straight (24.5 percent) or when the SUT was decelerating (18.8 percent).
- In more than 54 percent of the rear-end crashes, no avoidance maneuver was attempted by the struck vehicle's driver; however, it is unknown if the struck driver attempted an avoidance maneuver in 46.1 percent of the rear-end crashes.
- Within the SUT rear-end crashes, there were 53 fatalities, 696 incapacitating injuries, 906 non-incapacitating injuries, and 1,425 possible injuries. While most of the rear-end crashes occurred in the *Lead Vehicle Stopped* configuration followed by the *Lead Vehicle Traveling Slower* configuration, most of the fatalities occurred in the *Lead Vehicle Decelerating* configuration. The greatest number of serious injuries (i.e., non-incapacitating injuries and incapacitating injuries) occurred in the *Lead Vehicle Traveling Slower* configuration followed closely by the *Lead Vehicle Stopped* configuration.

The review of the 2006 data for CUTs found the following:

- The *Rear-end Stopped* crash configuration accounted for 46 percent of all CUT rear-end crashes. *Rear-end Slower* and *Rear-end Decelerating* crash configurations accounted for a combined 55 percent of the CUT-involved rear-end crashes.

- While a much higher percentage of rear-end SUT crashes occur off the IHS versus on the IHS (approximately 85.3 percent versus 14.7 percent), CUT-related rear-end crashes are more evenly divided between non-IHS and IHS rear-end crashes (58.1percent versus 42 percent).
- 58.8 percent of the CUT rear-end crashes occurred at *Non-interchange/Non-junction* areas. 25.8 percent of CUT rear-end crashes were *Non-interchange – intersection-related*, meaning that the crash occurs on the approach to the intersection. Only 1.4 percent of the rear-end crashes occurred within an intersection.
- The majority, 62.2 percent, of CUT rear-end crashes occurred on *Not Physically Divided Trafficways* versus 22.3 percent which occurred on *Divided Highways*.
- More than 44 percent of CUT rear-end crashes occurred on 2-lane roadways. Since 2001, there has been an almost 5 percent increase in the number of rear-end crashes occurring on roadways with four or more lanes (19.82 percent in 2006 compared to 15 percent in 2001).
- The CUT travel path was along a straight roadway in 92.5 percent of the rear-end crashes.
- Only 31 percent of rear-end crashes occurred on roadways where the speed limit was 45 mi/h (72.42 km/h) or less, while 60 percent occurred on roadways with speeds greater than or equal to 46 mi/h (74.03 km/h). The speed limit finding is consistent with the finding regarding number of lanes and roadway configuration as those roadways tend to have higher speed limits.
- Most CUT rear-end crashes occurred in good environmental conditions (88.1 percent) and during daylight *Lighting Conditions* (74.5 percent).
- In 43.1 percent of rear-end crashes, the CUT was stopped in a traffic lane. The configurations *CUT decelerating in the traffic lane* or *CUT going straight* were each responsible for approximately 24 percent of the rear-end crashes.
- In a high percentage of the rear-end crashes, 92.6 percent, the driver took no *Corrective Action* to avoid the crash.
- Within the CUT rear-end crashes, there were 82 fatalities, 907 incapacitating injuries, 1,167 non-incapacitating injuries, and 1,287 possible injuries. Most of the CUT rear-end crashes occurred in the *Lead Vehicle Stopped* configuration followed by *Lead Vehicle Traveling Slower* and *Lead Vehicle Decelerating*. The greatest number of serious injuries (i.e., non-incapacitating injuries and incapacitating injuries) and fatalities occurred in the *Lead Vehicle Stopped* configuration as well.

When examining the actions of the striking vehicles in SUT and CUT rear-end crashes, the following findings stand out:

- In both SUT and CUT rear-end crashes, the majority of crashes occurred when both vehicles were traveling straight prior to the crash. For SUTs, the second most common movement was starting in the traffic lane. For CUTs, the second most common movement was decelerating in the traffic lane.
- For SUTs, more than 34 percent of rear-end crashes occurred when the striking vehicle was traveling 5 to 35 mi/h (8.05 to 56.33 km/h). CUT rear-end crashes were more likely than SUT rear-end crashes to have occurred when the traveling speed of the striking vehicle was 36 mi/h (57.94 km/h) or greater (21 percent for CUTs versus 13.6 percent in SUTs).

- For both SUTs and CUTs, the critical event for the striking vehicles was that the SUT or CUT was in a stopped position.
- Of the crashes where an attempted maneuver was known, the driver of the striking vehicle attempted a braking maneuver in 70.7 percent of SUT rear-end crashes and 61.6 percent of CUT rear-end crashes. In CUTs, almost 12 percent of the braking maneuvers were accompanied by a steering maneuver.
- CUT rear-end crashes had a higher occurrence (29.1 percent versus 16 percent) of no avoidance maneuver than SUT rear-end crashes.
- In approximately 90 percent of both SUT and CUT rear-end crashes, the driver of the striking vehicle was tracking, indicating that the driver had control of the vehicle and was not in a panic mode.
- In neither SUT nor CUT rear-end crashes were vehicle contributing factors significant contributors to the crash.

Rear-end Crashes by Vehicle Type – Passenger Vehicles Versus CUTs

This section examined the overall rear-end crash profile for passenger vehicles and CUTs. The analyses in this section compared and contrasted passenger vehicles and CUTs: where rear-end crashes occur; roadway and environmental characteristics; actions of the struck vehicles prior to the rear-end crash; the distribution of injuries or fatalities resulting from rear-end crashes; and the profiles of striking vehicles and drivers. Key findings included:

- There was a larger number of rear-end crashes for passenger vehicles (1,405,695) than for CUTs (11,833). This is consistent with the larger number of passenger vehicles versus CUTs on the road.
- Although the majority of rear-end crashes for both passenger vehicles and CUTs are *Rear-end Stopped*, the percentage of *Rear-end Stopped* crashes is much greater for passenger vehicles (61 percent) than for CUTs (42 percent).
- A much higher percentage of passenger vehicle rear-end crashes occurred off the IHS as compared to on the IHS (approximately 90.6 percent versus 9.3 percent). Heavy-truck rear-end crashes were more evenly divided between non-IHS roadways and IHS roadways (58.1 percent and 41.9 percent, respectively).
- *Non-interchange* areas accounted for 96 percent of passenger vehicle rear-end crash locations and 97 percent of CUT rear-end crash locations.
- In the majority of crashes, for both passenger vehicle and CUT rear-end crashes, there were no traffic controls present at the crash. There was a traffic signal present in 33 percent of the passenger vehicle rear-end crashes and in18.2 percent of the CUT rear-end crashes.
- In both passenger vehicle and CUT rear-end crashes, at least 90 percent of the crashes occurred on roadways having straight alignment profiles.
- The *Roadway Profile* for both passenger vehicle and CUT rear-end crashes was level in at least 64 percent of the rear-end crashes.
- More than 85 percent of passenger vehicle rear-end crashes and 88 percent of CUT rear-end crashes occurred under good conditions (i.e., *No Adverse Atmospheric Conditions*).
- For passenger vehicle rear-end crashes, the majority of crashes were the result of another passenger vehicle (54.9 percent) or light truck (41.3 percent) striking the passenger vehicle. In CUT rear-end crashes, the largest percentage of striking vehicles was also

passenger vehicles (42.6 percent); however, light trucks and CUTs struck the rear of the CUTs at an almost even percentage (27.4 percent and 26.7 percent).

- CUTs struck other CUTs in approximately 27 percent of the CUT rear-end crashes, yet CUTs only struck passenger vehicles in 2.2 percent of passenger vehicle rear-end crashes.
- In more than 78 percent of both passenger vehicle and CUT rear-end crashes, the striking vehicle was going straight in the lane of travel.
- In 11.9 percent of passenger vehicle rear-end crashes, the striking vehicle attempted a braking-related maneuver. However, 9.1 percent of the time no *Corrective Action* was attempted. The striking vehicle attempted a braking-related action in a slightly greater percentage of CUT rear-end crashes (13.2 percent).
- When examining the charges against drivers of striking vehicles, in 9.2 percent of passenger vehicle rear-end crashes and 10.1 percent of CUT rear-end crashes drivers were charged with drugs, alcohol, reckless driving, or hit and runs. Drivers of the striking vehicle were charged with speeding in 9.3 percent of passenger vehicle rear-end crashes and 12.1 percent of CUT rear-end crashes.

Rear-end Crashes by the Trailer Number and Type

This section examined the type of trailer units involved in CUT rear-end crashes. The analyses included an examination of the characteristics associated with the roadway, including: *Roadway Type*, *Relation to Junction*, *Traffic Control Devices*, *Roadway Alignment*, *Roadway Profile*, and *Speed Limit Range*. Additionally, environmental conditions at the time of the rear-end crash were discussed. The section concluded with examinations of the actions of the truck being struck in the rear-end crash and the actions of the striking vehicle.

- Trucks pulling one trailer unit accounted for 92 percent of the body types involved in rear-end crashes. A much smaller percentage (4 percent) occurred with the tractor pulling no trailer, or in "bob tail" configuration. An even smaller percentage (3 percent) of rear-end crashes occurred with trucks pulling two trailer units.
- When looking at the configurations involving a single trailer unit, the most common trailer unit type was the van/enclosed box configuration, which accounted for 32.4 percent of the population of trucks pulling one trailing unit involved in rear-end crashes, followed by flatbed trailers (12.8 percent). Cargo tank trailers (4.8 percent), dump (5.5 percent), auto transporter (0.8 percent) and garbage/refuse (0.1 percent) accounted for the remainder.
- The van/enclosed box cargo body type accounts for more than 45 percent of CUT rear-end crashes for all three crash configurations.
- In all cargo body types (except for auto transporters) a consistent finding was that the primary *Relation to Junction* is *Non-interchange/Non-junction*.
- Rear-end crashes involving the van/enclosed box cargo body type occurred 23 percent of the time within an intersection. Looking at cargo tank-related rear-end crashes, 41 percent occurred when the truck was in a stopped position. Flatbeds were struck 615 times while stopped, 29 percent of which were *Intersection-related* and 4 percent occurred in *Intersections* and *Driveways/Alley access areas*. Of the 555 dump truck crashes, 69 percent occurred when the truck was in a stopped position, including 19 percent which occurred on *Rail Grade Crossings*. Auto transporter rear-end crashes were *Intersection-related* in 82 percent of the rear-end crashes. Of those, 100 percent occurred when the truck was stopped.

- The option *No Traffic Control* made up the largest percent of *Traffic Control Devices* with 86 percent. Of those rear-end crashes that occurred without a traffic control, the CUT was stopped 35 percent of the time, traveling slower 34 percent of the time, or decelerating 24 percent of the time.
- Regardless of cargo body type, 100 percent of the rear-end crashes that took place when a traffic signal was present occurred when the truck was stopped.
- For all cargo body types, the *Straight Roadway Alignment* accounted for 93 percent of CUT rear-end crashes.
- Only 7 percent of rear-end crashes occurred on roadways with *Curved Roadway Alignments*. When the *Roadway Alignment* was curved, 48 percent of rear-end crashes occurred when the CUT was stopped and 43 percent occurred when the truck was decelerating.
- Of all the body types, the dump body type has the highest percentage of rear-end crashes that occur on a grade with 42 percent. Ninety-five percent of the dump-involved rear-end crashes that occur on a grade take place when the dump is in the stopped position.
- With the exception of the dump and flatbed body types, the 55-65 mi/h (88.51-104.61 km/h) *Speed Limit Range* had the greatest percentage of rear-end crashes. Within the dump body type, 58 percent of rear-end crashes occurred when the truck was traveling 40-50 mi/h (64.37-80.47 km/h) as compared with the 24 percent that occurred when the truck was traveling 55-65 mi/h (88.51-104.61 km/h). The peak speed range for flatbed rear-end crashes was 25-35mi/h (40.23-56.33 km/h; 34 percent).
- Across the body types, when it was raining, 45 percent of the rear-end crashes occurred when the CUT was decelerating, 23 percent occurred when the truck was stopped, and 23 percent occurred when the CUT was traveling slower.
- Drivers of other/unknown cargo-body-type trucks most often identified braking maneuvers. Of the identified body types, drivers of van/enclosed box cargo-body-type trucks attempted braking maneuvers in 3 percent of the rear-end crashes involving vans/enclosed body cargo-type trucks.
- Of the total steering maneuvers identified, 93 percent were performed by drivers of flatbed cargo trucks and 97 percent of the time the steering maneuver was combined with the crash configuration lead-vehicle (i.e., the flatbed) decelerating.

Comparison of Daytime/Nighttime CUT Rear-end Crashes

This section compared rear-end crashes occurring during daytime conditions and nighttime conditions in good weather. Key findings from these analyses are as follows:

- Rear-end crashes occurred 26.4 percent of the time under nighttime conditions and 73.6 percent of the time during daytime conditions.
- The greatest percentage of daytime rear-end crashes, 49.2 percent, occurred when the CUT was in the stopped configuration. Nighttime rear-end crashes occurred predominantly when the CUT was the *Lead Vehicle Traveling Slower* (54 percent).
- During daytime conditions, more than 41 percent of the rear-end crashes were the result of a passenger vehicle striking a CUT. Other CUTs (28.5 percent) and light trucks (26.1 percent) were the next most frequent striking vehicles. Under nighttime conditions, passenger vehicles accounted for more than 46 percent of the rear-end crashes with light

trucks with other CUTs making up more than 52 percent of the remaining CUT rear-end crashes.

- Only 36 percent of daytime rear-end crashes occurred on the IHS. This marks a sharp reduction since 2001 when 67.3 percent of daytime rear-end crashes occurred on the IHS. Nighttime Interstate crashes also increased since 2001, from 38.5 percent to 55 percent.
- Of the rear-end crashes occurring at *Non-interchange/Non-junction areas*, 54.4 percent occurred during the daytime and 76.2 percent at nighttime. During daytime hours, it is interesting to note that 6.5 percent of rear-end crashes occur in driveways, alley access areas, etc.
- More than 90 percent of daytime and nighttime rear-end crashes occurred on roadways that were straight and level.
- Looking at daytime rear-end crashes, 62.3 percent occurred at speeds equal to or less than 55 mi/h (88.51 km/h), speeds which are often associated with non-Interstate roads. Conversely, 52.9 percent of nighttime crashes occurred at speeds equal to or greater than 55 mi/h (88.51 km/h), speeds more commonly associated with the IHS roadways, consistent with the finding that 55 percent of nighttime crashes were found to occur on *Interstate Highways*.
- Of the rear-end crashes that occurred at nighttime, 4.5 percent were fatal, while less than 0.5 percent of rear-end crashes that occurred during daytime conditions resulted in fatal crashes. Additionally, rear-end crashes that resulted in serious injuries (i.e., non-incapacitating injuries and incapacitating injuries) occurred 31.3 percent of the time under nighttime conditions, almost double the percentage that occurred as a result of daytime rear-end crashes.
- The striking vehicle was traveling at speeds equal to or greater than 46 mi/h (74.03 km/h) when 57.5 percent of nighttime rear-end crashes occurred. However, 34.6 percent of crashes occurred when drivers of striking vehicles were traveling at 26-35 mi/h (41.84-56.33 km/h). Daytime rear-end crashes occurred most often when the driver of the striking vehicle was traveling 5-25 mi/h (8.05-40.23 km/h; 25.5 percent) or 46-55 mi/h (74.03-88.51 km/h; 23.8 percent).
- In more than 50 percent of daytime and 45 percent of nighttime rear-end crashes, the driver of the striking vehicle was not charged. Alcohol, drugs, reckless driving, and hit and runs accounted for approximately 10 percent of both daytime and nighttime rear-end crash-related charges.

APPENDIX B. AUDITORY WARNING SYSTEM SPECIFICATIONS

PARABOLIC REFLECTOR SPECIFICATIONS

Development of equation describing the reflector parabola (see figure 168).

