Crash Data Analyses for Vehicle-to-Infrastructure Communications for Safety Applications

PUBLICATION NO. FHWA-HRT-11-040

NOVEMBER 2012

U.S. Department of Transportation
Federal Highway Administration

Research, Development, and Technology
Turner-Fairbank Highway Research Center
6300 Georgetown Pike
McLean, VA 22101-2296

FOREWORD

This report documents the results of crash data analyses to assess the potential safety benefits of vehicle-to-infrastructure (V2I) communication applications to improve highway safety. It provides estimates of the frequency and cost of crashes involving pre-crash scenarios addressed by V2I applications. It also evaluates pre-crash scenarios not addressed by those applications. This report will be useful to Federal, State, and local government agencies, research organizations, and private sector firms that research, develop, and deploy V2I technologies and safety applications.

Monique R. Evans
Director, Office of Safety
Research and Development

TECHNICAL DOCUMENTATION PAGE

<table>
<tr><td>1. Report No.
FHWA-HRT-11-040</td><td>2. Government Accession No.</td><td colspan="2">3. Recipient's Catalog No.</td></tr>
<tr><td colspan="2" rowspan="2">4. Title and Subtitle
Crash Data Analyses for Vehicle-to-Infrastructure Communications for Safety Applications</td><td colspan="2">5. Report Date
November 2012</td></tr>
<tr><td colspan="2">6. Performing Organization Code</td></tr>
<tr><td colspan="2">7. Author(s)
Kimberly Eccles, Frank Gross, Mindy Liu, and Forrest Council</td><td colspan="2">8. Performing Organization Report No.</td></tr>
<tr><td colspan="2" rowspan="2">9. Performing Organization Name and Address
Vanasse Hangen Brustlin, Inc. (VHB)
333 Fayetteville Street, Suite 1450
Raleigh, NC 27601-2951

University of North Carolina Highway Safety Research Center
730 Martin Luther King, Jr. Boulevard
Chapel Hill, NC 27599-3430</td><td colspan="2">10. Work Unit No. (TRAIS)</td></tr>
<tr><td colspan="2">11. Contract or Grant No.
DTFH61-06-C-00013</td></tr>
<tr><td colspan="2" rowspan="2">12. Sponsoring Agency Name and Address
Office of Safety Research and Development
Federal Highway Administration
6300 Georgetown Pike
McLean, VA 22101-2296</td><td colspan="2">13. Type of Report and Period Covered
Final Report
September 2009–March 2011</td></tr>
<tr><td colspan="2">14. Sponsoring Agency Code
Federal Highway Administration</td></tr>
<tr><td colspan="4">15. Supplementary Notes
This study was conducted with funding from the Intelligent Transportation Systems Joint Program Office. The Contracting Officer's Technical Representative (COTR) was Carol Tan. The task managers were Gregory Davis and Raymond Krammes.</td></tr>
<tr><td colspan="4">16. Abstract
This report presents the potential safety benefits of wireless communication between the roadway infrastructure and vehicles, (i.e., vehicle-to-infrastructure (V2I) safety). Specifically, it identifies the magnitude, characteristics, and cost of crashes that would be targeted with currently proposed V2I for safety application areas including intersections, speed management, vulnerable road users, and other safety applications areas. It also identifies the magnitude, characteristics, and cost of the remaining crashes that are not targeted by currently proposed V2I safety applications. The results of this study indicate that the applications are well conceived and can potentially treat large portions of U.S. crashes and crash costs. The characteristics of unaddressed crashes provide a starting point for identifying either new applications or modifications to current applications.</td></tr>
<tr><td colspan="2">17. Key Words
General Estimates System, Pre-crash scenarios, Vehicle safety research, Crash avoidance research, Crash frequency, Economic cost, Intersections, Speed, Pedestrians</td><td colspan="2">18. Distribution Statement
No restrictions. This document is available to the public through the National Technical Information Service; Springfield, VA 22161</td></tr>
<tr><td>19. Security Classif.(of this report)
Unclassified</td><td>20. Security Classif.(of this page)
Unclassified</td><td>21. No. of Pages
84</td><td>22. Price</td></tr>
</table>

Form DOT F 1700.7 (8-72) Reproduction of completed pages authorized

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

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

TABLE OF CONTENTS

CHAPTER 1. EXECUTIVE SUMMARY ... **1**

CHAPTER 2. INTRODUCTION ... **5**
2.1 BACKGROUND ... **5**
2.2 SCOPE ... **5**
2.3 METHODOLOGY ... **6**
2.3.1 NASS GES Data Analysis ... 6
2.3.2 HSIS ... 13
2.4 PREVIOUS CRASH TYPOLOGY EFFORTS RELATED TO V2I FOR SAFETY ... **14**
2.4.1 Pre-Crash Scenario Typology for Crash Avoidance Research ... 14
2.4.2 Heavy Vehicle Pre-Crash Scenario Typology for Crash Avoidance Research ... 15
2.4.3 Frequency of Target Crashes for IntelliDrive Safety Systems ... 17
2.4.4 Cooperative Intersection Collision Avoidance Systems Research on Comprehensive Costs of Intersection Crashes ... 18
2.4.5 Infrastructure-Based Intersection Collision Avoidance Concept Study ... 19
2.4.6 CICAS: Distribution of Crashes by Intersections—An Exploratory Analysis ... 20
2.4.7 Summary ... 21

CHAPTER 3. OVERVIEW OF CURRENT V2I APPLICATION AREAS ... **23**

CHAPTER 4. INTERSECTION APPLICATIONS ... **27**
4.1 RUNNING RED LIGHT ... **27**
4.1.1 Associated Pre-Crash Scenarios ... 27
4.1.2 Magnitude of Problem ... 27
4.1.3 Relevant Distributions ... 27
4.1.4 Relationships in HSIS Data ... 27
4.2 RUNNING STOP SIGN ... **28**
4.2.1 Associated Pre-Crash Scenarios ... 28
4.2.2 Magnitude of Problem ... 28
4.2.3 Relevant Distributions ... 29
4.2.4 Relationships in HSIS Data ... 29
4.2.5 Potential Extension to Pedestrian and Bicycle Crashes ... 30
4.3 DRIVER GAP ASSIST AT SIGNALIZED INTERSECTIONS ... **30**
4.3.1 Associated Pre-Crash Scenarios ... 30
4.3.2 Magnitude of Problem ... 31
4.3.3 Relevant Distributions ... 31
4.3.4 Relationships in HSIS Data ... 31
4.4 DRIVER GAP ASSIST AT STOP-CONTROLLED INTERSECTIONS ... **31**
4.4.1 Associated Pre-Crash Scenarios ... 32
4.4.2 Magnitude of Problem ... 32
4.4.3 Relevant Distributions ... 32
4.4.4 Relationships in HSIS Data ... 32

CHAPTER 5. SPEED APPLICATIONS 35
5.1 CURVE SPEED WARNING 35
5.1.1 Associated Pre-Crash Scenarios 35
5.1.2 Magnitude of Problem 35
5.1.3 Relevant Distributions 36
5.1.4 Relationships in HSIS Data 36
5.2 WORK ZONE WARNING FOR REDUCED SPEED IN WORK ZONES............. 37
5.2.1 Associated Pre-Crash Scenarios 37
5.2.2 Magnitude of Problem 37
5.2.3 Relevant Distributions 37
5.3 SPOT TREATMENT/WEATHER CONDITIONS.. 37
5.3.1 Associated Pre-Crash Scenarios 38
5.3.2 Magnitude of Problem 38
5.3.3 Relevant Distributions 38
5.4 SPEED ZONE WARNING 38
5.4.1 Associated Pre-Crash Scenarios 38
5.4.2 Magnitude of Problem 39
5.4.3 Relevant Distributions 39

CHAPTER 6. VULNERABLE ROAD USERS.. 41
6.1 WORK ZONE ALERTS 41
6.1.1 Associated Pre-Crash Scenarios 41
6.1.2 Magnitude of Problem 41
6.1.3 Relevant Distributions 41
6.2 INFRASTRUCTURE PEDESTRIAN DETECTION 42
6.2.1 Associated Pre-Crash Scenarios 42
6.2.2 Magnitude of Problem 42
6.2.3 Relevant Distributions 42
6.3 AT-GRADE RAIL CROSSING 43
6.3.1 Associated Pre-Crash Scenarios 43
6.3.2 Magnitude of Problem 43
6.3.3 Relevant Distributions 43

CHAPTER 7. OTHER APPLICATION AREAS 45
7.1 LANE DEPARTURE CRASHES... 45
7.1.1 Associated Pre-Crash Scenarios 45
7.1.2 Magnitude of Problem 45
7.1.3 Relevant Distributions 45

CHAPTER 8. UNADDRESSED CRASHES 47
8.1 DISTRIBUTION BY PRE-CRASH SCENARIOS... 47
8.2 CHARACTERISTICS OF LEADING UNADDRESSED CRASHES BY PRE-CRASH SCENARIO 52
8.2.1 Single-Vehicle Pedestrian Crashes 52
8.2.2 Single-Vehicle Bicycle Crashes.. 53
8.2.3 Single-Vehicle Animal Crashes.. 54

8.2.4 Rear-End Crashes 54
8.2.5 Straight Crossing Path Crashes at Non-Signals 55
8.2.6 Left Turn Across Path/Opposite Direction Crashes at Non-Signals 56
8.3 CHARACTERISTICS OF UNADDRESSED CRASHES BY VEHICLE, AREA, AND LOCATION TYPE 57
8.3.1 Vehicle Type 57
8.3.2 Area Type 57
8.3.3 Location Type 58
CHAPTER 9. CONCLUSIONS 59
ADDENDIX A: RELEVANT DISTRIBUTIONS 61
REFERENCES 75

