Naturalistic Study of Truck Following Behavior

Final Report

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April 2016

Prepared for:
Federal Highway Administration
Office of Research, Development & Technology
McLean, VA

U.S. Department of Transportation
John A. Volpe National Transportation Systems Center

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REPORT DOCUMENTATION PAGE			*Form Approved* *OMB No. 0704-0188*

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE April 2016	3. REPORT TYPE AND DATES COVERED Summary Report

4. TITLE AND SUBTITLE Naturalistic Study of Truck Following Behavior	5a. FUNDING NUMBERS IAA No. DTFH6115V00002
6. AUTHOR(S) Emily Nodine, Andy Lam, Mikio Yanagisawa, and Wassim Najm	5b. CONTRACT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) U.S. Department of Transportation Volpe, The National Transportation Systems Center Advanced Vehicle Technology Division Cambridge, MA 02142-1093	8. PERFORMING ORGANIZATION DOT-VNTSC-FHWA-16-06
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) U.S. Department of Transportation Federal Highway Administration Office of Operations R&D Turner-Fairbank Highway Research Center 6300 George Washington Memorial Pkwy McLean, VA 22101	10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

The agreement Officers Representative for this study was Govindarajan Vadakpat, PhD, PE, HRDO-30

12a. DISTRIBUTION/AVAILABILITY STATEMENT This document is available to the public on the Volpe website at	12b. DISTRIBUTION CODE

13. ABSTRACT

Volpe conducted the Naturalistic study of truck following behavior to gain a better understanding of how trucks follow other vehicles in the real world, with the ultimate goal of supporting the Federal Highway Administration in the development of automated truck platooning applications. Using two naturalistic heavy truck data sets collected from previous related research, Volpe quantified heavy truck following behavior in the following categories: how closely trucks follow other vehicles on freeways, how following behavior varies by road condition, weather and visibility, following distances at which cut-in events occur, and the safety impact of different headways. Key results from this 2015 study showed that trucks follow passenger cars at shorter distances and headways than they follow heavy trucks at distances under 60 mph, but follow other heavy vehicles at shorter distances and headways at speeds greater than 60 mph; truck drivers generally follow other vehicles at much shorter headways (around 2 seconds) than are recommended in CDL driver handbooks; vehicles rarely cut-in between two trucks who are following at a distance of 40 m or less; and crash risk increases considerably when trucks follow other vehicles at headways of less than 1 s.

14. SUBJECT TERMS Heavy-truck, tractor-trailer truck, naturalistic driving, driver behavior, following behavior, headway, truck platooning	15. NUMBER OF PAGES 92
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	Unlimited

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18
298-102

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")
oz	ounces	28.35	grams	g
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

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
mL	milliliters	0.034	fluid ounces	fl oz
		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
g	grams	0.035	ounces	oz
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE 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)

Acknowledgements

The U.S. Department of Transportation John A. Volpe National Transportation Systems Center (Volpe Center), in Cambridge, Massachusetts, prepared this report for the Federal Highway Administration's (FHWA) Office of Operations Research, and Development. The project team consisted of Emily Nodine, Andy Lam, Mikio Yanagisawa and Wassim Najm of Volpe's Advanced Vehicle Technology division. Govindarajan Vadakpat of FHWA's Office of Operations R&D provided project oversight.

The project team would like to thank Govindarajan Vadakpat for his valuable technical insight and guidance, as well as Govindarajan's FHWA colleagues Joe Peters, Osman Altan, Gene McHale, Robert Ferlis, Brian Routhier, and Charles Fay, for their support along the way. The team would also like to thank their incredible support staff who made the project feasible by maintaining the evaluation databases and software tools (Yefim Keselman and Russell Sikora), and the video analysists who validated many, many hours of video footage (Jordan Wainer, Fouad Attioui, and Deirdre McCombs).

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List of Acronyms

Abbreviation	Term
CDL	Commercial Driver License
DAS	Data Acquisition System
FCW	Forward Collision Warning
FHWA	Federal Highway Administration
FOT	Field Operational Test
GES	General Estimate System
GIS	Geographical Information System
HT	Heavy Truck
IVBSS	Integrated Vehicle-Based Safety System
LV	Light Vehicle
LVD	Lead Vehicle Decelerating
LVM	Lead Vehicle Moving
MDAT	Multimedia Data Analysis Tool
P&D	pick-up and delivery
SIM	Safety Impact Methodology
TTC	Time-to-Collision
TFHRC	Turner Fairbank Highway Research Center
UMTRI	University of Michigan Transportation Research Institute
Volpe	Volpe, the National Transportation Systems Center

Executive Summary

This report presents the method and results of the naturalistic study of truck following behavior. Volpe, The National Transportation Systems Center (Volpe) supported the Federal Highway Administration's (FHWA) Turner-Fairbank Highway Research Center by conducting a study to better understand truck following behavior in naturalistic driving environments. The ultimate goal is to support the development of automated truck platooning applications.

Background

A vehicle platoon is a series of vehicles traveling together with short following distances. Grouping vehicles into platoons can increase the capacity of roads by decreasing the distances between vehicles. Recent research also suggests there can be significant fuel, greenhouse gas, and emissions savings through the platooning of trucks on freeways [1] [2]. Enabling technologies for automated vehicle control functions are currently a major research focus of governments and the private sector. However, there is little data on current truck driving behavior, which constrains the assessment of possible impacts of automation technologies on truck performance.

This report addresses the following research questions:

1. How closely (time and distance) do trucks follow other trucks and light vehicles (i.e., passenger cars) on freeways?
2. How does this following behavior vary by highway type, road condition, weather, and visibility (day/night)?
3. Are there specific following safety events or conditions that should be considered in the development of automation technologies?
4. At what following distances do vehicles cut in between the truck and lead vehicle?
5. What is the safety impact of truck following at different headways?

Naturalistic Databases

Volpe used two naturalistic, heavy truck data sets collected from previous research to quantify heavy-truck following behavior and expand the understanding of how heavy trucks follow light vehicles and other trucks; the Safety Pilot Model Deployment heavy truck database, and the Integrated Vehicle-Based Safety System (IVBSS) database.

The Safety Pilot Model Deployment was a field test that collected empirical data on the performance of connected-vehicle crash warning applications in a naturalistic environment. The one-year test, which was conducted by the University of Michigan Transportation Research Institute (UMTRI), included approximately 2,800 cars, trucks, buses, and motorcycles equipped with dedicated short-range communication devices. The data used in the present study of truck platooning were collected from eight 2012-2013 Freightliner Cascadia tractors driven by approximately 10 different drivers[1] on pick-up and delivery (P&D) routes.

The IVBSS project involved a naturalistic driving field operational test (FOT) that evaluated the safety impact, driver acceptance, and capability of an integrated warning system for heavy trucks. Eighteen professional heavy truck drivers drove 10 instrumented 2008 International TransStar 8600 tractor-trailer trucks for 10 months (8 months with the safety system turned on and 2 months with the system disabled). Eight of the drivers drove P&D routes, and 10 drove line-haul routes.

Technical Approach

Volpe used a three-step approach to quantify and analyze following scenarios in the naturalistic truck driving databases:

- Step 1: Define and extract events (create a filter)
- Step 2: Validate events and conduct video analysis
- Step 3: Conduct statistical analysis

During the first step, Volpe defined following scenarios and defined criteria that could be used to identify following scenarios in the naturalistic databases. For this study, following scenarios were defined as constant speed, highway driving scenarios above 45 miles mph where trucks were following a lead vehicle that was less than 77 m (253 ft) away. All driving scenarios that fit these criteria for a minimum of 20 s were extracted from the databases.

During the second step, Volpe conducted video validation and analysis of each of the identified following scenarios. Analysts used Volpe's multimedia data analysis software to view video footage of each following event to a) validate that the event fit the defined criteria, and b) to extract additional information about the following scenario, including the type of lead vehicle, the weather (clear, raining, snowing), and the time of day (day, night, dusk). Events that did not satisfy the following event criteria were discarded from the analysis, and the information extracted from the videos was used in the analysis of independent variables.

In the final step of the technical approach, Volpe conducted statistical analyses to quantify the observed following scenarios and to determine the impact of independent variables on the truck following behavior. Evaluation metrics varied by research question, but included following distance, time

[1] Each truck was generally driven by a dedicated driver; however, occasionally an alternate driver would drive the equipped truck if the dedicated driver was not on his scheduled shift.

headway, lead vehicle deceleration/acceleration levels, minimum time-to-collision (TTC), minimum distance to lead vehicle, and the probability of a crash. The independent variables addressed in this research included lead vehicle type, speed, highway type, weather, and time of day.

Results

Key findings for each research question are presented below.

Following Behavior by Lead Vehicle Type

- Safety Pilot trucks followed other trucks at longer distances and headways than they followed light vehicles. Mean following distances were 53.3 m (175 ft) when following a heavy truck compared to 50.8 m (167 ft) when following a light vehicle. Mean headways were 2.05 s when following a heavy truck compared to 1.99 s when following a light vehicle.
- IVBSS trucks followed other trucks at longer distances and headways than they followed light vehicles at speeds under 60 mph, but at shorter distances and headways at speed over 60 mph.
- IVBSS trucks followed other cars and trucks at significantly shorter distances and headways than they followed fixed trucks.
- Overall, professional truck drivers followed other vehicles at significantly shorter headways than recommended in State Commercial Driver's License (CDL) handbooks. Safety Pilot trucks followed at an average of about 2.0 s headway (recommended headway = 5 s) and IVBSS trucks followed at an average of about 1.8 s headway (recommended headway = 6-7 s, depending on trailer length).

Following Behavior by Environmental Factors

- Safety Pilot trucks followed lead vehicles at longer distances and headways on interstates compared to state freeways.
- Safety Pilot trucks followed lead vehicles at shorter distances and headways in clear weather compared to in rain or snow.
- Both truck fleets followed lead vehicles at shorter distances and headways during the day compared to at night.

Following Conditions for Consideration in Automated Platooning Technologies

- In scenarios where the lead vehicle decelerated, light vehicles decelerated at an average rate of 1.14 m/s^2, and heavy trucks decelerated at a rate of 1.04 m/s^2.
- In scenarios where the lead vehicle accelerated away from the host truck, light vehicles accelerated at an average rate of 1.0 m/s^2, and heavy trucks accelerated at an average rate of 0.9 m/s^2.

- Host truck drivers changed lanes within 25 m (82 ft) of a lead vehicle in only 12 percent of lane change scenarios.

Lead Vehicle Cut-in Events

- No cut-in events were observed when the host truck was following within 30 m, or 1.5 s headway of another truck. Generally, vehicles will not cut in between two trucks if they are within 40 m (131 ft) of each other.
- Very few cut-in events were observed when the host truck was following within 30 m, or 1.5 s headway of a light vehicle. Generally, vehicles will not cut in between a truck and a light vehicle if they are within 35 m (115 ft) of each other.
- Light vehicles cut in between two trucks following at shorter distances and headways than when trucks were following a light vehicle. In other words, light vehicles cut in between trucks more aggressively than they cut in between a truck and a car.

Safety Impact of Trucks Following at Different Headways

- For slow and medium driver response times (1.88 s and 1.21 s respectively), crash risk increased slightly at 1.0 s headway, and increased considerably at headways of less than 1.0 s.
- For all reaction times and headways considered, lower speed (45-50 mph events) posed the greatest crash risk.[2]
- In the fast reaction time condition (0.30 s, which was used to model automatic braking), crash risk was extremely low, even at very short headways. There was no crash risk observed in any speed bin at headways over 0.5 s.

[2] This is due to initial range calculations. Initial range calculations between vehicles in these rear-end conflicts were calculated using host vehicle travel speed and headway timing. Shorter headway timing at slower speeds resulted in lower initial ranges. These lower initial ranges translated to higher crash probabilities when keeping braking levels constant across speed bins.

1 Introduction

This report presents the method and results of the naturalistic study of truck following behavior. Volpe, the National Transportation Systems Center (Volpe) supported the Federal Highway Administration's (FHWA) Turner-Fairbank Highway Research Center (TFHRC) in a study to better understand how heavy trucks follow other vehicles on highways in naturalistic driving environments. The ultimate goal of this research is to support the development of automated truck platooning.

1.1 Background

A vehicle platoon is a string of vehicles following each other in the same lane at short distances. Grouping vehicles into platoons can increase the capacity of roads by decreasing the distances between vehicles. Recent research also suggests there can be significant fuel, greenhouse gas, and emissions savings through the platooning of trucks on highways [1] [2]. Enabling technologies for automated vehicle control functions are currently a major research focus of the public and private sectors. However, there is little data on current heavy truck driving behavior, which constrains the assessment of possible impacts of automation technologies on truck performance.

Volpe used two naturalistic, heavy truck data sets collected from previous research to quantify heavy-truck following behavior on highways, and to expand the understanding of how heavy trucks follow light vehicles (i.e., passenger cars, vans and minivans, sport utility vehicles, and pickup trucks with gross vehicle weight rating (GVWR) under 10,000 pounds), and other heavy vehicles (i.e., large buses and medium/heavy trucks with GVWR over 10,000 pounds). These datasets are described in Section 1.3.

1.2 Research Questions

The objective of this naturalistic study of truck-following behavior is to generate baseline information for FHWA to use in developing automated truck platooning functions and estimating their potential benefits. A key parameter for truck platooning is the minimum headway[3] at which trucks follow each other. This minimum headway must:

- Be safe (minimize crash risk)
- Prevent other vehicles from cutting in between the platooning trucks
- Be acceptable and comfortable for truck drivers

An understanding of the dynamics of the lead vehicle will help to develop automated truck platooning applications with smooth following behavior by accounting for lead vehicle acceleration/deceleration

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[3] For the purpose of this study, headway is defined as the number of seconds it would take the front bumper of the following truck (at its current speed) to reach the location of the lead vehicle's rear bumper. This metric is also sometimes referred to as a "gap."

and cut-ins by other vehicles. Another baseline measure relevant to truck platooning is the speed profile of trucks following other vehicles, which can be used to infer fuel consumption and emissions.

This report addresses the following five research questions to capture baseline information on truck-following behavior that is relevant to the development of truck platooning applications:

1. How closely (time and distance) do trucks follow other trucks and light vehicles on highways?
2. How does this following behavior vary by highway type, road condition, weather, and visibility (day/night)?
3. Are there particular following safety events or conditions that should be considered when developing automation technologies?
4. At what following distances do vehicles cut in between the truck and the lead vehicle?
5. What is the safety impact of truck following at different headways?

1.3 Naturalistic Truck Driving Datasets

This subsection provides details about the content and quantity of data in the naturalistic heavy truck datasets that were available for this study.

1.3.1 Safety Pilot Model Deployment

The Safety Pilot Model Deployment was a naturalistic field test that collected empirical data on the performance of connected-vehicle crash warning applications in a naturalistic environment [3]. The one-year field test, which was conducted by the University of Michigan Transportation Research Institute (UMTRI), included approximately 2,800 cars, trucks, buses, and motorcycles equipped with dedicated short-range communication devices. Eight of these vehicles were 2012 and 2013 Freightliner Cascadia tractors equipped with data acquisition systems that collected detailed naturalistic driving data. They were driven by eight professional truck drivers, primarily on pick-up and delivery (P&D) routes.

The trucks in the Safety Pilot Model deployment were equipped with one safety application that is relevant to truck-following behavior; a forward collision warning (FCW). The Safety Pilot Model Deployment did not implement a traditional baseline period where the safety application was disabled, but was instead enabled continuously throughout the Model Deployment. However, since the applications were based on connected vehicle technologies, they only became enabled when the equipped truck was in close proximity to another equipped vehicle. During the Safety Pilot Model deployment, the heavy trucks were within range of another equipped vehicle less than 15 percent of the time they were driving (overall and on highways).

Overall, the trucks in the Safety Pilot Model Deployment were driven 259,247 miles; 102,490 of which (40 percent) were on highways. Each of the eight trucks was equipped with a Data Acquisition System (DAS) that collected objective numerical data continuously, any time the trucks were being driven. The numerical data collected by the DAS included vehicle dynamics (speed and acceleration of the truck), information about forward vehicles and the vehicle's location within their lane (using a vision-based ranging sensor), and GPS data. The DAS also collected four video views of the driver and truck surroundings.

1.3.2 Integrated Vehicle-Based Safety System Field Operational Test

The Integrated Vehicle-Based Safety System (IVBSS) project involved a naturalistic driving field operational test (FOT) that evaluated the safety impact, driver acceptance, and capability of an integrated warning system for heavy trucks [4]. Eighteen professional heavy truck drivers drove 10 instrumented 2008 International TransStar 8600 tractor-trailer trucks for 10 months (8 months with the safety system turned on and 2 months with the system disabled). Eight of the drivers drove P&D routes, and 10 drove line-haul routes.

The IVBSS trucks were equipped with two safety applications that are relevant to truck-following behavior; an FCW that alerted the driver to a stopped, slowing, or slower vehicle ahead in their lane; and a headway advisory that notified the truck driver when following another vehicle with less than a 3.0 s headway.

Overall, there are 484,162 miles of driving data in the IVBSS dataset with 235,083 of these miles (49 percent) on highways (in the baseline and treatment periods combined).

Similar to the trucks driven in the Safety Pilot Model Deployment, the trucks in the IVBSS FOT were each equipped with a DAS that collected objective numerical data and four views of continuous video.

1.4 Literature Review Summary

Volpe conducted a review of the existing literature on truck following behavior to determine if any of the research questions listed in Section 1.2 had previously been addressed. For this literature review, Volpe focused on studies that were conducted using naturalistic driving data or third party observations, rather than test-track or simulator studies. Overall, Volpe identified approximately 65 resources, eight of which contained objective measures of longitudinal truck following behavior.

The literature review revealed that very few studies have been conducted on naturalistic truck following behavior. Naturalistic driving studies are expensive and time consuming to conduct and, as a result, very few resources are available for this kind of research.

A number of studies summarized in this document quantified heavy-truck following behavior using the IVBSS data set (one of the data sets that Volpe plans to use for the present study), and provided information about the impact of environmental factors (weather, traffic, etc.) on following behavior. However, none of these studies looked at how following behavior varies by lead vehicle type, which is a key research question for this project.

Other studies provided some baseline measurements for headway in naturalistic environments and one study addressed following behavior based on the vehicle type of the lead vehicle.

Ultimately, none of the research questions for the current project could be addressed with the existing literature, so they were all addressed in the present analysis.

Appendix A contains the complete literature review.

2 Technical Approach

This section describes the three-step technical approach to identify, extract, validate, and analyze truck-following scenarios:

- Step 1: Define and extract following events (create a filter)
- Step 2: Conduct video analysis to validate following events and record relevant information
- Step 3: Perform statistical analyses

These steps, which were used to address research questions 1-4, are described in Sections 2.1 through 2.3. Section 2.4 describes the technical approach used to assess the safety impact of truck-following behavior at different gaps, based on the results from the naturalistic truck-following data analyses.

2.1 Step 1: Define and Extract Following Events

The first two steps of the technical approach involved the operational definition of following scenarios and writing the codes to identify events in the data that matched the operational definition. The criteria for defining a following scenario are as follows:

- The host truck[4] is traveling on the highway (based on GPS location and Geographical Information System (GIS) roadway type data).
- The host truck is traveling at a constant speed.
- The host truck is traveling at speeds greater than 45 mph, so as to focus the research on free-flow traffic scenarios.
- The relative speed to the lead vehicle is ± 2.5 mph (i.e., vehicles are traveling at similar speeds).
- The range to the lead vehicle is less than 77 m (253 ft), based on the maximum reliable range of the vision-based ranging sensor used on the Safety Pilot trucks.[5]
- The host truck follows a given lead vehicle for at least 20 s to remove following scenarios with very short durations.

The resulting events are steady-state, constant-speed following events where the host truck is following a lead vehicle within 77 m (253 ft) from the front of the host truck.

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[4] The host truck is the truck in which the DAS was installed. For the purpose of this research, the host truck is the following truck.

[5] While reliable data were available on forward vehicles for up to 100 m (328 ft) in the IVBSS dataset, only events with following distances of less than 77 m (253 ft) were used for this analysis. Using the same filter allowed Volpe to conduct a comparative analysis of the two different datasets in order to assess the impact of truck type.

2.2 Step 2: Conduct Video Analysis and Validate Events

After identifying truck-following events in the datasets, Volpe viewed the video from each following event to validate that the event was a true following scenario (i.e., the identified lead vehicle was not in an adjacent lane or the result of some other sort of data error) and to extract relevant information on independent variables from the video.

The video was viewed using Volpe's Multimedia Data Analysis Tool (MDAT), a software tool that synchronizes and displays all video views and numerical data fields of the viewer's choice. Figure 1 shows the MDAT video viewing window.

Figure 1. MDAT Video Viewing Software Used for Video Validation and Analysis

The events that did not qualify as following scenarios were discarded. Video analysts recorded the following information for the true following scenarios:

- Lead vehicle type: Heavy truck or light vehicle
- Road condition: Dry, wet, or snow

- Weather: Clear, rain, or snow
- Visibility/lighting: Day, night, or dusk

2.3 Step 3: Perform Statistical Analyses

Volpe extracted metrics for each of the validated following scenarios from the numerical databases. Table 1 lists the evaluation metrics used to address each research question, along with their source and the independent variables being used in the analysis. Evaluation metrics and independent variables are defined in sections 2.3.1 through 2.3.3.

Table 1. Evaluation Elements by Research Question

#	Research Question	Primary Evaluation Metrics	Independent Variables
1	How closely (time and distance) do trucks follow other trucks and light vehicles on highways?	Following distance Time headway	Lead vehicle type Speed bin Host truck type
2	How does this following behavior vary by driver, truck type, speed, highway type, road geometry, road condition, weather, visibility, etc.?	Following distance Time headway	Highway type Road condition Weather Visibility
3	Are there particular following safety events or conditions that should be considered in the development of truck automation technologies?	Lead vehicle mean deceleration Lead vehicle mean acceleration Minimum Distance	Lead vehicle type Speed bin
4	At what following distances do vehicles cut in between the truck and lead vehicle?	Following distance Time headway	Lead vehicle type Cut-in vehicle type Speed bin
5	What is the safety impact of truck-following behavior at different gaps?	Probability of a rear-end crash	Time headway Speed bin

2.3.1 Evaluation Metrics

The evaluation metrics used to assess the truck-following behavior are defined below:

- **Following distance**: Range from the front of the host truck to the rear of the lead vehicle.
- **Time headway:** Number of seconds it would take the front bumper of the host truck to reach the current location of the rear bumper of the lead vehicle (range to lead vehicle rear bumper/host vehicle speed).[6]

[6] In some literature, this metric is also referred to as a "gap."

- **Lead vehicle mean deceleration:** Mean rate of deceleration of the lead vehicle for lead-vehicle-decelerating closing scenarios.
- **Lead vehicle mean acceleration:** Mean rate of acceleration of the lead vehicle for lead-vehicle-accelerating separating scenarios.
- **Minimum distance:** Minimum range to the lead vehicle that the host truck experiences during a scenario for the host truck lane-change scenarios.
- **Probability of a crash:** Proportion of simulated crashes over the total number of simulation runs, as determined by conducting Monte Carlo simulations with input data from the results of the truck-following behavior analyses.

Following distance and time headway are the metrics for research questions 1, 2, and 4. Lead vehicle mean deceleration/acceleration and minimum distance represent the metrics for research question 3, while the probability of a crash is the metric for research question 5.

2.3.2 Independent Variables

Table 2 lists the independent variables that were used in the analyses and their source. Lead vehicle type describes if the vehicle that the heavy truck is following is a light vehicle (passenger car or another heavy truck). Host vehicle speed is the speed of the host vehicle at the beginning of the following scenario. Host truck type differentiates between tractor trailer (articulated) and fixed trucks. Highway type differentiates between interstate freeways and state freeways. Road condition describes the surface of the road, and whether it is dry, wet, or has accumulated show on it. Weather describes any precipitation that is occurring at the time of the following event, and visibility describes the lighting conditions.

Lead vehicle type, road condition, weather, and lighting were all obtained through video analysis of the following events. Host vehicle speed was obtained from the numerical database, while highway type was obtained by post-processing the vehicle's GPS data.