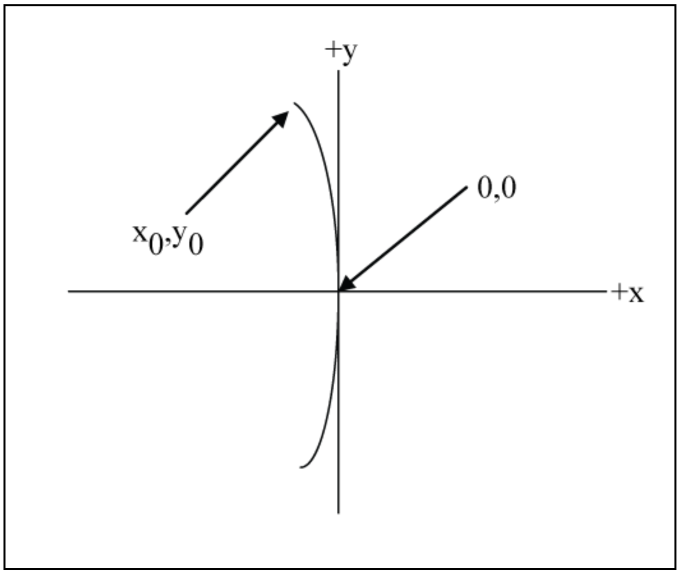

Figure 168. Diagram. Depiction of parabola equation.

The general equation for the parabola is:

$$x = ky^2 \qquad \text{Eq. 3}$$

$$y = \pm\left(\frac{x}{y}\right)^{0.5} \qquad \text{Eq. 4}$$

For the long focus,
x_0,y_0 = -3.5, 20 (inches)
-3.5 = k*400
k = -3.5/400 = -0.00875
Therefore, x= -0.00875y^2
See table 111 for final values.

Table 111. Values for the Long Focus in Inches

y	x
±20	-3.5
±15	-1.97
±10	-0.875
±5	-0.219
±0	0

For the short focus,
x_0,y_0= -4.25,20
-4.25 = k*400
k= -4.25/400 = -0.010625
Therefore, x= -0.010625y^2
See table 112 and table 113 for final values.

Table 112. Values for the Short Focus in Inches

y	x
±20	-4.25
±15	-2.39
±10	-1.0625
±5	-0.266
±0	0

Table 113. Average Values for the Two Foci in Inches

y	x
±20	3.875
±15	2.18
±10	0.969
±5	0.243
±0	0

Recommended adjustments: 22.00 in (55.88 cm), and 18.50 in (46.99 cm). One value between plus two values on each outside end:

- 15.00 in (38.1 cm)
- 16.75 in (42.55 cm)
- **18.50 in (46.99 cm)**
- 20.25 in (51.44 cm)
- **22.00 in (55.88 cm)**
- 23.75 in (60.33 cm)
- 25.50 in (64.77 cm)

See figure 169 for final parabolic reflector diagram.

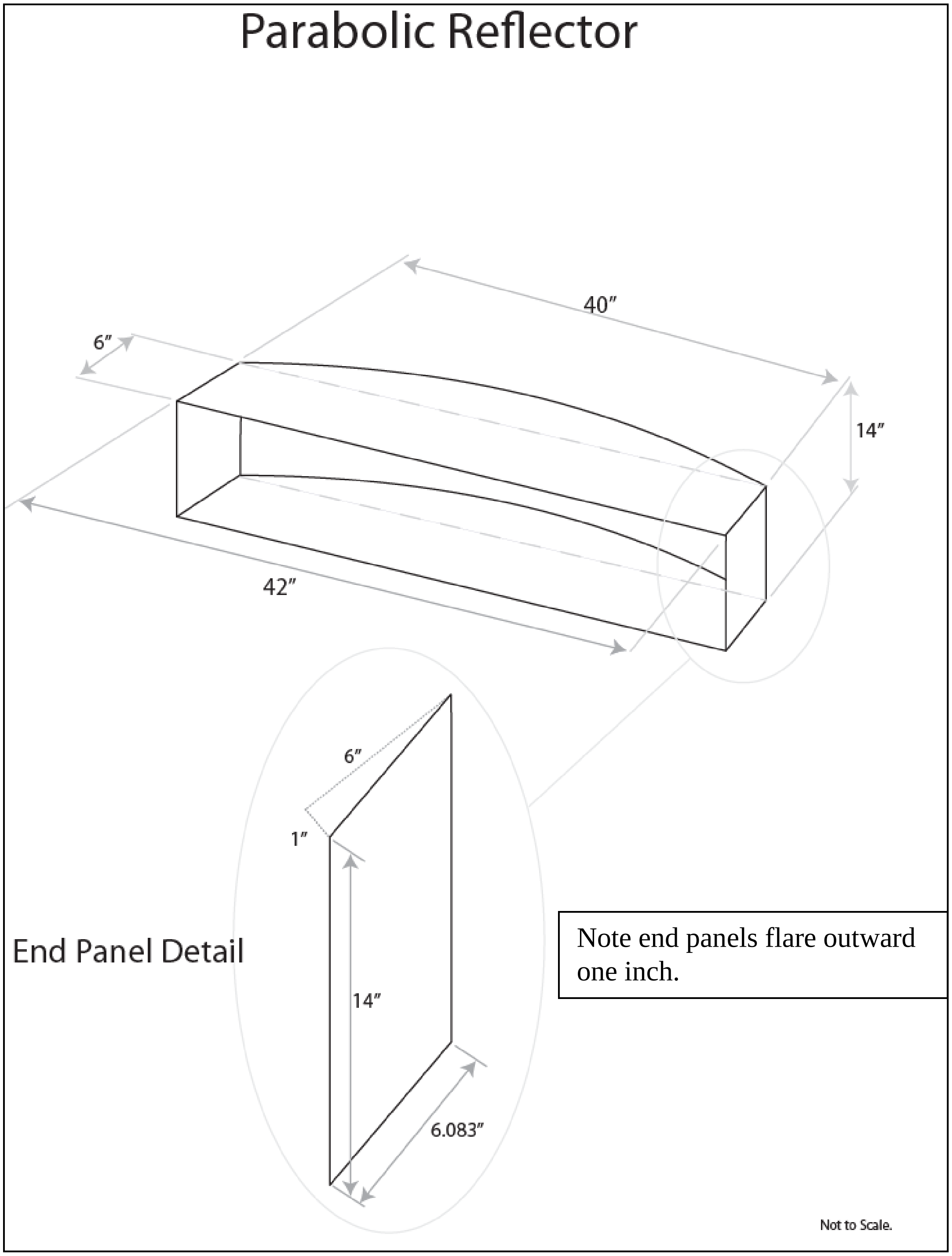

Figure 169. Diagram. Parabolic reflector.

Note that outer edge of horn to inside center of parabolic reflector is the distance measurement that is adjusted.

The speaker used for generating the sound in the parabolic reflector was the Interm HS-40RT Paging Horn Speaker (HS-40RT) shown in figure 170.

Figure 170. Photo. Paging horn speaker.

Specifications for the paging horn speaker are in table 114.

Table 114. Paging Horn Speaker Specifications

Specification Parameter	Value
Rated Input	40W
Impedance	250Ω (w)
Impedance	500Ω (G)
Frequency Response	380Hz - 6.5kHz
SPL (1m/1W)	109dB
Weight	2.95Kg
Dimension (mm)	320x210x365

TUBE DESIGN SPECIFICATIONS

The audio testing with the directional tube was performed using a polyvinylchloride (PVC) tube. The PVC tube was 7.875 in (20 cm) inner diameter by 96 in (243.84 cm) in length. The speaker was a horn loudspeaker. The horn loudspeaker was approximately 6.875 in (17.46 cm) outer diameter with a flange mounted outer ring that extended the overall diameter by 0.875 in (2.22 cm). The body diameter of the horn loudspeaker is 5.375 in (13.65 cm) with a depth measurement of 5.5 in (13.97 cm).

Powering the horn loudspeaker was a public address amplifier. The specifications for the amplifier are shown in table 115 below.

Table 115. Public Address Amplifier Technical Specifications

Parameter	Sub-Parameter	Value
Power Supply	AC	110V/60Hz
Power Supply	Dissipation	=120W
Input	Microphone	Input Level: -50dB, Input Impedance = 18K
Input	Line	Input Level: -20dB, Input Impedance = 10K
Output	Mode	8O, or 70/100 Volts
Output	Rated Power	60W
Distortion		60Hz ~ 12KHz ≤ 2%
Frequency Range		60Hz ~ 12KHz ≤ +/- 2dB
Signal to noise Ration	Microphone	≥ 50dB
Signal to noise Ration	Line	≥ 70dB
External Dimensions		19"w x 16"d x 3.5"h (48.26 cm w x 40.64 cm d x 8.89 cm h)
Weight		16 lbs (7.26 kg)

AUDITORY SIGNAL TYPE SPECIFICATIONS

Three signal types (sounds) were used for testing. Two of these sounds were acquired and one developed in a laboratory. Of the three sounds used for testing, one sound was similar to a tire screech. Another was an alarm sound developed by an engineering company that contained both low and high frequency sound waves combined to produce a single signal. The final sound was created by the research team which consisted of two tones each with their own frequency simultaneously played to produce a single signal. In all cases, the created sounds consisted of a narrow band of frequencies, rather than just one frequency; accordingly, listeners with notch hearing deficiencies would be able to hear the sounds.

Tire Screech – WAV file that was found and used. Difficult to measure as was previously recorded. Estimated frequency range of 500-1500 Hz with varying levels of cycles per min.

Piercer – Frequency range of 800-1600 Hz at 800 cycles per min.

Dual Frequency Tone – Developed by the research team. Two tones played simultaneously. Tone 1 played at a frequency of 783.99 Hz, and Tone 2 played at a frequency of 1567.98 Hz.

APPENDIX C. REAR-LIGHTING SPECIFICATIONS

LED UNIT SPECIFICATIONS

The LED units used in this project were purchased from www.anythingtruck.com (product code 440RHW). This LED unit contains a polycarbonate lens and housing. The actual outside diameter measurement is 4.29 in (10.90 cm) and is 1.38 in (3.51 cm) thick. Other specifications found during lab testing in previous research are shown below in the table 116.[6]

Table 116. LED Unit Specifications

Lamp Description	On-axis Output Measurement at 8m (lux)	On-axis Equivalent Source Output (cd)	Half Output Total Horizontal Beam-width (deg)	Number of Active LEDs	Approximate On-axis Output per LED (cd/LED)	Current Draw at 13.5V (milliamps)	Power Consumed at 13.5V (watts)
Round 4” Diameter Stop lamp Type: anythingtruck.com 440RHW	4.11	263	7	40	6.58	271	3.66

As the table above shows, the half output total horizontal beam-width was found to be 7 deg. However, a value of 6 deg was used during vertical and horizontal aiming calculations for a more conservative capture of the following target vehicle.

LED UNIT VERTICAL AND HORIZONTAL AIMING EQUATIONS

Equations used for vertical aiming of LED units on trailer:

$$\tan\theta = \frac{|h_L - h_E|}{d} \qquad \text{Eq. 5}$$

$$A = 3 \pm \theta \qquad \text{Eq. 6}$$

In these equations,

h_L = the height of the LED unit of interest
h_E = the eye-height of the following vehicle driver of interest (minimum or maximum)
d = distance from trailer to following vehicle (minimum or maximum)
A = angle of final vertical aim (upward or downward)

Equation used for horizontal aiming of LED units on trailer:

$$\tan\theta = \frac{|d_L|}{|d_E|} \qquad \text{Eq. 7}$$

In this equation,

d_L = the horizontal distance (perpendicular to travel direction) from the rear of the trailer to eye position of the adjacent lane following vehicle driver
d_E = the travel distance from the rear of the trailer to the eye position of adjacent lane following vehicle driver

If $\theta \geq 3$, then lights could be adjusted inward accordingly. This condition represents a scenario where horizontal aiming of lights can be very accurately performed. However, most lighting used in visual lighting experiments for this project were aimed inward at 2.5 deg in order to concentrate the majority of light in the lane immediately behind the trailer (with the exception of LED units located near the center of the ICC bumper).

REAR-LIGHTING CONFIGURATION SPECIFICATIONS

Baseline Light Configuration (Normal Brake lights)

No change in vertical or horizontal aim applied to normal brake lights (originally installed from trailer manufacturer) (see figure 171).

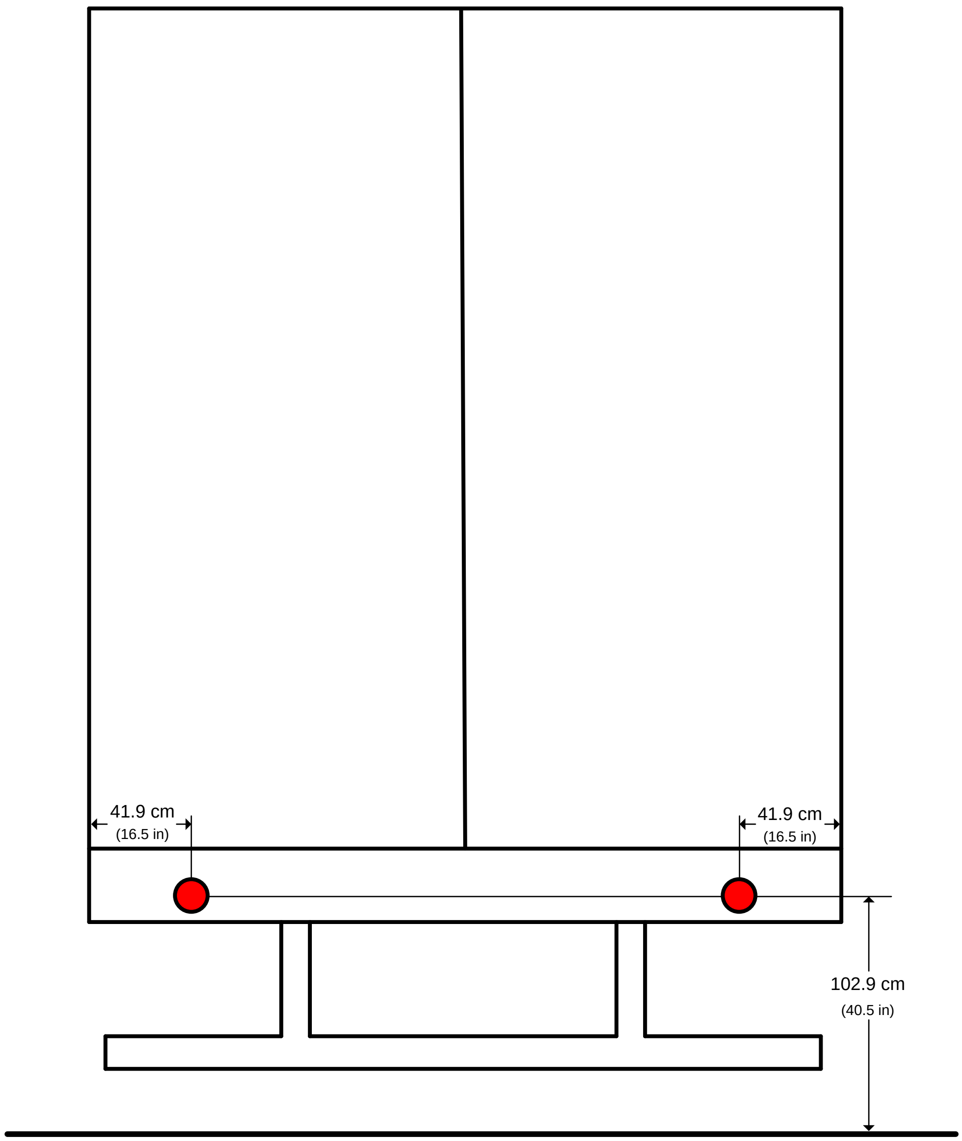

Figure 171. Diagram. LED unit positioning for the *Baseline* light configuration.

Rear Warning-light Configurations

See table 117, figure 172, and figure 173 for detailed specifications on the rear warning-light configurations tested.