LIST OF TABLES

Table 1. Overview of estimates for targeted and unaddressed single-vehicle crashes identified in NASS GES 2
Table 2. Overview of estimates for targeted and unaddressed multi-vehicle crashes identified in NASS GES 2
Table 3. Vehicle type assignment criteria 8
Table 4. MAIS comprehensive crash costs (based on 2007 U.S. dollars) 9
Table 5. Cost per maximum severity (based on 2007 U.S. dollars) 10
Table 6. Distribution of crash location—average annual national crashes 12
Table 7. Area type assignment criteria 12
Table 8. Summary of annual estimated targeted crashes based on current applications 24
Table 9. Single-vehicle unaddressed crashes by pre-crash scenario 48
Table 10. Multi-vehicle unaddressed crashes by pre-crash scenario 50
Table 11. Distribution of crash location for annual national (weighted) unaddressed pedestrian crashes 53
Table 12. Distribution of crash location for annual national (weighted) unaddressed bicycle crashes 53
Table 13. Distribution of area type for annual national (weighted) unaddressed animal crashes 54
Table 14. Distribution of crash location for annual national (weighted) unaddressed rear-end crashes 55
Table 15. Distribution of area type for annual national (weighted) unaddressed rear-end crashes 55
Table 16. Distribution of crash location for annual national (weighted) straight crossing path crashes at non-signals 55
Table 17. Distribution of area type for annual national (weighted) straight crossing path crashes at non-signals 56
Table 18. Distribution of crash location for annual national (weighted) unaddressed left turn across path/opposite direction crashes at non-signals 56
Table 19. Distribution of vehicle type for unaddressed crashes 57
Table 20. Distribution of area type for unaddressed crashes 57
Table 21. Distribution of crash location for unaddressed crashes 58
Table 22. Overview of annual target crashes and associated costs identified in NASS GES for currently identified application areas 59
Table 23. Frequency of annual observed and annual weighted single-vehicle and multi-vehicle crashes by pre-crash scenario 61
Table 24. Cost of annual single-vehicle crashes by pre-crash scenario and injury type 63
Table 25. Cost of annual multi-vehicle crashes by pre-crash scenario and injury type 65
Table 26. Single-vehicle pre-crash scenarios by vehicle type—annual crashes (observed) 67
Table 27. Single-vehicle pre-crash scenarios by vehicle type—annual national crashes (weighted) 69
Table 28. Multi-vehicle pre-crash scenarios by vehicle type—annual crashes (observed) 71
Table 29. Multi-vehicle pre-crash scenarios by vehicle type—annual national crashes (weighted) 73

LIST OF ABBREVIATIONS

Abbreviation	
AIS	Abbreviated injury scale
AV	Autonomous vehicle
CICAS	Cooperative Intersection Collisions Avoidance System
CICAS-SLTA	Cooperative Intersection Collision Avoidance System—Signalized left-turn assist
CICAS-SSA	Cooperative Intersection Collision Avoidance System—Stop-sign assist
CICAS-V	Cooperative Intersection Collision Avoidance System—Violation
FARS	Fatality Analysis Reporting System
FHWA	Federal Highway Administration
GES	General Estimates System
HSIS	Highway Safety Information System
ITS	Intelligent Transportation System
KABCO	Scale used to record injury severity by crash victim
LTAP/OD	Left-turn across path/opposite direction
LVA	Lead vehicle accelerating
LVD	Lead vehicle decelerating
LVM	Lead vehicle moving at lower constant speed
LVS	Lead vehicle stopped
MAIS	Maximum abbreviated injury scale
NASS	National Automotive Sampling System
NHTSA	National Highway Traffic Safety Administration
PDO	Property damage only
SAS®	Statistical Analysis Software®
SCP	Straight crossing path
USDOT	United States Department of Transportation
UVC	*Uniform Vehicle Code*
V2I	Vehicle-to-infrastructure
V2V	Vehicle-to-vehicle
Volpe	John A. Volpe National Transportation Systems Center

CHAPTER 1. EXECUTIVE SUMMARY

The United States Department of Transportation (USDOT) Intelligent Transportation System (ITS) Strategic Plan has the potential to transform travel through safety, mobility, and environmental improvements in surface transportation. Two major programs under this plan are the Vehicle-to-Infrastructure (V2I) and Vehicle-to-Vehicle (V2V) Communications for Safety Initiatives. Both programs are composed of technologies and application areas that use wireless communication to enhance connectivity within the surface transportation network. This report focuses on the potential safety benefits of wireless communication between the roadway infrastructure and vehicles. Specifically, it identifies the magnitude, characteristics, and cost of crashes that would be targeted with currently proposed V2I for safety application areas that have been identified by USDOT with stakeholder input. It also identifies the magnitude, characteristics, and cost of the remaining crashes that are not targeted by a currently proposed V2I for safety application area (unaddressed crashes) for insight into potentially new applications or modifications to proposed applications. The V2I applications investigated in this study comprise four areas: (1) intersection safety, (2) speed management, (3) vulnerable road users, and (4) other safety application areas.

The primary analysis was conducted using the National Automotive Sampling System General Estimates System (NASS GES) database, which provides a national estimate of crashes by weighting a sample of crashes.(1) Other databases, including the Highway Safety Information System (HSIS) and the Fatality Analysis Reporting System (FARS), were used to supplement the NASS GES analysis.(2,3) Pre-crash[1] scenarios, developed through previous efforts, were used to define each crash in the NASS GES database from 2005 to 2008.(1) The frequency and severity of crashes in each pre-crash scenario were summarized, and total costs were assigned to each scenario based on the severity of crashes. Pre-crash scenarios were associated with the respective V2I application areas, and crash frequencies and associated costs were totaled within each application area to determine the potential safety benefits.

Table 1 and table 2 present an overview of the findings from the NASS GES analysis for single-vehicle and multi-vehicle crashes. The tables provide annual data averaged over a 4-year period from 2005 to 2008. Specifically, they present the total annual crashes nationally, the subset of those crashes that would be targeted by current V2I application areas, and the remaining unaddressed crashes. Unaddressed crashes are calculated by subtracting the crashes that would be targeted by current application areas to those application areas from the total number of annual crashes. The associated cost for each group of crashes is also shown in the tables. Note that there is some overlap in the crashes targeted by the application areas. This overlap is accounted for in table 1 and table 2.

[1] There were 32 single-vehicle pre-crash scenarios and 44 multi-vehicle pre-crash scenarios for which there were observed crashes during the analysis period. Some of the pre-crash scenarios included the phrase "no maneuver," which refers to the driver's action before the crash, not if the driver maneuvered to avoid the crash. For example, if a motor vehicle turned right and then crashed into a pedestrian, it is considered a pedestrian/maneuver crash as opposed to a motor vehicle that was driving straight and then crashed into a pedestrian, which is considered a pedestrian/no maneuver crash.

Table 1. Overview of estimates for targeted and unaddressed single-vehicle crashes identified in NASS GES.[1]

Item	Estimated Annual National Crashes (Based on Weighted Data)	Estimated Cost
Total single-vehicle crashes	1,877,663	$164,132,235,633
Crashes potentially targeted by current application areas	1,106,966 (59 percent)	$120,078,331,482 (73 percent)
Unaddressed crashes	770,697 (41 percent)	$44,053,904,151 (27 percent)

Table 2. Overview of estimates for targeted and unaddressed multi-vehicle crashes identified in NASS GES.[1]

Item	Estimated Annual National Crashes (Based on Weighted Data)	Estimated Cost
Total multi-vehicle crashes	4,099,936	$175,110,889,497
Crashes potentially targeted by current application areas	1,181,055 (29 percent)	$82,265,278,363 (47 percent)
Unaddressed crashes	2,918,881 (71 percent)	$92,845,611,134 (53 percent)

NASS GES estimates that approximately 6 million crashes (including both single- and multi-vehicle crashes) occurred each year from 2005 to 2008, totaling more than $339 billion in annual crash costs.[1] The total annual cost for single-vehicle crashes was $164 billion. The leading single-vehicle pre-crash scenarios were control loss/no vehicle action, road edge departure/no maneuver, and pedestrian/no maneuver. Collectively, these three scenarios represented 73 percent of the costs for single-vehicle crashes.

The total annual cost for multi-vehicle crashes was $175 billion. The leading multi-vehicle pre-crash scenarios were straight crossing path at non-signal, rear-end/lead vehicle stopped (LVS), and opposite direction/no maneuver. Collectively, these three scenarios represented 45 percent of the total costs for multi-vehicle crashes.

Currently identified V2I safety application areas could potentially target approximately 2.3 million crashes and $202 billion in costs. The remaining unaddressed crashes represent approximately 3.7 million crashes, totaling approximately $137 billion annually.

These unaddressed crashes represent potential targets for new V2I applications and are presented in this report by pre-crash scenario within single- and multi-vehicle categories. For single-vehicle crashes, pedestrian/no maneuver was the leading unaddressed pre-crash scenario, followed by bicyclist/no maneuver and animal/no maneuver. Collectively, these scenarios represented 56 percent of the costs of unaddressed single-vehicle crashes. From a practical perspective, V2I applications developed to mitigate these crashes would need to be carefully targeted due to the large number of potential miles for treatment.

The leading unaddressed multi-vehicle pre-crash scenario was rear-end/LVS, followed by straight crossing path at non-signal and left turn across path/opposite direction at non-signal. Collectively, these scenarios represented 50 percent of the costs of unaddressed multi-vehicle crashes. Although these scenarios represented a large potential target for V2I applications, a primary concern is whether these scenarios might be better addressed by autonomous vehicle (AV) or V2V communication applications.