Table 2. Independent Variables and Data Sources

Independent Variable	Source
Lead vehicle type	Video analysis
Host vehicle speed	Numerical database
Host truck type (tractor trailer/fixed)	Numerical database
Highway type (interstate/state)	GIS data
Road condition	Video analysis
Weather	Video analysis
Visibility/lighting	Video analysis

2.3.3 Statistical Analyses

The results of each research question provide descriptive statistics of the primary research metrics, broken down by relevant independent variables. Mean values are presented, along with error bars that represent the 95 percent confidence interval from the mean.

In instances where Volpe directly compared two test conditions (e.g., to determine the impact of different independent variables), two-tail *t*-tests were performed. A *t*-test determines if there is a statistically-significant difference between the means of the same subjects under different circumstances. For all *t*-tests conducted in this analysis, a *p* value of 0.05—or 95 percent confidence—was used to imply statistical significance. Significant *p* values are identified using red font in tables throughout this report.

2.4 Safety Impact Assessment

Volpe assessed the safety impact of different truck-following behaviors (research question number five) using the rear-end crash risk, as measured by the probability of a rear-end crash. This measure is estimated using the Safety Impact Methodology (SIM) tool, with input from the results of the analyses described in Section 2.3.3. The SIM tool is a Monte Carlo computer-based simulation tool, created by Volpe, that estimates how crash frequency in various driving conflicts would be impacted by different conditions (i.e., initial scenario conditions and driver/vehicle responses) [5]. The basic function of the SIM tool is to simulate the kinematics of driving conflicts that could lead to crashes (also called *pre-crash scenarios*), based on a combination of naturalistic driving data and data collected in driving simulators.

2.4.1 Safety Impact Assumptions

The safety impact analysis focused on heavy trucks following other vehicles on highways and made the following assumptions:

- Events were modeled using basic kinematic equations where only the host following truck responded to the event and the lead vehicle stayed the course.
- The driver of the host truck responded to the event by braking only (not by steering).
- No external conflicts or unintended consequences were modeled (i.e., the host truck was not struck from behind as a consequence of braking heavily to avoid the initial conflict).
- Host truck braking was assumed to be instantaneous and constant (i.e., braking intensity does not vary during the driver response).
- Three different driver response times were used in simulations. Both 1.88 s and 1.21 s were used to represent a range of manual response times (see Section 2.4.3 for details and references), while 0.30 s represents an automated response time.

2.4.2 Basic Equations and Parameters

The safety impact analysis examines the rear-end crash risk of different truck-following behaviors. This risk is measured by the probability of a crash occurring in rear-end pre-crash scenarios given the initial conditions of the following behavior (i.e., travel speeds and headways) and driver/vehicle response. The probability of a crash, ***pCrash***, in a specific pre-crash scenario was computed using the following equation:

$$pCrash(i,j) = \frac{n_{crashes}(i,j)}{n_{iteration}\ (i,j)}$$

where:
$n_{crashes}(i,j)$ = Number of crashes for travel speed bin, ***i***, with headway gap, ***j***
$n_{iterations}(i,j)$ = Number of iterations in the SIM tool for travel speed bin, ***i***, with headway gap, ***j***

Volpe obtained the ***pCrash*** estimates for various headways and travel speeds from the SIM tool to determine the impact of headway on the rear-end crash risk in the lead-vehicle-decelerating (LVD) pre-crash scenario. In this scenario, the lead vehicle in front of the host truck in the following scenario suddenly decelerates. Initial conditions of this scenario include the speed of the following host truck, speed of the lead vehicle, distance/headway between them, and average deceleration of the lead vehicle. The driver/vehicle response to the LVD scenario consists of the driver brake reaction time and average deceleration of the following host truck.

2.4.3 Data Sources

Volpe used the following sources as input data to the SIM tool when estimating the ***pCrash*** values of heavy trucks following other vehicles at different headways:

Initial Conditions from Naturalistic Truck-Following Study
The results from this study provided the initial conditions for input to the SIM simulations. Specifically, the results of the lead vehicle mean deceleration levels (research question number three) were used for the LVD pre-crash scenario simulation. Table 3 breaks down the average deceleration levels by lead vehicle type (heavy truck and light vehicle) and by travel speed. In addition, the initial conditions included the time headway results by the travel speed from lead-vehicle braking events (research question number three) and other vehicle cut-in events (research question number four).

Table 3. Average Deceleration Levels (m/s^2) by Lead Vehicle Type and Speed Bin

Speed Bin (mph)	Lead Light Vehicle				Lead Heavy Truck			
	Max	Min	Avg	Std Dev	Max	Min	Avg	Std Dev
45-50	-3.52	-0.11	-1.15	0.73	-3.28	-0.11	-1.03	0.68
50-55	-3.65	-0.06	-1.14	0.75	-3.20	-0.03	-1.11	0.77
55-60	-3.95	-0.01	-1.14	0.73	-3.90	-0.03	-1.02	0.71
60-75	-3.97	-0.09	-1.16	0.78	-3.91	-0.02	-1.14	0.75

Braking Level Response by Heavy Trucks from Test Track Data

The emergency braking levels of heavy trucks were obtained from data collected on a test track [6]. UMTRI conducted this data collection study using the fully-loaded five-axle tractor-semi shown in Figure 2. The maximum braking capacity was approximately 0.6g (5.9 m/s^2), with mean braking level of 0.3g (2.9 m/s^2) in emergency braking scenarios.[7] These data were supplemented with calculations based on the National Highway Traffic Safety Administration's amended Federal Motor Vehicle Safety Standard for air brake systems. The standard required substantial improvements in stopping distance performance on new truck tractors [7]. Heavy vehicle brakes must allow a vehicle to stop in a maximum distance of 310 ft (94.5 m) at 60 mph, which would require 0.4g (3.9 m/s^2) deceleration level.

Figure 2. Tractor-Trailer Truck used in UMTRI Track Tests

Braking Response Reaction Time from Past Analyses

UMTRI estimated the values of driver brake reaction time in response to LVD events from the analysis of IVBSS heavy truck data [8]. This reaction time had a mean value of 1.88 s.[8] The UMTRI study looked at drivers' reaction time to forward-conflict events during the baseline period; i.e., drivers did not receive forward-collision alerts. Moreover, the truck drivers in the IVBSS FOT were looking ahead at the lead vehicle in most forward-conflict events. The reaction time was measured as the interval from the start time of the forward conflict to the time when the truck driver applied the brakes. Volpe's safety impact analysis refers to this IVBSS-derived brake reaction time as the "slow" response to the LVD scenario.

In addition, the safety impact analysis considered the mean brake reaction time of unalerted drivers. A past study measured brake reaction times from unalerted drivers who were following a test car, while being followed by a monitoring vehicle. This study collected 1,644 data points and recorded only brake reaction times of less than 3.0 s. The mean value of the data was 1.21 s [9]. The safety impact analysis refers to this brake reaction time as the "medium" response to the LVD scenario. In addition to the "slow" and "medium" response times by drivers, this analysis also considered a "fast" response reaction time by automatic braking (i.e., automated platooning) at a mean value of 0.3 s.

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[7] See Section 7.2 of referenced document.

[8] Results represent reaction time in the baseline condition, where the IVBSS safety system was disabled and forward collision alerts were not issued to the driver (page 694 of referenced document).

3 Results

This section present the results for each research question listed in Section 1.2. The dataset(s) used for specific analyses is identified in each sub-section.

3.1 Following Behavior by Lead Vehicle Type

Volpe addressed research question number one using both Safety Pilot Model Deployment and IVBSS datasets:

How closely do heavy trucks follow other vehicles on highways?

Results are broken down by lead vehicle type (light vehicle or heavy truck) and the speed of the host truck. The results of the two datasets were also compared to determine if there was a difference in the truck-following behavior between the Safety Pilot and IVBSS host trucks. The research hypotheses for research question number one are as follows:

- There will be no difference in truck-following behavior when the lead vehicle is another heavy truck, compared to when the lead vehicle is a light vehicle.
- There will be no difference in the following behavior of IVBSS host trucks compared to Safety Pilot host trucks.

3.1.1 Safety Pilot Truck Results

Overall, there were 17,075 highway following events identified in the Safety Pilot database and validated with video analysis. Table 4 shows the breakdown of these events by lead vehicle type and host vehicle speed bin. Table B-1 in Appendix B lists descriptive statistics of the evaluation metrics within each independent variable. About half of the following events occurred when the Safety Pilot trucks were following other heavy trucks, and the other half occurred when the truck was following a light vehicle. Even though the majority of following events occurred between 55 and 60 mph, the other speed bins had sufficient sample sizes to conduct statistical analyses.

Table 4. Safety Pilot Following Event Sample Size by Independent Variable

Independent Variables		Count	%
Lead Vehicle Type	Heavy truck	8,280	48%
	Light vehicle	8,795	52%
Speed Bin (mph)	45-50	915	5%
	50-55	2,114	12%
	55-60	12,714	74%
	>60	1,332	8%

3.1.1.1 Following Distance

Figure 3 shows the distribution of following distance when the host heavy truck (HT) is following another heavy truck compared to when it is following a light vehicle (LV). Overall, Safety Pilot trucks followed other trucks at a larger distance (mean = 53.3 m or 175 ft) than they followed light vehicles (mean = 50.8 m or 167 ft). This difference was statistically significant ($p<0.0001$). Figure 4 shows the cumulative distribution of these data.

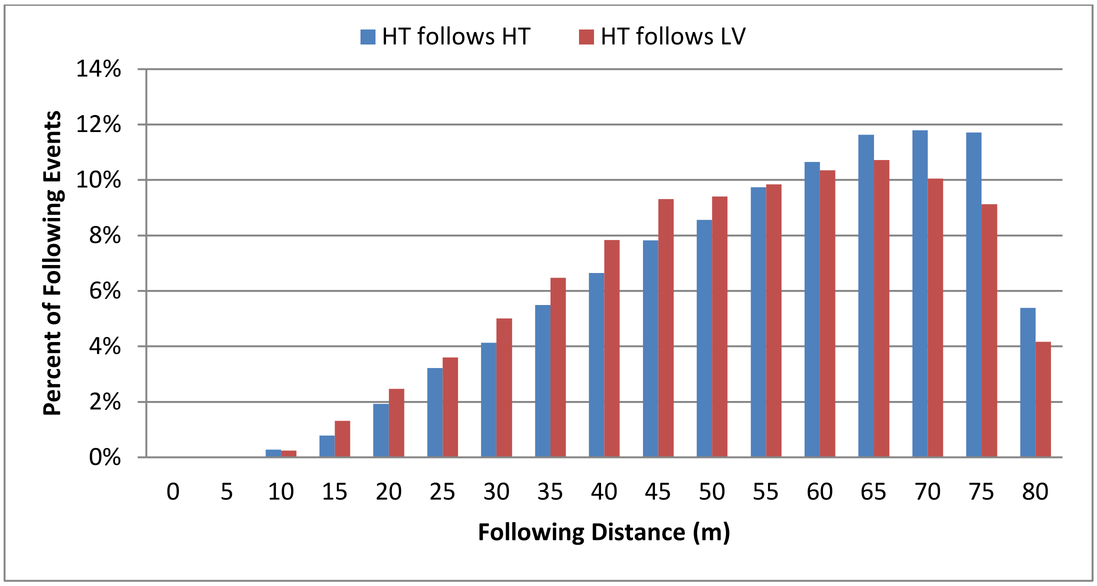

Figure 3. Distribution of Following Distance by Lead Vehicle Type – Safety Pilot Trucks

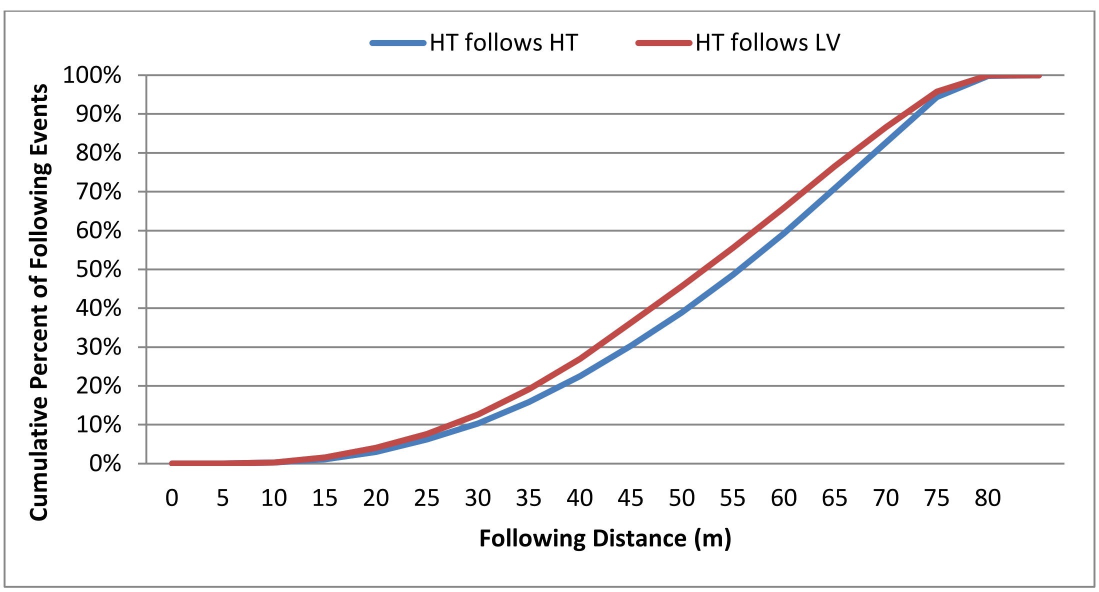

Figure 4. Cumulative Distribution of Following Distance by Lead Vehicle Type – Safety Pilot Trucks

Figure 5 shows the mean following distance when the host trucks are following other heavy trucks and light vehicles, broken down by speed bin. The *p* values in the figure represent the comparison between lead vehicle type within each speed bin. While trucks followed other trucks at a greater distance than they followed light vehicles within every speed bin, the differences were only significant for the speed bins under 60 mph (significant *p* values are identified using red font). Generally, trucks followed vehicles at a greater distance when traveling faster.

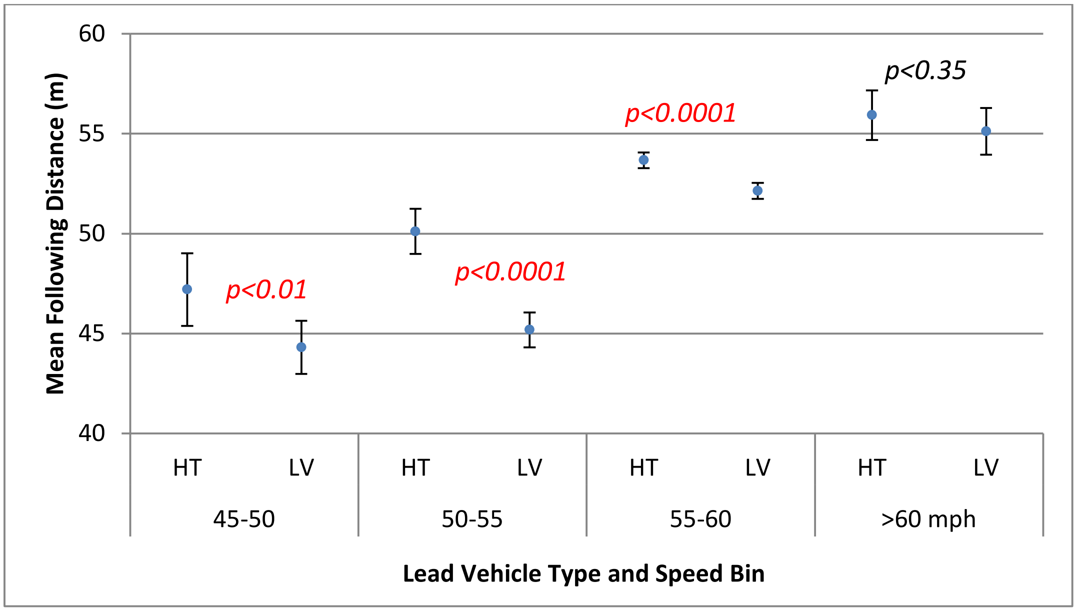

Figure 5. Mean Following Distance by Lead Vehicle Type and Speed Bin – Safety Pilot Trucks

3.1.1.2 Headway

Figure 6 shows the distribution of following headway when the host truck is following heavy trucks and light vehicles. Similar to following distance, trucks follow light vehicles at a slightly shorter headway (mean = 2.0 s) than they follow other heavy trucks (mean = 2.1 s). This difference was statistically significant (p<0.0001). Figure 7 shows the cumulative distribution of these data.

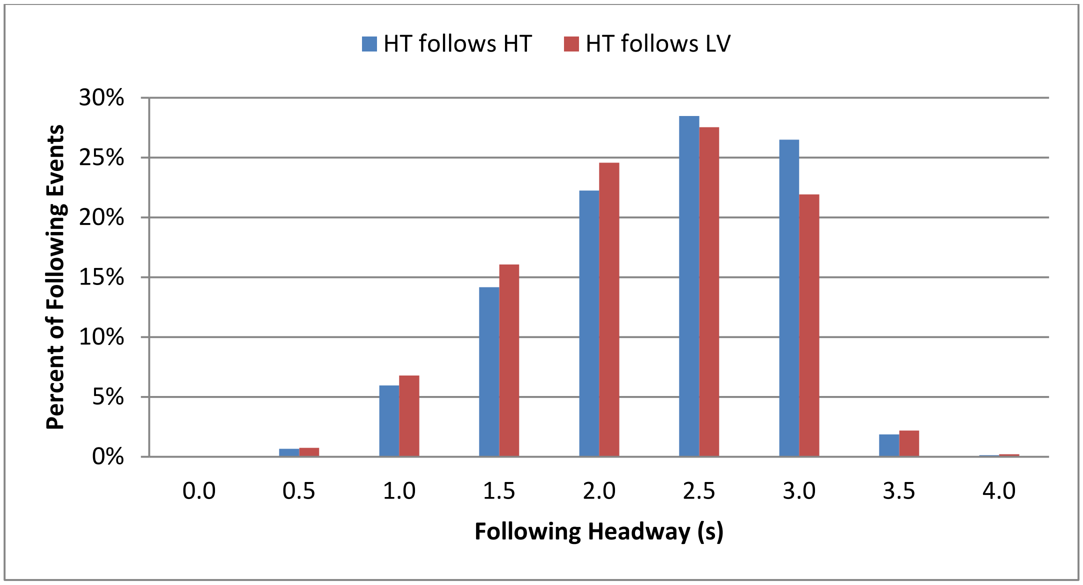

Figure 6. Distribution of Following Headway by Lead Vehicle Type – Safety Pilot Trucks

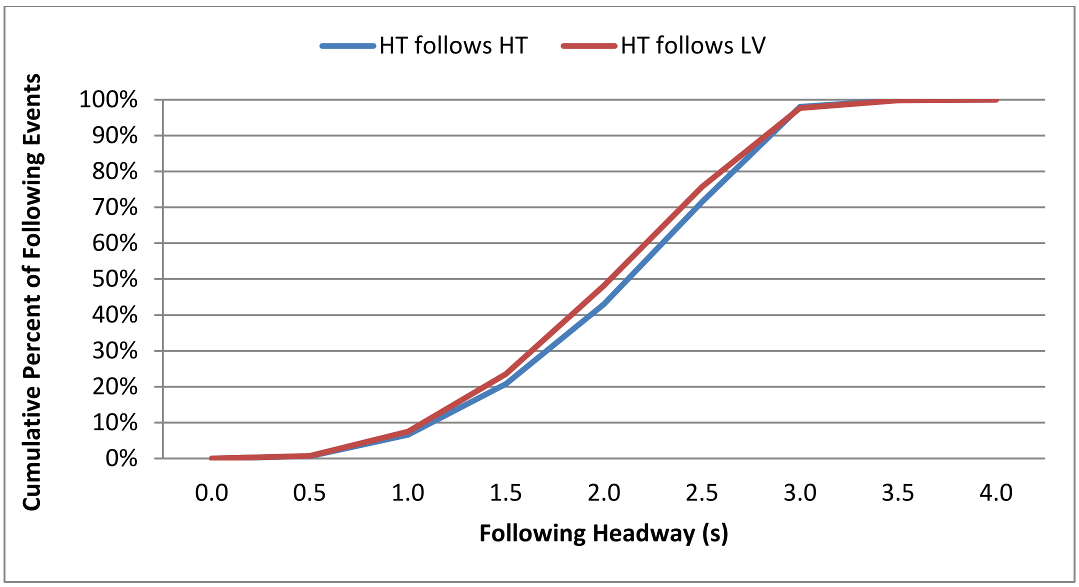

Figure 7. Cumulative Distribution of Following Headway by Lead Vehicle Type – Safety Pilot Trucks

Figure 8 shows the mean following headway for following events in each speed bin, broken down by lead vehicle type. The *p* values in the figure represent the comparison between lead vehicle types within each speed bin; statistically significant results are identified using red font. Similar to following distance, trucks follow light vehicles at a shorter headway than they follow other heavy trucks, but the difference was significant only at speeds under 60 mph.

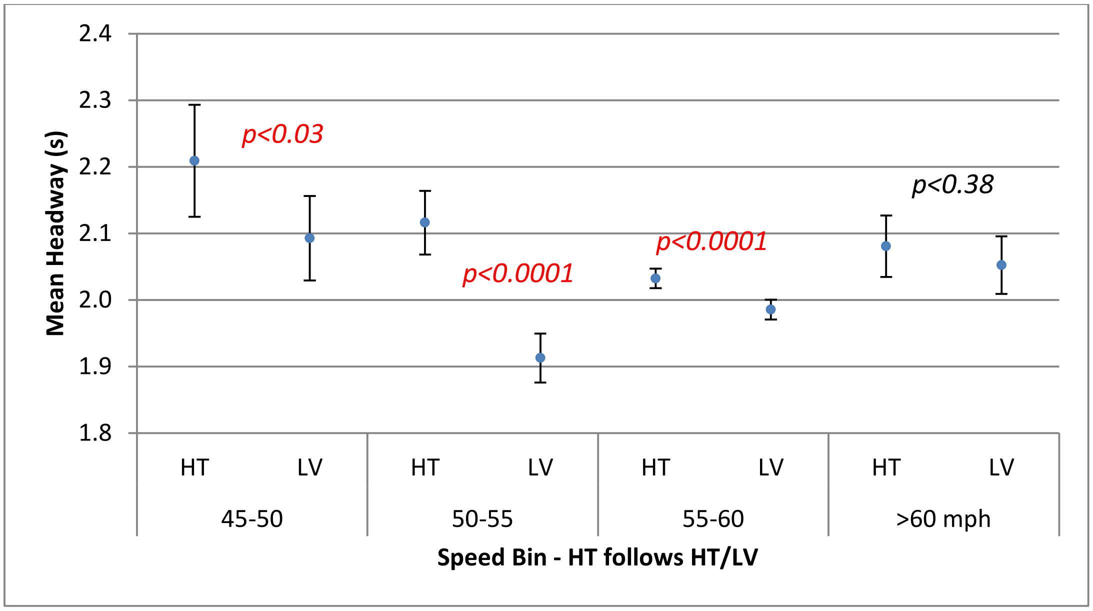

Figure 8. Mean Following Distance by Lead Vehicle Type and Speed Bin – Safety Pilot Trucks

3.1.2 IVBSS Truck Results

Overall, there were 18,132 highway following events identified in the IVBSS database. Since video analysis is time consuming and an adequate sample of events from the Safety Pilot database had been previously validated and analyzed using video, Volpe randomly selected 3,000 following events, spread across all four speed bins, for video analysis. Video validation resulted in a total sample size of 2,879 IVBSS following events (events that were not determined to be true following events; e.g., the lead vehicle was in an adjacent lane) were discarded from analysis. The host truck was following a light vehicle in 57 percent of the sampled events and was following a heavy truck in 43 percent of events. Table B- 2 in Appendix B lists descriptive statistics of the evaluation metrics within each independent variable.

Table 5. IVBSS Following Event Sample Size by Independent Variable

Independent Variables		Count	%
Lead Vehicle Type	Heavy truck	1241	43
	Light vehicle	1638	57
Speed Bin (mph)	45-50	461	16
	50-55	780	27
	55-60	949	33
	>60	689	24

3.1.2.1 Following Distance

Figure 9 shows the distribution of following distances broken down by lead vehicle type for the IVBSS tractor trailer trucks. Overall, the IVBSS trucks followed light vehicles at a shorter distance (mean = 45.1 m or 148 ft) than heavy trucks (mean = 46.8 m or 154 ft). This difference was statistically significant (p <0.01). Figure 10 shows the cumulative distribution of these data.