Table 117. Vertical and Horizontal Aims for LED Unit Positions on Rear of Trailer for All Experimental Testing

Position on Trailer	Vertical Aim Angle	Horizontal Aim Angle
Main bumper	2.64 deg upward	2.5 deg inward
ICC bumper (Sides)	3.75 deg upward	2.5 deg inward
ICC bumper (Center)	3.75 deg upward	0 deg inward
Lower unit on door	1.33 deg upward	2.5 deg inward
Middle unit on door	1.45 deg downward	2.5 deg inward
Top unit on door	3.88 deg downward	2.5 deg inward

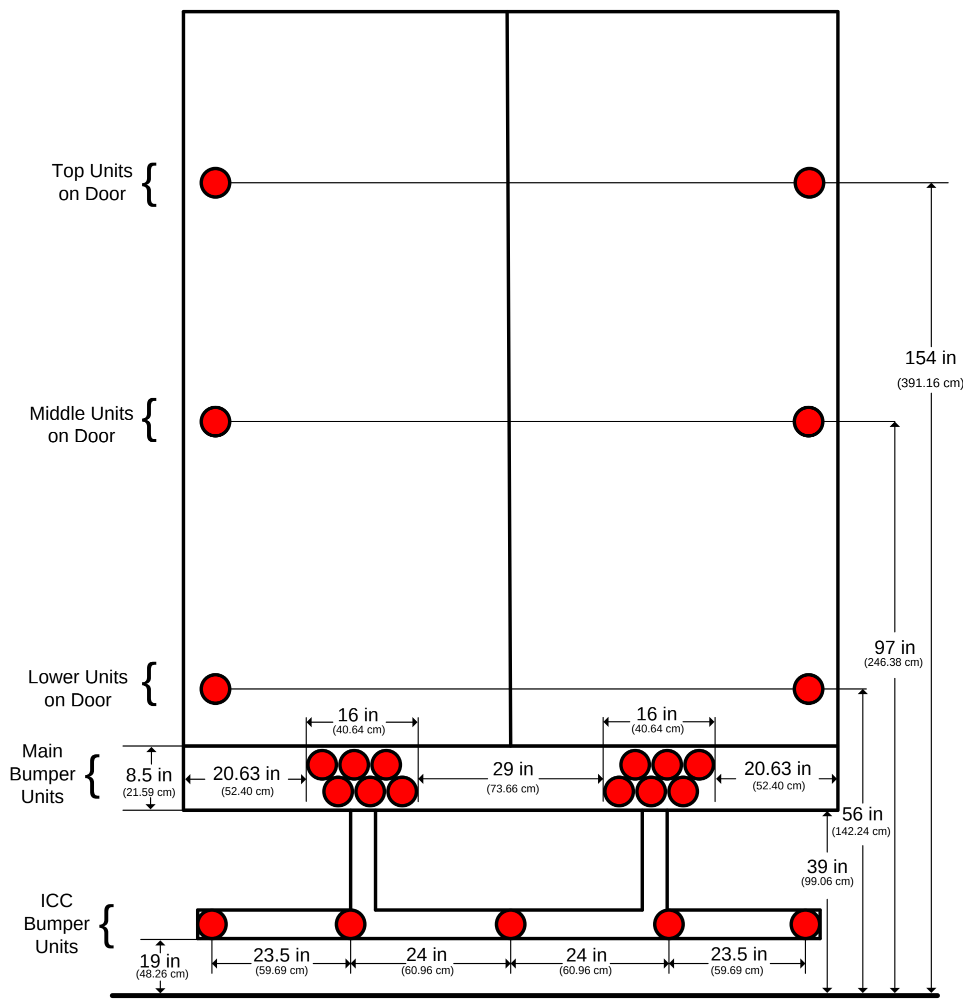

Figure 172. Diagram. LED unit positioning for the initial rear warning-light configurations.

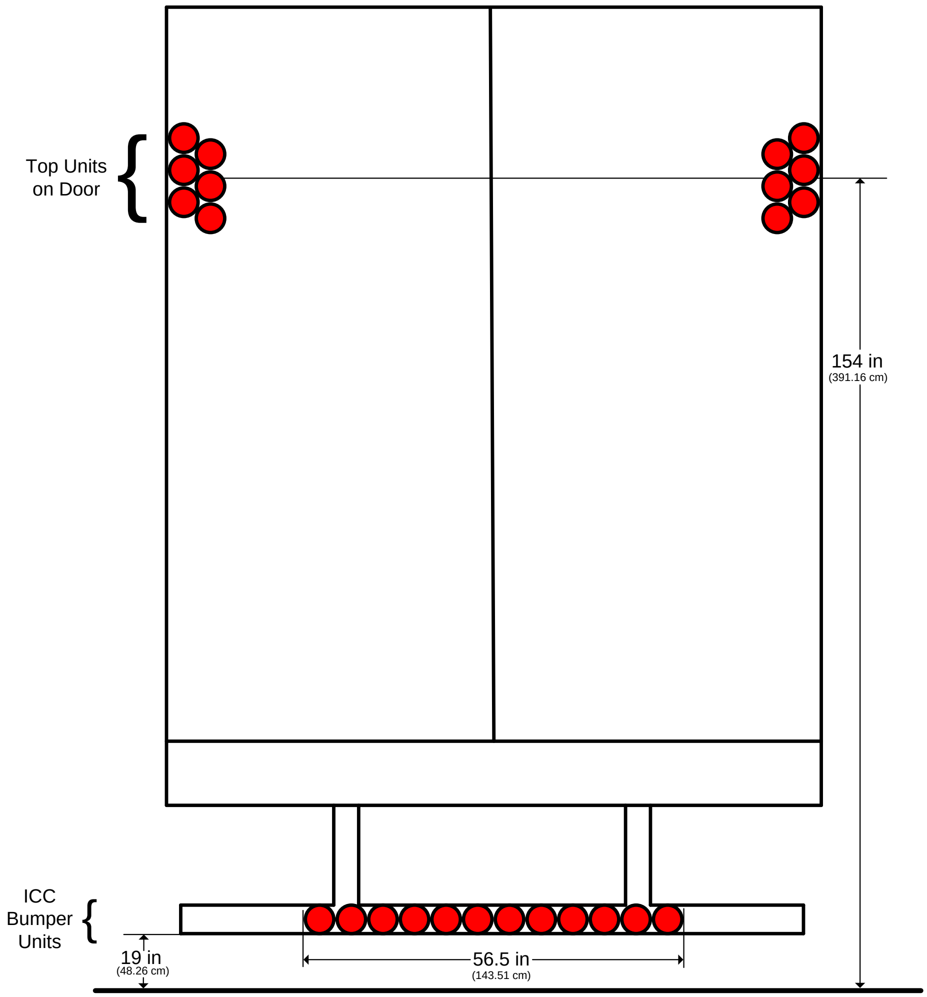

Figure 173. Diagram. LED unit positioning for the follow-up rear warning-light configurations.

APPENDIX D. VISION AND HEARING SCREENING PROTOCOLS

VISUAL ACUITY TEST PROTOCOL AND SCRIPT

Protocol:

1. The participant can wear glasses or contact lenses to meet these criteria but not transition lenses.

2. Attach a Snellen eye chart to a wall in a well lit area that is not too bright. The center of the chart should be positioned at approximately eye-level of the participant (see figure 174). Use a measuring tape to set this up. Tests can be given in any room as long as: (i) there is enough distance to administer the test, (ii) the lighting is consistent for every participant, and (iii) there is no glare on the vision chart that could prevent the participant from accurately viewing the chart.

3. Have the participant stand directly facing the chart with his/her toes on a tape line marked on the floor 20 ft (6.096 m) from the wall (see figure 174).

4. Sterilize the occluder with an alcohol swab and hand it to the participant.

5. Instruct the participant to not press the occluder on the eye, for it could result in altered vision. The participant should keep both eyes opened (one of them covered).

6. Following the script for the vision test, instruct the participant to look at the wall and read aloud the smallest line that he/she can see.

7. If the participant gets every letter on that line correct, have him/her read the next line down in the same manner. Continue this process until the participant can no longer read an entire line correctly. Record the visual acuity of the last completed line.

8. If the participant did not get every letter correct in the first line read, have him/her read the line above in the same manner. Repeat as necessary until a line is read correctly. Record the visual acuity of the first completed line.

9. Repeat the entire process for the other eye, and record the visual acuity for that eye.

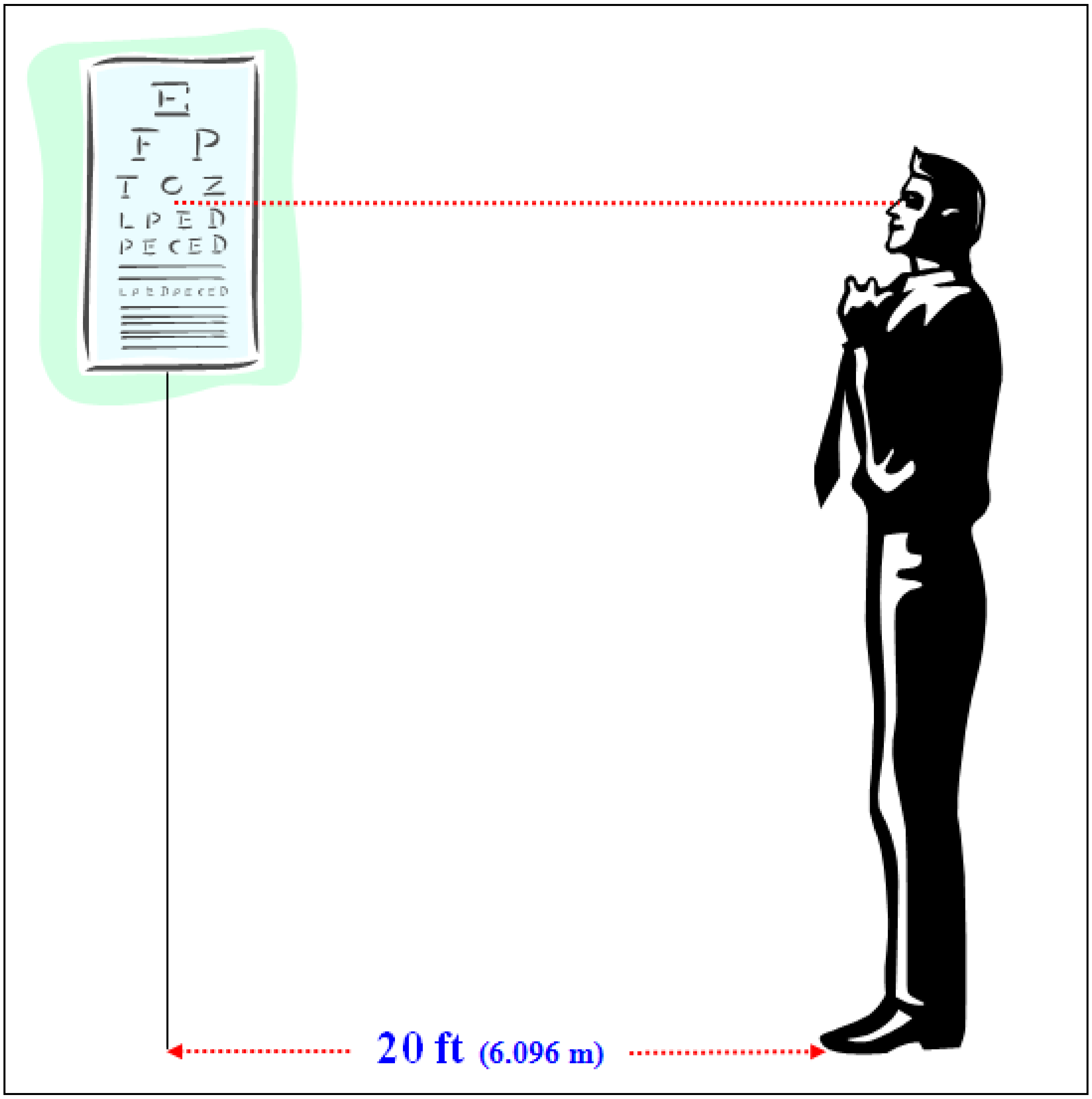

Figure 174. Diagram. Visual acuity test chart positioning.

Script:

> ***Next we are going to be performing an informal vision test. You should wear your corrective glasses or contact lenses if prescribed. Please stand with your toes on the tape line that you see on the floor, and face the eye chart ahead. Use this occluder to cover one of your eyes at a time. Don't press the occluder against the eye. Keeping both eyes open, place it over your left eye, and using only your right eye, read aloud the smallest line that you can see.***

If the line is read successfully, read:

> ***Please read the line below that.***

Repeat until a line is missed, then record the vision number from the line above.

If the line is not read successfully, read:

> ***Please read the line above that one.***

Repeat until one full line is read correctly, and record the vision number from that line.

> ***Now, give your eyes as long as they need to rest and refocus. When you are ready, keeping both eyes open, place the occluder over your right eye, and read aloud the smallest line that you can see using only your left eye.***

If the line is read successfully, read:

> ***Please read the line below that.***

Repeat until a line is missed, then record the vision number from the line above.

If the line is not read successfully, read:

> ***Please read the line above that one.***

Repeat until one full line is read correctly and record the vision number from that line.

> ***Thank you for your time.***

VISION AND HEARING FORM

Vision/Hearing/Measurement

---

1. **Acuity Test**

    - Acuity Score:________

2. **Ishihara Test for Color Blindness**

1._____	4._____	7.____
2._____	5._____	
3._____	6._____	

3. **Informal Hearing Test:**

    - A car is approaching in the left lane. ____
    - Please turn left at the next intersection. ____
    - The vehicle is riding smoothly. ____
    - The car ahead of me has its high-beams on. ____

4. **UFOV scores:**

    - Processing Speed: __________
    - Divided Attention: __________
    - Selective Attention: __________
    - Overall: __________

APPENDIX E. RADAR SPECIFICATIONS

A diagram of radar positioning is shown in figure 175.

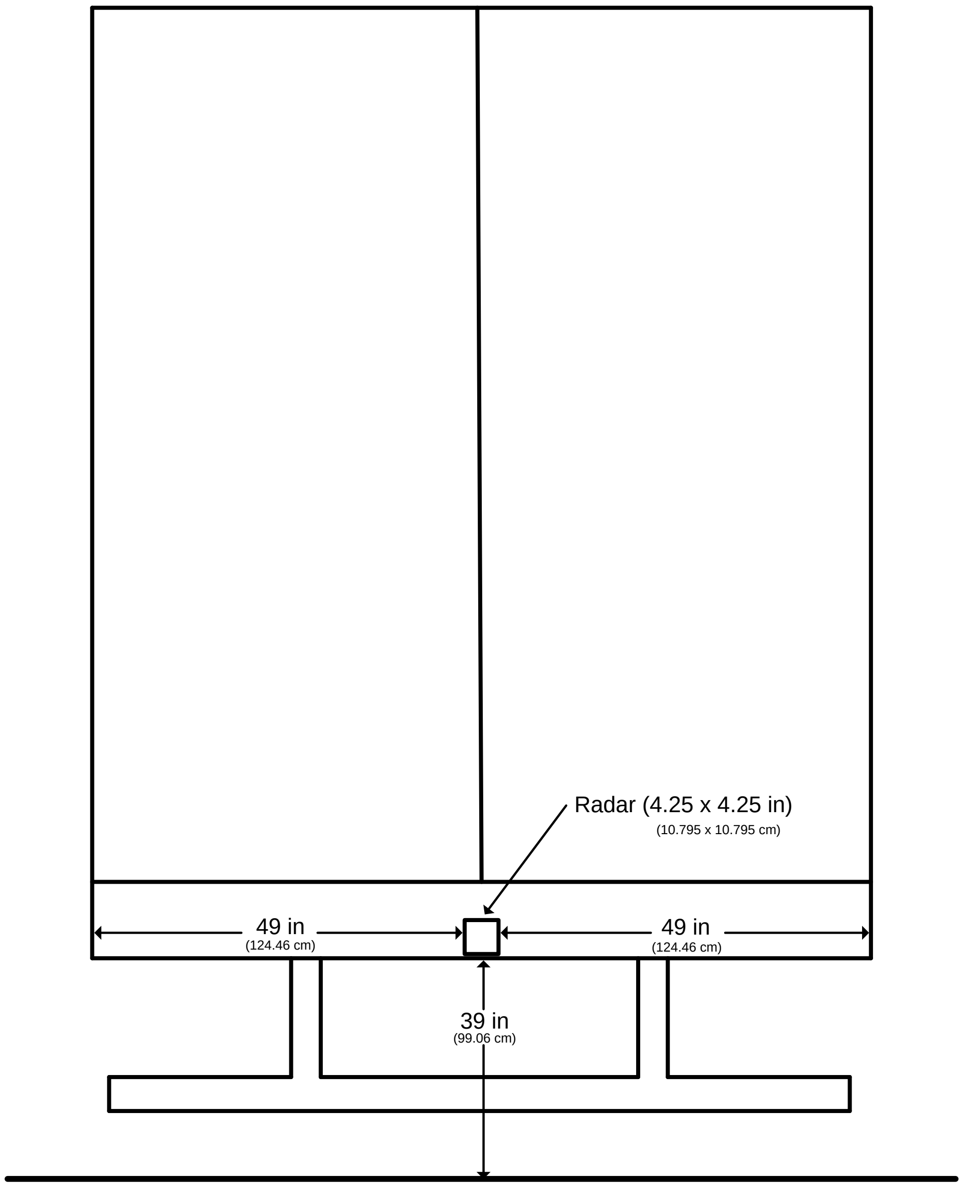

Figure 175. Diagram. Radar positioning on rear of trailer for all dynamic testing.