The results indicated that the currently identified V2I safety applications discussed in this report are well conceived and can potentially treat large portions of the country's crashes and crash costs. However, there are many crashes that are not addressed by the applications analyzed in this report. The characteristics of unaddressed crashes that are presented in this report provide a starting point for identifying new applications or modifications to current applications.

CHAPTER 2. INTRODUCTION

2.1 BACKGROUND

V2I communication for safety enables vehicles with 360-degree awareness to inform drivers of hazards and situations they cannot see. The following levels of action are envisioned:

- **Advisories**: A driver receives information in a non-time-critical manner.

- **Warnings**: An alarm signals to the driver that a crash is imminent and immediate action is required.

The V2I communication focuses on applications in which safety can be enhanced through connectivity that enables the exchange of information from a vehicle to the roadway infrastructure, from the infrastructure to a vehicle, or from the infrastructure to some other wireless-enabled device. Both original equipment and aftermarket solutions are being considered.

2.2 SCOPE

The objective of this study was to conduct and document crash data analyses of the primary V2I for safety application areas being evaluated by the Federal Highway Administration (FHWA) Safety Program. The goal was to determine which subsets of crashes are potentially treatable with currently identified V2I for safety application areas and which additional subsets could be treated either with modifications to the current application areas or with new application areas. The primary application areas of interest were intersection safety, speed, vulnerable road users, and others (i.e., applications that cannot be classified in the aforementioned areas of interest).

The specific objectives of the crash data analyses were as follows:

- Estimate the magnitude of the crash problem (i.e., number of crashes, fatalities, injuries, property damage, and the cost of the crashes) that could be impacted by currently identified V2I for safety application areas.

- Characterize the locations on the roadway for the crash types that could be impacted by currently identified V2I for safety application areas.

- Characterize pre-crash scenarios and contributing factors that would need to be addressed for currently identified V2I for safety application areas to be effective.

- Identify other significant crash types, pre-crash scenarios, and contributing factors, including currently identified and unidentified application areas, which might be amenable to solutions involving vehicle-infrastructure connectivity.

- Assess the relative potential safety benefits of currently identified and alternative V2I for safety application areas.

This report documents the most salient findings of this effort. It includes a description of the data used, the methods employed, and results by V2I application area. Supporting materials are provided in the appendix.

Throughout this report, crashes are described as either targeted crashes or unaddressed crashes with respect to V2I for safety application areas. Targeted crashes are crashes that could potentially be eliminated through the deployment of a specific V2I application or set of applications (i.e., researchers should determine the potential benefit of an application area, assuming 100 percent effectiveness and 100 percent deployment). The actual number of crashes mitigated depends on the effectiveness of the application and the extent of deployment. Unaddressed crashes are those that are not eliminated even if a V2I application, or set of applications, is 100 percent effective and fully deployed. That is not to say that unaddressed crashes cannot be mitigated by V2I application areas. Rather, currently identified application areas and potential extensions do not target these crashes. Unaddressed crashes might be covered through the development of new V2I application areas or by V2V and AV applications.

2.3 METHODOLOGY

The primary analysis involved an examination of the NASS GES database and several State databases from HSIS.[1,2] These databases and analysis methodologies are briefly described in the following sections.

2.3.1 NASS GES Data Analysis

NASS GES contains data on a representative random sample of thousands of reported minor, serious, and fatal crashes involving passenger cars, pickup trucks, vans, large trucks, motorcycles, and pedestrians.[1] It is based on cases selected from a sample of police crash reports within randomly selected areas of the country.

The crash reports are chosen from 60 urban and rural areas that are representative of the geography, roadway mileage, population, and traffic density of the United States. Data collectors make weekly visits to approximately 400 police jurisdictions in the 60 areas throughout the United States and randomly sample approximately 50,000 police crash reports each year. Weights are provided so the sample data can be weighted to a national estimate. NASS GES data from 1988 to 2008 (crash, vehicle, and person files) are available online from the National Highway Traffic Safety Administration (NHTSA).[1]

This study analyzed the most recent 4 years of crash data from NASS GES, which was from 2005 through 2008. The analysis used the following five datasets for each year:

- **Accident:** This file contains data on crash characteristics and environmental conditions.
- **Vehicle:** This file contains data on the vehicles and drivers involved in the crash.
- **Person:** This file contains data on people involved in the crash, including age, gender, and injury severity.

- **Trafcon:** This file contains data on traffic control devices at the crash level.
- **Violatn:** This file contains data on violations charged to the driver(s) involved in the crash.

Analyses were conducted using both raw and imputed variables in the database. Raw data reflect the probability sample of police-reported crashes. The NHTSA report *Imputation in the NASS General Estimates System* describes imputation as the process of fabricating data when data are unknown.[4] Imputed variables are used to fill in unknown values. This is done because of historical precedence, convenience, consistency of data, and potential reduction in bias. Weighted variables are national estimates of crash characteristics based on weights established by NHTSA. According to the *NASS GES Analytical User's Manual 1988–2008*, the weight is the product of the inverse of the probabilities of selection at each of the three stages in the sampling process and is used to produce national estimates from the data.[5] Information on national estimates can be found in the *National Accident Sampling System General Estimates System Technical Note.*[6]

2.3.1.1 Pre-Crash Scenarios

Crashes have multiple characteristics that can be grouped in an almost infinite number of ways. The research for this report used work conducted by The John A. Volpe National Transportation Systems Center (Volpe) to categorize each crash in the NASS GES database in a pre-crash scenario. The pre-crash scenarios were assigned using a Statistical Analysis Software® (SAS®) program developed by Volpe. Detailed criteria for assigning pre-crash scenarios are summarized in *Pre-Crash Scenario Typology for Crash Avoidance Research.*[7] Volpe classifies crashes by 38 single-vehicle pre-crash scenarios and 46 multi-vehicle pre-crash scenarios. During the 2005–2008 analysis period, there were observed crashes for 32 single-vehicle pre-crash scenarios and 44 multi-vehicle pre-crash scenarios. Distributions of crashes by pre-crash scenarios and vehicle type are presented in the appendix.

2.3.1.2 Vehicle Type

The Volpe SAS® program assigns one of six vehicle types to each vehicle involved in a crash. The vehicle types are light vehicle, transit vehicle, specialty vehicle, single-unit truck, combination-unit truck, and other. These vehicle types are assigned based on the NASS GES data variables for vehicle body type (bdytyp_h), special use type (spec_use), and trailer type (trailer) (see table 3). Definitions for vehicle body, special use, and trailer types can be found in the *National Automotive Sampling System (NASS) General Estimates System (GES) Analytical User's Manual 1988–2008*.[5] Motorcycles are included in the "other" and "specialty" vehicle types.

Table 3. Vehicle type assignment criteria.

Vehicle Type	Assignment Criteria
Light vehicle	If (((1 ≤ bdytyp_h ≤ 22) or (28 ≤ bdytyp_h ≤ 41) or (45 ≤ bdytyp_h ≤ 49)) and spec_use = 0)
Transit vehicle	If (bdytyp_h in (25, 58, 59)) and (spec_use < 1 or spec_use = 3 or spec_use = 8 or spec_use = 9 or spec_use > 12)
Specialty vehicle	If ((80 ≤ bdytyp_h ≤ 89) or bdytyp_h in (23, 24, 42, 50, 65, 93, 97)) and ((4 ≤ spec_use ≤ 7) or spec_use = 2 or spec_use = 12)
Single-unit truck	If ((bdytyp_h in (60, 64, 66, 78, 79)) and (trailer in (1, 6)))
Combination-unit truck	If (bdytyp_h in (60, 64, 66, 78, 79)) and ((2 ≤ trailer ≤ 5))
Other	Else

Note: NASS GES data variables and codes used in these assignment criteria are defined in the *National Automotive Sampling System (NASS) General Estimates System (GES) Analytical User's Manual 1988–2008*.(5)

2.3.1.3 Crash Costs

Crash costs developed by Volpe were employed in this study as part of the economic analysis to ensure consistency between these results and those from past studies. All costs associated with NASS GES crash costs in this report were based on 2007 U.S. dollars.

The crash costs associated with each pre-crash scenario were calculated based on procedures used in a previous crash typology study, *Heavy Vehicle Pre-Crash Scenario Typology for Crash Avoidance Research*.(8) The conversion from crashes to economic costs was based on the severity of the crash. Specifically, DaSilva et al. used the maximum abbreviated injury scale (MAIS).(8) The crash costs used in this study are based on MAIS (see table 4).

Table 4. MAIS comprehensive crash costs (based on 2007 U.S. dollars).[(8)]

Consumer Price Index	Factor	MAIS 1	MAIS 2	MAIS 3	MAIS 4	MAIS 5	MAIS 6
1.346066	Medical	$3,204	$21,032	$62,585	$176,747	$447,509	$29,741
1.204077	Emergency medical services	$117	$255	$443	$999	$1,026	$1,003
1.277512	Market produce	$2,234	$31,960	$91,283	$135,977	$560,451	$760,577
1.277512	Household produce	$731	$9,354	$26,924	$35,782	$190,743	$244,696
1.204077	Insurance	$892	$8,319	$22,749	$38,934	$82,114	$44,695
1.277512	Workplace	$322	$2,495	$5,450	$6,002	$10,464	$11,117
1.204077	Legal	$181	$5,998	$19,034	$40,559	$96,153	$122,982
1.277512	Travel delay	$993	$1,081	$1,201	$1,276	$11,697	$11,687
1.204077	Property damage	$4,628	$4,761	$8,187	$11,840	$11,374	$12,369
1.277512	Quality-adjusted life years (QALYs)	$9,118	$186,525	$262,189	$784,777	$2,674,628	$4,889,799
New comprehensive costs		$22,420	$271,780	$500,045	$1,232,893	$4,086,149	$6,128,666
Injury subtotal		$16,799	$265,938	$490,657	$1,219,777	$4,063,088	$6,104,610
QALY relatives		0.0019	0.0381	0.0536	0.1605	0.547	1

Note: MAIS severity levels are as follows: MAIS 0 = no injury, MAIS 1 = minor, MAIS 2 = moderate, MAIS 3 = serious, MAIS 4 = severe, MAIS5 = critical, and MAIS 6 = fatal.