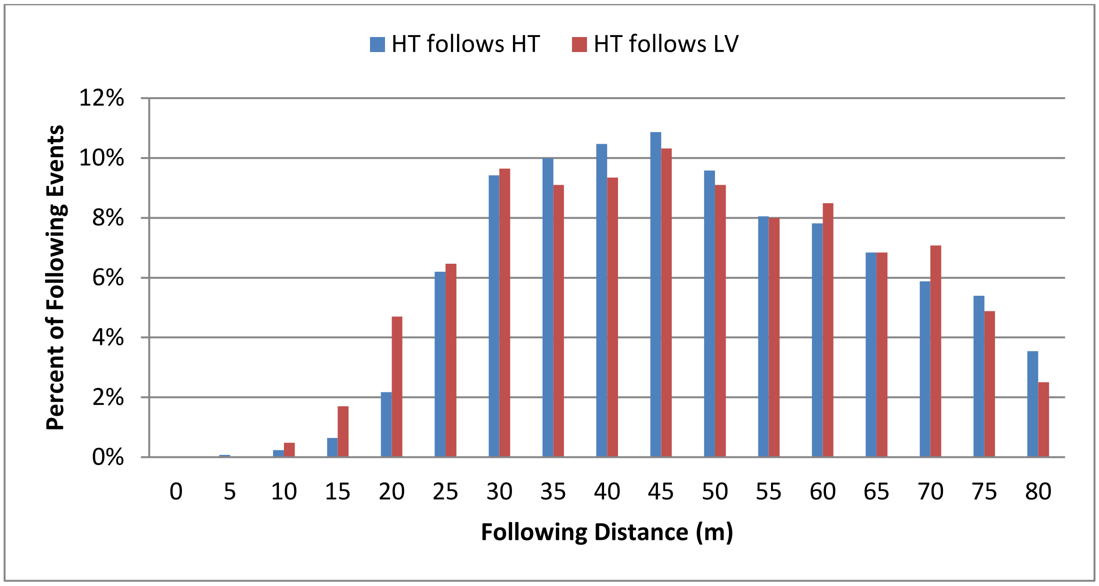

Figure 9. Distribution of Following Distance by Lead Vehicle Type – IVBSS Trucks

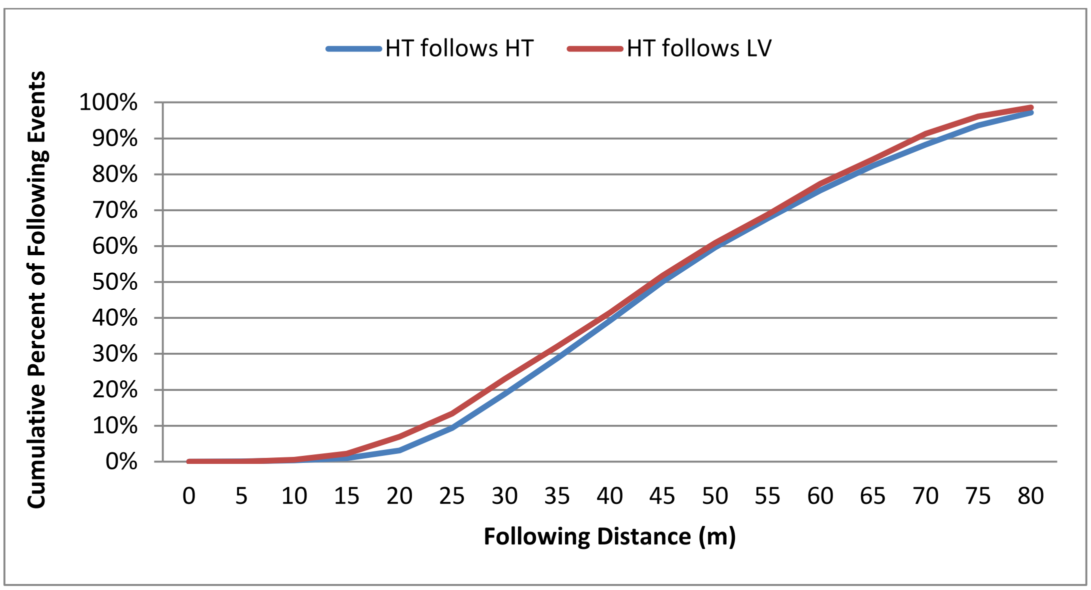

Figure 10. Cumulative Distribution of Following Distance by Lead Vehicle Type – IVBSS Trucks

Figure 11 shows the mean following distance of IVBSS following scenarios, broken down by lead vehicle type and speed bin. The p values in the figure represent the comparison between lead vehicle type within each speed bin. In the three lower speed bins, trucks followed heavy trucks at a greater distance than light vehicles; however above 60 mph, trucks followed other trucks at a closer distance than they followed light vehicles. Only the results in the 50-55 mph and >60 mph speed bin were statistically significant (identified using red font on the p values).

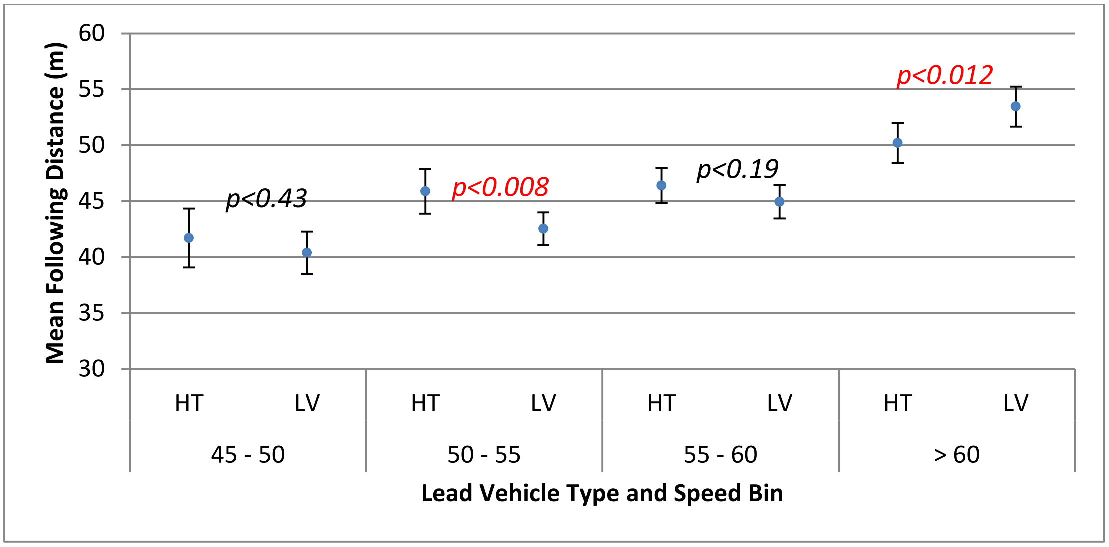

Figure 11. Mean Following Distance by Lead Vehicle Type and Speed Bin – IVBSS Trucks

3.1.2.2 Headway

Figure 12 shows the distribution of following headway when the host truck is following heavy trucks and light vehicles. The IVBSS tractor trailer trucks followed both heavy trucks and light vehicles at a mean headway of 1.8 s. The paired *t*-test revealed no significant difference between the means of these two populations (*p*=0.731). Figure 13 shows the cumulative distributions of these data.

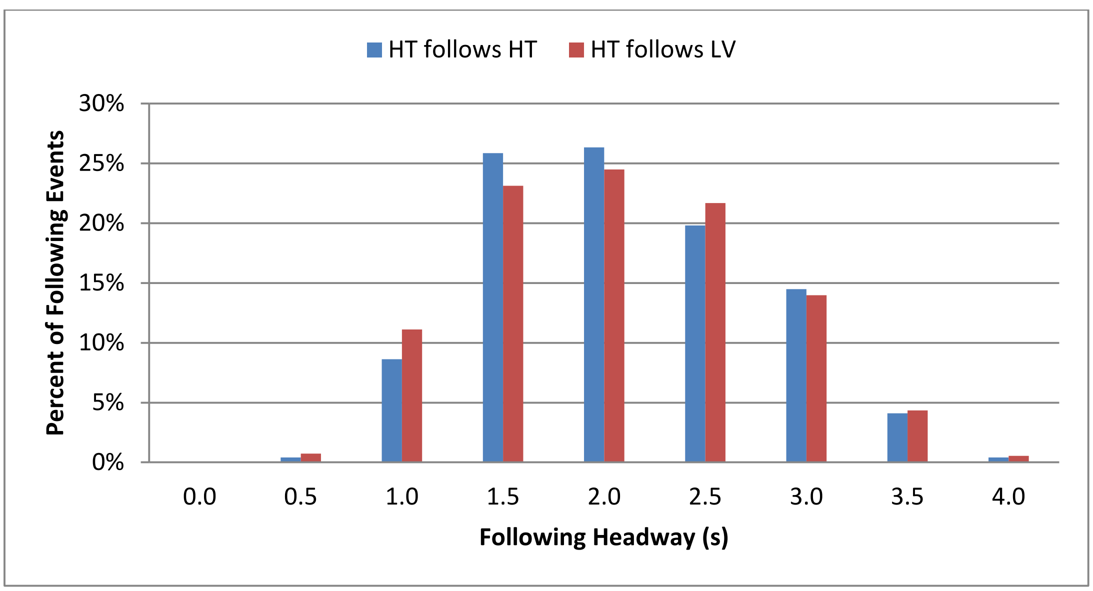

Figure 12. Distribution of Following Headway by Lead Vehicle Type – IVBSS Trucks

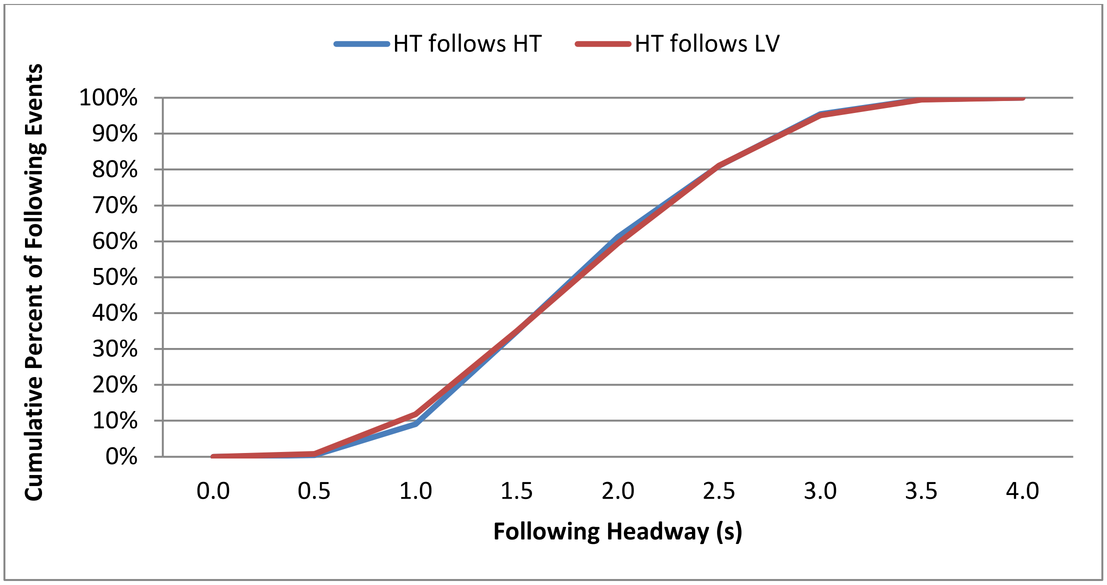

Figure 13. Cumulative Distribution of Following Headway by Lead Vehicle Type – IVBSS Trucks

However, when headway data were broken down by speed bin, there were significant differences in following headway in two speed bins. Figure 14 shows IVBSS tractor-trailer truck mean headway broken down by lead vehicle type and speed bin. The *p* values represent comparisons between lead vehicle type within each speed bin. Similar to the results of following distance for tractor trailer trucks, trucks followed light vehicles at shorter headways at speeds less than 60 mph, but followed heavy trucks at shorter headways at speeds over 60 mph. Significant *p* value comparisons are identified using red font.

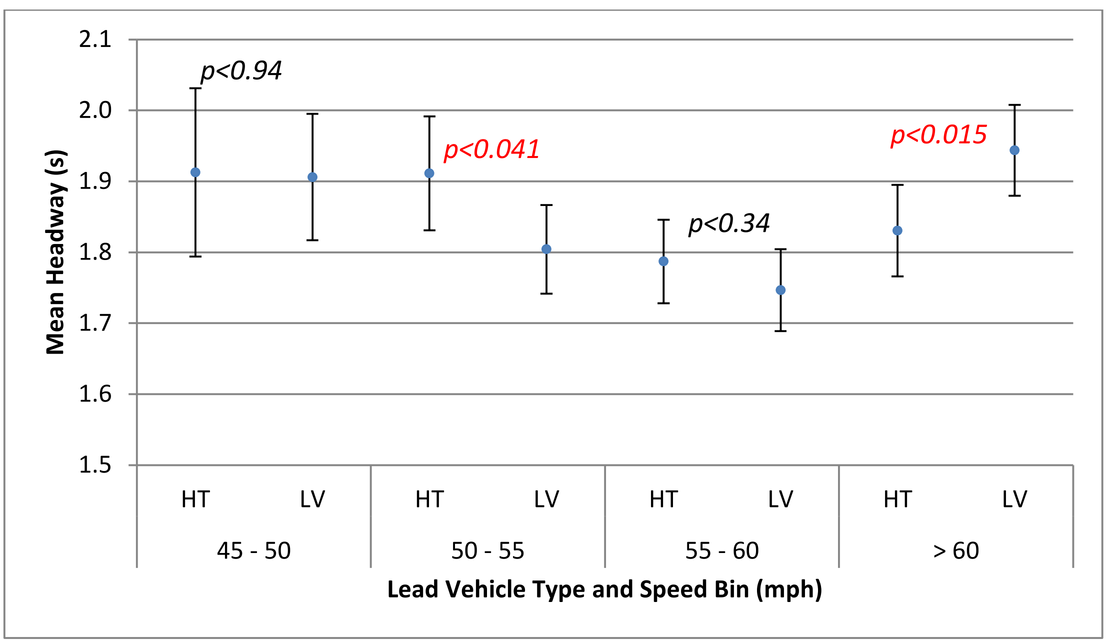

Figure 14. Mean Headway by Lead Vehicle Type and Speed Bin – IVBSS Trucks

3.1.3 Safety Pilot versus IVBSS Truck Following Behavior

To identify following events for comparing IVBSS and Safety Pilot data, Volpe analyzed the IVBSS dataset by driving route type. Drivers in the Safety Pilot Model Deployment drove short P&D routes around Ann Arbor, MI, during the day. In the IVBSS FOT, half of the drivers drove P&D routes and the other half drove longer, overnight routes (line-haul). Volpe first conducted an analysis to determine if there was a difference in following behavior by route type. The results showed that P&D drivers followed lead vehicles with shorter distances and headways than line-haul drivers. Table 6 lists results by route type. The differences in following behavior are likely due to traffic conditions, as P&D drivers drove primarily during the day, and line-haul drivers drove overnight.

Table 6. IVBSS Following Results by Route Type

Route Type	Event Count	% of IVBSS Events	Following Distance Mean (m)	Following Distance *p*-value	Headway Mean (s)	Headway *p*-value
P&D	1,078	37	42.9	<0.0001	1.73	<0.0001
Line-haul	1,801	63	47.6		1.91	

To ensure the most direct comparison between Safety Pilot trucks and IVBSS trucks, Volpe used only the following events from P&D drivers in the IVBSS database (1,078 events), since they drove similar route types (and therefore similar traffic conditions) as the Safety Pilot drivers. Figure 15 shows the mean following distance for Safety Pilot and IVBSS trucks overall, when following heavy trucks, and when following light vehicles. IVBSS trucks followed lead vehicles more closely overall and in each lead-vehicle category (all results were statistically significant).

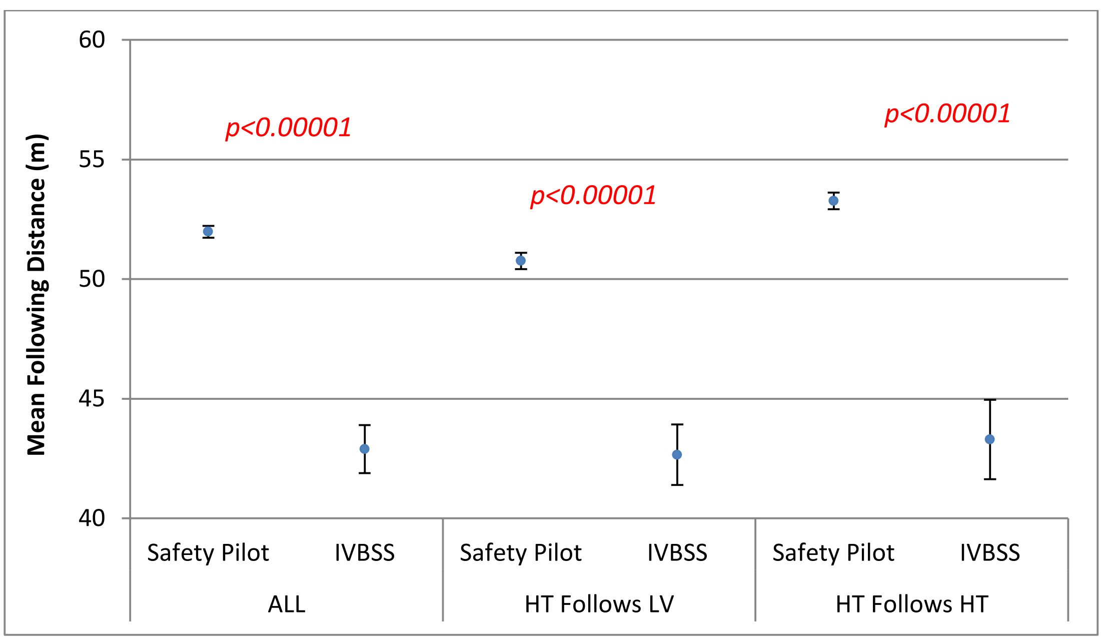

Figure 15. Mean Following Distance for Safety Pilot versus IVBSS Trucks

The same result occurred during the analysis of following headway. IVBSS trucks followed lead vehicles at shorter headways overall, and in each lead-vehicle category. Figure 16 shows these results.

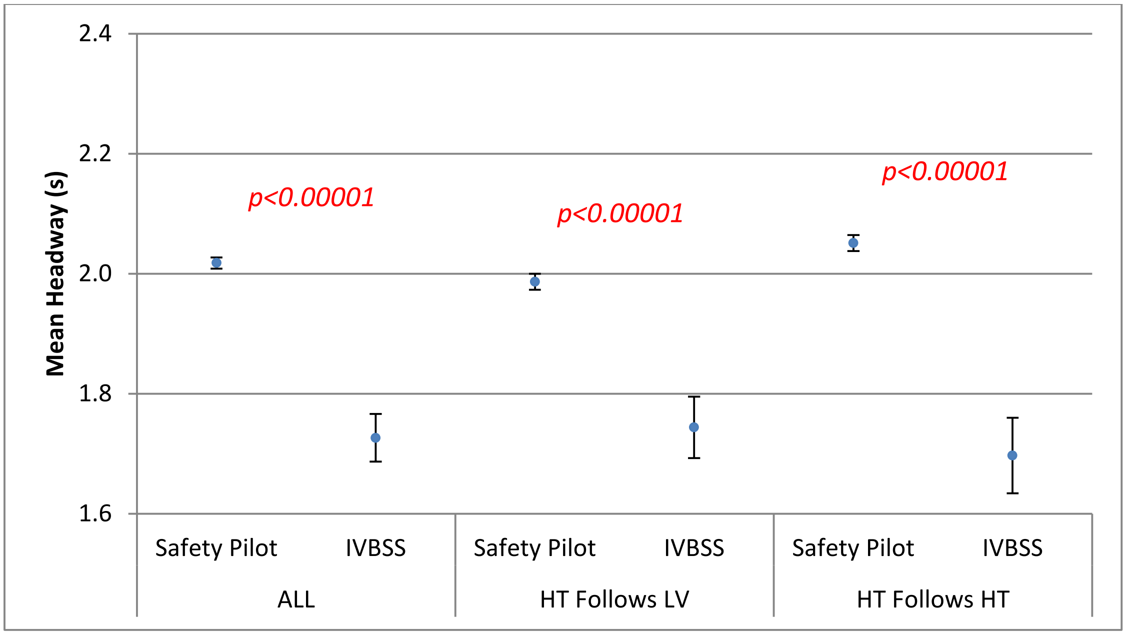

Figure 16. Mean Following Headway for Safety Pilot versus IVBSS Trucks

3.2 Following Behavior by Environmental Factors

Volpe addressed research question number two using both the Safety Pilot Model Deployment and IVBSS datasets:

How does this following behavior vary by highway type, road condition, weather, and visibility?

The research hypothesis for research question number two is as follows:

- There will be no difference in the distance and headway at which heavy trucks follow lead vehicles:
    - on state highways compared to interstate highways
    - on dry roads compared to wet or snow-covered roads
    - in clear weather compared to in rain or snow
    - during the day compared to at night or during dusk

3.2.1 Safety Pilot Truck Results

Figure 17 shows mean following distance by environmental factors for Safety Pilot trucks. For environmental factors with more than two categories, the dotted circles show which categories were compared with the paired *t*-test. Trucks in the Safety Pilot field test followed lead vehicles at a shorter distance under the following conditions: when driving on state highways compared to interstates, when driving on dry or wet road conditions compared to snow (there were no significant differences between following distance in dry or wet road conditions), when driving in the rain compared to in clear weather or when it was snowing, and when driving in the day compared to at night or dusk.

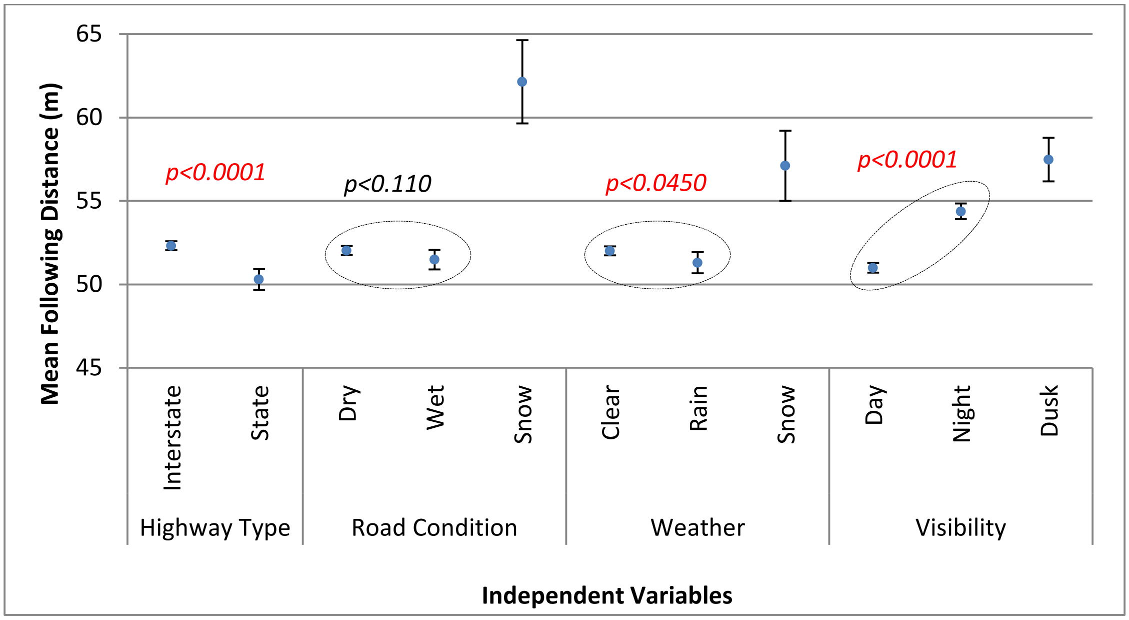

Figure 17. Mean Following Distance by Independent Variable – Safety Pilot Trucks

Figure 18 shows the mean headway by independent variable for Safety Pilot trucks. The results of the paired *t*-tests on headway revealed significant differences in following behavior in every environment factor category. Safety pilot trucks followed other vehicles at shorter headways under the following conditions: when driving on state roads, on dry roads, in clear weather, and during the day. The finding that trucks follow other vehicles at a shorter distance, but at a greater headway in the rain compared to in clear weather, indicates that trucks drive more slowly in the rain (mean speed in clear weather was 57.9 mph compared to 55.5 mph in the rain).