APPENDIX F. HELPFULNESS AND USEFULNESS RATINGS

Helpfulness and Usefulness Ratings

Please choose the vertical line on the scale below that best matches your opinion.

1. How helpful was the system in directing your attention?

How Helpful?

NOT AT ALL HELPFUL	SLIGHTLY HELPFUL	MODERATELY HELPFUL	VERY HELPFUL	EXTREMELY HELPFUL

2. How useful do you think the system would be on the roadway?

How Useful?

NOT AT ALL USEFUL	SLIGHTLY USEFUL	MODERATELY USEFUL	VERY USEFUL	EXTREMELY USEFUL

APPENDIX G. DYNAMIC TESTING PROTOCOL FOR VIRGINIA SMART ROAD

SCRIPT PRIOR TO CAR FOLLOWING/IN-VEHICLE TASKS

(Sections in *italics* are statements read to each participant by the experimenter)

The heavy vehicle is at a safe distance in front of you right now. Your job will be to maintain that same distance from the heavy vehicle, regardless of the speed; if the truck in front of you speeds up, you speed up to maintain the distance, and if the truck in front of you applies the brakes to slow down, you slow down to maintain the distance. Do you understand? You don't need to watch your own speed at all, but the lead heavy vehicle will probably maintain around 25 miles an hour.

I will ask you to perform tasks while you drive, so I'm going to point out some of the controls you'll be using to follow my instructions.

- *This area controls the radio. Press this button to turn it ON and OFF, and turn it to adjust the volume. These buttons are for AM ,FM, and XM and this knob tunes the exact frequency. To choose a category while in the FM mode, use this button. These are the preset station buttons. Any questions?*

- *This area also controls the navigation system. Press this button to turn it ON and this button to turn it OFF. To zoom in and out of the map, use these buttons. Touch the clock/time button to see further details about the date and time.*

- *When I am about to present a task, I will say OK. Then I will give you a short list of instructions, followed by the word "Begin." Do not begin the task until I say "Begin." For example, I may say "OK, when I say begin turn on the radio by pressing the ON button, adjust the volume to a comfortable level, then turn the radio off. Begin." Do you have any questions about the tasks or instructions?*

- *In order that you can focus your full attention to the car-following task, I will not be able to speak to you during the periods between tasks. I just wanted to tell you this so that you won't think I'm being unfriendly. Feel free to ask me any questions relating to the experiment at any time, however.*

- *We're going to take a practice loop first so you can practice following the truck as well as performing the types of tasks you'll be doing. Then we'll collect data during the following loops. Remember that the purpose of the experiment is to investigate how well drivers can maintain a set safe following distance while performing various types of in-vehicle tasks.*

- *As soon as I tell the lead heavy vehicle we're ready, they'll pull onto the road going about 25 mph. We'll go a total of three loops around the road, and we'll stop right here* *to recalibrate after every loop. Take a minute to gauge the distance from this car to the heavy vehicle.*

PROTOCOL AND SCRIPT FOR CAR FOLLOWING/IN-VEHICLE TASK EXPERIMENT

Loop 1, Downhill

1. END OF INTERSECTION. Press button to initiate normal truck brake lighting.

2. MIDDLE OF FIRST BRIDGE. *Turn on the Navigation System by pressing the ON button. Then turn the navigation system off. Begin*

3. BEGINNING OF RAIN TOWERS. Press button to initiate normal truck brake lighting.

4. TWO BIG BLOCKS ON RIGHT SIDE OF ROAD. *Turn on navigation system, then zoom right to 1 mile. Then turn off the navigation system. Begin.*

Loop 1, Uphill

1. FIRST OVERHEAD LIGHTING TOWER. *Turn on navigation system, than zoom left to 1/8 mile. Then turn off the navigation system. Begin.*

2. SIGN TRANSOM ACROSS ROAD. *Turn on the radio by pressing the ON button. Change it to AM, and then turn the radio off. Begin.*

3. BLACK WIND GAUGE ON RIGHT. Press button to initiate normal truck brake lighting.

4. IMMEDIATELY AFTER LAST RAIN TOWER. *Turn on Radio, Select FM, then category, then turn radio off. Begin.*

Recalibrate

We're going to recalibrate the distance now. Follow the heavy truck around the curve. We will line up in the same position as we started. When you are ready to continue, let me know so I can tell the truck driver.

Loop 2, Downhill

1. END OF FIRST BRIDGE. *Read the In-vehicle Display Screen, and then tell me aloud what it reads. Begin.*

2. BEFORE RIGHT SIDE POWER LINE (BLACK PAVEMENT). Press button to initiate normal truck brake lighting.

3. TWO BLOCKS INSIDE GUARD RAIL. Press button to initiate normal truck brake lighting.

4. BEFORE TRANSFORMER BOX. *Turn navigation system on, select time/clock area, then turn it off. Begin.*

Loop 2, Uphill

1. AT THE 4th OVERHEAD LIGHT. *Turn on the radio by pressing the ON button. Change it to AM, then tune it to 1260 AM using the Tuning knob (not the Seek button). Turn the radio off. Begin.*

2. DEBRIEF while stopped, using debriefing form.

3. END OF RAIN TOWERS. Press button to initiate normal truck brake lighting.

END OF FIRST BRIDGE. Press button to initiate normal truck brake lighting.

Recalibrate

We're going to recalibrate the distance now. Follow the heavy truck around the curve. We will line up in the same position as we started. When you are ready to continue, let me know so I can tell the truck driver.

READ ADDITIONAL STATEMENT EXPLAINING REAR LIGHTING

Statement for Subjects Receiving an Imminent-warning Lighting Configuration

In the remainder of your drive, please remember that In-Vehicle Tasks and Braking may occur either separately or at the same time. You are to maintain the safe distance at all times behind the heavy vehicle. The braking may be at a low level in which only the ordinary brake lights of the trailer will come on. The braking may also be at a high level or you may be approaching too quickly, in which case the Additional Imminent-warning Lighting will come on. So, remember, if you see only the ordinary brake lights come on, you will need to brake somewhat to maintain the safe distance. If, on the other hand, you see the imminent-warning lighting come on, it is an indication that the truck is braking relatively hard or you are approaching the rear of the trailer too fast and YOU will need to brake relatively hard to maintain the desired safe distance.

Do you have any questions?

Statement for Subjects Receiving the Ordinary Brake Light Configuration

In the remainder of your drive, please remember that In-Vehicle Tasks and Braking may occur either separately or at the same time. You are to maintain the safe distance at all times behind the heavy vehicle. The braking may be at a low level or at a high level or you may be approaching too quickly. In both cases the brake lights will come on. So, *remember, if the brake lights come on, you should be prepared to brake at an appropriate level to maintain the desired safe distance.*

Do you have any questions?

Loop 3, Downhill

1. AT FIRST RAIN TOWER. Press button to initiate normal truck brake lighting.
2. AS SOON AS POSSIBLE AFTER END OF BRAKING IN ABOVE. *Report the time on the in-vehicle display on the console. Begin.*
3. AT BEGINNING OF RIGHT SIDE GUARD RAIL. Press button to initiate normal truck brake lighting.
4. AS SOON AS POSSIBLE AFTER BRAKING IN #4. *Turn on the radio by pressing the ON button. Select XM radio button. Turn the radio off. Begin.*

Loop 3, Uphill

1. AT FIRST OVERHEAD LIGHT. Press button to initiate normal truck brake lighting.
2. AT SIGN TRANSOM ABOVE ROAD. *Turn the radio on and tune it FM using the FM button, then turn the radio off. Begin.*
3. HALFWAY THROUGH RAINTOWERS (BLACK PAVEMENT AREA). Press button to initiate normal truck brake lighting.
4. AT LAST RAIN TOWER (change L #). *Turn on the Navigation System by pushing the ON button. Zoom to right 4 miles. Turn the navigation system off. Begin.*

DEBRIEF

APPENDIX H. ACTIVATION ALGORITHMS FOR CLOSED-LOOP TESTING

This appendix first appeared as appendix A of Wierwille, Lee, and DeHart (2003).[(21)] It has been edited to remove material that is irrelevant to heavy truck rear lighting activation and modified according to the necessary developmental process.

Main Program

This program is intended to activate a rear warning lighting system when a rear-end collision is imminent. Criteria to be met include range, R, equal to or less than R_{min}, and return angle within specifications, to be described later.

To understand how this program can be developed, it is first necessary to understand how a typical radar unit mounted at the rear of the lead vehicle transfers data. Figure 176 shows a typical data format. As the radar scans and detects a target, it provides a target designation number, range, range-rate, and angle to the target in a serial datastream. If there is more than one target, the datastream continues until all of the target ranges, range-rates, and angles are specified, as shown in figure 176.

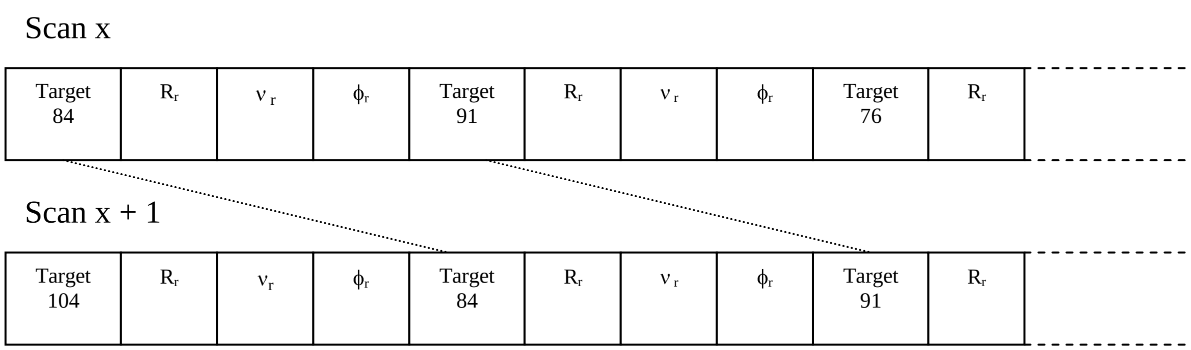

Figure 176. Diagram. Depiction of the datastream from the radar antenna unit (note that the stream length varies with the number of targets detected).

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

Figure 177 shows the main blocks of the activation program. The program is intended to provide rapid response in activating the rear warning lighting while minimizing false triggering. The program begins by examining two consecutive scans (datastreams) from the radar. Only when data in the two scans are consistent in all indications that a rear-end collision is imminent is the rear lighting activated. Once activated, the rear lighting remains activated for t_1 s, which is estimated to be about 2 s. If later scans continue to indicate that a collision is imminent, the t_1 s timeout is renewed. Thus, under ordinary circumstances, the rear lighting would be continuously renewed, without extinguishing, as long as the collision danger persists.

As the program indicates, the two scans are read and stored. Any targets that do not appear in both scans are deleted. For those remaining, the first and second scans are analyzed and compared. First the returns are analyzed with respect to angle. This is primarily a comparison subroutine, which will be described later. If any return pair is "qualified" in angle, it is transferred (along with other qualified pairs) to a second subroutine that is used to determine if both scans in each target pair are "qualified" in range. If any target pair is qualified in both angle and range, the rear-lighting system is activated or reactivated for a specified time, t_1 s. If there are no pairs qualified in both angle and range, the lighting is not activated/reactivated, and the process is repeated.

Generally, the time required to complete one pass through the program is expected to be relatively short, that is, about 100ms. This would include the time for the radar to produce the two scans and for the processing system to arrive at a decision regarding whether or not to activate/reactivate the lighting. To account for this time in the computations, that is, to offset the computation lag, it is only necessary to increase the perception-reaction time value, t_{pr}, in the equation for R_{min} by the amount of the expected lag. [1]

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

---

[1] Mathematical quantities are defined later in this appendix.
[2] This description corresponds to Condition 2, to be presented later.

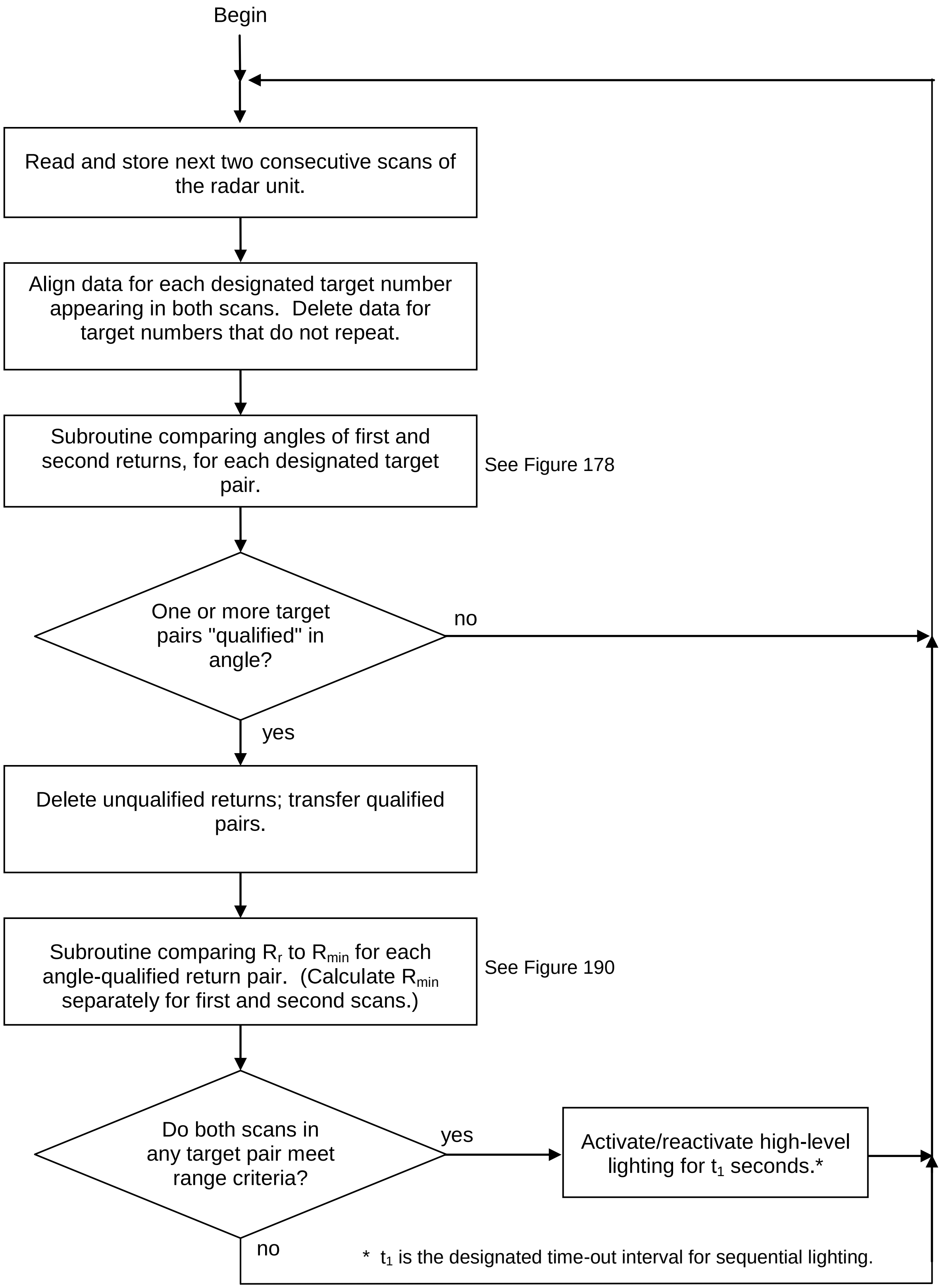

Figure 177. Diagram. Overall flow diagram for activation of closed-loop system.