NASS GES does not provide detailed information regarding injury severity based on the MAIS coding scheme. Instead, it records injury severity by crash victim based on the KABCO scale as follows:

- **K:** Killed.
- **A:** Incapacitating injury.
- **B:** Non-incapacitating injury.
- **C:** Possible injury.
- **O:** No apparent injury.

NASS GES also provides information for "injury severity unknown" and "died prior." Because there were not many "died prior" crashes, they were not considered in the analysis. DaSilva et al. used a conversion matrix to estimate MAIS injuries from the KABCO scale.[(8)] The series of multiplicative factors that were applied to convert injury severity from KABCO to MAIS designations were obtained from the NHTSA report, *Preliminary Regulatory Evaluation*.[(9)]

The conversion factor was multiplied by MAIS subtotal dollar values in table 4 to obtain a weighted cost for each severity (travel delay and property damage are not included in this value).

For MAIS 0 (no injury), $2,423 was used based on unpublished values provided by Volpe. It should be noted that the goal of the current research was not to determine the exact dollar values associated with various crash types and pre-crash scenarios. Rather, the goal was to identify the relative magnitude of the crash problem for specific scenarios. As such, it was acceptable to use the unit costs in 2007 dollar values from the report by DaSilva et al.[8]

The resulting crash cost per maximum severity as reported in NASS GES was calculated using the procedure previously described and is shown in table 5. The crash cost per maximum severity was applied to the imputed crashes for each single-vehicle and multi-vehicle pre-crash scenario by maximum severity from 2005 to 2008.

Table 5. Cost per maximum severity (based on 2007 U.S. dollars).

NASS GES Code	Description	Cost
0	No injury	$4,597
1	Possible injury	$42,217
2	Non-incapacitating injury	$83,059
3	Incapacitating injury	$284,718
4	Fatal	$6,128,666
5	Injured, unknown severity	$118,770

For single-vehicle crashes, the total cost from 2005 to 2008 was $657 billion, with an annual average cost of $164 billion. The three highest-cost single-vehicle pre-crash scenarios represented 73 percent of the total costs for single-vehicle crashes ($478 billion of the $657 billion total) and included the following:

- Control loss/no vehicle action: $237 billion total and $59 billion annual average.
- Road edge departure/no maneuver: $168 billion total and $42 billion annual average.
- Pedestrian/no maneuver: $72 billion total and $18 billion annual average.

For multi-vehicle crashes, the total cost from 2005 to 2008 was $700 billion, with an annual average of $175 billion. The three highest-cost multi-vehicle pre-crash scenarios represented 45 percent of the total costs for multi-vehicle crashes ($315 billion of the $700 billion total) and included the following:

- Straight crossing path at non-signal: $131 billion total and $33 billion annual average.
- Rear-end/LVS: $96 billion total and $24 billion annual average.
- Opposite direction/no maneuver: $88 billion total and $22 billion annual average.

Detailed cost information for each pre-crash scenario by injury type is presented in the appendix (see table 24 for single-vehicle crashes and table 25 for multi-vehicle crashes).

2.3.1.4 Intersection Crashes

Many application areas required the identification of crashes related to various types of intersections and non-intersection segments. The location of the crash was characterized by the location where the first harmful event occurred. The *first harmful event* is defined as the occurrence of injury or damage involving a motor vehicle in transport, which can result from an impact or non-collision event. The variable imputed relation to junction (*RELJCT_I [A09I]*) specifies whether the crash occurred at a junction or non-junction area and whether it occurred at an interchange or non-interchange area. This variable was used to identify intersection-related and segment-related crashes.

Crashes were identified as either intersection, intersection-related, or segment crashes. Intersection crashes were crashes that occurred within the intersection, while intersection-related crashes occurred on the approach to or exit from an intersection and resulted from an activity, behavior, or control related to the movement of traffic through the intersection. Crashes were identified as intersection or intersection-related if the relationship to the junction was coded as any of the following:

- Non-interchange area, intersection (*RELJCT_I = 1*).
- Non-interchange area, intersection-related (*RELJCT_I = 2*).
- Non-interchange area, rail grade crossing (*RELJCT_I = 5*).
- Interchange area, intersection (*RELJCT_I = 11*).
- Interchange area, intersection-related (*RELJCT_I = 12*).

All other crashes were considered segment crashes, which included crashes that occurred at non-interchange areas (i.e., non-junctions, driveways or alley accesses, bridges, and crossovers) or at interchange areas (i.e., non-junctions, ramp exits/entrances, and other interchange locations). While crashes associated with driveways and other access points are similar to crashes at intersections, the V2I application areas discussed in this report did not target driveway crashes.

2.3.1.5 Location—Traffic Control and Alignment

Table 6 presents single-vehicle and multi-vehicle crashes by location. Intersection and intersection-related crashes were analyzed by type of traffic control, which was identified using the crash-level NASS GES data variable imputed traffic control device (*TRFCON_I[A16I]*) and, in some cases, the similarly named vehicle-level variable. Intersection crashes were classified by traffic control device as signalized intersection crashes (*TRFCON_I = 1*), stop-controlled intersection crashes (*TRFCON_I = 21*), and other intersection crashes. NASS GES determines the intersection control by the control affecting every vehicle in the crash. In a situation where two vehicles crash on an uncontrolled approach of a two-way, stop-controlled intersection, the intersection control for the crash is coded as uncontrolled.

Segment-related crashes were analyzed by presence of curvature (i.e., tangents [*ALIGN_I = 1*] versus curves [*ALIGN_I = 2*]). The majority of single-vehicle crashes occurred on tangent sections (67 percent) and curve sections (20 percent). The primary locations of multi-vehicle crashes were tangent sections (42 percent) and signalized intersections (28 percent).

Table 6. Distribution of crash location—average annual national crashes.

Location of Crash		Single-Vehicle Crashes	Single-Vehicle Percent	Multi-Vehicle Crashes	Multi-Vehicle Percent	Total Crashes	Total Percent
Intersections and intersection-related	Signalized	67,520	4	1,147,720	28	1,215,240	20
	Stop-controlled	55,362	3	506,840	12	562,202	9
	Other intersections	122,171	7	518,938	13	641,109	11
Segments	Tangents	1,257,706	67	1,730,728	42	2,988,434	50
	Curves	374,904	20	195,710	5	570,614	10
Total		1,877,663	100	4,099,936	100	5,977,599	100

2.3.1.6 Area Type

Table 7 shows the assignment criteria and variable description for the area types defined in the NASS GES data. Area type was determined using the crash-level NASS GES data variable land use *(Land_Use[A05])*. Crashes that occurred within areas with a population greater than 25,000 people were considered urban, and areas reported as "other area" were considered rural.

Table 7. Area type assignment criteria.

Area Type	Assignment Criteria	Variable Description
Urban	Land_use = 1	Area population of 25,000–50,000
	Land_use = 2	Area population of 50,000–100,000
	Land_use = 3	Area population of 100,000 or more
Rural	Land_use = 8	Other area
Unknown	Land_use = 9	Unknown

2.3.1.7 Speed-Related Crashes

Several application areas required the identification of crashes that were related to speeding. Speed-related crashes for single- and multi-vehicle pre-crash scenarios were identified using the NASS GES data speed-related variable (*SPEEDREL [D9N] = 1*). This variable was coded at the vehicle level to indicate whether speed was a contributing factor in the crash. If speed was coded as a factor for any of the involved vehicles, the crash was considered speed related.

2.3.1.8 Adverse Conditions

Some application areas required the identification of crashes that occurred during adverse driving conditions, which were defined based on the crash-level NASS GES data variables for roadway surface condition (*Sur_Cond[A15]*) and weather (*Weather[A20]*). Crashes were considered to be related to adverse conditions if conditions for the crash were coded as any of the following:

- Wet (*Sur_Cond = 2*).
- Snow or slush (*Sur_Cond = 3*).

- Ice (*Sur_Cond* = *4*).
- Sand, dirt, or oil (*Sur_Cond* = *5*).
- Rain (*Weather* = *2*).
- Sleet (*Weather* = *3*).
- Snow (*Weather* = *4*).
- Fog (*Weather* = *5*).
- Rain and fog (*Weather* = *6*).
- Sleet and fog (*Weather* = *7*).

2.3.2 HSIS

HSIS is a roadway-based system maintained by FHWA that provides quality data on crash, roadway, and traffic variables linked to homogeneous sections of the highway system under State control.[2] It is the only multi-State database that allows for the safety analysis of roadway design factors through its file system and that has the capability to link roadway inventory and exposure data to crash data for a large sample of primary route mileage. It is also the only file system that includes both roadway sections with and without crashes. Currently, seven States are part of HSIS: California, Illinois, Maine, Minnesota, North Carolina, Ohio, and Washington. Historical data from Michigan and Utah are also available, but updated data are no longer captured. This study analyzed crash data for the most recent 3 years for California, Illinois, Minnesota, and Washington, which was from 2005 through 2007.