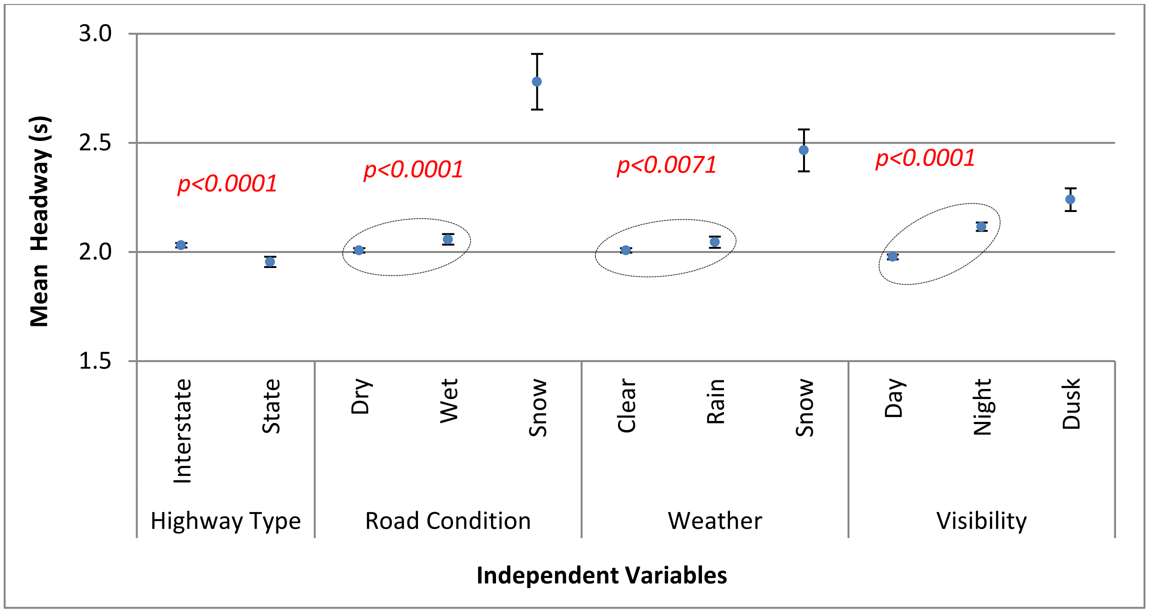

Figure 18. Mean Headway by Independent Variable – Safety Pilot Trucks

3.2.2 IVBSS Truck Results

Figure 19 shows the mean following distance of IVBSS trucks, broken down by environmental factors. Significant differences in following distance were only observed when driving during the day compared to at night (drivers followed vehicles more closely during the day).

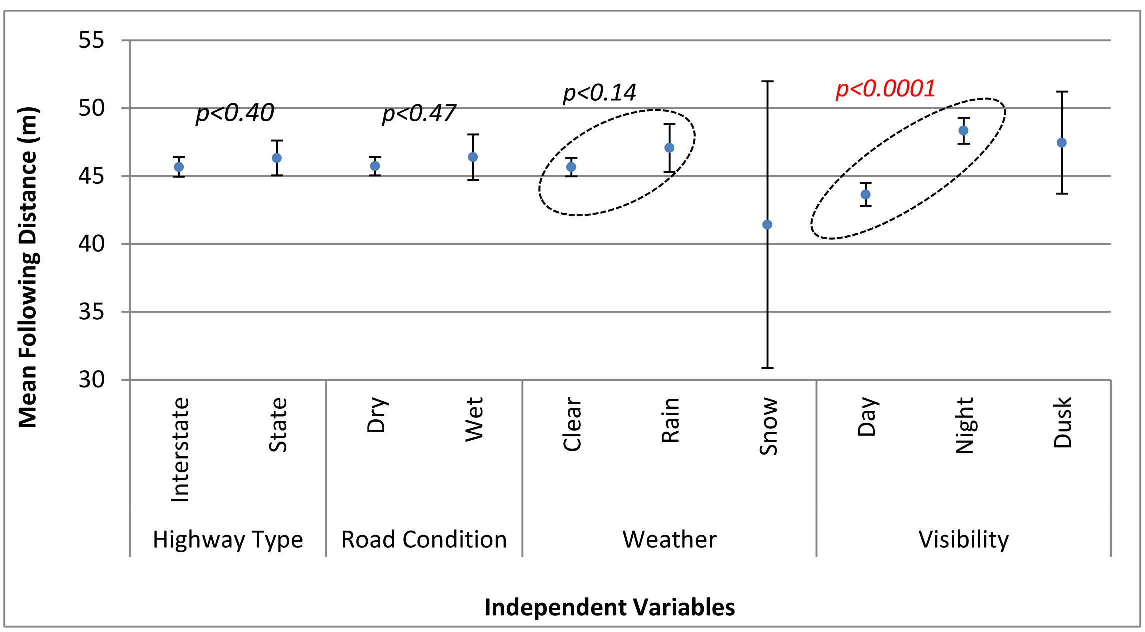

Figure 19. Mean Following Distance by Independent Variable – IVBSS Trucks

Figure 20 shows the mean headway of IVBSS trucks, broken down by environmental factors. Similar to the results of following distance for IVBSS trucks and following distance and headway for Safety Pilot trucks, IVBSS trucks followed at shorter headways during the day compared to at night. However, while Safety Pilot trucks followed other vehicles at shorter headways on state highways compared to interstates, IVBSS trucks followed other vehicles at significantly longer headways on state highways.

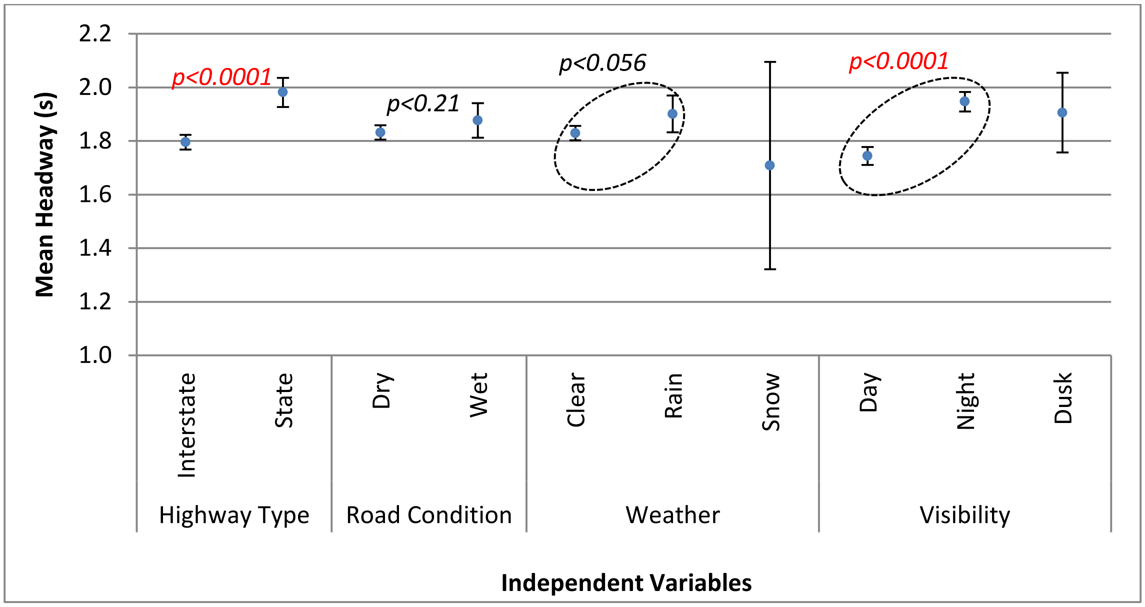

Figure 20. Mean Headway by Independent Variable – IVBSS Trucks

3.3 Truck-Following Conditions for Consideration in Automated Platooning

Research question number three for the naturalistic truck-following study asked:

Are there particular following safety events or conditions that should be considered in the development of automation technologies?

Since following scenarios in this research are defined only as steady-state following scenarios, Volpe looked at dynamic events that occurred directly after truck-following scenarios ended, using data from the Safety Pilot Model Deployment. Since this analysis only describes the behavior of the lead vehicle, analyses were not conducted for both truck fleets (IVBSS and Safety Pilot). Since the goal of this research question was not to conduct a comparative analysis, but rather to quantify and present data on dynamic truck-following scenarios, no hypotheses were developed.

Figure 21 shows the distribution of the events that ended the 17,075 steady-state truck-following events from the Safety Pilot Model Deployment dataset. Ending type categories are defined below:

- **Closing**: Distance between the host truck and the lead vehicle got smaller (either because the host truck accelerated or the lead vehicle decelerated).
- **Cut-in:** Another vehicle cut in between the host truck and the lead vehicle.

- **Cut-out:** Lead vehicle in the truck-following scenario moved to an adjacent lane.
- **HV lane change:** Host truck moved to an adjacent lane.
- **Separating:** Distance between the host truck and the lead vehicle got larger (either because the host truck decelerated or the lead vehicle accelerated).

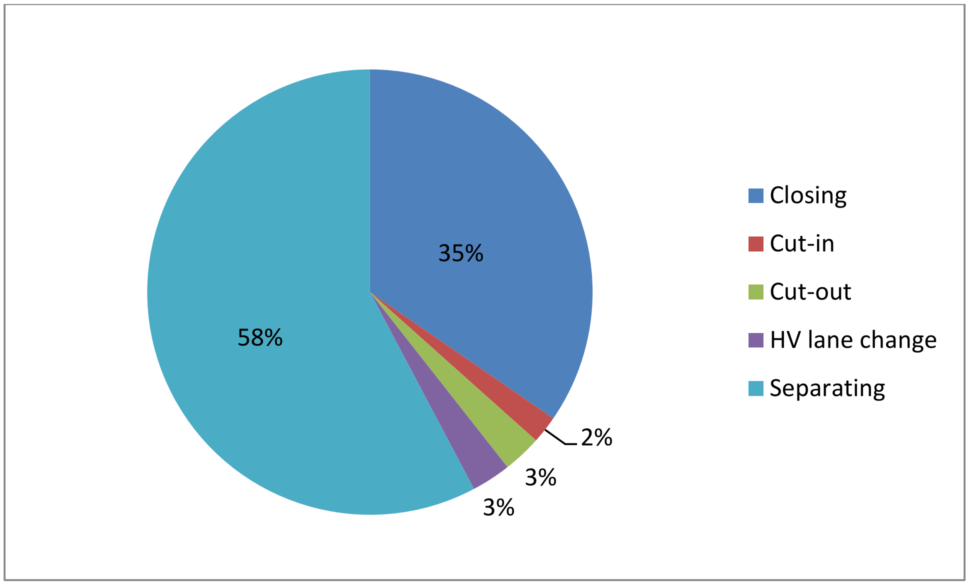

Figure 21. Breakdown of Truck-Following Scenario Ending Types in Safety Pilot Dataset

Two following scenario ending types were chosen for further analysis because they described behavior of lead vehicles that may need to be accounted for to maintain a consistent headway in automated truck platooning:

- Closing scenarios where the lead vehicle decelerated
- Separating scenarios where the lead vehicle accelerated

The host truck lane-change scenarios were also examined to better understand scenarios in which truck drivers end their following scenarios by changing lanes. Cut-in scenarios were analyzed independently (refer to Section 3.4 for results) and cut-out scenarios were not examined since they do not mimic a scenario that would need to be accounted for in platooning. Sections 3.3.1 through 3.3.3 provide descriptive statistics for each of the three following scenario ending types of interest.

3.3.1 Lead Vehicle Decelerating

The 5,776 Safety Pilot steady-state following scenarios ended because the lead vehicle decelerated, causing the distance between the host truck and the lead vehicle to decrease. Figure 22 shows the distribution of lead vehicle mean deceleration, broken down by lead vehicle type. Figure 23 shows the overall mean for each lead vehicle type (error bars represent 95 percent confidence interval of the mean). On average, light vehicles decelerated at an average rate of 1.14 m/s^2 (0.12g), and heavy trucks decelerated at an average rate of 1.04 m/s^2 (0.11g).

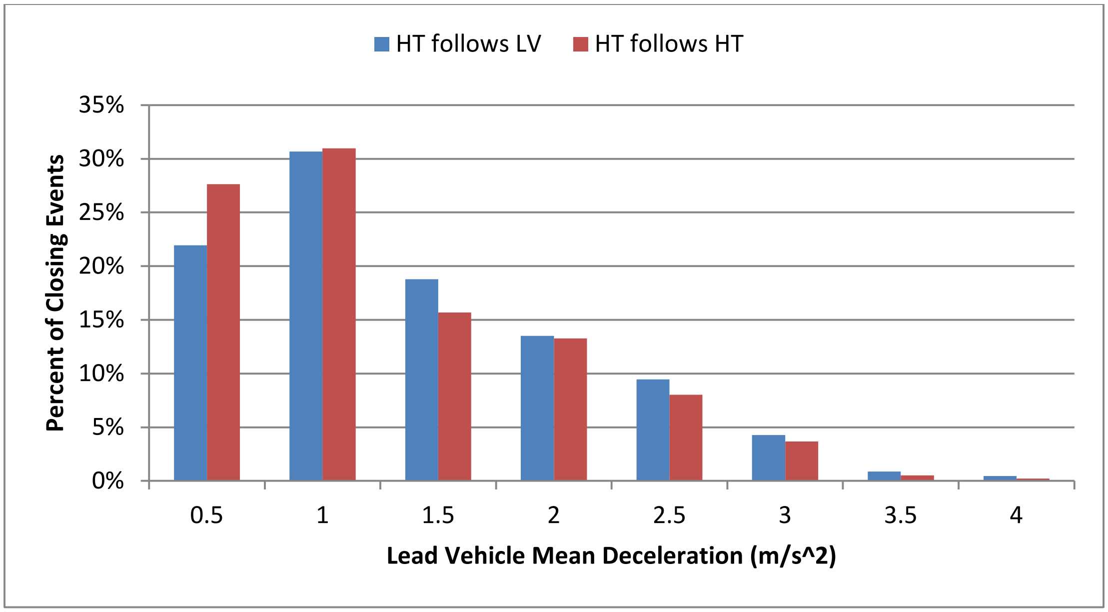

Figure 22. Distribution of Lead Vehicle Mean Deceleration during Lead Vehicle Decelerating Events

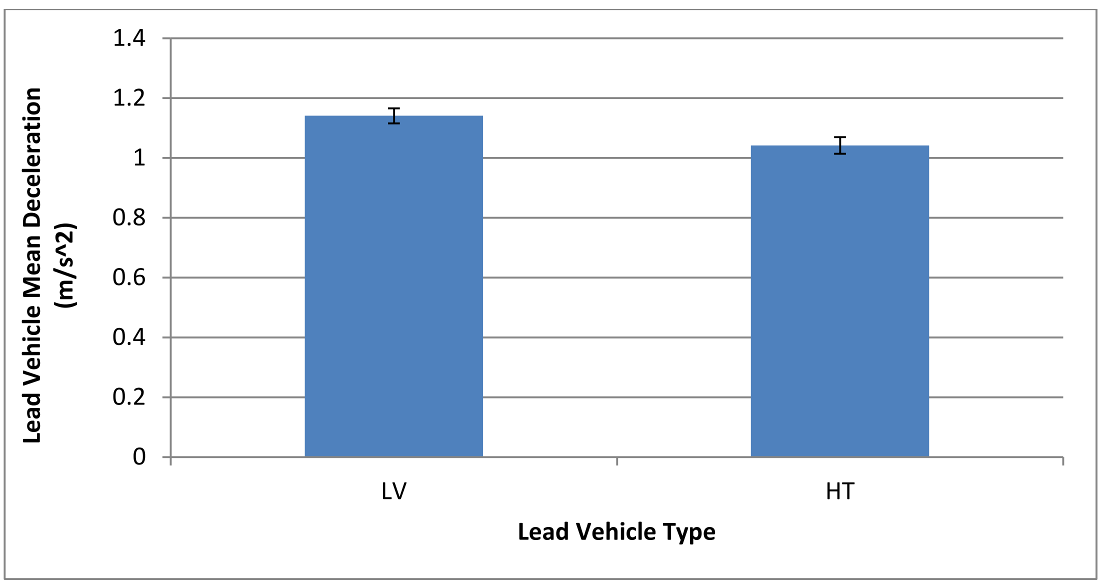

Figure 23. Mean Lead Vehicle Deceleration by Lead Vehicle Type

Figure 24 shows the mean lead vehicle deceleration levels during closing scenarios, broken down by lead vehicle type and speed bin. Lead light vehicles decelerated slightly more aggressively than heavy trucks in each of the four speed bins.

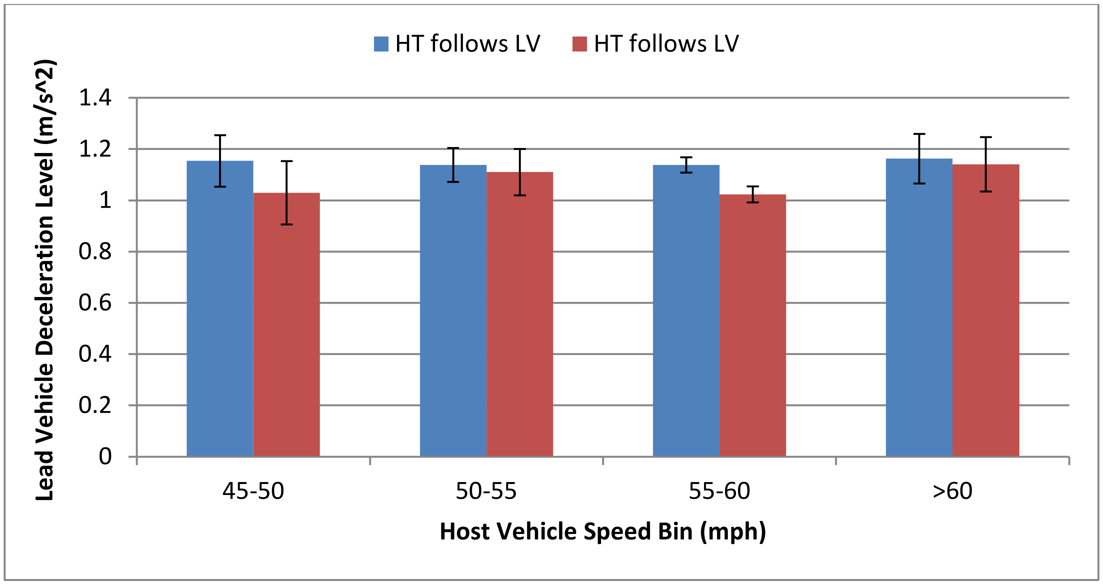

Figure 24. Mean Lead Vehicle Deceleration by Lead Vehicle Type and Speed Bin

Table B- 3 in Appendix B lists descriptive statistics of lead vehicle decelerating behavior in each speed bin.

3.3.2 Lead Vehicle Accelerating

The 7,123 Safety Pilot steady-state following scenarios ended because the lead vehicle accelerated, causing the distance between the host vehicle and the lead vehicle to increase. Figure 25 shows the distribution of lead vehicle mean acceleration, and Figure 26 shows the overall mean for each lead vehicle type and the 95 percent confidence interval to the mean. Light vehicles accelerated away from the host heavy truck at an average rate of 1.00 m/s^2 (0.1g), and heavy trucks accelerated away at a rate of 0.90 m/s^2 (0.09g). Figure 27 shows the cumulative distributions of these data.

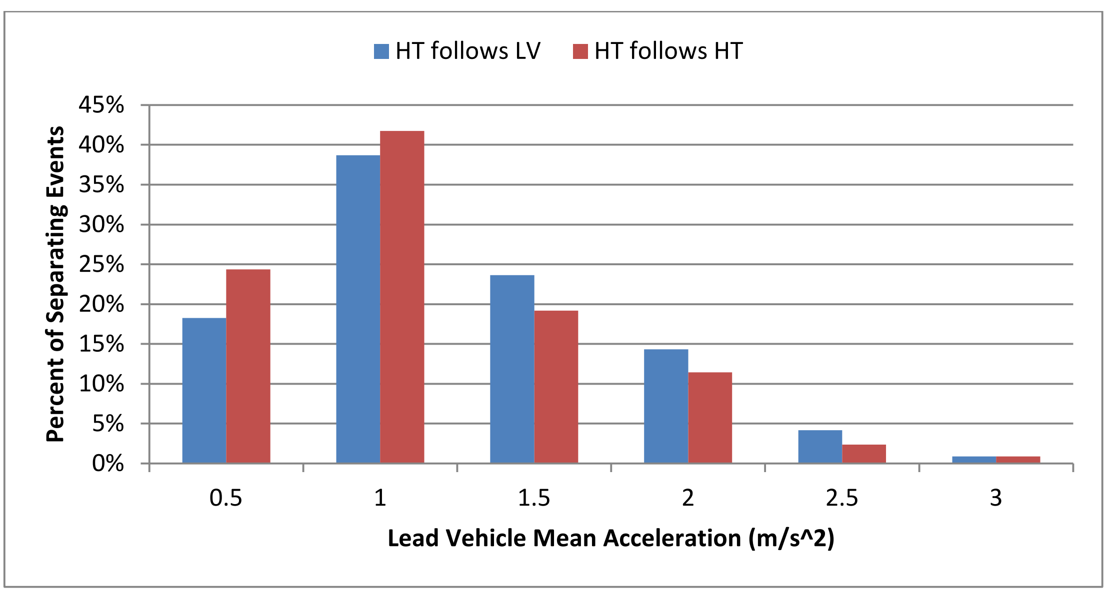

Figure 25. Distribution of Lead Vehicle Mean Acceleration during Lead Vehicle Accelerating Events

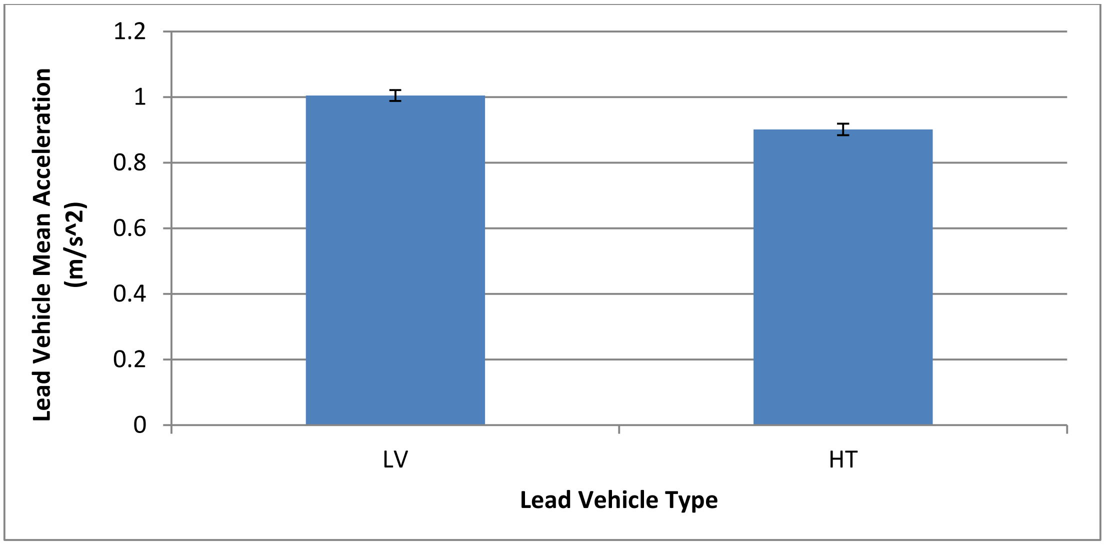

Figure 26. Mean Lead Vehicle Acceleration by Lead Vehicle Type

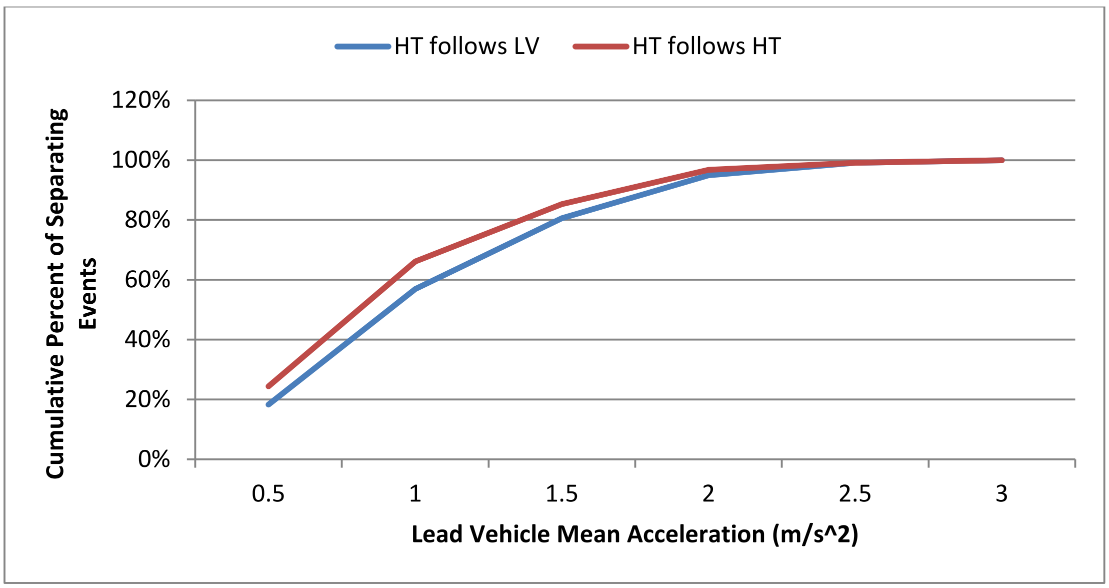

Figure 27. Cumulative Distribution of Lead Vehicle Mean Acceleration during Lead Vehicle Accelerating Events

Figure 28 shows the mean lead vehicle acceleration levels during separating scenarios, broken down by lead vehicle type and speed bin. Light vehicles and heavy trucks accelerated similarly in the lower speed bins (45-50 and 50-55 mph bins), but light vehicles accelerated more aggressively (based on the 95 percent confidence interval) in the higher speed bins (55-60 mph and >60 bins).