The next sections describe the two subroutines in detail. The first is used to qualify a given target in regard to angle, and the second to qualify it in regard to range. Note that each target pair must be passed through the subroutines until it reaches a "no threat" condition, or until it passes completely through as "qualified."

Introduction to the Angle and Range Subroutines

Determining whether a rear-end collision is likely to occur must be based on whether the target to the rear is on an intersecting trajectory and is at or within the minimum stopping distance. A radar (or scanning laser) mounted at the rear bumper of the lead vehicle provides information about the "target" following vehicle. Specifically, it returns range, range rate, and target angle. Using these values as well as parameters taken from the lead vehicle, a decision must be made as to whether the following vehicle represents a "threat," that is, the following vehicle is very likely to "rear-end" the lead vehicle.

As previously indicated, two subroutines are required. One deals primarily with angle, and the other deals with range and range rate. If either subroutine returns an indication that the target is "not a threat," there is no need to activate the rear-lighting countermeasures. On the other hand, if both of the subroutines return a "threat" indication, the countermeasures should be activated. These concepts are taken into account in the overall block diagram of figure 177.

Subroutine for Qualifying a Target Return in Terms of Angle

There are two possible conditions for qualifying whether the return angle is from a threat vehicle. They can be expressed simply as follows:

1. For a following vehicle to strike a lead vehicle in the rear, the probability is high that the following vehicle will approach the rear within a <u>small</u> angle to the longitudinal axis of the lead vehicle, and

2. For a following vehicle to strike a lead vehicle, the probability is high that the following vehicle will approach the rear at a <u>constant</u> angle to the longitudinal axis of the lead vehicle.

The first condition results from the fact that most rear-end collisions occur with vehicles traveling in the same direction. If a vehicle is traveling at an off-angle position, it is either on a trajectory that will not intersect, or it will pass quickly across the previous path of the lead vehicle. Crashes at large rear angles (say, 15 deg) are rare, and it is doubtful that enhanced rear lighting would prevent them.

The second condition is a result of the well-known "necessary" condition used in navigation, namely, that vehicles on a collision course (ships and aircraft, for example) are at a constant angle to one another prior to collision. (There are some assumptions associated with this condition, but they are not particularly constraining.)

The two conditions can be used to "qualify" a target in regard to angle. Usually this requires two returns, because the radars that are available do not compute angular rate.

The subroutine for qualifying a target in angle is shown in figure 178. In this diagram, a "no-threat" indication is used to indicate that the next target should be examined, if there is one. If not, the subroutine should be exited and control returned to the "Begin" point of figure 16.

In figure 178, R_{r_1}, ϕ_{r_1} represent the range and angle to the first return, and R_{r_2}, ϕ_{r_2} represent the range and angle to the second return (of a designated target). The maximum absolute angle, ϕ_{max}, is measured from the longitudinal axis of the lead vehicle. This angle should initially be specified as 0.07 radian (4.0 deg); this was adjusted to 3.0 deg after initial testing.

The first two decisions (diamonds) determine if the two returns are within the specified maximum allowable angle. Thereafter, the third decision is associated with determining if the angle remains relatively constant. This represents a complex tradeoff between allowance for radar scintillation and qualifying targets that are not actually at a constant angle to the lead vehicle. Examination of one radar system indicates that scintillation does not exceed approximately 2.0 ft (.61 m) in the target lateral position. Therefore, the maximum allowable scintillation (y_{max}) should be specified at about 1.0 ft (.3 m) in each direction. Converting this to an angle involves dividing by the average range. Thus, the absolute difference in the angle between returns (in radians) should be less than y_{max} divided by the average range.

Subroutine for Qualifying a Target Return in Terms of Range

The subroutine qualifying a return in terms of range makes use of multiple computations and is the main discrimination method. The angle criteria just described are intended to delete targets that clearly do not qualify. Thereafter, range-related criteria are used as the method of precise determination. Because the presentation is quite involved, it is presented next in a separate main section.

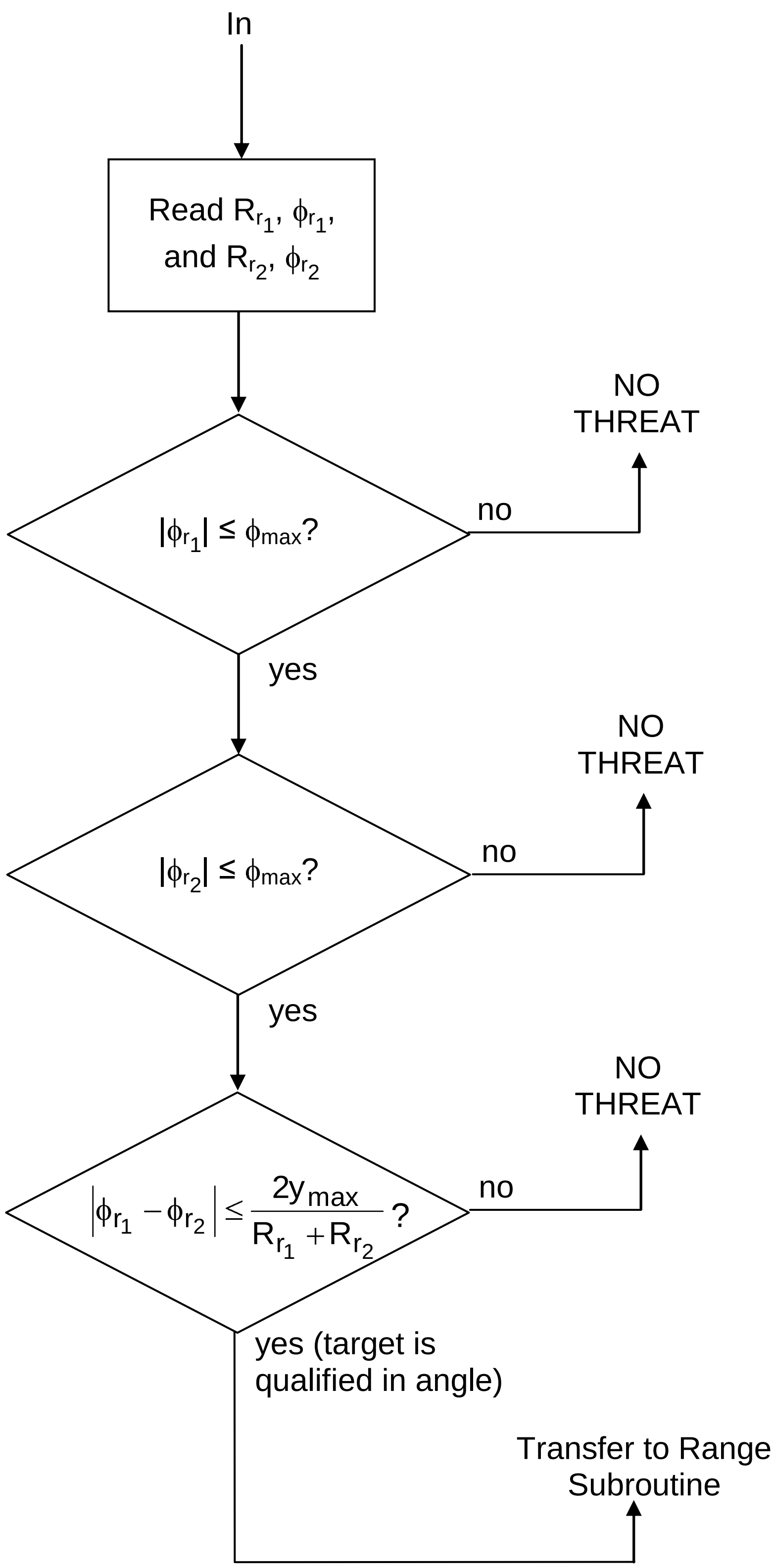

Figure 178. Diagram. Subroutine diagram to determine if a given target is "qualified" with regard to angle.

DETERMINATION OF WHETHER A RADAR RETURN IS FROM A "QUALIFIED" THREAT RANGE

Background

Five scenarios have been developed for determining whether or not a radar (target) return from the following vehicle represents a "qualified" threat. A qualified threat is one that will lead to a rear-end crash unless appropriate action is taken. The derivation process is very involved and requires many pages. Therefore, results of all five scenarios will be presented, along with a graphical depiction of each.

To begin, it is first necessary to frame the problem. Consider figure 179, which shows the relative movements of the following vehicle and the lead vehicle for the specific case in which the lead vehicle is at a constant-slower velocity equal to v_{L_i}.[2] The vehicles are initially separated by R_{min}, the minimum distance for which there will be no collision. During the perception-reaction time of the following driver, the following vehicle moves a distance d_{F_p}. The lead vehicle travels a corresponding distance d_{L_p}. Once braking begins, the following vehicle travels a distance d_{F_b}, while the lead vehicle continues to travel at a constant velocity for a corresponding distance d_{L_b}. For minimum separation, both vehicles have the same forward velocity at the instant they touch. Thereafter, the following vehicle once again falls behind due to continued deceleration, but there is no collision.

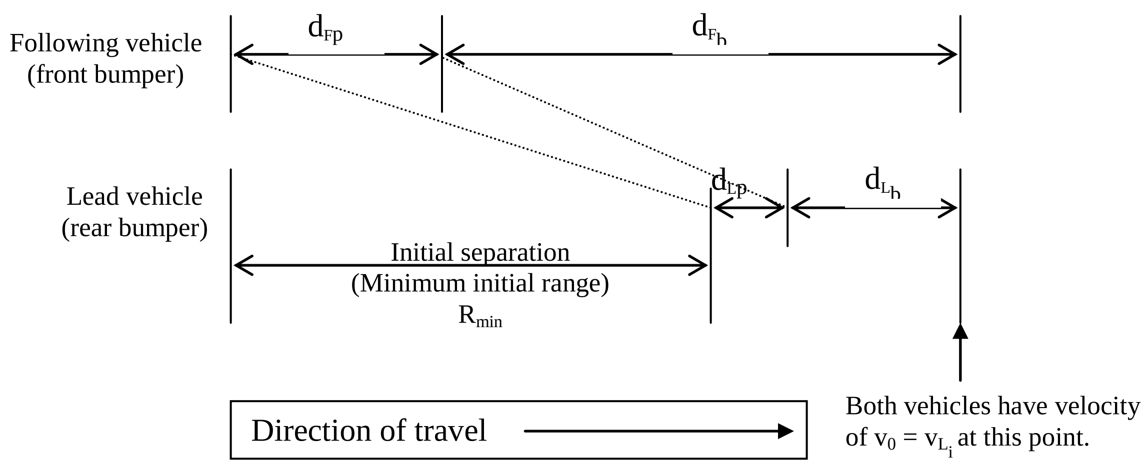

Figure 179. Diagram. Depiction of the limit condition for a constant velocity lead vehicle.

If the radar return range, R_r, is equal to or less than R_{min}, and if it is from a "qualified" angle, then the following vehicle represents a "threat," and countermeasures should be activated. The elements of the problem, as depicted in figure 179, must be kept in mind as the various

[2] This description corresponds to Condition 2, to be presented later.

conditions are presented. The five scenarios will be individually presented. Thereafter, a computer subroutine block diagram is presented for implementation of the results.

Nomenclature

a_L = acceleration of the lead vehicle in g's ($a_L = -c_L$)

c_F = deceleration of the following vehicle in *g*'s during braking (positive for deceleration)

c_L = deceleration of the lead vehicle in *g*'s during braking (positive for deceleration) ($c_L = -a_L$)

d_{F_b} = distance traveled by the following vehicle from the initiation of deceleration until the "touch point" is reached

d_{F_p} = distance traveled by the following vehicle during perception-reaction time, t_{pr}

d_L = distance traveled by the lead vehicle from t = 0 to the "touch point"

g = acceleration due to gravity; 32.2 ft/sec^2 (9.81 m/sec^2)

R_{min} = the minimum initial separation without a collision, measured between the lead vehicle rear bumper and the following vehicle front bumper

R_r = range of the return from the radar, measured from the rear bumper of the lead vehicle

t = running time from the start of the problem, or the time axis

t_0 = time when the touch point is reached

t_L = time when the lead vehicle stops due to deceleration

t_{pr} = following driver's perception-reaction time

v = general velocity, or the velocity axis

v_0 = velocity when the two vehicles reach the touch point (in Conditions 1 and 4 to be presented, $v_0 = 0$)

v_{F_i} = initial velocity of the following vehicle; also the velocity (assumed constant) during the perception-reaction time period

$v_F(t)$ = following vehicle velocity (after the perception-reaction time period)

v_{L_0} = the minimum velocity of the lead vehicle for which a time-headway calculation should be carried out

v_{L_i} = the initial velocity of the lead vehicle (velocity at t = 0); $v_{L_i} = v_L(0)$

v_L (t) = lead vehicle velocity

v_r = initial closing rate between vehicles; negative for following vehicle closing on lead vehicle ($v_r = v_{L_i} - v_{F_i}$)

x = general distance, or the distance axis

ϕ_r = angle of the return from the radar, measured from the longitudinal axis (and at the rear bumper) of the lead vehicle

τ_H = minimum allowable time-headway for the following vehicle without countermeasure activation

Units: All distances are in ft.
All velocities are in ft/sec
All accelerations and decelerations are in *g*'s, except that g = 32.2 ft/sec^2
All times are in s

Limit Condition 1

In this condition, the lead vehicle is standing still on the pavement as the following vehicle approaches. The following vehicle brakes (to a stop) after the perception-reaction time of its driver. The two vehicles touch at $t = t_0$, with both vehicles having zero velocity. Figure 180 shows the plot of distance as a function of time for each vehicle, and figure 181 shows vehicle velocities as a function of time. Since the lead vehicle is standing, its velocity is zero throughout the interval. Note that the following vehicle velocity is assumed constant during perception-reaction time, and linearly decreasing during deceleration.