There are six types of data files available within HSIS, and all States maintain three basic files: a crash file, a roadway inventory file, and a traffic volume file. Additional roadway geometry files are also available within selected States, including a horizontal curve file (Illinois, Ohio, and Washington) and a vertical grade file (Illinois and Washington). Intersection and interchange data are also available for a limited number of States.

California and Minnesota were selected for detailed intersection analyses since these States provide intersection datasets. Illinois and Washington were used to conduct detailed analyses of curves and curve crashes since both States have a curvature file.

It is important to note that HSIS data are only available for State-maintained roadways in each State. As such, HSIS represents more rural than urban areas since roadways in urban areas are often maintained by a municipality. Quality data are largely unavailable for municipalities but would be helpful to better define the magnitude of the safety problems and potential impacts of V2I application areas in urban areas.

2.4 PREVIOUS CRASH TYPOLOGY EFFORTS RELATED TO V2I FOR SAFETY

Previous studies have provided the foundation for this study, including the development of pre-crash scenarios and the investigation of the potential benefits of specific V2I for safety application areas. The following sections review select studies that were used as a basis for the analyses conducted as part of this current research. A brief overview of each study is provided, including the types of crash analyses performed and any gaps that were addressed as part of this project.

2.4.1 Pre-Crash Scenario Typology for Crash Avoidance Research

Najm et al. analyzed 2004 NASS GES data to develop a new typology of pre-crash scenarios for all police-reported crashes that involved at least one light vehicle (e.g., passenger car, sports utility vehicle, van, minivan, and light pickup truck).[7] A total of 37 pre-crash scenarios were defined based on two existing typologies: the 44 crashes typology developed by General Motors® and the pre-crash scenarios typology developed by USDOT.[10,11] Najm et al.'s new typology defines pre-crash scenarios that describe the vehicle movements, vehicle dynamics, and critical events that occurred immediately prior to the crash.

Each pre-crash scenario was ranked by three measures: crash frequency, functional years lost, and economic cost. Functional years lost and economic costs were estimated for each pre-crash scenario based on the severity of each crash assigned to that scenario. A summary table was provided for each pre-crash scenario that included the number of vehicles and people involved as well as the distribution of crashes by severity using the KABCO injury scale and the abbreviated injury scale (AIS). AIS uses a score of 1 (minor injury) through 6 (unsurvivable injury) to describe the injury severity of the crash victim. A detailed summary also described the typical scenario for a crash, factors that are overrepresented, dynamic variations of the scenario, and the general severity of crashes.

Single light-vehicle crashes resulted in an estimated economic cost of about $37 billion and 1.1 million functional years lost. The top three scenarios accounted for about two-thirds of all single light-vehicle crashes. In terms of economic costs and functional years lost, the top three pre-crash scenarios were as follows:

- Control loss without prior vehicle action (36.7 percent of economic costs and 38.4 percent of functional years lost).
- Road edge departure without prior vehicle maneuver (24 percent of economic costs and 24.7 percent of functional years lost).
- Pedestrian crash without prior vehicle maneuver (10.3 percent of economic costs and 12.6 percent of functional years lost).

Two-vehicle crashes involving at least one light vehicle resulted in an estimated economic cost of about $69 billion and 1.4 million functional years lost. The top three pre-crash scenarios accounted for about 40 percent of all two-vehicle crashes. In terms of economic costs, the top three scenarios were as follows:

- LVS: 14.9 percent.
- Vehicle(s) turning at non-signalized junctions: 10 percent.
- Straight crossing path at non-signalized junctions: 9.9 percent.

Multi-vehicle light-vehicle crashes (i.e., crashes involving more than two vehicles where at least one is a light vehicle) resulted in an estimated economic cost of about $14 billion and 292,000 functional years lost. The top three pre-crash scenarios accounted for 68 percent of all multi-vehicle crashes and were mostly related to rear-end crashes. In terms of economic costs, the top three scenarios were as follows:

- LVS: 35.9 percent.
- Lead vehicle decelerating (LVD): 14.8 percent.
- Opposite direction without prior vehicle maneuver: 7.1 percent.

These findings will help establish research priorities and provide a framework for a more consistent approach to identify interventions. The research also consolidates existing crash typologies into a single set of pre-crash scenarios from which all police-reported crashes can be categorized. While the study provided a basis for the current research, it was only based on a single year of data from 2004 and did not associate pre-crash scenarios or crash costs with specific V2I for safety application areas. The study also focused on light vehicles and did not specifically address crashes and costs related to other vehicle types (e.g., heavy vehicles and motorcycles). Crashes related to other vehicle types were included in the analysis but only when a single vehicle was involved. There is still a need to identify crashes and costs related to specific vehicle types.

2.4.2 Heavy Vehicle Pre-Crash Scenario Typology for Crash Avoidance Research

Similar to Najm et al.'s study on light vehicles, DaSilva et al. developed a new typology of pre-crash scenarios involving single-unit and combination-unit heavy vehicles (gross vehicle weight more than 10,000 lb) based on NASS GES data from 1996 through 2005.[(8)] A total of 46 pre-crash scenarios were defined by describing the vehicle movements, vehicle dynamics, and critical events that occurred immediately prior to the crash.

Each pre-crash scenario was ranked by three measures: crash frequency, functional years lost, and economic cost. Functional years lost and economic costs were estimated for each pre-crash scenario based on the severity of each individual crash assigned to that scenario. A summary table was provided for each pre-crash scenario, including the number of vehicles and people involved and the distribution of crashes by severity using both KABCO and AIS. A detailed summary was also provided describing the typical scenario for each crash, factors that were overrepresented, dynamic variations of the scenario, and the general severity of the crashes.

Heavy vehicles accounted for approximately 6.5 percent (411,000 crashes) of all police-reported crashes annually. Of those, single-unit trucks accounted for an annual average of 214,000 crashes, and the remaining 197,000 crashes per year were associated with combination-unit trucks. The most common crash types for single-unit and combination-unit trucks were “off-the-roadway” and “changing lanes,” respectively. Annually, approximately 974,000 people were involved in a crash with a heavy truck, and approximately 14 percent were injured or killed in those crashes. The annual economic cost of crashes involving heavy trucks, both single-unit and combination-unit, was estimated at $10.4 billion. More than 292,000 functional years were lost annually due to death and injury.

Single-unit truck crashes involving only one vehicle accounted for nearly 29 percent of all single-unit truck crashes, with an economic cost of approximately $877 million and 23,800 functional years lost. The top three pre-crash scenarios in terms of economic costs and functional years lost were as follows:

- Road edge departure/no maneuver.
- Pedestrian/no maneuver.
- Pedestrian/maneuver.

Two-vehicle single-unit truck crashes accounted for 67 percent of all single-unit truck crashes. These crashes resulted in an annual economic cost of $3.1 billion and 77,100 functional years lost. The top three pre-crash scenarios in terms of economic costs and functional years lost were as follows:

- Changing lanes/same direction.
- Turn at non-signal.
- Opposite direction/no maneuver.

Multi-vehicle (i.e., three or more vehicles) single-unit truck crashes accounted for 4 percent of all single-unit truck crashes. These crashes resulted in an annual economic cost of $458 million and 11,800 functional years lost. The top three pre-crash scenarios in terms of economic costs and functional years lost were as follows:

- Rear-end/LVS.
- Changing lanes/same direction.
- Opposite direction/no maneuver.

Single-vehicle combination-unit truck crashes represented 22 percent of all combination-unit truck crashes. These crashes resulted in an annual economic cost of $1 billion and

32,000 functional years lost. The top three pre-crash scenarios in terms of economic costs and functional years lost were as follows:

- Road edge departure/no maneuver.
- Control loss/no maneuver.
- Pedestrian/no maneuver.

Two-vehicle combination-unit truck crashes accounted for 73 percent of all combination-unit truck crashes. These crashes resulted in an annual economic cost of $4.3 billion and 125,400 functional years lost. The top three pre-crash scenarios in terms of economic costs and functional years lost were as follows:

- Changing lanes/same direction.
- Opposite direction/no maneuver.
- Turn at non-signal.

Multi-vehicle combination-unit truck crashes represented 5 percent of all combination-unit truck crashes. These crashes resulted in an annual economic cost of $712 million and 21,600 functional years lost. The top three pre-crash scenarios in terms of economic costs and functional years lost were as follows:

- Changing lanes/same direction.
- Rear-end/LVS.
- Rear-end/LVD.

These findings will help establish research priorities and provide a framework for a more consistent approach to identify countermeasures to target heavy truck crashes. The analysis identified the magnitude of the problem for 46 different pre-crash scenarios.[(5)] While the study provided a basis for the current research, it did not associate pre-crash scenarios or crash costs with specific V2I for safety application areas.

2.4.3 Frequency of Target Crashes for IntelliDrive Safety Systems

Najm et al. conducted a high-level analysis of potential collisions impacted by three general IntelliDrive safety systems.[(12)] The report employed the crash typologies developed in the *Pre-Crash Scenario Typology for Crash Avoidance Research* to estimate the potential safety effects of V2V, V2I, and AV communication systems.[(7)] The study looked at all light vehicles, heavy vehicles, and all vehicles combined. The analyses were based on NASS GES statistics from 2005 through 2008.

Target crashes were measured by the number of police-reported crashes that involved all vehicle types. Target crashes represented the maximum potential safety benefit if the fully deployed system was 100 percent effective in reducing target crashes. To avoid double counting, target crashes were first determined for a primary system category (e.g., V2V), and the remainder of the crash population was later assigned to the other two system categories (e.g., V2I and AV). Several analyses were reported, allowing each system to represent the primary countermeasure.