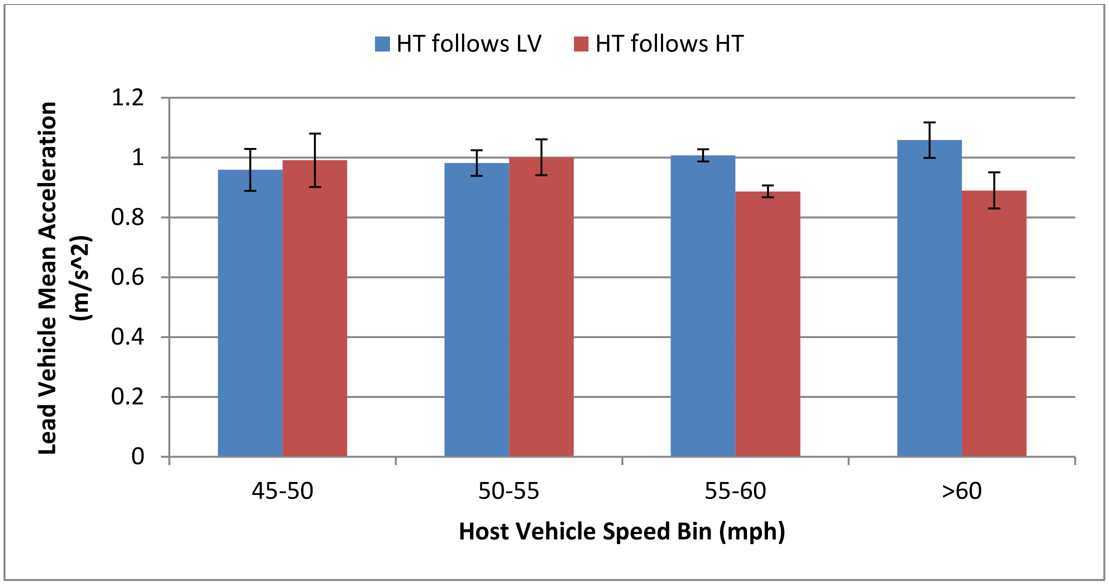

Figure 28. Mean Lead Vehicle Acceleration by Lead Vehicle Type and Speed Bin

Table B- 4 in Appendix B lists descriptive statistics of lead vehicle accelerating behavior in each speed bin.

3.3.3 Host Truck Lane-Change Events

The 485 Safety Pilot steady-state following scenarios ended because the host truck changed lanes and was no longer following the lead vehicle. Figure 29 shows the distribution of minimum range to the lead vehicle before the host truck changed lanes. Generally, heavy trucks did not come within close range of a lead vehicle prior to a lane change. Drivers changed lanes within 25 m (82 ft) of the lead vehicle in only 12 percent of lane change scenarios, with an overall average minimum range of 40.8 m (134 ft). Figure 30 shows the cumulative distribution of these data.

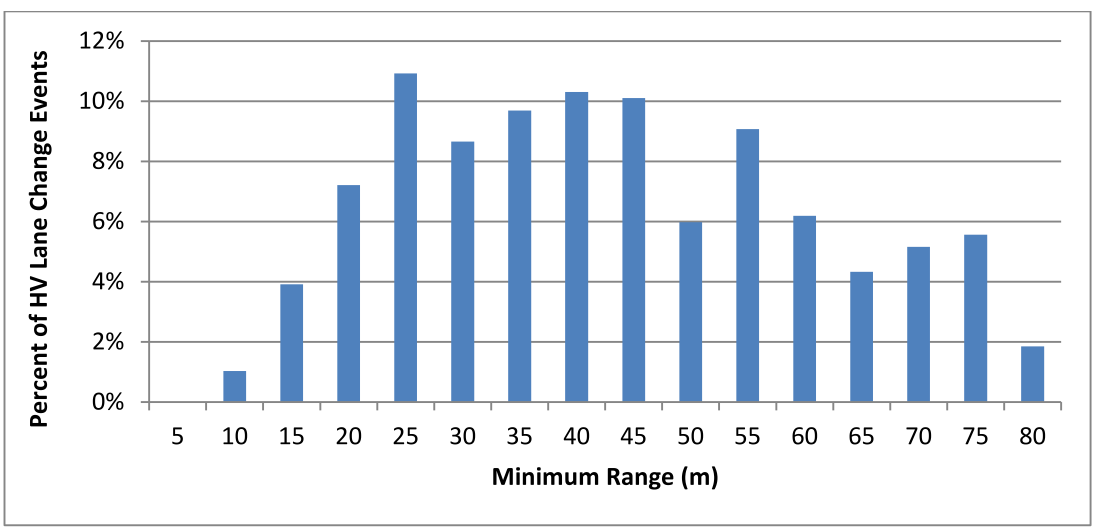

Figure 29. Distribution of Minimum Range to Lead Vehicle during Host Vehicle Lane-Change Events

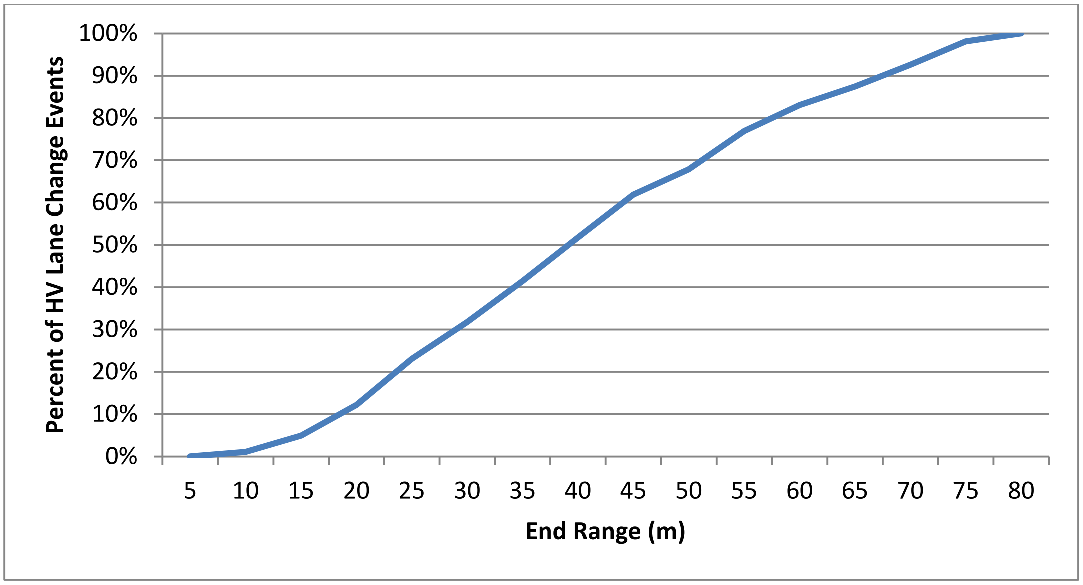

Figure 30. Cumulative Distribution of Minimum Range to Lead Vehicle during Host Vehicle Lane-Change Events

3.4 Lead Vehicle Cut-in Events

The fourth research question in the naturalistic truck-following study asked:

At what following distances do vehicles cut in between the truck and the lead vehicle?

The goal of this research question is to understand how closely trucks in a platoon would need to follow the lead vehicles to avoid cut-ins by other vehicles. In addition to looking at cut-in scenarios where trucks were following other trucks, this analysis also looked at cut-in scenarios where the truck is following light vehicles and examined how close other vehicles cut in ahead of the host truck. These data will be used as part of the assessment of safety impact in research question number five.

Volpe identified cut-in scenarios in the Safety Pilot dataset by identifying instances where steady-state following scenarios ended due to a sudden, instantaneous decrease in the measurement of range to the lead vehicle. Volpe used the following filter criteria to identify cut-in scenarios from the numerical data:

- Steady-state following scenario is occurring
- Range to lead vehicle decreases ≥ 5.5 m
- New target identified by forward ranging sensor
- Host vehicle is not using turn signal (to filter out host vehicle lane changes)

With these criteria, Volpe identified 4,974 cut-in events in the Safety Pilot following event database and selected a random sample of 1,500 events for video validation and analysis. Analysts verified that the event was truly a cut-in event, and identified the type of vehicle that was cutting in (lead vehicle type had been identified in the video validation task for research question number one). The video validation exercise yielded 1,046 cut-in events to include in the analysis.

Table 7 shows the sample size for the cut-in analysis, broken down by the type of lead vehicle and type of vehicle that cut in. Overall, trucks were following other heavy trucks in 96 events (9 percent) and were following light vehicles in 950 events (91 percent). The cut-in vehicle was a heavy truck in only four percent of the analyzed cut-in events. Table B- 5 in Appendix B lists descriptive statistics of the evaluation metrics within each lead vehicle and cut-in vehicle type.

Table 7. Cut-in Sample Size by Lead Vehicle Type and Cut-in Vehicle Type

Lead Vehicle Type	Cut-in Vehicle Type	Event Count	Percent
HT	HT	18	2%
	LV	78	7%
LV	HT	26	2%
	LV	924	88%

Similar to research question number three, the goal of this research question is to provide descriptive data that will be helpful to creating an automated truck platooning application. An additional research hypothesis is also addressed:

- There will be no difference in the distance at which vehicles cut in to a following scenario when a heavy truck is following a light vehicle, compared to when a heavy truck is following another heavy truck.

3.4.1 Lead Vehicle Distance and Headway at Cut-in Time

Figure 31 shows the distribution of following distances prior to cut-in events between two heavy trucks, or a heavy truck and a lead light vehicle in a steady-state following scenario. When trucks were following another truck, no cut-in events were observed when the two trucks were within less than 30 m (98 ft) from each other. Only four percent of the observed cut-in events occurred when the trucks were following between 30 and 40 m (98 and 131 ft). Generally, other vehicles do not cut in between two trucks that are following at less than 40 m distance.

The distribution for following distance prior to cut-in events is similar to when the host truck is following a light vehicle (mean following distance prior to cut-in when the lead vehicle is a heavy truck = 57.2 m (188 ft), compared to 58.3 m (191 ft) when the lead vehicle is a light vehicle). Unlike the scenario when trucks were following heavy trucks, a small number of cut-in events occurred (0.7 percent of the events) when trucks were following light vehicles at less than 30 m (98 ft).

Figure 32 shows cumulative distributions for these data.

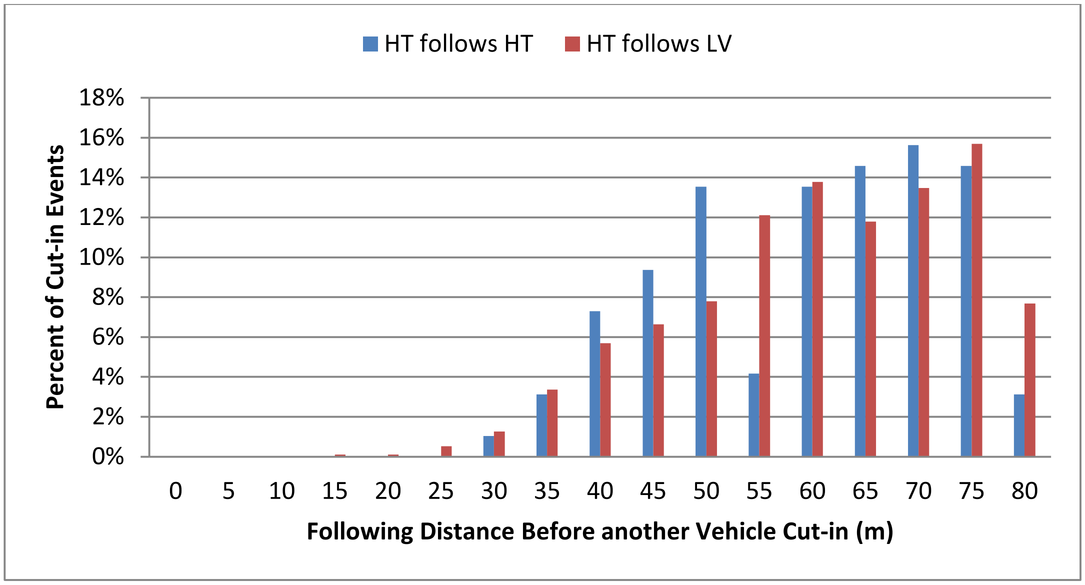

Figure 31. Distribution of Distances to Lead Vehicle when another Vehicle Cuts in

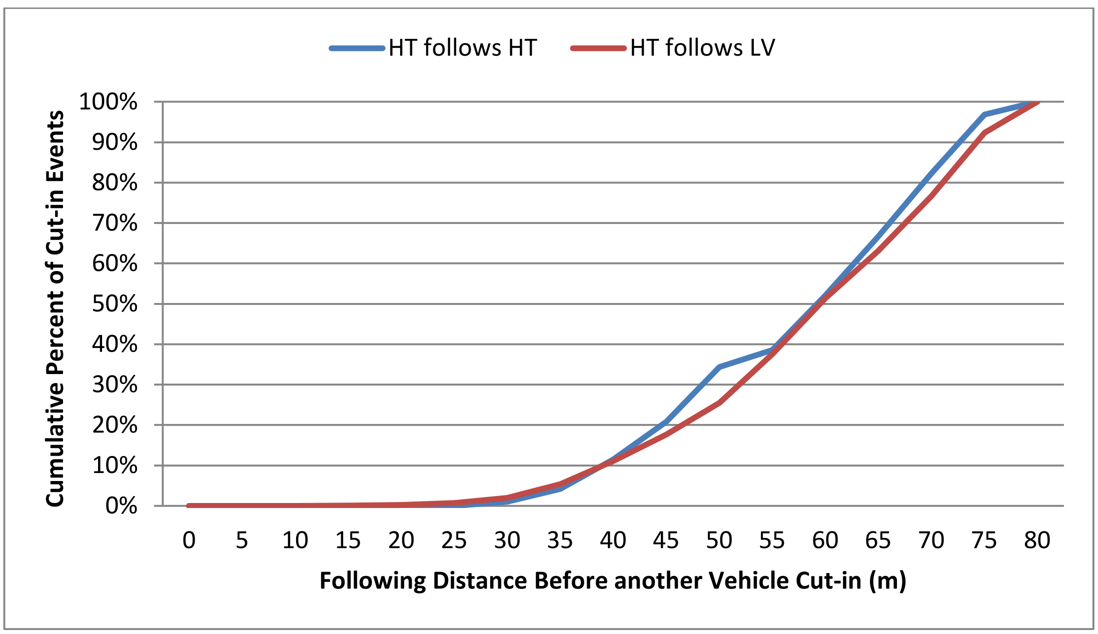

Figure 32. Cumulative Distribution of Distances to Lead Vehicle when another Vehicle Cuts in

Figure 33 shows the distributions for the headway to the lead vehicle at the time another vehicle cuts in, when heavy trucks are following other heavy trucks, and when they are following light vehicles. No cut-in events were observed at less than 1.5 s when a heavy truck was following another heavy truck. Like following distance, the distribution of headway at cut-in events when a truck was following another heavy truck was similar to when they were following a light vehicle. However, a small percent of events (0.7 percent) occurred at headways of less than 1.5 s. The mean headway at cut-in time for both truck following trucks and trucks following light vehicles was 2.2 s. Figure 34 shows the cumulative distribution of these data.

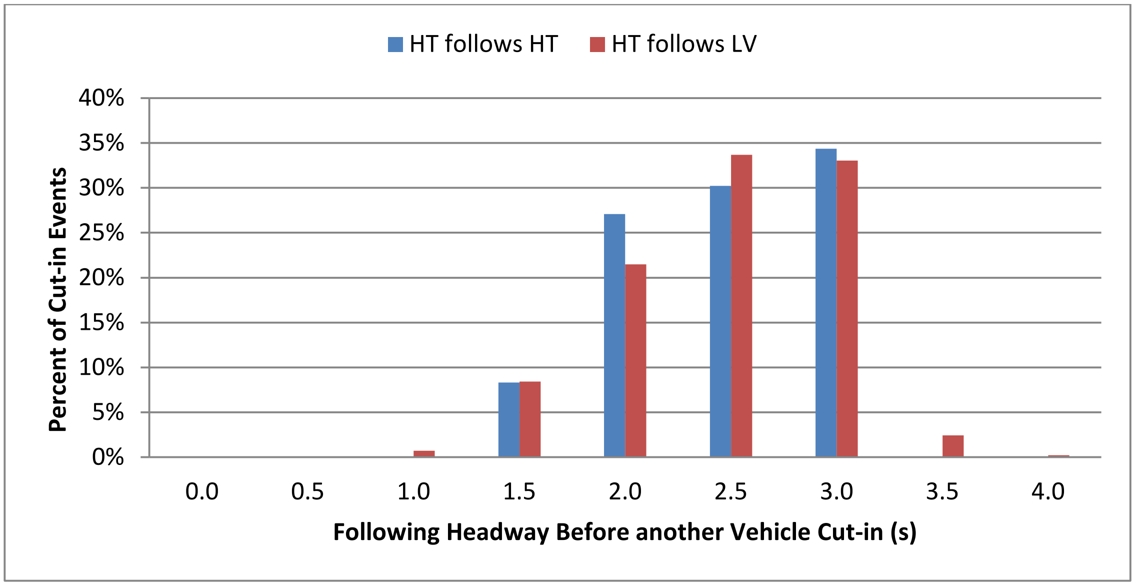

Figure 33. Distribution of Following Headway when another Vehicle Cuts in

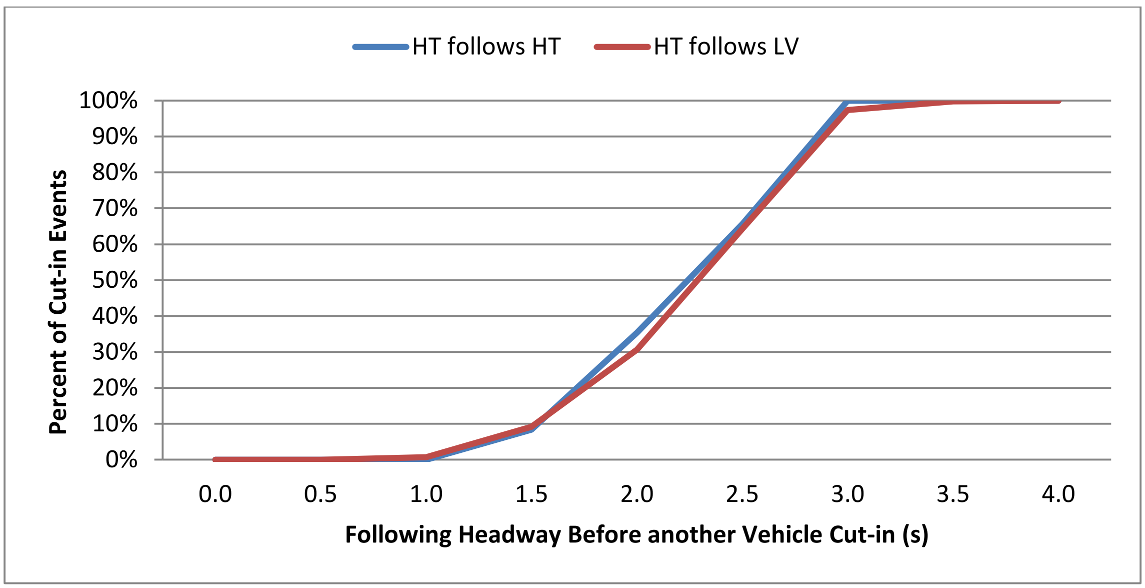

Figure 34. Cumulative Distribution of Following Headway when another Vehicle Cuts in

3.4.2 Distance and Headway to Lead Vehicle during Cut-in Events

Figure 35 shows the mean following distance when another vehicle cuts in, broken down by the lead vehicle type and cut-in vehicle type. Heavy trucks showed a trend of cutting-in between a truck following a light vehicle at a shorter distance than a truck following another truck, but the distance was not statistically significant. Light vehicles cut in between trucks following other trucks at shorter distance than they cut in between trucks following light vehicles. This difference is statistically significant. In other words, light vehicles make more aggressive cut-ins when they are cutting-in between two trucks than when they are cutting in between a truck and a lead-light vehicle. Since the available sample of heavy trucks cutting in was only one-tenth the size of the light vehicles cutting in, it is possible that the lack of significant difference between trucks cutting between two trucks and a truck following a light vehicle was due to the limited sample size.

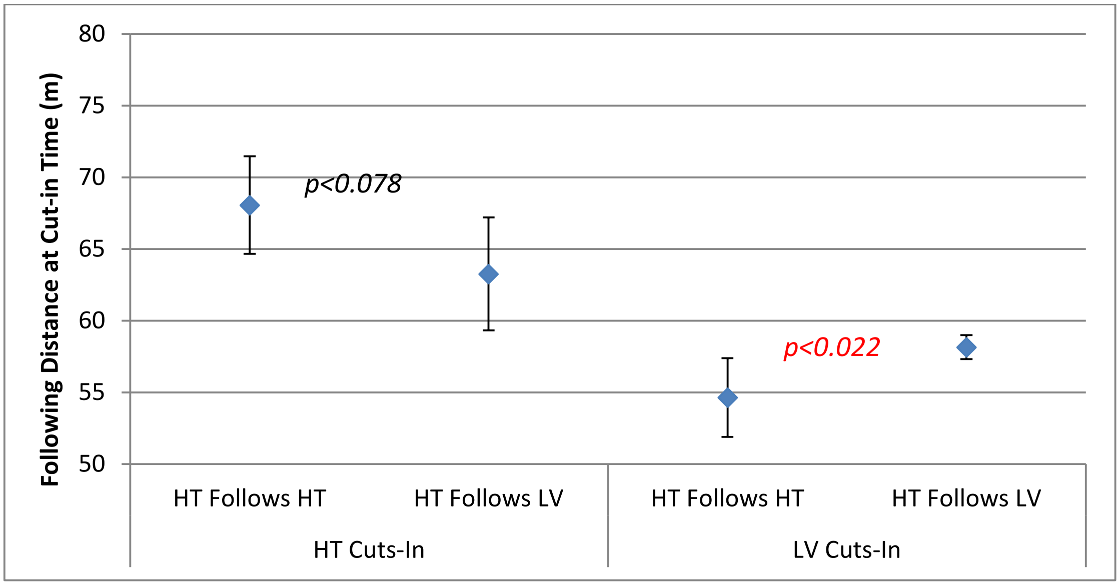

Figure 35. Mean Following Distance at Cut-in Time, by Lead and Cut-in Vehicle Type

Figure 36 shows the same results for headway. Similar to the results for following distance during cut-in events, light vehicles cut in between two trucks following with a shorter headway than they cut in between a truck and a lead-light vehicle (results are statistically significant). Heavy truck cutting-in did not show a difference in cut-in headway by lead vehicle type.