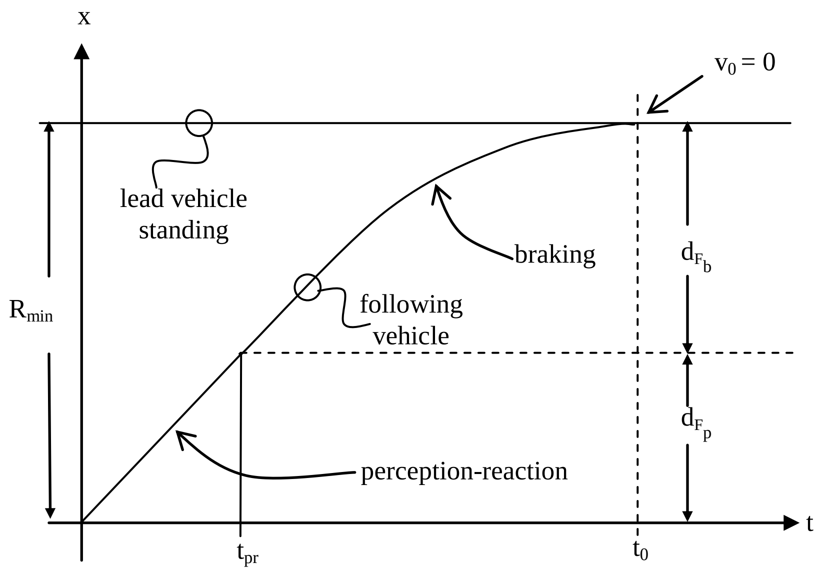

Figure 180. Diagram. Position of each vehicle as a function of time; *Condition 1*.

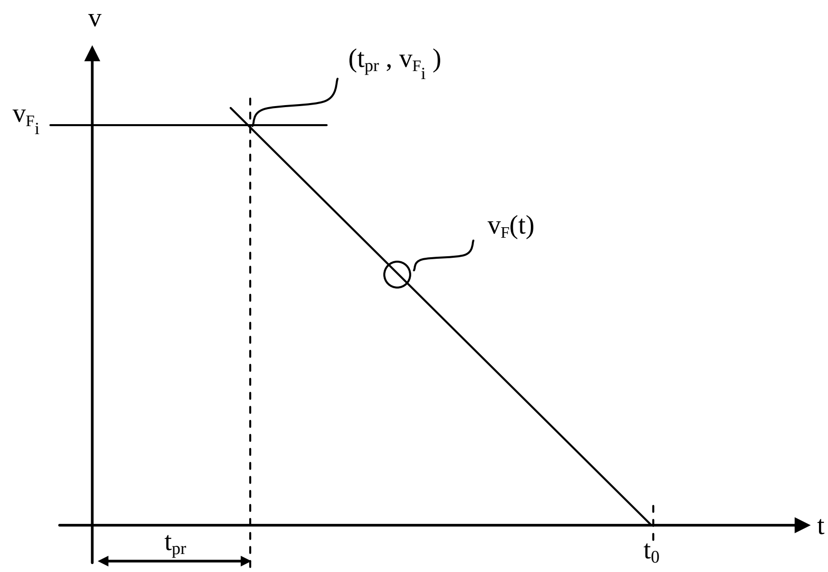

Figure 181. Diagram. Velocity of the following vehicle as a function of time; *Condition 1*.

The equations governing this scenario are as follows:

Minimum range:

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

Time to touch:

$$t_0 = t_{pr} - \frac{v_r}{gc_F}$$

Necessary conditions for the equation to be valid:

$v_{L_i} = 0$

$c_L = 0$

$v_r < 0$

Limit Condition 2

In this condition, the lead vehicle is traveling at a slower (constant) velocity than the following vehicle. The following vehicle brakes after the perception-reaction time of its driver. The two vehicles eventually touch at t_0, with both instantaneously at velocity v_0. Note that this is the situation depicted earlier in the background section. Figure 182 shows the plot of distance as a function of time for each vehicle, and Figure 183 shows vehicle velocities as a function of time.

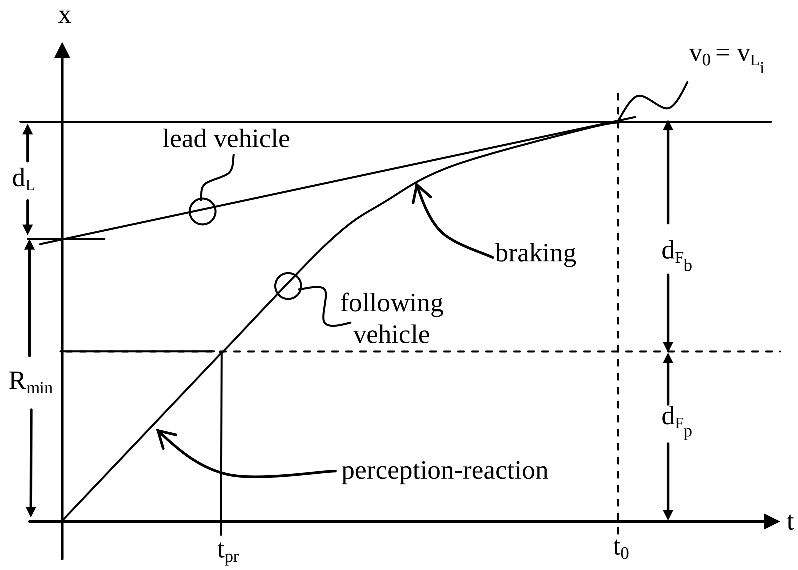

Figure 182. Diagram. Position of each vehicle as a function of time; *Condition 2*.

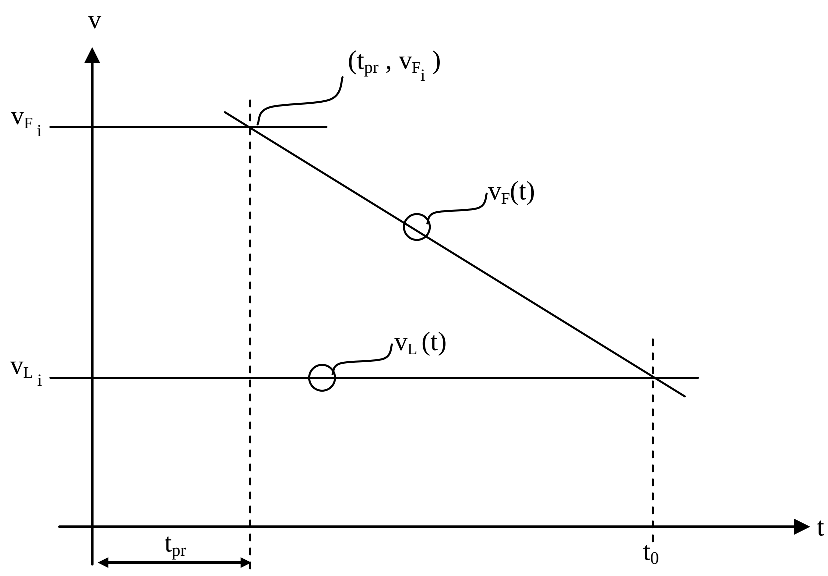

Figure 183. Diagram. Velocity of each vehicle as a function of time; *Condition 2*.

The equations governing this scenario are as follows:

Minimum range:

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

Time to touch:

$$t_0 = t_{pr} - \frac{v_r}{gc_F}$$

Necessary conditions for the equation to be valid:

$v_{L_i} > 0$

$c_L = 0$

$v_r < 0$

Limit Condition 3

In this condition, the lead vehicle decelerates. The following vehicle brakes after the perception-reaction time of its driver. The two vehicles eventually touch at $t = t_0$, with both instantaneously at velocity v_0. Note that the deceleration of the lead vehicle is relatively small; otherwise the lead vehicle will stop before it is touched (corresponding to Condition 4). Figure 184 shows the plot of distance as a function of time for each vehicle, and figure 185 shows the vehicle velocities as a function of time.

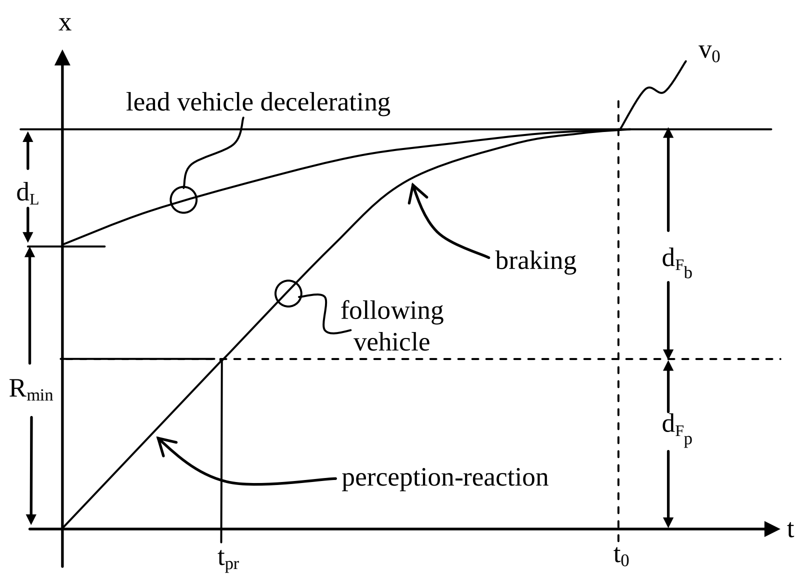

Figure 184. Diagram. Position of each vehicle as a function of time; *Condition 3*.

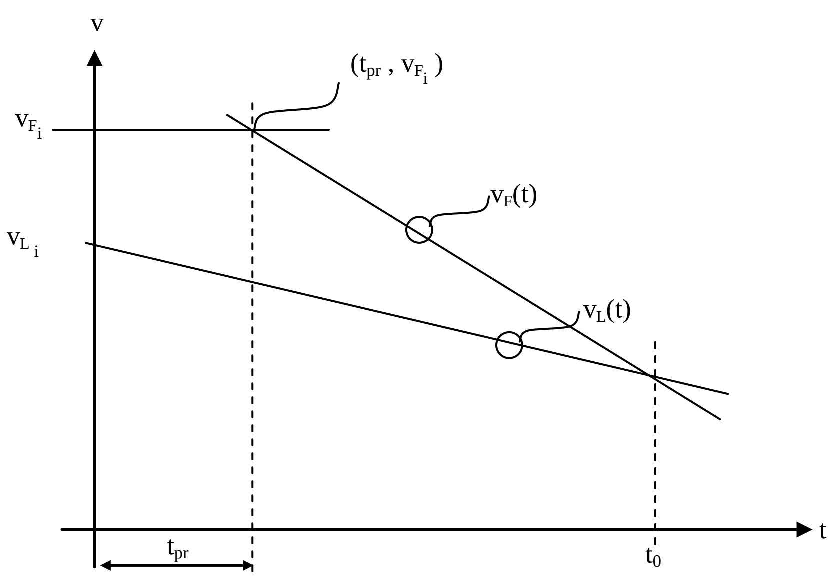

Figure 185. Diagram. Velocity of each vehicle as a function of time; *Condition 3*.

The equations governing this scenario are as follows:

Minimum range:

$$R_{min} = \frac{v_r^2 - 2v_r c_F g t_{pr} + c_F c_L g^2 t_{pr}^2}{2(c_F - c_L)g}$$

Time to touch:

$$t_0 = \frac{-v_r + c_F g t_{pr}}{(c_F - c_L)g}$$

Necessary conditions for the equation to be valid:

$(c_F - c_L) v_{L_i} + c_L v_r - c_L c_F g t_{pr} \geq 0$

$v_{L_i} > 0$

$c_L > 0$

$v_r < 0$

Limit Condition 4

In this condition, the lead vehicle decelerates to a stop and then stands on the pavement. The following vehicle brakes (to a stop) after the perception-reaction time of its driver. The two vehicles eventually touch at $t = t_0$, with both vehicles having zero velocity. Figure 186 shows the plot of distance as a function of time for each vehicle, and figure 187 shows the vehicle velocities as a function of time.

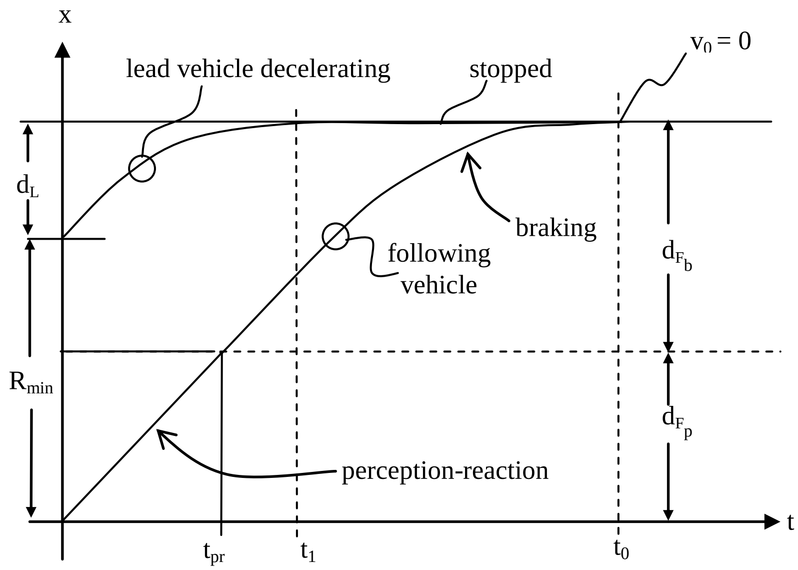

Figure 186. Diagram. Position of each vehicle as a function of time; *Condition 4*.

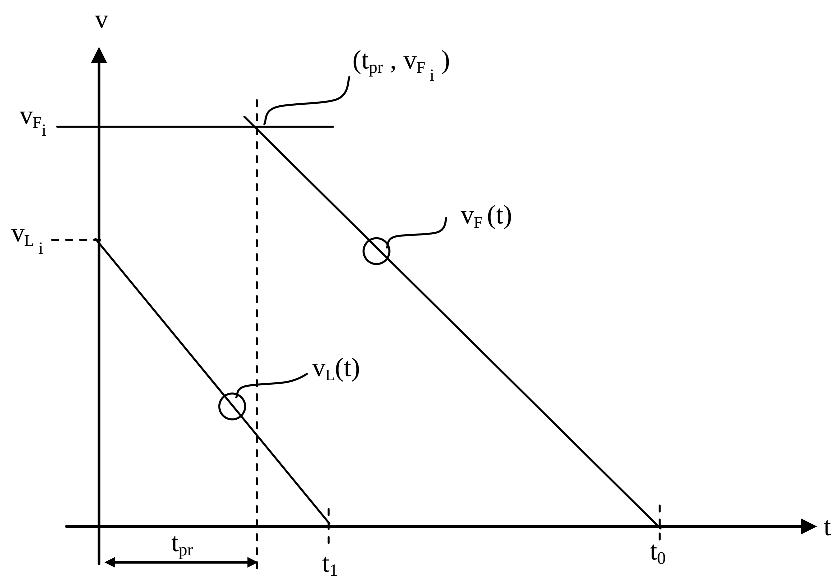

Figure 187. Diagram. Velocity of each vehicle as a function of time; *Condition 4*.

The equations governing this scenario are as follows:

Minimum range:

$$R_{min} = \frac{\left(v_{L_i} - v_r\right)^2}{2c_F g} + \left(v_{L_i} - v_r\right) t_{pr} - \frac{v_{L_i}^{\ 2}}{2c_L g}$$

Time to touch:

$$t_0 = \frac{v_{L_i} - v_r + c_F\ g\ t_{pr}}{c_F\ g}$$

Necessary conditions for the equation to be valid:

$0 \le (c_L - c_F)\ v_{L_i} - c_L\ v_r + c_L c_F\ g\ t_{pr}$

$c_L > 0$

$v_{L_i} > 0$

Limit Condition 5

In this condition, the lead vehicle accelerates, but at a sufficiently low value so that braking (after perception-reaction time) is required of the following vehicle. The two vehicles touch at $t = t_0$, with both vehicles at velocity v_0. Thereafter, the lead vehicle continues to accelerate and the following vehicle continues to decelerate. Figure 188 shows the plot of distance as a function of time for each vehicle, and figure 189 shows the plot of velocity for each vehicle as a function of time.