The study presented the results for each individual system and included tables and figures comparing the total percentage of crashes that could be targeted. Comparing each system individually as the primary countermeasure, V2V had the greatest potential to address crashes (4,409,000 target crashes), representing 74 percent of all police-reported crashes. AV systems represented the second greatest potential to address crashes (3,591,000 target crashes), accounting for 60 percent of all police-reported crashes. V2I was ranked third with respect to the potential to address total crashes (1,465,000 target crashes), representing 25 percent of all police-reported crashes.

The study also included results for the combination of the V2V and V2I systems. This combination accounted for the highest percentage of potential crashes targeted (4,503,000 crashes and 75 percent of all police-reported crashes).

The study also estimated potential benefits based on annual police-reported crashes involving at least one light vehicle and at least one heavy vehicle. Light vehicles include all passenger cars, vans, minivans, sports utility vehicles, and light pickup trucks with a gross vehicle weight rating less than 10,000 lb. Heavy vehicles included pickup, single-unit, and multi-unit trucks with a gross vehicle weight rating greater than 10,000 lb.

Results showed that the combination of V2V and V2I systems targeted the highest percentage of all light-vehicle crashes (77 percent) and crashes involving one heavy vehicle (71 percent). The V2V system alone targeted 76 percent of all light-vehicle crashes when it was considered the primary countermeasure. When considered individually as the primary countermeasure, AV systems targeted 60 percent of all light-vehicle crashes, and V2I systems targeted 25 percent of all light-vehicle crashes. The V2V system targeted 70 percent of all heavy-vehicle crashes when considered the primary countermeasure. When considered individually as the primary countermeasure, AV systems targeted 64 percent of all heavy-vehicle crashes, and V2I systems targeted 14 percent of all heavy-vehicle crashes.

These findings will help establish research priorities with respect to the various systems. While the study compared various systems in general, it did not associate pre-crash scenarios or crash costs with specific V2I for safety application areas.

2.4.4 Cooperative Intersection Collision Avoidance Systems Research on Comprehensive Costs of Intersection Crashes

Chang et al. estimated the magnitude of fatal and injury crashes as well as comprehensive crash costs associated with signalized and stop-controlled intersections.[13] Specifically, the study estimated the potential benefits of Cooperative Intersection Collision Avoidance Systems (CICAS) in terms of comprehensive crash costs. Three CICAS application areas were investigated: violation (CICAS-V), signalized left-turn assist (CICAS-SLTA), and stop sign assist (CICAS-SSA).

National estimates of crashes at signalized and stop-controlled intersections were identified based on data from FARS, NASS GES, and the Crashworthiness Data System.[3,1,14] Crashes were assigned to various crash types for both signalized and stop-controlled intersections corresponding to the CICAS application areas. For signalized intersections, crashes were assigned to violations (crossing path or non-crossing path) and signalized left-turn assist (left-turn across path/opposite direction (LTAP/OD) or left-turn and pedestrian). For stop-controlled intersections, crashes were assigned to violations (crossing path or non-crossing path) and stop sign assist (various crossing path crashes). Crash costs were assigned to each crash by allocating a unit cost to people and vehicles involved in a crash depending on four different categories: fatalities, injured people, non-injured people in injury vehicles, and property damage only (PDO). These costs were assigned based on the level of injury as indicated by MAIS.

In 2000, 43,000 fatalities were reported, with 9,500 occurring at intersections. In the same year, 2.7 million people were injured in vehicle crashes, of which, 1.3 million were related to crashes at intersections. A total of 8.9 million vehicles were involved in PDO crashes, of which, 4 million involved crashes at intersections. Intersection-related crashes and costs were further analyzed to identify the potential benefit of the CICAS application areas. The following results were reported for signalized intersections:

- CICAS-V (crossing path): $12 billion and 1,200 fatalities annually.
- CICAS-V (non-crossing path): $440 million and 100 fatalities annually.
- CICAS-SLTA (LTAP/OD): $9.1 billion and 420 fatalities annually.
- CICAS-SLTA (left-turn and pedestrian): $700 million and less than 100 fatalities annually.

The results for stop-controlled intersections were as follows:

- CICAS-V (crossing path): $6.2 billion and 1,300 fatalities annually.
- CICAS-V (non-crossing path): $600 million and 130 fatalities annually.
- CICAS-SSA (crossing path): $15 billion and 1,400 fatalities annually.

These findings will help establish research priorities with respect to the various CICAS systems. While the study compared specific CICAS systems, it did not identify the potential benefits of other V2I for safety application areas. The results also did not identify contributing factors or specific locations (e.g., urban/rural) where the CICAS applications could be most effective.

2.4.5 Infrastructure-Based Intersection Collision Avoidance Concept Study

A 2000 FHWA study explored the potential to reduce crossing path intersection crashes using advanced technology.[15] The primary objective of this study was to define and evaluate infrastructure-only concepts complementary to AV and V2I cooperative concepts to reduce the number of intersection crashes. High-priority intersection locations were chosen in three States

(California, Minnesota, and Virginia), and a crash analysis was conducted at each location to identify the types of crossing path crashes and the potential causes of those crashes.

The three States provided the selection of high-priority intersections and hard copies of crash reports at these intersections. In total, 61 intersection locations were studied (21 locations in California, 20 locations in Minnesota, and 20 locations in Virginia). Crash data covered a 3-year period from 1997 through 1999 in California and from 1998 through 2000 in Minnesota and Virginia.

Crash reports showed that more than 50 percent of all crashes analyzed at intersection locations were crossing path crashes. Results from the crash analysis revealed that of all the crossing path crashes identified, LTAP/OD crashes were the predominant crash type at urban intersections, while straight cross path (SCP) crashes were the dominant crash type at rural intersections. As part of the crash analysis, two main causes of those crashes were identified: traffic control violations and insufficient gap. For insufficient gap crashes, the predominant causes were as follows:

- A total of 55 percent of drivers did not see other vehicle.
- A total of 15 percent of drivers thought the other vehicle would stop.
- A total of 11 percent of drivers had a view obstruction.
- A total of 9 percent of drivers misjudged the gap and thought they had a sufficient gap.
- A total of 5 percent of drivers did not look for oncoming vehicles.

The remaining 5 percent of the insufficient gap acceptance crashes were varied in their causes.

2.4.6 CICAS: Distribution of Crashes by Intersections—An Exploratory Analysis

A 2005 FHWA study investigated the magnitude and distribution of crossing path crashes at intersections.(16) A diverse set of data was used to conduct the analyses, including data from two States (Maine and California) and two cities (Detroit, MI, and San Francisco, CA). State-level crash and intersection data were obtained from HSIS. City-level data were obtained from a database developed as part of a previous effort; the data only included signalized intersections.(2)

For the State-level analyses, the study identified the number of signalized and stop-controlled intersections by area type (i.e., rural or urban). The total number of crossing path crashes and crossing path crashes by severity for each intersection type and area type were also identified. In both States, crashes were overrepresented at signalized intersections. While the vast majority of intersections were stop-controlled (98 percent rural and 76 percent urban), the percentage of crashes at stop-controlled intersections was substantially less (61 percent rural and 56 percent urban). Crashes were also more prevalent in urban areas, accounting for 88 to 95 percent of crashes at signalized intersections and 57 to 65 percent of crashes at stop-controlled intersections.

For the city-level analyses, the study identified the number of crashes, injuries, and fatalities for various crossing path crash types, including left-turn, straight, and right-turn crossing paths. Left-turn crossing path was the leading crossing path crash type in both cities, followed by straight crossing path and right-turn crossing path. However, the severity was greatest for straight crossing path crashes.

While this study provided a basis for estimating the potential benefits of specific V2I for safety application areas, namely the CICAS application areas, it did not provide estimates at the national level. This study was also limited in that it only researched crossing path collisions and did not produce crash cost estimates for other scenarios.

2.4.7 Summary

Previous research efforts have defined pre-crash scenarios and quantified the relative safety issues in terms of crashes and economic costs. Research studies have explored potential safety impacts of V2I for safety applications. Some studies provided general comparisons of various ITS-related systems (i.e., V2I, V2V, and AV), while others focused on a specific subset of V2I applications (e.g., CICAS). While previous efforts have helped establish general research priority areas and have provided a foundation for subsequent efforts, they were either too general to identify benefits of specific applications or too specific (i.e., only focused on a subset of applications). Many of the studies focused on light vehicles with limited analysis of trucks, motorcycles, and pedestrians.

This study provides a comprehensive evaluation of the V2I for safety applications by the FHWA Safety Program to fill in gaps identified from the review of previous studies. Specifically, this report quantifies the national safety issue with respect to crashes and economic costs and shows the potential safety impacts of currently identified applications as well as the locations (e.g., rural/urban) where those applications could be deployed. It also identifies unaddressed crashes (i.e., those not targeted by current V2I applications). The results are presented in terms of all potential crashes targeted, with details for specific vehicle types and user groups when appropriate.

CHAPTER 3. OVERVIEW OF CURRENT V2I APPLICATION AREAS

The V2I application areas currently being considered by the FHWA Safety Program are characterized as intersection applications, speed applications, applications for vulnerable road users, and others.

Intersection applications are intended to prevent crashes at intersections and include the following:

- Drivers running red lights.
- Drivers running stop signs.
- Driver gap assist at signalized intersections.
- Driver gap assist at stop-controlled intersections.