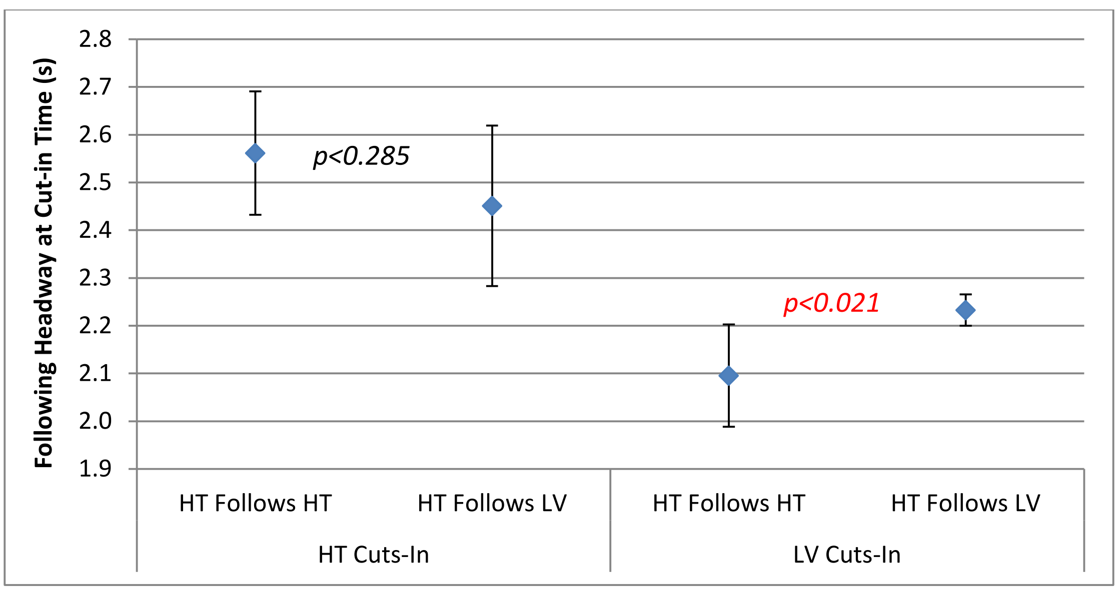

Figure 36. Headway at Cut-in Time, by Lead and Cut-in Vehicle Type

3.4.3 Distance and Headway to Cut-in Vehicle during Cut-in Events

Figure 37 shows the distance to the cut-in vehicle, broken down by cut-in vehicle type. Heavy trucks cut in front of the host trucks during following scenarios at a closer distance compared to light vehicles. On average, heavy trucks cut in 22.8 m (75 ft) in front of the host truck (from the front bumper of the host truck, to the rear bumper of the cut-in truck) and light vehicles cut in 27.0 m (89 ft) in front of the host truck. This distance is statistically significant ($p < 0.004$). Figure 38 shows the cumulative distribution for these data.

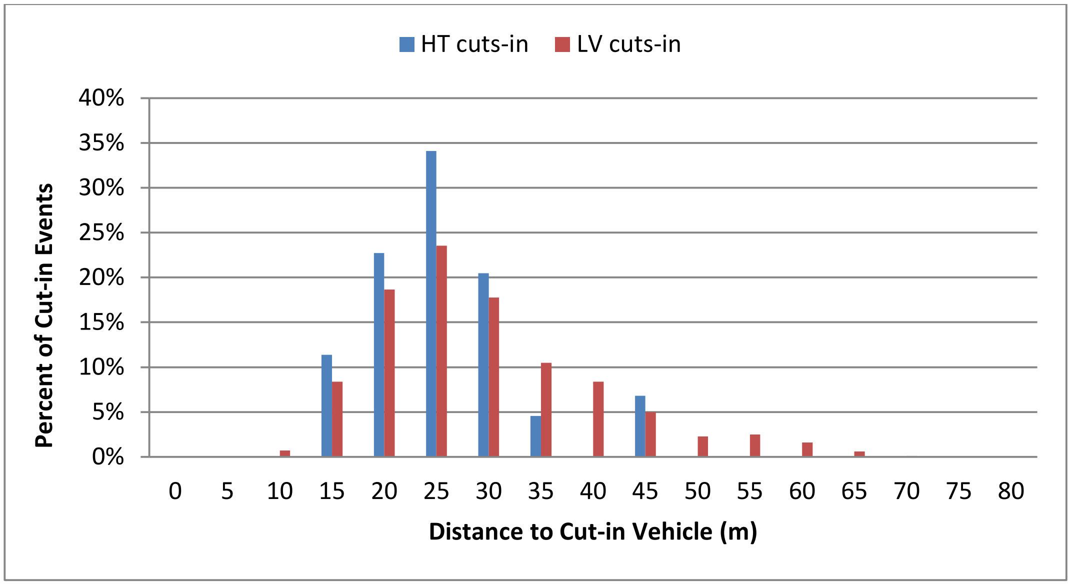

Figure 37. Distance to Cut-in Vehicle by Cut-in Vehicle Type

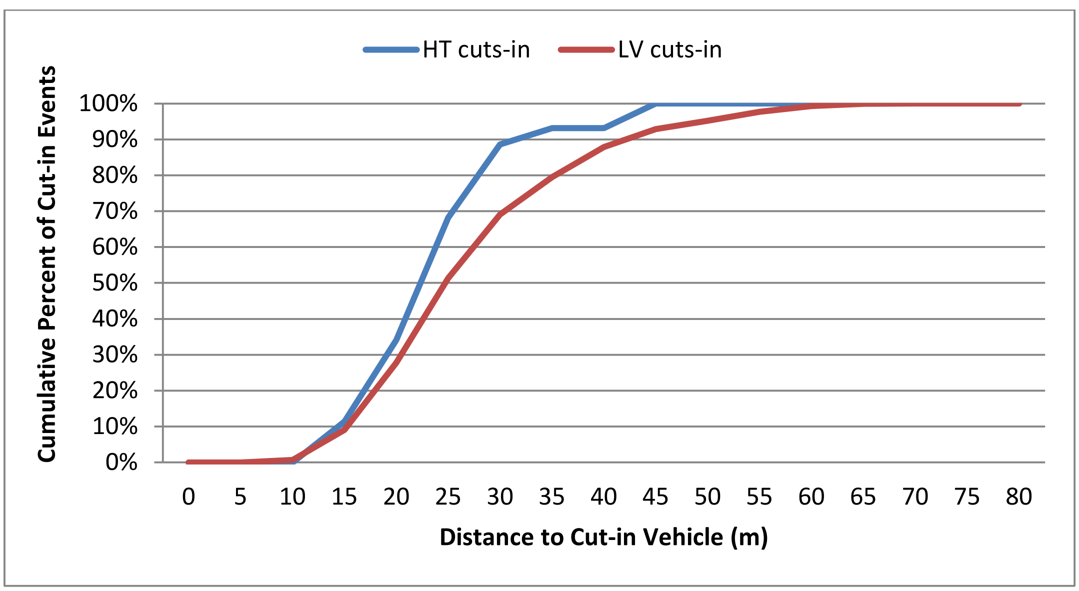

Figure 38. Cumulative Distance to Cut-in Vehicle by Cut-in Vehicle Type

Figure 39 shows the headway to the cut-in vehicle during cut-in events, broken down by cut-in vehicle type. Heavy trucks cut in front of the host trucks at shorter headways compared to light vehicles. On average, heavy trucks cut in with 0.9 s in front of the host truck and light vehicles cut in with 1.0 s in front of the host truck. This distance is statistically significant ($p < 0.02$). Figure 40 shows the cumulative distribution for these data.

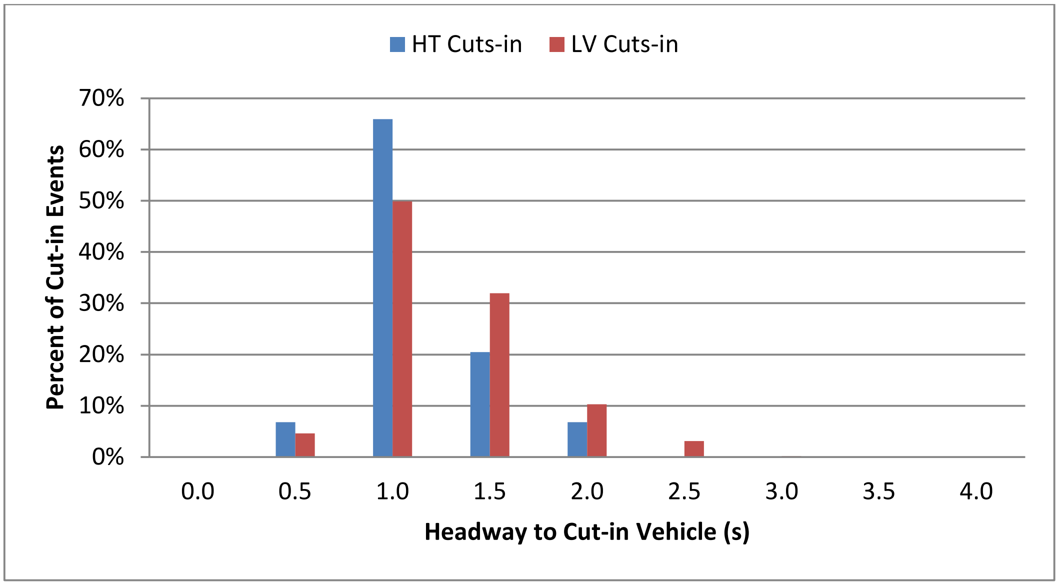

Figure 39. Headway to Cut-in Vehicle by Cut-in Vehicle Type

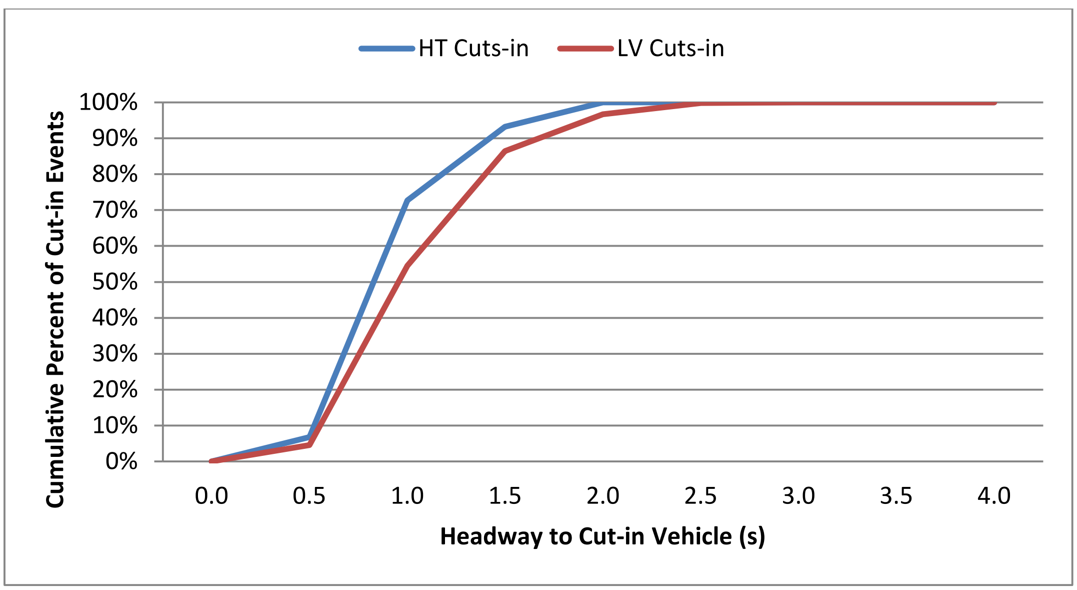

Figure 40. Cumulative Headway to Cut-in Vehicle by Cut-in Vehicle Type

Table B-5 in Appendix B lists descriptive statistics for cut-in events.

3.5 Safety Impact of Truck-Following at Different Gaps

Volpe assessed the rear-end crash risk of the truck-following behavior at different gaps. These gaps were based on estimates of the probability of a rear-end crash obtained from Monte Carlo simulations using the SIM tool. This analysis addressed research question number five:

What is the safety impact of truck following at different headways?

The analysis considered the safety impact of truck-following scenarios that may end by the sudden deceleration of the lead vehicle (light vehicle or heavy truck), or by the sudden deceleration of another vehicle that just cut in between the host truck and the initial lead vehicle. Thus, the LVD rear-end pre-crash scenario was simulated using the SIM tool with the following input data:

- **Lead vehicle deceleration level:** Truncated normal distribution with values listed in Table 3 for lead light vehicles and heavy trucks.
- **Travel speed bin:** Uniform distribution of 5 mph speed intervals – 45-50, 50-55, 55-60, and 60-65 mph.[9] In each speed bin, the speed of the lead vehicle was assumed to be in the lower half of the speed bin, while the speed of the host truck was assumed to be in the upper half of the speed bin. For example, the lead vehicle speed varied between 45 and 47.49 mph while the host truck speed varied between 47.5 and 50 mph in the 45-50 mph speed bin.
- **Time headway:** Discrete values of time headway between 0.5 and 4.5 s with 0.5 s increments simulated.
- **Brake reaction time:** Lognormal distribution with mean values of 1.88 s (slow) and 1.21 s (medium), assuming manual driver response. Both reaction times had a standard deviation of 0.3 s. In addition, a constant reaction time of 0.3 s (fast) was assumed for automated truck response.
- **Crash avoidance braking level:** Truncated normal distribution between 0.2 and 0.6g with a mean value of 0.4g and a standard deviation of 0.1g for manual driver response, and between 0.4 and 0.6g with a mean of 0.5g and standard deviation of 0.1g for automated truck response.

Table 8 lists the estimated values of the probability of a rear-end crash in an LVD pre-crash scenario. These values are based on Monte Carlo simulations of 10,000 runs for each cell combination of response type, headway up to 3.0 s, speed bin, and lead vehicle type deceleration level. Appendix C displays six individual plots of the ***p*Crash** estimates as a function of time headway up to 4.5 s at 4 different speed bins: 2 lead vehicle types (light vehicle and heavy truck) × 3 response types (slow, medium, and fast). As shown in Table 8, the ***p*Crash** estimates are almost zero (cells highlighted in green) for speeds between 45 and 60 mph, and under 1 percent for only two speed bins for the automated fast response. For the

[9] The maximum speed was capped at 65 mph to maintain uniform speeds bins. Naturalistic driving data supports this cap. In the Safety Pilot Model Deployment the maximum heavy truck speed in a conflict was 63 mph. In the IVBSS study, only 0.25% of conflicts had a speed greater than 65 mph.

driver manual response (i.e., slow and medium), the ***pCrash*** estimates are very high at 0.5 s headway and drastically decrease for over 1.0 s headway.

Table 8. Probability of a Rear-End Crash Simulation Results

Driver Response Time	Headway (s)	Lead Light Vehicle Speed (mph) 45-50	50-55	55-60	60-65	Lead Heavy Truck Speed (mph) 45-50	50-55	55-60	60-65
Slow (1.88 s)	**0.5**	55.92%	44.18%	35.63%	31.51%	49.93%	43.64%	30.24%	28.48%
	1.0	9.24%	7.15%	5.77%	5.72%	5.62%	7.40%	4.07%	4.85%
	1.5	3.40%	3.15%	2.68%	3.06%	2.06%	2.83%	1.74%	2.20%
	2.0	1.87%	1.77%	1.26%	1.72%	1.00%	1.52%	1.08%	1.28%
	2.5	0.97%	0.80%	0.70%	1.05%	0.39%	0.63%	0.42%	0.75%
	3.0	0.30%	0.43%	0.34%	0.48%	0.18%	0.35%	0.23%	0.42%
Medium (1.21 s)	**0.5**	22.95%	16.13%	11.32%	10.10%	36.87%	31.01%	20.21%	19.30%
	1.0	3.11%	2.67%	2.21%	2.30%	3.29%	5.04%	3.10%	3.35%
	1.5	1.55%	1.16%	0.88%	1.47%	1.54%	2.13%	1.22%	1.56%
	2.0	0.80%	0.57%	0.54%	0.65%	0.66%	1.01%	0.55%	0.83%
	2.5	0.18%	0.28%	0.20%	0.43%	0.25%	0.48%	0.28%	0.52%
	3.0	0.06%	0.13%	0.07%	0.18%	0.15%	0.20%	0.15%	0.21%
Fast (0.30 s)	**0.5**	0.00%	0.00%	0.00%	0.01%	0.00%	0.00%	0.01%	0.00%
	1.0	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
	1.5	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
	2.0	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
	2.5	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
	3.0	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%

*: Mean values obtained from the results of this study

Table 9 and Table 10 list the ***pCrash*** estimates for lead light vehicle and lead heavy truck, respectively, based on the mean values of observed headways from the Safety Pilot Model Deployment and IVBSS datasets. Headway values were obtained from the LVD events that ended the truck-following behavior and from vehicle cut-in events. In the latter events, the ***pCrash*** analysis assumes that the cut-in vehicle suddenly decelerates[10] due to unexpected slowing down of the traffic ahead. However, this assumed event rarely happened in the analysis datasets. The results in both tables show that shorter headway and slower response lead to higher ***pCrash*** values. Below 1.0 s headway to a cut-in vehicle that might suddenly decelerate, the ***pCrash*** estimate could be as high as 2 percent for a lead light vehicle and 5 percent for a lead heavy truck, at speeds over 60 mph with a medium driver reaction time. In contrast, the ***pCrash*** estimates could be as high as 0.7 percent for a lead light vehicle and 0.5 percent for a lead heavy truck in the LVD truck-following ending type, at speeds over 60 mph with a medium driver reaction time.

[10] For the purposes of the model deceleration is assumed to be constant.

Table 9. Probability of a Rear-End Crash Estimates Based On Observed Headways to Lead Light Vehicle

Event	Speed (mph)	Mean Headway (s)	Response		
			Slow	Medium	Fast
Lead Vehicle Decelerating	45-50	2.15	1.38%	0.54%	0.00%
	50-55	1.89	1.91%	0.68%	0.00%
	55-60	2.00	1.45%	0.65%	0.00%
	60-65	2.08	1.56%	0.72%	0.00%
Lead Vehicle Cut-in and Decelerating	45-50	1.16	7.39%	2.62%	0.00%
	50-55	1.07	6.61%	2.46%	0.00%
	55-60	1.03	5.59%	2.13%	0.00%
	60-65	1.03	5.63%	2.24%	0.00%

Table 10. Probability of a Rear-End Crash Estimates Based On Observed Headways to Lead Heavy Truck

Event	Speed (mph)	Mean Headway (s)	Response		
			Slow	Medium	Fast
Lead Vehicle Decelerating	45-50	2.04	0.87%	0.26%	0.00%
	50-55	2.10	1.50%	0.52%	0.00%
	55-60	2.06	0.68%	0.37%	0.00%
	60-65	2.20	0.97%	0.41%	0.00%
Lead Vehicle Cut-in and Decelerating	45-50				
	50-55	1.09	6.59%	2.50%	0.00%
	55-60	0.85	11.79%	3.76%	0.00%
	60-65	0.79	14.73%	4.90%	0.00%

4 Conclusions and Discussion

This study successfully quantified and defined baseline heavy truck driver behavior during steady-state following scenarios and cut-in events. It also quantified the behavior of the lead truck and the host truck in various following scenario ending types, including when the lead vehicle was decelerating or accelerating, and when the host truck made a lane change. These results provide useful information in FHWA's development of automated truck platooning applications.

The study also estimated the safety impact of trucks following at different gaps (headways) based on a range of human reaction times and compared them to an automated reaction time, to understand the impact that automated platooning would have on driver safety.

This section presents key findings followed by a more extensive discussion for each research question.

4.1 Following Behavior by Lead Vehicle Type

Key findings for research question number one are as follows:

- Safety Pilot trucks followed other trucks at longer distances and headways than they followed light vehicles.
- IVBSS trucks followed other trucks at longer distances and headways than they followed light vehicles at speeds under 60 mph, but at shorter distances and headways at speeds over 60 mph.
- IVBSS trucks followed other cars and trucks at significantly shorter distances and headways than fixed trucks.
- Overall, professional truck drivers followed other vehicles at significantly shorter headways than recommended in State Commercial Driver's License (CDL) handbooks.

The finding that Safety Pilot trucks followed light vehicles more closely than other heavy trucks is intuitive because drivers have a better line of sight over light vehicles than over other trucks. If the driver can see the traffic queue in front of the vehicle they are following, they may feel comfortable following at a closer distance.

While IVBSS trucks showed the same trend as Safety Pilot trucks in the lower speed bins (following light vehicles more closely than trucks) they showed the opposite trend at speeds above 60 mph. This is likely due to traffic patterns; speeds greater than 60 mph on freeways represent free-flow traffic and heavy truck drivers may feel more comfortable following other trucks closely when traffic flow is more predictable. Additionally, professional truck drivers tend to trust other professional drivers more than light vehicle drivers, so it is very likely that trucks leave themselves more space when following a light vehicle at high speeds than they would a heavy truck, in case the light vehicle driver behaves erratically.

The finding that the IVBSS pick-up and delivery trucks had highly significant, shorter following distances and headways than the Safety Pilot trucks is surprising. One possible reason for this difference could be due to the type of payload the truck is carrying (the contents of the truck). If a truck is carrying very heavy or fragile cargo, the driver will drive more conservatively (leaving more headway) than they would otherwise. The Safety Pilot trucks carried food and beverage products, while the IVBSS trucks carried packaged freight (dry goods), which could have led to the measureable difference in driving behavior. Additionally, the two types of trucks were owned and operated by different truck fleets, which could have different driver training procedures or company policies.

It is worth noting that the drivers of both truck fleets maintained much shorter following headways than the headways recommended by the CDL handbooks (Figure 41). Volpe conducted research on the recommended following distances for heavy trucks based on CDL drivers' license manuals in Michigan [10] (the state in which both datasets used in this study were collected) and nine other states.[11] All of the states researched provided the recommendations shown in Figure 41, which are based on vehicle length and speed. Overall, Safety Pilot trucks followed other vehicles at an average headway of around 2.0 s and IVBSS trucks followed other vehicles at an average headway of around 1.8 s. According to the CDL guidelines, at highway speeds these trucks should allow between 5.0 s and 7.0 s headway to the lead vehicle.

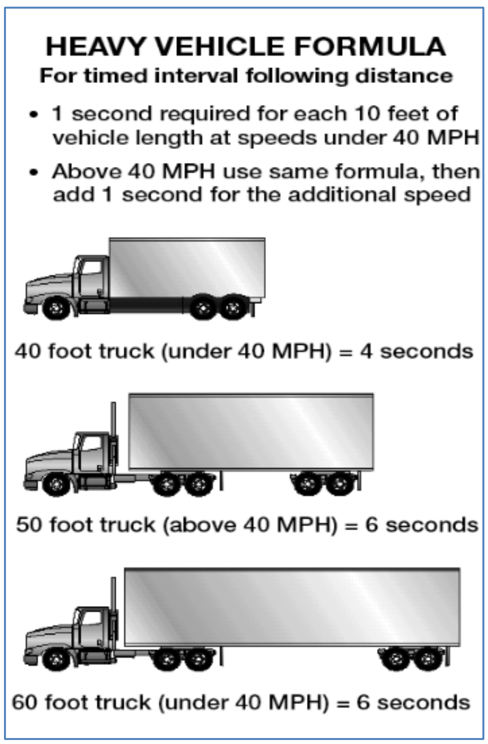

Figure 41. Recommended Following Behavior in State DOT CDL Handbooks

[11] Florida [12], Texas [13], California [14], Virginia [15], Colorado [16], Arizona [17], Wisconsin [18], New York [19], Massachusetts [20].