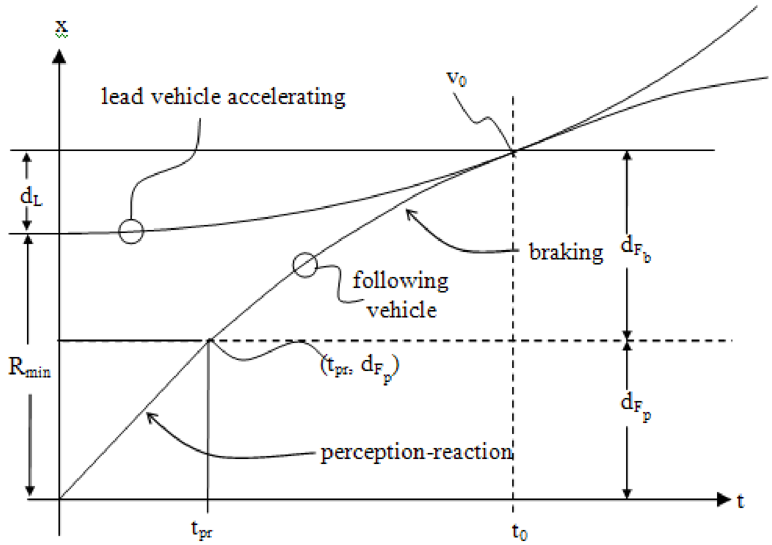

Figure 188. Diagram. Position of each vehicle as a function of time; *Condition 5*.

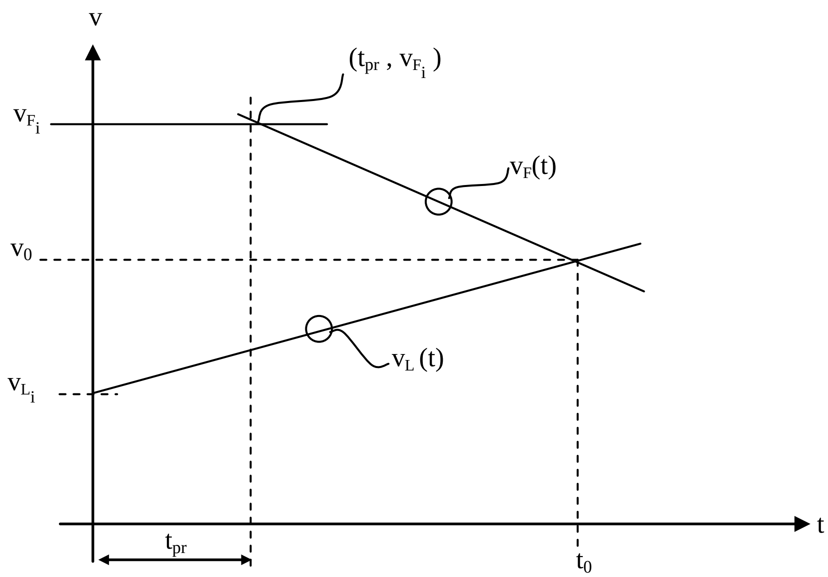

Figure 189. Diagram. Velocity of each vehicle as a function of time; *Condition 5*.

The equations governing this scenario are as follows:

Minimum range:

$$R_{min} = \frac{v_r^2 - 2v_r\, c_F\, g\, t_{pr} - c_F\, a_L\, g^2\, t_{pr}^2}{2(c_F + a_L)g}$$

Time to touch:

$$t_0 = \frac{-v_r + c_F\, g\, t_{pr}}{(c_F + a_L)g} \qquad \text{where } v_r = v_{L_i} - v_{F_i}$$

Necessary conditions for the equation to be valid:

$- v_r - a_L\, g\, t_{pr} \geq 0$

$a_L > 0$

$v_{L_i} > 0$

$v_r < 0$

Additional Notes on the Conditions

In all of the 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.

The equations have been derived so that closing (relative range) rate and range are the only required values. (Target angle is needed elsewhere, but not in these equations.) A radar placed at the rear bumper of the lead vehicle is capable of providing these parameters. An inexpensive longitudinal accelerometer on the lead vehicle (for lead vehicle acceleration/deceleration) and velocity were required, but due to accelerometers producing inconsistent data, only lead vehicle velocity was used (retrieved from the tractor's network). Thus, the measures needed for the computations are v_r, v_{L_i}, and c_L (or a_L). The range to the following vehicle, R_r, is also required to determine how it compares to R_{min}.

Other parameters must be specified for the solution. Essentially, these are assumed values for the following vehicle. Included are c_f, the deceleration of the following vehicle during braking, and t_{pr}, the following driver's perception-reaction time. A typical value for c_F is 0.70 (this value should probably be lowered for the general case), and a typical value for t_{pr} is 1.5 s (Burgett, Carter, Miller, Najm, and Smith, 1998; Roess, McShane, and Prassas, 1998).[28,29] Another issue not addressed in the previous algorithm work was the need for the addition of a *Time To Look-up* variable. Although a value of 1.5 s has been provided for perception-reaction time, the time it takes for a driver involved in a distracting task to have his/her eyes drawn to the rear warning-lights must be included (and can be added to the perception-reaction time variable t_{pr}). During dynamic testing it was found that on average it took drivers approximately 1.5 s to look up after lighting was activated. Therefore, for the purpose of closed loop testing the t_{pr} value was increased to 3.0 s.

It should be noted that in computing R_{min}, there may be computational lags. If, for example, two consecutive radar returns are used (one for detection and one for verification), then there will be a short resulting delay. Other small delays may occur in computation. The easiest way to handle these is to artificially increase t_{pr} by the total computation lag, possibly resulting in a value such as t_{pr} = 1.75 s (or 3.25 s if the *Time To Look-up* value has been added). Equivalently, t_{pr} may be replaced by the sum of two values: one being the perception-reaction time and the other being the computational lag. The equations would have exactly the same form.

Finally, in regard to Conditions 3 and 4, note that the first necessary conditions for each of them are the exact opposites of one another. In other words, if the parameters do not satisfy the first necessary condition for *Condition 3*, they will satisfy the first necessary condition for *Condition 4*, and vice versa. Thus, the decision as to whether *Condition 3* or *Condition 4* exists is a straightforward one. Also, the first necessary condition under *Condition 5* determines whether a collision is possible. If the acceleration of the lead vehicle is too high, there is no threat of a collision; the first necessary condition tests for this.

PRELIMINARY SUBROUTINE FLOW DIAGRAM TO DETERMINE WHETHER THE TARGET IS WITHIN THE THREAT RANGE

The purpose of this subroutine is to apply the proper equation to a radar return to determine if $R_r \leq R_{min}$. The value R_r is the range to the target at the rear, as provided by the rear-looking radar. The radar also supplies v_r, the closing rate, and ϕ_r, the angle of the return. To qualify the return in terms of angle, ϕ_r is also used elsewhere. If $R_r \leq R_{min}$, and the angle is qualified, then the countermeasure should be initiated. These conditions indicate that a rear-end crash is imminent.

The subroutine "qualifying" range uses a logic procedure to determine which equation is the correct one. It then evaluates the value of R_{min} and compares it to R_r for a decision. Figure 190 is the portion of the flow diagram that separates the computation into one of three classes: *Condition 1* or *2*, *Condition 3* or *4*, or *Condition 5*. First, it is determined whether the following vehicle is closing. If not, it is assumed that the following vehicle is not in danger of colliding. A time-headway option can be included and is described in the next section.

Assuming that the following vehicle is closing, the "class" decision is based entirely on the state of acceleration of the lead vehicle, as shown in figure 190. Figure 191 corresponds to Conditions 1 and 2 in which the lead vehicle is either standing or moving forward at a constant velocity. Similarly, figure 192 corresponds to the lead vehicle decelerating (Conditions 3 and 4), while figure 193 corresponds to the lead vehicle accelerating. Note in figure 192 and figure 193 that the qualifying conditions are computed first. In figure 193, if the qualifying condition is not met, there is no threat. Assuming that R_{min} does get calculated by a logic path shown in figure 191, figure 192, or figure 193, the value is compared to R_r in figure 194, and the corresponding threat indication is returned.

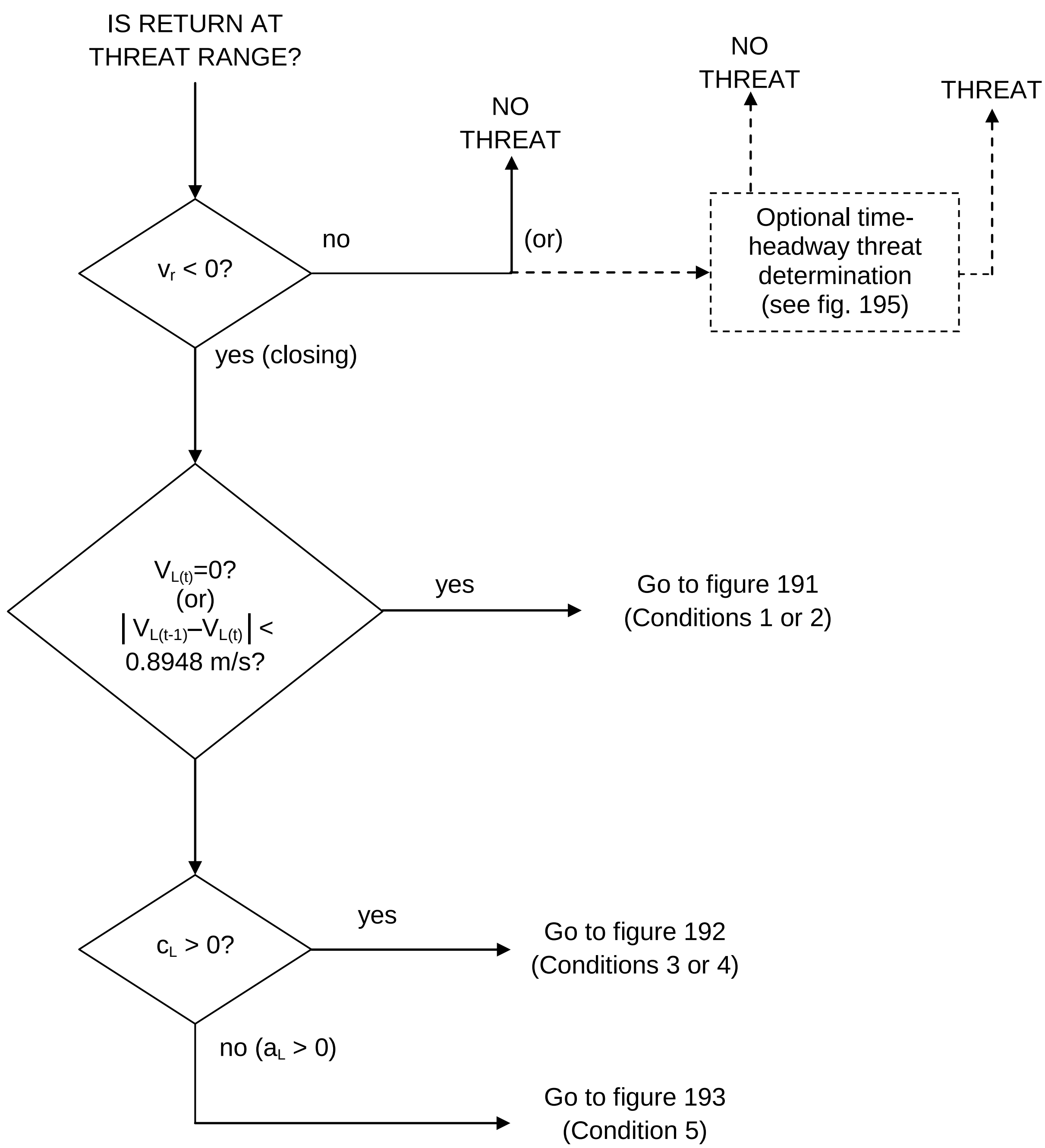

Figure 190. Diagram. Subroutine to determine if return is at threat range (classification).

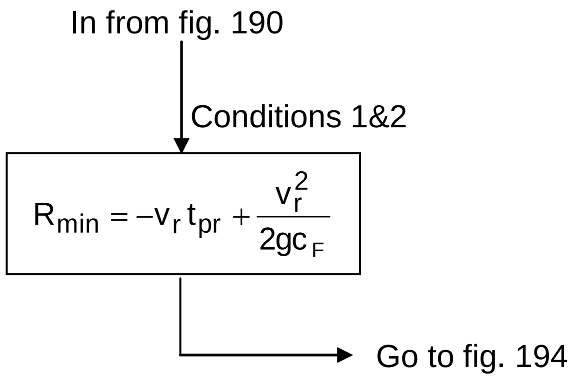

Figure 191. Diagram. Subroutine to determine if return is at threat range (for *Conditions 1* and *2*).

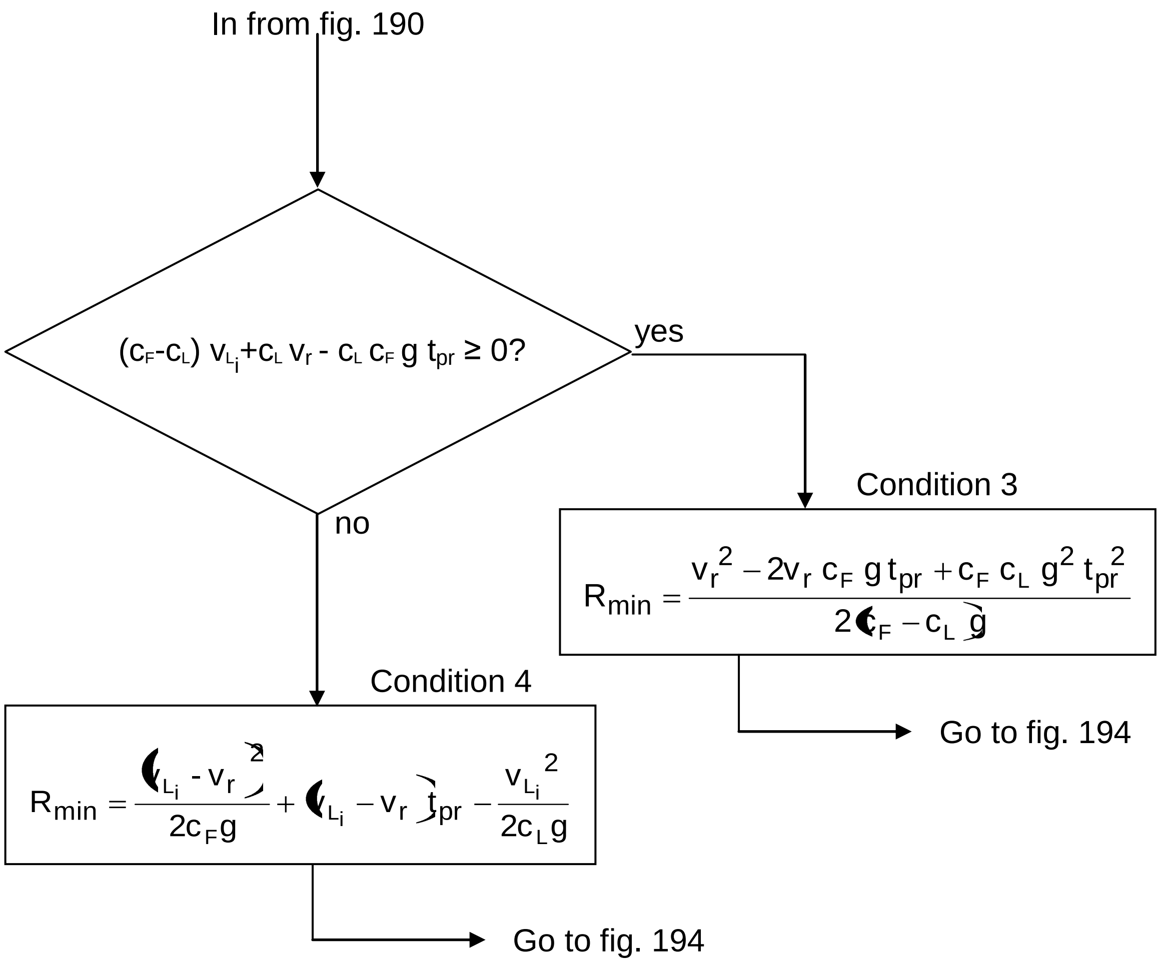

Figure 192. Diagram. Subroutine to determine if return is at threat range (for *Conditions 3* and *4*).