Speed applications are intended to target crashes involving one or more vehicles when speeding contributed to the crash. These applications include the following:

- Curve speed warning.
- School zone speed warning.
- Work zone warning for reduced speed in work zones.
- Spot treatment/weather conditions.
- Speed zone warning.

Vulnerable road user applications are intended to target crashes involving users, such as pedestrians or vehicles, in vulnerable situations. These applications include the following:

- Work zone alerts.
- Infrastructure pedestrian detection.
- Priority assignment for emergency vehicle preemption.
- At-grade rail crossing.
- Bridge clearance warning.

Other applications that do not fit into the aforementioned categories include the following:

- Secondary accident warning.
- Lane departure warning.

Table 8 summarizes estimates that could be derived from a NASS GES-based analysis of the number of annual crashes that could be targeted by the current application areas. Note that it does not include data for several current application areas including school zone warning, emergency vehicle preemption priority, bridge clearance warning, and secondary accident warnings. The NASS GES system is based on a sample of police-reported crashes and is limited to the variables collected by the police. This restricts the ability to identify some of the circumstances of the crash that would be needed for these four applications. For example, the secondary accident warning application is intended to target crashes that occur, at least in part, following another crash (e.g., a rear-end crash in congestion that was caused by an earlier crash). This scenario is not specifically recorded by the police, and these crashes cannot be identified in NASS GES.

Table 8. Summary of annual estimated targeted crashes based on current applications.

Application Area		Annual Single-Vehicle Crashes	Annual Multi-Vehicle Crashes
Intersection applications	Drivers running red lights	868	234,013
	Drivers running stop signs	3,586	40,838
	Driver gap assist at signalized intersections	N/A	200,212
	Driver gap assist at stop-controlled intersections	N/A	278,886
Speed applications	Curve speed warning	149,317	19,676
	Work zone warning for reduced speed	3,844	12,520
	Spot treatment/weather conditions	168,021	43,283
	Speed zone warning	154,339	206,356
Vulnerable road users applications	Work zone alerts	19,731	66,880
	Infrastructure pedestrian detection	17,812	N/A
	At-grade rail crossing	1,314	N/A
Other applications	Lane departure warning	1,041,460	195,187

N/A = Not applicable.

There is some overlap in the crashes targeted by the application areas, and some of these crashes can be targeted by more than one application. For example, some crashes can be targeted by the curve speed warning and the spot treatment/weather conditions applications.

The following sections provide information on the estimated annual crashes that may be targeted by each application area based on the analyses of NASS GES data. Crashes are described as targeted crashes or unaddressed crashes with respect to V2I application areas. Targeted crashes are crashes that could potentially be eliminated through the deployment of a specific V2I application or set of applications (i.e., after determining the potential benefit of an application area assuming 100 percent effectiveness and 100 percent deployment). The actual number of crashes addressed will depend on the effectiveness of the application and the extent to which they are deployed. Unaddressed crashes are those that would not be eliminated even if a V2I application or set of applications were 100 percent effective and fully deployed. Unaddressed crashes might be covered through the development of new applications or by other technologies.

CHAPTER 4. INTERSECTION APPLICATIONS

4.1 RUNNING RED LIGHT

This application area is intended to target crashes that result from signal violations. The running red light application provides a warning to drivers who are in danger of violating the signal.

4.1.1 Associated Pre-Crash Scenarios

The running red light application targets both the single-vehicle and multi-vehicle pre-crash scenario red light running. All of the crashes in this pre-crash scenario were considered potential targets for this application area.

4.1.2 Magnitude of Problem

There were an estimated 234,881 annual national target crashes based on weighted NASS GES data, and the estimated total annual cost of these crashes was more than $13 billion (note that annual refers to 2005 through 2008).(1) Additionally, 45 percent of the target crashes resulted in fatalities or injuries.

4.1.3 Relevant Distributions

The distribution of target crashes by the six vehicle-type categories indicated that crashes involving two light vehicles represented 92 percent of the total crashes. All other vehicle types, including motorcycles, represented only a small portion (2 percent or less each) of the involved vehicles.

The distribution of target crashes by area type revealed that the majority of the crashes (78 percent) occurred in urban areas, and the remainder occurred in rural areas, indicating that signalized intersections are more prevalent in urban areas. The distribution of target crashes by posted speed limit indicated that the majority of the crashes (70 percent) occurred on roadways posted between 35 and 45 mi/h and were more prevalent in urban areas.

4.1.4 Relationships in HSIS Data

HSIS data from 2005 through 2007 were also investigated to determine the distribution of crash types by intersection traffic control.(2) While the NASS GES data indicated the magnitude of potential crashes impacted by the running red light application area, the HSIS analysis showed the magnitude of potential target crash types relative to other crash types at similar locations (i.e., the proportion of total signalized intersection collisions that could potentially be targeted by the application). There were 32,925 crashes identified at signalized intersections from the HSIS data in California from 2005 through 2007. The distribution by crash type showed that a large proportion of crashes at signalized intersections were broadside (angle), accounting for approximately 25.8 percent of crashes. A similar analysis was conducted for the 13,996 signalized intersection crashes from the HSIS data in Minnesota from 2005 through 2007. One of the leading crash types at signalized intersections was right-angle crashes, comprising 20.3 percent of signalized intersection crashes.

Of the 32,925 total crashes at signalized intersections in California from 2005 through 2007, 2,377 (7.2 percent) involved at least one heavy vehicle, and 775 (2.4 percent) involved at least one motorcycle. Fatal and severe injury crashes represented 1.9 percent of total crashes, 3.1 percent of heavy vehicle crashes, and 12.6 percent of motorcycle crashes at signalized intersections. Of those crashes involving at least one heavy vehicle at a signalized intersection, sideswipe crashes were the most prevalent (34.8 percent), followed by rear-end (28.6 percent) and broadside (18.9 percent). Of those crashes involving at least one motorcycle at a signalized intersection, broadside crashes were the most prevalent (28.4 percent), followed by rear-end (27.6 percent) and sideswipe (17.2 percent).

Of the 13,996 total crashes at signalized intersections in Minnesota from 2005 through 2007, 1,051 (7.5 percent) involved at least one heavy vehicle, and 153 (1.1 percent) involved at least one motorcycle. Similar to California, heavy vehicles and motorcycles were overrepresented in fatal and severe injury crashes at signalized intersections in Minnesota. Fatal and severe injury crashes represented 1.5 percent of total crashes, 2.3 percent of heavy vehicle crashes, and 11.1 percent of motorcycle crashes at signalized intersections. Of those crashes involving at least one heavy vehicle at a signalized intersection, rear-end crashes were the most prevalent (40.7 percent), followed by right-angle (18.9 percent) and sideswipe (18.8 percent). Of those crashes involving at least one motorcycle at a signalized intersection, rear-end crashes were the most prevalent (34.6 percent), followed by right-angle (18.3 percent) and other (18.3 percent).

4.2 RUNNING STOP SIGN

The running stop sign application area is intended to target crashes that result from stop sign violations at stop-controlled intersections. These intersections include two-way, four-way, and other stop-controlled intersections. The application provides a warning to drivers who are about to run a stop sign.

4.2.1 Associated Pre-Crash Scenarios

The running stop sign application area targets single-vehicle and multi-vehicle running stop sign pre-crash scenarios. All crashes in both scenarios are targeted for this application regardless of whether the intersection is two- or four-way stop-controlled. There are potentially other multi-vehicle crashes that result from a stop sign violation, but they were not coded as such by the police and are not included in these pre-crash scenarios. These crashes would have been included as straight crossing path at non-signals and turn at non-signals pre-crash scenarios. It is not possible to determine how many crashes in these pre-crash scenarios may be the result of stop sign violations versus other contributing factors, such as poor gap judgment; therefore, they were not counted in the estimate of targeted crashes. However, these pre-crash scenarios are targeted by the driver gap assistance at stop-control application addressed in section 4.4.

4.2.2 Magnitude of Problem

There were an estimated 44,424 annual national target crashes based on weighted NASS GES data, and the estimated total annual cost of these crashes was more than $2.0 billion. Additionally, 45 percent of all the target crashes resulted in fatalities or injuries.

4.2.3 Relevant Distributions

The distributions of target crashes by the six vehicle-type categories were considered for both single-vehicle and multi-vehicle crashes (multi-vehicle crashes referred to the first two vehicles involved). Crashes involving light vehicles represented the majority for both single-vehicle and multi-vehicle crashes. All other vehicle types represented only a small portion (2 percent or less each) of the involved vehicles.

The distribution of target crashes by area type indicated that the majority of multi-vehicle crashes (62 percent) occurred in urban areas, while the majority of single-vehicle crashes (59 percent) occurred in rural areas. This may highlight the need for different design considerations for applications in urban and rural areas.

4.2.4 Relationships in HSIS Data

HSIS data were investigated to determine the distribution of total crashes by intersection traffic control and area type.[2] While the NASS GES data indicated the magnitude of potential crashes impacted by this application, the HSIS analysis showed the prevalence of target intersections by area type and the magnitude of total crashes at those intersections. Based on the magnitude of total crashes at stop-controlled intersections, the HSIS intersection data analysis found that this application may be best targeted to two-way stop-controlled intersections. This was particularly true in rural areas, where crashes were more prevalent at two-way stop-controlled intersections compared to all-way stop-controlled intersections.

There were 35,758 crashes (51.7 percent of total) identified at two-way stop-controlled intersections from the HSIS data in California from 2005 through 2007. There were only 450 crashes (less than 1 percent of all intersection crashes) at all-way stop-controlled intersections in California. These results are based on total crashes (i.e., are not limited to specific crash types) and indicate the relative safety issue at two-way stop-controlled intersections when compared to all-way stop-controlled intersections.