4.2 Following Behavior by Environmental Factors

Key findings for research question number two are as follows:

- Safety Pilot trucks followed lead vehicles at longer distances and headways on interstates compared to state freeways.
- Safety Pilot trucks followed lead vehicles at shorter distances and headways in clear weather compared to in rain or snow.
- Trucks from both fleets followed lead vehicles at shorter distances and headways during the day compared to at night.

For the most part, the results of following behavior by environmental factors are intuitive. Trucks follow at longer distances and headways in situations when visibility is worse and when more distance is required to stop safely (in rain and snow and at night). The observed result of trucks following at greater distances and headways at night is also probably related to traffic patterns; drivers might leave more space when there is less traffic density. [11]

Unexpectedly, Safety Pilot and IVBSS fleets showed opposite results of following headway by road type; Safety Pilot trucks followed at shorter headways on state freeways (compared to interstates) while IVBSS trucks followed at longer headways on state freeways. State freeways generally have fewer lanes—and therefore less predictable traffic flow than interstate freeways—which may have caused IVBSS drivers to leave themselves extra space.

4.3 Following Conditions for Consideration in Automated Platooning Technologies

The objective of research question number three was to quantify the driving dynamics of following event types that would be relevant when creating automated truck platooning applications. These dynamics include lead vehicle decelerating events, lead vehicle accelerating events, and events where the host vehicle changed lanes. The analysis conducted for research question number three focused on producing distributions and data profiles that would be useful to FHWA in creating truck platooning applications. Therefore, the key findings from this analysis really lie in the results themselves.

Key findings for research question number three are as follows:

- In scenarios where the lead vehicle decelerated, light vehicles decelerated at an average rate of 1.14 m/s^2, and heavy trucks decelerated at a rate of 1.04 m/s^2.
- In scenarios where the lead vehicle accelerated away from the host truck, light vehicles accelerated at an average rate of 1.0 m/s^2, and heavy trucks accelerated at an average rate of 0.9 m/s^2.
- Host truck drivers changed lanes within 25 m (82 ft) of a lead vehicle in only 12 percent of lane change scenarios.

4.4 Lead Vehicle Cut-in Events

Key findings for research question number four are as follows:

- No cut-in events were observed when the host truck was following within 30 m (98 ft) or 1.5 s headway of another truck. Generally, vehicles will not cut in between two trucks that are following at less than 40 m (131 ft) distance.
- Very few cut-in events were observed when the host truck was following within 30 m, or 1.5 s headway of a light vehicle. Generally, vehicles will not cut in between a truck and a light vehicle if they are within 35 m (115 ft) of each other.
- Light vehicles cut in between two trucks following at shorter distances and headways than when trucks were following a light vehicle. In other words, light vehicles cut in between trucks more aggressively than they cut in between a truck and a car.

As a general rule, very few vehicles will cut in between a heavy truck and a lead vehicle that is following if the vehicles are within 35 m (115 ft) of each other or within 1.5 s headway. Designing a truck platooning application following these guidelines would nearly eliminate cut-in events. A platooning application that reduced following distance to 30 m (98 ft) or headway to 1.0 s would eliminate cut-in events if the truck was following a heavy truck, and would result in only very rare cut-ins if the truck were following a light vehicle.

The finding that light-vehicles cut in between two trucks following at closer distance than they would a truck following a car is unexpected. This could be due to the fact that drivers of heavy trucks generally drive more predictably than the drivers of light vehicles (drivers execute fewer erratic maneuvers), so light vehicle drivers may feel more comfortable with less headway to the lead vehicle when the lead vehicle is a heavy truck.

4.5 Safety Impact of Trucks Following at Different Headways

Key findings for research question number five are as follows:

- For slow and medium drive response times (1.88 s and 1.21 s respectively), crash risk increased slightly at 1.0 s headway, and increased considerably at headways of less than 1.0 s.
- For all reaction times and headways considered, lower speed (45-50 mph events) posed the greatest crash risk.[12]
- In the fast reaction time condition (0.30 s, which was used to model automatic braking) crash risk was extremely low, even at very short headways. There was no crash risk observed in any speed bin at headways over 0.5 s.

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[12] This is due to initial range calculations. Initial range calculations between vehicles in these rear-end conflicts was calculated using host vehicle travel speed and headway timing. Shorter headway timing slower speeds resulted in lower initial ranges. These lower initial ranges translated to higher crash probabilities when keep braking levels constant across speed bins.

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Appendix A: Literature Review

Survey of Truck Following Literature and Naturalistic Driving Data Sources

Project Memorandum

February 25, 2015

Prepared for:
Federal Highway Administration
Turner-Fairbank Highway Research Center
Washington, DC

List of Abbreviations

Abbreviation	Term
ESV	Enhanced Safety of Vehicles
FHWA	Federal Highway Administration
FOT	Field Operational Test
IEEE	Institute of Electrical and Electronics Engineers
IVBSS	Integrated Vehicle-Based Safety System
TRID	Transport Research International Documentation
UMTRI	University of Michigan Transportation Research Institute

Introduction

This document presents a review of relevant literature and available naturalistic data sources for the naturalistic study of truck following behavior. The Federal Highway Administration's (FHWA) Turner Fairbank Highway Research Center has tasked the Volpe National Transportation System Center (Volpe) to conduct a study on truck following behavior. The purpose of this project is to better understand truck following behavior in naturalistic driving environments, with the ultimate goal of supporting the development of automated truck platooning applications.

The project will address the following research questions:

- How closely (time and distance) do trucks follow other trucks and light vehicles (i.e., passenger cars) on freeways?
- How does this following behavior vary by driver, type of truck, speed, highway type, road geometry, road condition, weather, visibility (day/night), etc.?
- Are there particular following safety events or conditions that should be considered in the development of automation technologies?
- At what following distances do vehicle cut-ins between the truck and lead vehicle occur?
- What is the safety impact of truck following at different gaps?

Objective

This purpose of this literature and data review is to 1) determine if any of the above research questions have already been answered in the literature, and 2) identify available data sources that are suitable for addressing the remaining research questions. This literature and data review will be used to identify gaps in the research and currently available resources, and will be used to shape the research and analysis plan for the naturalistic study of truck following behavior.

Methodology

The focus of the literature review was national and international studies that collected naturalistic driving data from heavy trucks on public roadways, from traffic observations, or from in-vehicle data collection equipment. To locate relevant literature, Volpe used the following resources and libraries:

Transport Research International Documentation (TRID)
ACM Digital Library
EBSCOhost Applied Science & Technology Source
EBSCOhost MEDLINE Complete
Google Scholar
Elsevier Science Direct
IEEE Conference Proceedings Series
IEEE Journals
Metapress
ProQuest Environmental Science Collection New Platform

SAGE Premier 2009
SpringerLINK
Taylor and Francis Engineering, Computing, and Technology Online Archive

Researchers used the following keyword combinations to identify relevant studies:

Naturalistic, truck, behavior
Longitudinal driving behavior
Truck driving behavior
Naturalistic driving
Naturalistic longitudinal
Naturalistic
Traffic platooning with keywords containing truck
Traffic platooning with keywords containing trucks
Traffic platoon
Platooning
Heavy truck

These keyword searches returned approximately 50 abstracts of relevant articles for review. The Volpe team also acquired approximately 15 additional resources cited in the relevant articles and subsequent web searches, for a total of approximately 65 resources. Only references that contained objective measures of longitudinal truck following behavior were summarized in this document.

Volpe reviewed the in-house naturalistic driving data sources by first summarizing relevant variables, and then identifying the number of highway driving miles collected in each data set for each source.

Literature Review

Table 12 through Table 26 summarize the findings from Volpe's literature review of relevant national and international studies on the driving behavior of heavy trucks as they follow other vehicles on freeways under a multitude of driving conditions. The focus was studies that collected naturalistic driving data on public roadways from traffic observations and from controlled or uncontrolled field operational experiments.

The first subsection describes research from the IVBSS project; a naturalistic driving study that tested the safety impact, driver acceptance, and capability of an integrated safety system. The following subsection describes other national and international studies.

Two measures of truck following behavior were used in the articles summarized in this section. These metrics are listed and defined in Table 11.

Table 11. Truck Following Metrics Used in Summarized Articles

Metric	Definition
Headway	The number of seconds required for the front bumper of the following vehicle to reach the location of the rear bumper of the lead-vehicle
Gap	The number of seconds required for the front bumper of the following vehicle to reach the location of the front bumper of the lead-vehicle

IVBSS Research

University of Michigan Transportation Research Institute (UMTRI) IVBSS Key Findings Report

Table 12. Summary of UMTRI IVBSS Key Findings

Summary	Data Source	Metrics	Results
"Integrated Vehicle-Based Safety System Heavy-Truck Field Operational Test Key Findings Report," James R. Sayer, et al., University of Michigan Transportation Research Institute, Ann Arbor, DOT HS 811362, December, 2010.			
The Integrated Vehicle-Based Safety System (IVBSS) study was a naturalistic driving study that exposed 18 heavy truck drivers to an integrated vehicle-based warning system. Drivers drove for 2 months with the safety system disabled, and then for 8 months with the system enabled. UMTRI conducted the field test for the study. This report is the key findings report.	IVBSS data set	Headway Constraints used in event filter: • Range rate to lead vehicle: ± 2 m/s • Truck speed ≥ 25 mph • Event lasts 5 seconds or longer • Headway between 0 and 3 seconds	Longer headways observed when driving with IVBSS: • System disabled: 2.04 seconds • System enabled: 2.11 seconds

UMTRI IVBSS Methodology and Results Report

Table 13. Summary of UMTRI IVBSS Methodology and Results

Summary	Data Source	Metrics	Results
"Integrated Vehicle-Based Safety System Heavy-Truck Field Operational Test Methodology and Results Report," James R. Sayer, et al., University of Michigan Transportation Research Institute, Ann Arbor, UMTRI-2010-27, August, 2010.			
The IVBSS study was a naturalistic driving study that exposed 18 heavy truck drivers to an integrated vehicle-based warning system. Drivers drove for 2 months with the safety system disabled, and then for 8 months with the system enabled. UMTRI conducted the field test for the study. This report is the detailed methodology and results report.	IVBSS data set	• Headway Independent variables: • Safety system enabled • Windshield wiper use • Route type (short vs. long distance routes) • Trailer type • Road type • Traffic • Hours of service • Truck load Constraints used in event filter: • Range rate to lead vehicle: $\pm$ 2 m/s • Truck speed $\geq$ 25 mph • Event lasts 5 seconds or longer • Headway between 0 and 3 seconds	Longer headways observed when driving: • With IVBSS enabled • On surface streets compared to highways • At night compared to during the day • In dense and sparse traffic conditions compared to moderate traffic • With a heavier load compared to a lighter load • With wipers on compared to without wipers on

UMTRI Human Factors Journal Paper on Truck Following Behavior

Table 14. Summary of UMTRI Truck Following Behavior Field Evaluation

Summary	Data Source	Metrics	Results	Comment
"Heavy Truck Drivers' Following Behavior With Intervention of an Integrated, In-Vehicle Crash Warning System: A Field Evaluation," Shan Bao, David LeBlanc, James R. Sayer, and Carol Flanagan, University of Michigan Transportation Research Institute, Ann Arbor, Human Factors, Vol 54, (5), October 2012, pp 687-697.				
The IVBSS study was a naturalistic driving study that exposed 18 heavy truck drivers to an integrated vehicle-based warning system. Drivers drove for 2 months with the safety system disabled, and then for 8 months with the system enabled. This is a paper published in *Human Factors* that looked at the impact that driving with IVBSS had on headway maintenance and reaction time to forward driving conflicts. The 10-month study looked at local pick-up and delivery (daytime) and long-haul (nighttime) routes. There was 601,844K valid driving mileage and 13,678 driving hours.	IVBSS data set	Mean time headway Minimum time headway <u>Independent variables</u>: • Safety System Enabled • Driver shift (day/night) • Roadway type • Traffic density • Wiper state • Trailer configuration <u>Constraints used in event filter</u>: • Range rate to lead vehicle: ± 2 m/s • Truck speed ≥ 25 mph • Event lasts 5 seconds or longer	Mean time headway: • Daytime: 3.10 s, nighttime: 2.71s • Wipers on: 2.93 s, wipers off: 2.79 s • Surface streets: 3.43 s, freeways: 2.35 s • Dense traffic: 2.61 s, moderate traffic: 2.84 s, sparse traffic: 2.94 s • IVBSS disabled: 2.78 s, IVBSS enabled: 2.89 s Table 15 shows mean time headway interaction effects. Minimum time headway: • Wipers on: 1.12 s, wipers off: 0.82 s • Surface streets: 1.27 s, freeways: 0.71 s Dense traffic: 1.26 s, moderate traffic: 0.92 s, sparse traffic: 0.89 s. Minimum time headway interaction effects are in Table 17.	The article has detailed background statistics (and sources) on driver-related factors and environmental factors. The article states that in-vehicle, forward-crash avoidance warning system would help alert heavy truck drivers to upcoming events – but there are few studies on this.

Table 15. UMTRI Truck Following Behavior Metric Results – Mean Time Headway

Variable	System Enabled	System Disabled
Mean Time Headway		
	2.89 s	2.78 s
System Enabled x Traffic Density		
	Longer when drivers warned	
	0.28s increase in dense traffic (11% increase)	
System Enabled x Wiper State		
	0.20-s increase with wipers on (7% increase)	
Shift Type vs. Traffic Density		
	Dense traffic conditions (mean difference 0.3) s vs. sparse traffic (mean difference 0.16)	

Table 16. UMTRI Truck Following Behavior Metric Results – Minimum Time Headways for Pooled Following Events

Variable	System Enabled	System Disabled
Minimum Time Headways for Pooled Following Events		
Minimum Time Headway		
	0.98 s	0.96 s
Minimum Time Headway 1.0 s or less		
	15.9%	16.3%
Mean Time Headway 1.0 s or less		
	2.9%	3.2%

Table 17. UMTRI Truck Following Behavior - Aggregate Minimum Time Headways in Traffic Density x Wiper State x Roadway Type (in Seconds)

Traffic Density	Wipers Off		Wipers On	
	Freeway	Surface	Freeway	Surface
Note: there was no statistically significant difference between system disabled and system enabled				
Sparse	0.55	0.91	0.78	1.49
Moderate	0.54	1.11	0.72	1.62
Dense	**0.93**	**1.35**	**1.35**	**2.7**

UMTRI ESV Paper on IVBSS Key Findings

Table 18. Summary of UMTRI ESV Key Findings

Summary	Data Source	Metrics	Results	Comment
"Driver Acceptance and Behavioral Changes with an Integrated Warning System: Key Findings from the IVBSS FOT," David J. Leblanc, et al., Technical Conference on the Enhanced Safety of Vehicles (ESV) Washington, DC, June 13-16, 2011				
The IVBSS study was a naturalistic driving study that exposed 18 heavy truck drivers to an integrated vehicle-based warning system. Drivers drove for 2 months with the safety system disabled, and then for 8 months with the system enabled. This paper was written for the 2011 ESV conference, and is a summary of key findings from IVBSS.	IVBSS data set	Headway Constraints used in filter not stated, but references Human Factors article (previous subsection) which states: • Range rate to lead vehicle: $\pm$ 2 m/s • Truck speed $\geq$ 25 mph • Event lasts 5 seconds or longer	Longer headways observed when driving with IVBSS: • System disabled: 2.84 seconds • System enabled: 2.97 seconds	These results directly reference the Human Factors IVBSS article, but values stated are different. Volpe's research cannot explain the discrepancy between these results.

Volpe IVBSS Heavy-Truck Field Operational Test Evaluation

Table 19. Summary of Volpe IVBSS Heavy Truck Field Operational Test

Summary	Data Source	Metrics	Results
"Integrate Vehicle-Based Safety System Heavy-Truck Field Operational Test Independent Evaluation Report," Emily Nodine, et al., Volpe, The National Transportation Systems Center, DOT HS 811 464, Washington, DC, August 2010.			
The IVBSS study was a naturalistic driving study that exposed 18 heavy truck drivers to an integrated vehicle-based warning system. Drivers drove for 2 months with the safety system disabled, and then for 8 months with the system enabled. This report describes the methodology and results of the Independent Evaluation of IVBSS conducted by Volpe. This independent evaluation addressed safety impact, system performance, and driver acceptance of IVBSS.	IVBSS data set	Time headway Independent variables: • IVBSS enabled • Route type Constraints used in event filter: • Both vehicles traveling at constant speed • Truck speed between 35 and 55 mph OR over 55 mph	See Table 20. No results are statistically significant.

Table 20. Volpe IVBSS Heavy Truck Field Operational Test – Mean Time Headway in Seconds by Speed Bin and Route Type

Route Type	Speed (mph)	System Disabled	System Enabled	System Enabled – Last 2 Months
Pick-up and delivery	35-55	3.16	3.27	3.23
	55+	2.26	2.30	2.20
Line-haul	35-55	2.52	2.56	2.53
	55+	2.30	2.32	2.32
All	35-55	2.81	2.88	2.84
	55+	2.28	2.31	2.27

Other Research

Light and Commercial Vehicle Behavior Study of Conversing on Cell Phone Using Naturalistic Data

Table 21. Summary of naturalistic Driver Data When Conversing on a Cell Phone

Summary	Data Source	Metrics	Results	Comments
"Investigating Light Vehicle and Commercial Motor Vehicle Driver Compensatory Behavior when Conversing on a Cell Phone Using Naturalistic Driving Data," Gregory M. Fitch et al., Transportation Research Record: *Journal of the Transportation Research Board*, No. 2434, Transportation Research Board of the National Academies, Washington, DC, 2014, pp 1-8.				
Study to determine whether the drivers recorded in light-vehicle and commercial motor vehicle (CMV) naturalistic driving studies (NDSs) compensated for the increased workload when conversing on a cell phone by changing their driving performance.	Naturalistic. CMV data sets 5/2004 – 5/2005 and 11/2005 – 5/2007	Speed Headway Inclination to travel in right-most lane Inclination to change lanes Unintentional lane departures	Drivers significantly increased their speed when conversing on a hand-held or hands-free cell phone by 4 km/h (2.5 mph) but traveled at the same headway (Table 22).	This 2013 study covers heavy trucks and light vehicles. Metrics and Results are for heavy trucks only. This study is included in Literature Review because even though there is not much information on truck following behavior, the study states that some experimental studies conducted in a driving simulator have found that drivers decrease their travel speed and increase their following distance, and become less likely to change lanes when talking on a cell phone. See Table 22 for metrics.

Table 22. Mean Speed and headway When Conversing on a Cell Phone

Drivers	Cell Phone Type	Baseline Mean (SE)	Subtask Mean (SE)	n	df1	df2	F Statistic	*p* value
Mean Speed When Conversing on a Cell Phone (km/h*)								
CMV	Hand-held	**90.6 (.87)**	**94.3 (.61)**	**549**	1	**106**	**10.11**	**.0019**
	Hands-free	**88.2 (.93)**	**93.5 (.93)**	**437**	1	**63**	**8.65**	**.0046**
Mean Headway When Conversing on a Cell Phone (seconds)								
CMV	Hand-held	2.9 (0.2)	2.6 (0.1)	115	1	54	1.46	.2321
	Hands-free	2.8 (0.2)	2.5 (0.2)	86	1	30	0.11	.7387

*1 km/h = .62 mph)

In-depth Analysis on Vehicle Following Gaps in Highway Work Zones

Table 23. Summary of Leading Vehicle Following Gaps in Highway Work Zones

Summary	Data Source	Metrics	Results	Comments
"An In-depth Analysis on Vehicle Following Gaps in Highway Work Zones: The Direct and Interdependent Impact of Leading Vehicle," Dazhi Sun, Rahim F. Benekohal, and William Arya, Transportation Research Board Annual Meeting 2007, Washington, DC, 2007, Paper #07-1990.				
Study analyzing the impacts of heavy truck and car following patterns on the vehicle following distance (gap) in short-term (few days) and long-term (more than a few days) highway work zones on interstate highways. Average speed for platooning vehicles is 39.8 mph in short-term work zones and 50.78 mph in long-term work zones. Part one studies the direct impact of the leading vehicle on the following vehicle platoons (car-car, car-truck, truck-car, truck-truck). Part two studies the interdependent impact of the leading vehicle on the gap between different vehicle following patterns for 2 and 3 vehicle platoons. Part three identifies how the types of work zones influence the vehicle following gap.	Naturalistic observation from infrastructure	Average gap* Number of observations Standard deviation Standard error Co-efficient of metrics	• Truck drivers maintain a significantly longer gap than car drivers when led by the same type of vehicle in both short-term and long-term work zones. • In either long-term or short-term work zones, if the middle vehicle is a truck in 3-vehicle platoons, there is no significant impact of the leading vehicle type on the vehicle following gap between the second and third vehicles. • The work zone type appears to have no influence over the vehicle following gap between the second and third vehicles, when the third vehicle is a truck. • Further study may include the impact of the leading vehicle on car-following gap between the third and fourth vehicles for a longer platoon.	Authors state it is well known that car-following patterns have an impact on the vehicle following distance (gap) to some extent. There is Inadequate information and very limited research on the impact of different vehicle following patterns on vehicle following distances. * In this study, authors define gap as the distance measured between the rear bumper of a leading vehicle and the front bumper of its following vehicle and headway as the distance measured between the front bumper of a leading vehicle and the front bumper of its following vehicle. Gap is analyzed rather than headway because gap characteristics provide a better measure of car-following behaviors. See Table 24 and Table 15 for metrics.

Table 24. Vehicle Patterns in Long and Short Term Work Zones

Vehicle Pattern (Leading - Following)	Car-Truck	Truck-Truck
Long Term Work Zone		
Avg. Gap (s)	2.02	1.62
Number of Observations	579	202
Standard Deviation	0.7312	0.5318
Standard Error	0.0304	0.0374
Co-efficient of Variation	36.2%	32.8%
Short Term Work Zone		
Avg. Gap (s)	2.18	1.79
Number of Observations	103	52
Standard Deviation	0.7691	0.6671
Standard Error	0.076	0.093
Co-efficient of Variation	35.28%	37.27%

Table 25. Vehicle Patterns in Following/Middle/Leading Long and Short Term Work Zones

Vehicle Pattern (Following/Middle/Leading)	Truck-Truck-Car	Truck-Truck-Truck	Truck- Car-Car	Truck- Car-Truck
Long Term Work Zone				
Avg. Gap (s)	1.57	1.65	2.08	1.91
Short Term Work Zone				
Avg. Gap (s)	1.63	1.58	2.23	1.63

Drowsy Driver Warning System Field Operational Test

Table 26. Summary of Naturalistic Study of Heavy and Light Truck Driver Behavior

Summary	Data Source	Metrics	Results	Comments
"Data Processing and Driver Performance Analysis Using Field Data from a Drowsy Driver Warning System," Bruce Wilson and Paul Rau, Volpe, The National Transportation Systems Center, 2004				
The Drowsy Driver Warning System (DDWS) project was a naturalistic field test that deployed a DDWS on heavy trucks. During the field test, 75 commercial truck drivers drove the DDWS-equipped trucks for 16 weeks (4 weeks with the system disabled, and 12 weeks with the system enabled), while 25 control group drivers drove unequipped trucks for 16 weeks. This document presents the data processing and analysis plans for the field test, and presents preliminary baseline results based on 15 early FOT drivers.	Naturalistic.	Median time headway Constraints used in filter not stated	• Median time headway, 2.94s • Large differences between drivers (1.7 s to 3.45 s)	This is a Volpe document that was never published. Final analysis was never completed due to data quality issues.

Naturalistic Data Sources

Naturalistic driving data is data that is collected from vehicles driving in an uncontrolled manner in their natural driving environment. In these studies, drivers are instructed to drive and behave as they normally would in their everyday driving activities, and data is collected to observe vehicle dynamics and driver behavior. Volpe currently has two heavy truck naturalistic driving data sets from prior studies in-house. These data sets are described in the following subsections.

While doing research for this project memorandum, two additional naturalistic heavy truck data sets were identified; the Drowsy Driver Warning System Field Operational Test and a naturalistic truck study conducted by VTTI. These data sets are not currently available to Volpe or FHWA and were therefore not included in the summary of data sources.

Integrated Vehicle Based Safety System Data Set

The IVBSS project was a naturalistic driving study that tested the safety impact, driver acceptance, and capability of an integrated safety system. Eighteen professional heavy truck drivers drove 10 instrumented heavy trucks for a period of 10 months (8 months with the safety system turned on, and 2 months with the system disabled). Eight of the drivers drove pick-up and delivery routes, and 10 drove line-haul routes.