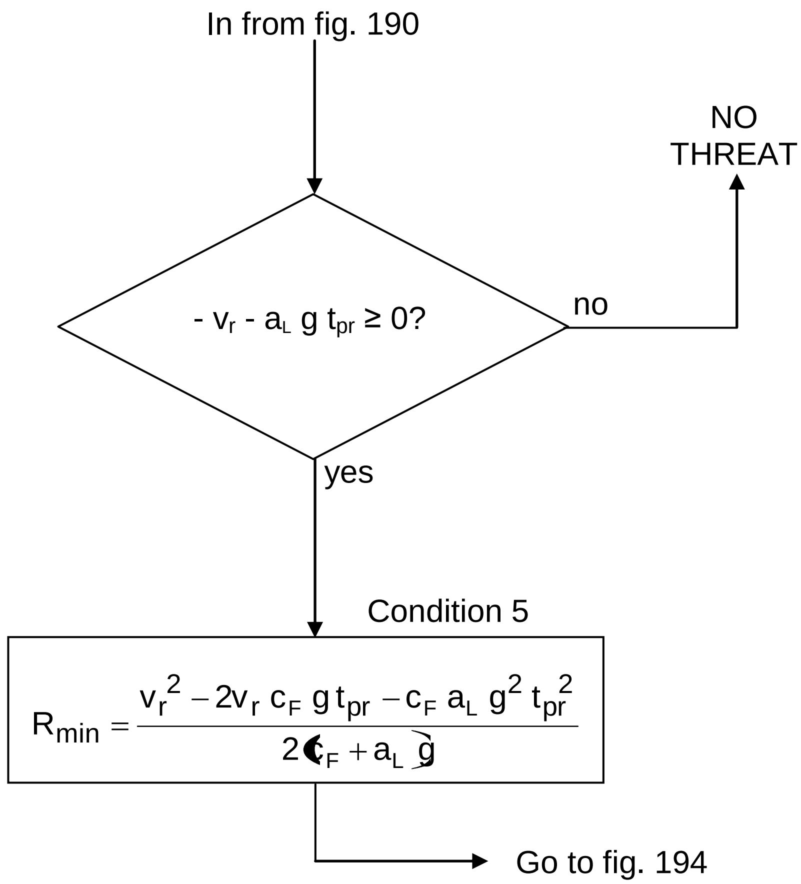

Figure 193. Diagram. Subroutine to determine if return is at threat range (for *Condition 5*).

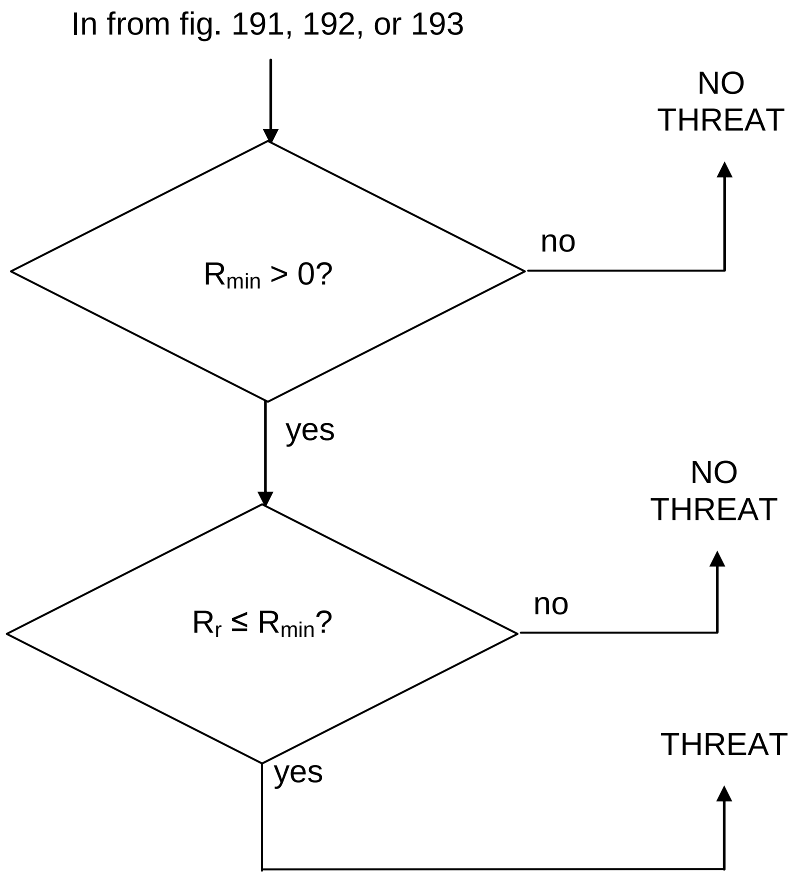

Figure 194. Diagram. Subroutine to determine if return is at threat range (comparison).

Short Time-Headway Option

As shown in figure 179, unless v_r is negative, the subroutine returns a "no threat" condition. In other words, if the following vehicle is not closing on the lead vehicle, it is assumed that a rear-end collision would not occur. In fact, for a collision to occur, the following vehicle must eventually close on the lead vehicle. Therefore, there should be a future radar return with v_r negative, in which case the possibility of a threat would be re-determined.

There is, however, an optional condition that might be included when v_r is zero or positive. It is the case of following too closely. Some drivers will tailgate to such an extent that they are creating a hazard; that is, they could not avoid a rear-end collision if the lead vehicle had to brake for an emergency. Under such circumstances, it might be desirable to initiate the countermeasure.

To include the "following too closely" case, time-headway can be computed and compared to a minimum acceptable time-headway, τ_H (in s). This value might be set at 0.5 to 0.75 s, well within the instructed time-headway of 2.0 s. It would probably be desirable to include a minimum permissible velocity under which this time-headway computation is performed. If, for example, the lead vehicle is traveling at less than approximately 20 mph

(v_{L_0} = 30 ft/sec), a no-threat condition is returned. This would prevent actuation of countermeasures in slow-moving, heavy traffic (except as determined through the R_r versus R_{min} comparison). Figure 195 shows the additional logic for inclusion of a time-headway option.

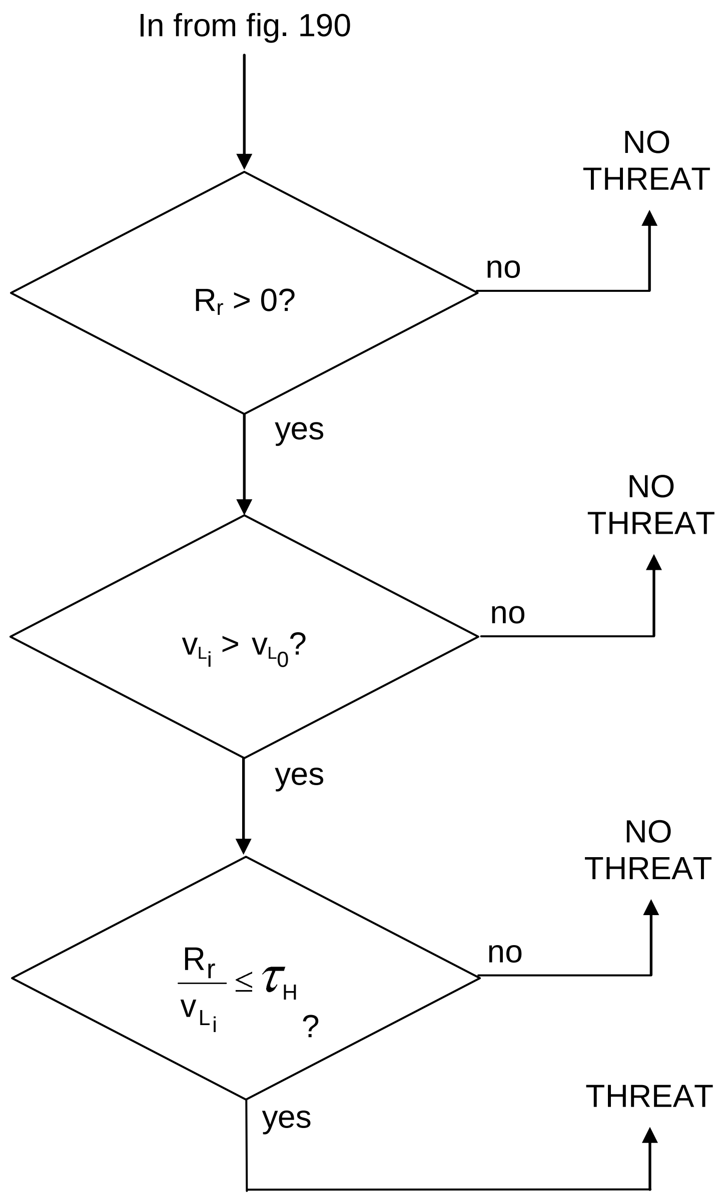

Figure 195. Diagram. Optional time-headway threat determination.

APPENDIX I. CAMERA AND LENS SPECIFICATIONS: REAL-WORLD DATA COLLECTION

CAMERA SPECIFICATIONS

Model
Dallmeier MDF3000A-M

Description
High-resolution Cam_inPIX® color module camera designed for indoor use.

Technical Data

Sensor:	1/3” DPS CMOS
Signal Processing:	17-bit Digital Signal Processing
Video Standard:	NTSC/PAL
Video Capture:	Progressive Scan
Video Capture Rate:	30 fps (NTSC), 25 fps (PAL)
Video Transfer Format:	PsF (Progressive segmented Frame)
Video Transfer Rate:	60 fields per second (NTSC), 50 fields per second (PAL)
Number of effective pixels:	720 (H) x 540 (V)
Horizontal resolution:	540 TV lines
Dynamic range:	102 dB typical, 120 dB max
S/N ratio:	>48 dB
Weight:	Approximately 80 g
Dimensions:	Approximately 47 x 45 x 34 (W x H x D) mm
Power Supply:	12V DC ±5 percent (including permitted tolerance)
Power Consumption:	Approximately 2 Watts
Temperature:	-10 deg Celsius to 50 deg Celsius
Humidity:	0 percent to 90 percent (non condensing)

LENS SPECIFICATIONS

Description
Four lenses of different focal length were used.

Lens 1:	50mm
Lens 2:	25mm
Lens 3:	14mm
Lens 4:	4.3mm

APPENDIX J. FOLLOWING-VEHICLE UNINTENDED CONSEQUENCE FOT PARAMETERS

The presence or absence of following-vehicle unintended consequences during rear-lighting activation will be determined in a similar procedure as was performed during the ERS Real-world Data Collection and serve as the DV (*Yes* or *No*). There will be two categories of interest for investigation with regard to roadway type. The first roadway type investigated will be a *Single-lane Roadway*, while the second roadway type investigated will be *Multi-lane Roadway*.

SINGLE-LANE ROADWAY TYPE

As previously mentioned, the main DV will be the presence or absence of an unintended consequence (*Yes* or *No*). The main IVs and the sub-levels of each were presented in table 26 (rear lighting and following-vehicle distance). For an event to be considered an unintended consequence in the *Single-lane Roadway* category, the following vehicle has to be positioned in the same lane directly behind the heavy truck as well as fall into at least one of the categories below:

- Following vehicle accelerated within 3 s after rear-lighting activation,
- Following vehicle swerved inside lane within 3 s after rear-lighting activation,
- Following vehicle performed lane deviation within 3 s after rear-lighting activation,
- Following vehicle performed heavy deceleration (brake lockup) within 3 s after rear-lighting activation, and/or
- Any combination of above four statements.

Acceleration will be determined by calculating the closing rate of the following vehicle during the 3 s prior to light activation and comparing it to the 3 s immediately following light activation. If the difference between values is greater than or equal to 5 ft/s (1.52 m/s), then the event will be labeled as an acceleration. The value of 5 ft/s (1.52 m/s) is the equivalent of 3.41 mi/h (5.49 km/h). Also, if the following vehicle was not closing on the experimental heavy truck for the 5 s prior to light activation, but was found to be closing on the experimental heavy truck for the 5 s immediately following light activation, the event will be labeled as an acceleration (even if the difference between closing rate values is less than 5 ft/s (1.52 m/s).

It is important to note that following-vehicle normal deceleration behavior should not considered an unintended consequence during the single-lane roadway category. It was determined that light to moderate following-vehicle deceleration should be considered normal behavior during actual lead-vehicle braking and/or rear warning-light activity in a real-world driving environment.

MULTI-LANE ROADWAY TYPE

Identical to the *Single-lane Roadway* category, the DV for the *Multi-lane Roadway* category will be the presence or absence of an unintended consequence (*Yes* or *No*). The main IVs and the sub-levels of each were presented in table 27 (rear lighting, following-vehicle distance, and following-vehicle lane position). For an event to be considered an unintended consequence in the *Multi-lane Roadway* category, the following vehicle has to fall into at least one of the categories below:

- Following-vehicle positioned in *Same* lane
    - Following vehicle accelerated within 3 s after rear-lighting activation,
    - Following vehicle swerved inside lane within 3 s after rear-lighting activation,
    - Following vehicle performed lane deviation within 3 s after rear-lighting activation,
    - Following vehicle initiated lane change within 1-3 s of rear-lighting activation (if vehicle initiated lane change between 0-1 s after rear-lighting activation, maneuver was considered predetermined by the following-vehicle driver),
    - Following vehicle performed heavy deceleration (brake lockup) within 5 s after rear-lighting activation, and/or
    - Any combination of above five statements.
- Following-vehicle positioned in *Right* lane
    - Following vehicle accelerated within 3 s after rear-lighting activation,
    - Following vehicle swerved inside lane within 3 s after rear-lighting activation,
    - Following vehicle performed lane deviation within 3 s after rear-lighting activation,
    - Following vehicle initiated lane change within 1-3 s of rear-lighting activation (if vehicle initiated lane change between 0-1 s after rear-lighting activation, maneuver was considered predetermined by the following-vehicle driver),
    - Following vehicle decelerated within 3 s after rear-lighting activation,
    - Following vehicle performed heavy deceleration (brake lockup) within 3 s after rear-lighting activation, and/or
    - Any combination of above six statements.
- Following-vehicle positioned in *Left* lane
    - Following vehicle accelerated within 3 s after rear-lighting activation,
    - Following vehicle swerved inside lane within 3 s after rear-lighting activation,
    - Following vehicle performed lane deviation within 3 s after rear-lighting activation,
    - Following vehicle initiated lane change within 1-3 s of rear-lighting activation (if vehicle initiated lane change between 0-1 s after rear-lighting activation, maneuver was considered predetermined by the following-vehicle driver),
    - Following vehicle decelerated within 3 s after rear-lighting activation,
    - Following vehicle performed heavy deceleration (brake lockup) within 3 s after rear-lighting activation, and/or
    - Any combination of above six statements.

Accelerations and decelerations will be determined by calculating the mean closing rate of the following vehicle during the 3 s prior to light activation, and comparing it to the 3 s immediately following light activation. If the difference between values is greater than or equal to 5 ft/s (1.52 m/s), then the event will be labeled as an acceleration or deceleration. Also, if the following vehicle was not closing on the heavy truck for the 3 s prior to light activation, but was found to be closing on the heavy truck for the 3 s immediately following light activation, the event will be labeled as an acceleration (even if the difference between mean closing rate values was less than 5 ft/s (1.52 m/s). If the following vehicle was closing on the heavy truck for the 3 s prior to light activation, but was not found to be closing on the heavy truck for the 3 s immediately following light activation, the event will be labeled as a deceleration (even if the difference between mean closing rate values was less than 5 ft/s (1.52 m/s).

It is important to note that following-vehicle normal deceleration behavior should not be considered an unintended consequence during scenarios involving the following-vehicle positioned in the *Same* lane. It was determined that light to moderate following-vehicle deceleration while positioned in the *Same* lane should be considered normal behavior during actual lead-vehicle braking and/or rear warning-light activation in a real-world driving environment.

APPENDIX K. ACKNOWLEDGEMENTS

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