Table 27 shows the driving mileage for each driver in the IVBSS naturalistic driving study. The category "Highway Following Miles" represents the number of miles where the truck was traveling on the highway and the forward radar was tracking a lead vehicle. Overall, the IVBSS dataset contains 61,246 miles of following data on highways.

Table 27. IVBSS Driving Mileage

Driver	Total Vehicle Miles	Highway Miles	Highway Following Miles
1	9,263	3,204	1,305
2	9,621	94	31
4	10,047	1,023	428
5	10,981	2,503	968
6	4,392	109	35
7	11,230	1,686	742
8	6,669	162	57
10	9,440	1,679	542
21	22,522	20,523	2,736
22	68,964	64,165	5,841
23	57,017	51,730	7,001
24	52,126	45,801	8,897

Driver	Total Vehicle Miles	Highway Miles	Highway Following Miles
25	20,443	16,216	3,023
26	72,473	63,284	12,751
27	57,475	52,435	6,558
28	28,100	24,800	4,440
29	25,809	14,289	3,136
30	20,813	15,435	2,753
TOTAL	**497,385**	**379,139**	**61,246**

The IVBSS data set contains the following data channels that may be relevant to truck platooning research. All data channels are available at a rate of 10 Hz for all driving miles.

- Accelerator pedal
- Longitudinal acceleration
- Lateral acceleration
- Brake
- Range to forward target
- Range rate to forward target
- Speed
- Yaw rate
- Time to collision to forward target
- Headway
- Cruise control
- Turn signal
- Forward target driving state (closing, separating, constant)

Safety Pilot Data Set

The Safety Pilot Model Deployment was a naturalistic field test to collect imperial data on the performance of connected vehicles in a naturalistic environment. It included approximately 2,800 cars, trucks, buses, and motorcycles equipped with Designated Short Range Communication devices and ran for a period of one year. Eleven of these vehicles were heavy trucks equipped with data acquisition systems to collected detailed naturalistic driving data. These vehicles were driven by professional truck drivers, primarily on pick-up and delivery routes.

Table 28 shows the driving mileage for the 11 heavy trucks in the Safety Pilot Model Deployment. The dataset contains a total of 27,180 miles of highway driving where the truck is following a lead vehicle.

Table 28. Safety Pilot Heavy Truck Driving Mileage

Device #	Total Vehicle Miles	Highway Miles	Highway Following Miles
13101	29,522	1,717	516
13103	34,711	2,310	644
13105	34,857	2,640	739
13106	35,650	3,203	1,085
13107	27,952	1,162	420
13108	31,205	1,522	452
13109	22,182	1,342	380
13110	43,168	4,398	1,090
15101	41,606	29,912	5,043
15501	36,900	22,768	7,048
15901	39,738	24,929	9,764
TOTAL	**377,491**	**95,902**	**27,180**

The Safety Pilot data set contains the following data channels that may be relevant to truck platooning research. All data channels are available at a rate of 10 Hz. .

- Accelerator pedal
- Longitudinal acceleration
- Lateral acceleration
- Brake
- Range to forward target
- Range rate to forward target
- Speed
- Yaw rate
- Time to collision to forward target
- Headway
- Cruise control
- Turn signal
- Forward target type (car, truck, pedestrian, etc.)

While the Safety Pilot data set is smaller than the IVBSS data set in terms of the number of highway driving miles, it is unique in that it uses a vision-based forward ranging sensor (made by MobilEye), instead of forward radar, to track the forward target. The MobilEye ranging sensor identifies the vehicle type of the forward target. This information is very valuable to the present study, which will identify the differences in following behavior based on lead vehicle type.

Findings and Next Steps

Overall, this literature review revealed that very few studies have been conducted on naturalistic truck following behavior. Naturalistic driving studies are expensive and time consuming to conduct and, as a result, very few resources are available for this kind of research.

A number of studies summarized in this document quantified heavy-truck following behavior using the IVBSS data set (one of the data sets that Volpe plans to use for the present study), and provided information about the impact of environmental factors (weather, traffic, etc.) on following behavior. However none of these studies looked at how following behavior varies by lead vehicle type, which is a key research question for this project.

Other studies provide some baseline measurements for headway in naturalistic environments and one study addressed following behavior based on the vehicle type of the lead vehicle.

The next step for this Naturalistic Study of Truck Following Behavior is to use the results of this literature and data review to develop a research and analysis plan. Volpe will map these findings to the research questions listed in the Introduction and detail a plan for how to address each research question and independent variable with the existing literature and available data sources. Volpe will also identify any research questions that cannot be addressed with the available resources, and any technical issues or challenges in characterizing truck following behavior

Appendix B: Detailed Results Tables

Table B- 1. Safety Pilot Following Event Descriptive Statistics by Independent Variable

				Following Distance (m)				Following Headway (s)			
Independent Variables		Count	%	Average	Min	Max	Standard Deviation	Average	Min	Max	Standard Deviation
Lead Vehicle Type	Heavy truck	8,280	48%	53.3	8.1	89.2	16.2	2.05	0.30	3.73	0.62
	Light vehicle	8,795	52%	50.8	6.4	85.0	16.4	1.99	0.28	3.75	0.63
Speed Bin	45-50	915	5%	45.3	6.4	77.4	16.6	2.13	0.29	3.75	0.78
	50-55	2,114	12%	46.9	6.5	78.5	16.4	1.99	0.28	3.49	0.69
	55-60	12,714	74%	52.9	7.4	86.3	16.1	2.01	0.28	3.30	0.61
	>60 mph	1,332	8%	55.5	8.8	89.2	15.8	2.07	0.33	3.33	0.59
Highway Type	Interstate	14,207	83%	52.3	6.4	89.2	16.2	2.03	0.28	3.73	0.62
	State	2,868	17%	50.3	8.8	81.2	16.9	1.95	0.34	3.75	0.65
Road Condition	Dry	14,369	84%	52.0	6.4	89.2	16.5	2.01	0.28	3.73	0.63
	Snow	62	0%	62.1	35.3	77.3	9.8	2.78	1.58	3.75	0.50
	Wet	2,644	15%	51.5	9.6	79.2	15.4	2.06	0.36	3.71	0.62
Weather	Clear	14,627	86%	52.0	6.4	89.2	16.5	2.01	0.28	3.73	0.62
	Rain	2,237	13%	51.3	9.6	79.2	15.5	2.05	0.36	3.71	0.62
	Snow	211	1%	57.1	14.1	77.4	15.5	2.47	0.53	3.75	0.71
Visibility	Day	12,515	73%	51.0	6.4	89.2	16.6	1.98	0.28	3.75	0.63
	Dusk	472	3%	57.5	9.6	86.3	14.4	2.24	0.42	3.61	0.57
	Night	4,088	24%	54.4	8.2	85.0	15.4	2.12	0.31	3.73	0.60

Table B- 2. IVBSS Following Event Descriptive Statistics by Independent Variable

Independent Variables		Count	%	Following Distance (m) Average	Following Distance (m) Min	Following Distance (m) Max	Following Distance (m) Standard Deviation	Following Headway (s) Average	Following Headway (s) Min	Following Headway (s) Max	Following Headway (s) Standard Deviation
Lead Vehicle Type	Heavy truck	1241	43	46.8	8.5	88.8	17.1	1.84	0.33	3.55	0.66
	Light vehicle	1638	57	45.1	5.5	88.9	17.4	1.83	0.24	3.68	0.69
Speed Bin	45-50	461	16	40.9	5.5	78.1	16.7	1.91	0.25	3.68	0.77
	50-55	780	27	43.7	5.5	87.3	16.7	1.84	0.24	3.57	0.70
	55-60	949	33	45.6	8.5	88.8	17.0	1.77	0.33	3.35	0.65
	>60 mph	689	24	51.8	15.5	88.9	16.9	1.89	0.56	3.21	0.61
Highway Type	Interstate	2221	77	45.7	5.5	88.9	17.4	1.80	0.25	3.61	0.66
	State	658	23	46.3	5.5	86.6	16.7	1.98	0.24	3.68	0.71
Road Condition	Dry	2463	86	45.7	5.5	88.6	17.2	1.83	0.24	3.68	0.68
	Wet	416	14	46.4	9.6	88.9	17.4	1.88	0.41	3.54	0.67
Weather	Clear	2488	86	45.7	5.5	88.6	17.2	1.83	0.24	3.68	0.68
	Rain	376	13	47.1	9.6	88.9	17.5	1.90	0.41	3.54	0.67
	Snow	15	1	41.4	21.3	79.3	19.1	1.71	0.96	3.21	0.70
Visibility	Day	1522	53	43.6	5.5	88.1	16.9	1.74	0.24	3.68	0.67
	Night	1261	44	48.4	5.5	88.9	17.2	1.95	0.25	3.61	0.67
	Dusk	96	3	47.5	9.3	82.1	18.6	1.91	0.39	3.49	0.74

Table B- 3. Descriptive Statistics of Lead Vehicle Decelerating Events by Lead Vehicle Type and Speed Bin

Lead Vehicle Type	Light Vehicle				Heavy Truck			
Speed Bin (mph)	45-50	50-55	55-60	>60	45-50	50-55	55-60	>60
Mean	-1.15392	-1.13835	-1.137786	-1.16247	-1.02897	-1.11021	-1.02306	-1.14047
Standard Deviation	0.73486	0.749546	0.7298992	0.781278	0.675148	0.771282	0.711299	0.746984
Range (m)	3.410821	3.586104	3.9401398	3.88282	3.173228	3.163181	3.861103	3.888901
Minimum	-3.51911	-3.6493	-3.951416	-3.9679	-3.27865	-3.19704	-3.89582	-3.90886
Maximum	-0.10829	-0.06319	-0.011276	-0.08508	-0.10542	-0.03386	-0.03472	-0.01995
Confidence Level (95.0%)	0.100211	0.066193	0.0301219	0.097124	0.123626	0.090734	0.031405	0.106054

Table B- 4. Descriptive Statistics of Lead Vehicle Accelerating Events by Lead Vehicle Type and Speed Bin

Lead Vehicle Type	LV				HT			
Speed Bin (mph)	45-50	50-55	55-60	>60	45-50	50-55	55-60	>60
Mean	0.95928	0.982313	1.0074366	1.058701	0.991303	1.000931	0.886916	0.890267
Standard Deviation	0.530085	0.531469	0.5300954	0.533869	0.521907	0.53634	0.512834	0.511903
Range (m)	2.710926	2.828995	2.9296913	2.83242	2.169422	2.686611	2.961792	2.611988
Minimum	0.01651	0.069431	0.0321159	0.072052	0.263737	0.111118	0.031242	0.154514
Maximum	2.727436	2.898426	2.9618073	2.904472	2.433159	2.797729	2.993034	2.766502
Confidence Level (95.0%)	0.070114	0.042791	0.020211	0.059374	0.089519	0.060135	0.019642	0.060112

Table B- 5. Cut-in Event Descriptive Statistics by Speed Bin

Speed Bin (mph)	Lead Vehicle Type	Cut-in Vehicle Type	Count	Distance to Lead Vehicle at Cut-in Time (m)				Cut-in Distance (m)			
				Average	Standard Deviation	Min	Max	Average	Standard Deviation	Min	Max
45 - 50	Heavy truck	Light vehicle	3	54.1	14.9	37.3	65.5	26.8	6.8	20.7	34.1
	Light vehicle	Light vehicle	34	53.3	16.0	14.8	75.3	25.1	10.5	8.4	59.8
50 - 55	Heavy truck	Light vehicle	7	51.9	13.6	26.0	65.0	24.1	12.2	8.5	48.6
	Light vehicle	Heavy truck	5	64.1	7.4	55.2	74.7	25.4	10.2	14.4	40.1
		Light vehicle	79	55.5	14.0	26.2	76.8	26.1	11.5	9.9	67.9
55 - 60	Heavy truck	Heavy truck	17	68.1	7.1	52.9	76.8	23.2	4.0	16.4	30.0
		Light vehicle	60	54.2	11.9	30.7	74.4	25.2	10.6	11.1	61.5
	Light vehicle	Heavy truck	20	63.6	10.4	37.4	77.0	22.0	8.3	10.2	42.8
		Light vehicle	722	58.7	12.7	19.9	77.0	27.4	10.7	8.6	64.1
>60	Heavy truck	Heavy truck	1	67.6		67.6	67.6	18.2		18.2	18.2
		Light vehicle	8	60.2	13.6	30.6	71.4	26.9	17.0	9.1	61.0
	Light vehicle	Heavy truck	1	52.8		52.8	52.8	23.9		23.9	23.9
		Light vehicle	89	57.8	13.2	22.8	76.9	27.0	9.7	10.5	51.1

Appendix C: Safety Impact Results Details

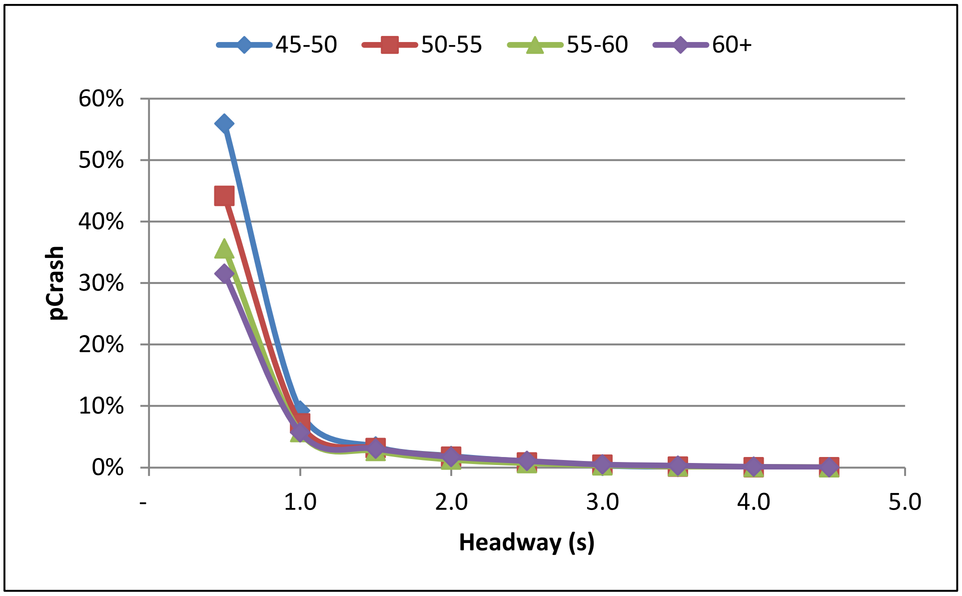

Figure C- 1 Probability of a Crash for LVD Events with a Lead Light Vehicle- Driver Reaction Time = 1.88s

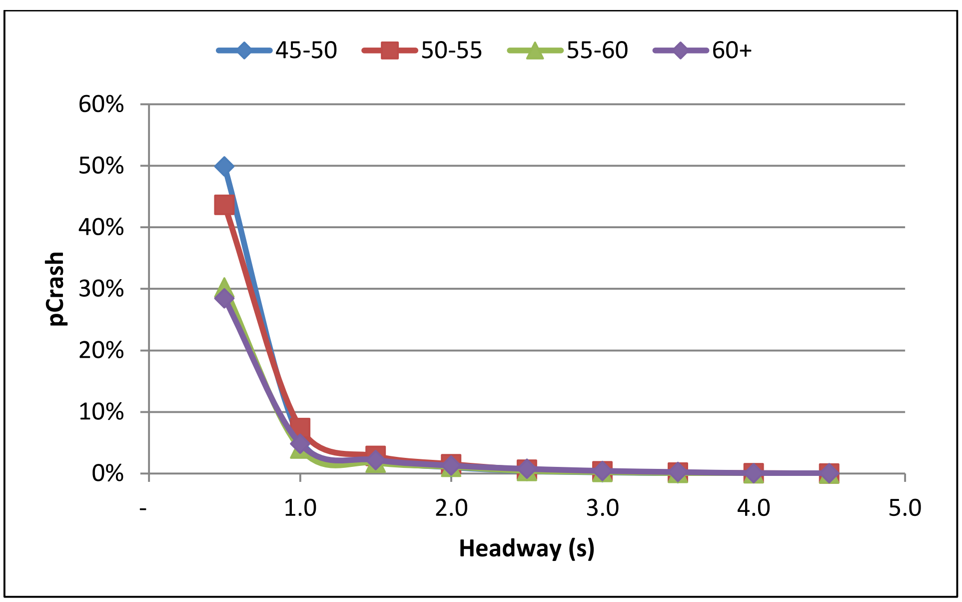

Figure C- 2. Probability of a Crash for LVD Events with a Lead Heavy Truck- Driver Reaction Time = 1.88s

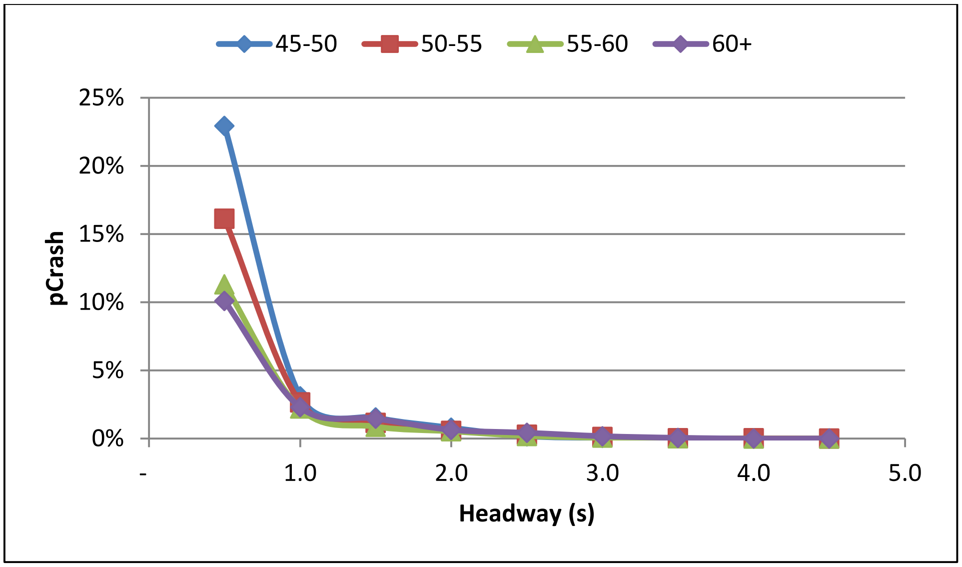

Figure C- 3 Probability of a Crash for LVD Events with a Lead Light Vehicle- Driver Reaction Time = 1.21s

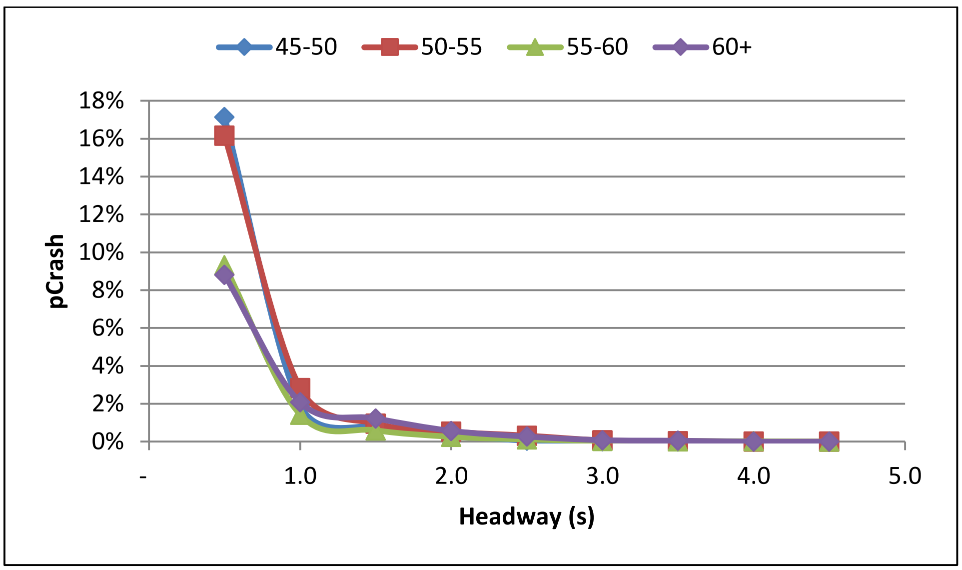

Figure C- 4. Probability of a Crash for LVD Events with a Lead Heavy Truck- Driver Reaction Time = 1.21s

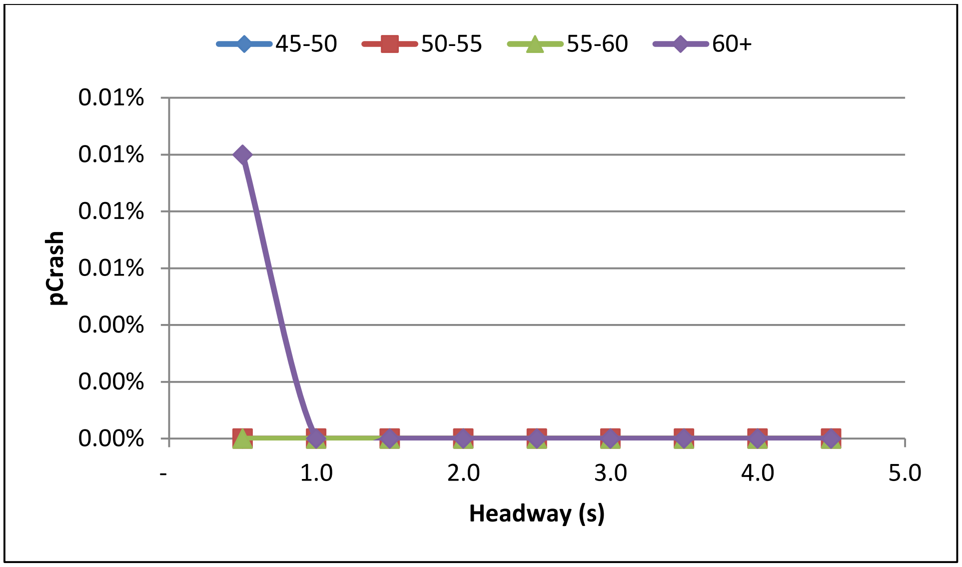

Figure C- 5. Probability of a Crash for LVD Events with a Lead Light Vehicle- Driver Reaction Time = 0.3 s

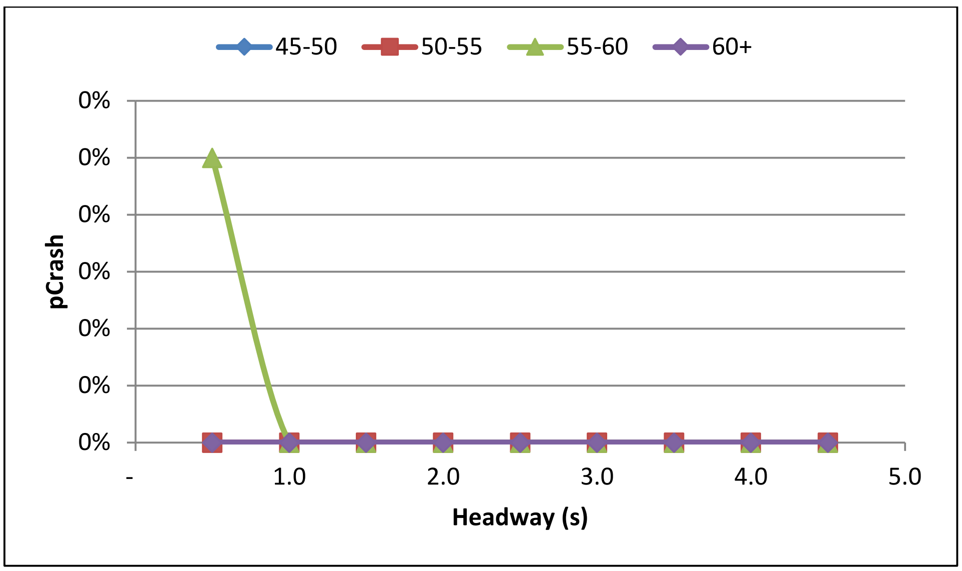

Figure C- 6. Probability of a Crash for LVD Events with a Lead Heavy Truck- Driver Reaction Time = 0.3 s

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