A similar analysis identified 5,179 two-way stop-controlled intersection crashes (26.4 percent of total) from the HSIS data in Minnesota from 2005 through 2007. Similar to California, there were significantly fewer crashes (466 crashes, 2.4 percent of all intersection crashes) at all-way stop-controlled intersections. The distribution of two-way stop-controlled crashes in California and Minnesota by area type showed a large percentage (59.2 and 61.2 percent, respectively) of crashes in rural areas.

These results should be considered in the context of exposure. It may be expected that intersections with the greatest exposure (e.g., number of intersections and annual average daily traffic) will have the greatest number of crashes. In California and Minnesota, two-way stop-controlled intersections represented the greatest proportion of intersections from 2005 through 2007, accounting for 84 and 86 percent of all intersections in those States, respectively. All-way stop-controlled intersections accounted for less than 1 percent of all intersections by frequency and entering volume in both States. In California, both two-way and all-way stop-controlled intersections were more prevalent in rural areas, representing 73 percent of two-way stop-controlled intersections and 72 percent of all-way stop-controlled intersections. In Minnesota, two-way stop-controlled intersections were more prevalent in rural areas, accounting for 64 percent of all two-way stop-controlled intersections; however, all-way stop-controlled intersections were more prevalent in urban areas.

When compared to injuries at intersections with other traffic control types, two-way stop-controlled intersections in both California and Minnesota represented the greatest percentage of fatal and severe injury intersection crashes. In California, approximately 1.2 percent of two-way stop-controlled crashes resulted in fatalities, while 3.2 percent of these crashes resulted in severe injuries. In Minnesota, approximately 1.6 percent of two-way stop-controlled crashes resulted in fatalities, while 2.7 percent of these crashes resulted in incapacitating injuries.

Analysis of HSIS data by crash type showed a large number of angle and left-turn crashes at two-way stop-controlled intersections. The distribution by crash type in California indicated that 29.5 percent of crashes at two-way stop-controlled intersections were broadside (angle) type. California data did not include a specific crash type for left-turn crashes. Analysis of Minnesota data indicated that 49.7 percent of crashes at two-way stop-controlled intersections were right-angle crashes, and 6.8 percent were coded as left-turn crashes.

4.2.5 Potential Extension to Pedestrian and Bicycle Crashes

The running stop sign application area could potentially be extended to target vehicle-pedestrian crashes and vehicle-bicycle crashes at stop-controlled intersections. As a result, drivers would be warned of the presence of a crossing pedestrian or bicyclist, and pedestrians or bicyclists could be warned of a conflicting motor vehicle.

The single-vehicle pre-crash scenarios pedestrian/maneuver and bicyclist/maneuver were identified as target crashes for this application area. Specifically, the target crashes included crashes at stop-controlled intersections. Based on weighted GES data, there were an estimated 3,843 annual national target crashes, and the estimated total annual cost for these crashes was nearly $465 million.

4.3 DRIVER GAP ASSIST AT SIGNALIZED INTERSECTIONS

The driver gap assist at signalized intersections application area is intended to help drivers waiting to turn left at signalized intersections with permitted left turns through gap acceptance. The relevant crash type is a multi-vehicle crash involving a left-turning motor vehicle and a through motor vehicle.

4.3.1 Associated Pre-Crash Scenarios

This application targets the multi-vehicle pre-crash scenario left turn across path/opposite direction at signals. All of the crashes in this pre-crash scenario were considered potential targets for this application area. All crashes occurred at signalized intersections and involved a left-turning vehicle colliding with a through vehicle from the opposite direction. If the crash occurred because of a signal violation and not gap acceptance, it was included in a separate scenario.

4.3.2 Magnitude of Problem

There were an estimated 200,212 annual national target crashes based on weighted NASS GES data, and the estimated total annual cost of these crashes was more than $10.3 billion. Additionally, 44 percent of all the target crashes resulted in fatalities or injuries.

4.3.3 Relevant Distributions

Considering only the first two vehicles involved, the distribution of target crashes by the six vehicle-type categories indicated that crashes involving two light vehicles represented 94 percent of the total crashes. All other vehicle types accounted for only a small portion (2 percent or less each) of involved vehicles.

The distribution of target crashes by area type indicated that the majority of the crashes (77 percent) occurred in urban areas, and the remainder (23 percent) occurred in rural areas. This distribution reflects the prevalence of signalized intersections in urban areas.

4.3.4 Relationships in HSIS Data

Analysis of HSIS intersection data by area type confirmed the NASS GES analysis findings, which indicated the potential to impact a large number of signalized crashes in urban areas through the driver gap assist at signalized intersections application area despite the HSIS bias toward rural roads. There were 32,925 crashes identified at signalized intersections from the HSIS data in California from 2005 through 2007. The distribution by area type showed that crashes at signalized intersections occurred more frequently in urban areas: 83.5 percent of signalized intersection crashes occurred in urban areas compared to 16.5 percent in rural areas. A similar analysis was conducted for the 13,996 signalized intersection crashes from the HSIS data in Minnesota from 2005 through 2007. The majority of signalized intersection crashes were also in urban areas: 85 percent of signalized intersection crashes occurred in urban areas compared to 14.6 percent in rural areas. The remaining 0.4 percent of crashes occurred in area types coded as "other."

These results should be considered in the context of exposure. In California, signalized intersections were more prevalent in urban areas, representing 79 percent of intersections by number and 85 percent by entering volume. Additionally, 83.5 percent of crashes at signalized intersections occurred in urban areas. There was a similar trend in Minnesota, where signalized intersections in urban areas represented 83 percent of intersections by number and 79 percent by entering volume, as compared to 85 percent of the crashes.

4.4 DRIVER GAP ASSIST AT STOP-CONTROLLED INTERSECTIONS

The driver gap assist at stop-controlled intersections application area is intended to target crashes that result from poor gap acceptance at two-way stop-controlled intersections. These crashes include stop-controlled motor vehicles that are traveling straight or turning at an intersection. *Gap acceptance*, in this case, is defined as the process by which a driver on the minor road stops at the stop sign and then makes a maneuver (right or left turn) onto or across the major road. This process requires the driver to judge the speed of conflicting traffic and the adequacy of "gaps" in traffic to complete the maneuver.

4.4.1 Associated Pre-Crash Scenarios

The driver gap assist at stop-controlled intersections application area targets straight crossing path at non-signal and turn at non-signal multi-vehicle pre-crash scenarios, which include crashes at unsignalized intersections and driveways. This application area is targeted to the subset of crashes that occur at two-way stop-controlled intersections. Multi-vehicle crossing path crashes at two-way stop-controlled intersections can be classified as resulting from gap acceptance or stop sign violations. This application is intended for crashes resulting from poor gap acceptance and not from stop sign violations. The assumption is that the majority of cases in which the investigating officer coded the crash as a violation would involve a vehicle that failed to stop at the sign rather than a vehicle that stopped and then proceeded. Crashes resulting from stop sign violations (e.g., a driver is ticketed for violating a stop sign) were categorized in a separate pre-crash scenario, running stop sign.

4.4.2 Magnitude of Problem

There were an estimated 278,886 annual national target crashes based on weighted NASS GES data, and the estimated total annual cost of these crashes was nearly $18.3 billion. Additionally, 38 percent of the target crashes resulted in fatalities or injuries.

4.4.3 Relevant Distributions

Considering only the first two vehicles involved, the distribution of target crashes by the six vehicle-type categories indicated that crashes involving two light vehicles represented 93 percent of the total crashes. All other vehicle types represented only a small portion (2 percent or less each) of the involved vehicles. Crashes involving motorcycles accounted for 2 percent of multi-vehicle target crashes, which is slightly greater than the occurrence of motorcycles in all multi-vehicle crashes. Motorcycles represented 1.4 percent of all multi-vehicle crashes.

The distribution of target crashes by area type indicated that the majority of the crashes (68 percent) occurred in urban areas. Roadways with five or more approach lanes represented 34 percent of the crashes. This is particularly noteworthy because it underscores the need for assistance with gap acceptance when crossing wider approaches. Roadways with two approach lanes represented 46 percent of the crashes, which can likely be attributed to the prevalence of this lane configuration.

4.4.4 Relationships in HSIS Data

HSIS data were investigated to determine the distribution of crash severity by intersection traffic control. This application area addresses potentially severe crashes at two-way stop-controlled intersections. The HSIS data support that these intersections represent a greater percentage of fatal and severe crashes when compared to other intersections. Of the 35,758 crashes at two-way stop-controlled intersections in California from 2005 through 2007, 1,543 crashes (4.4 percent) were fatal or severe injury. There were relatively fewer fatal and severe injury crashes at signalized and all-way stop-controlled intersections in terms of both frequency and percentage. Of the 32,925 crashes at signalized intersections, 639 crashes (1.9 percent) were fatal or severe injury. Of the 450 crashes at all-way stop-controlled intersections, 14 crashes (3.1 percent) were fatal or severe injury.

A comparable analysis was conducted using the HSIS data in Minnesota from 2005 through 2007. Similar to California, the frequency and percentage of fatal and severe injury crashes were greater at two-way stop-controlled intersections than at signalized and all-way stop-controlled intersections. Of the 5,179 crashes at two-way stop-controlled intersections, 222 crashes (4.3 percent) were fatal or severe injury. There were 13,996 crashes at signalized intersections and 466 crashes at all-way stop-controlled intersections during the same period. Of these, 218 crashes at signalized intersections (1.5 percent) and 5 crashes at all-way stop-controlled intersection (1.1 percent) were classified as fatal or severe injury crashes.

Analysis of HSIS intersection data by area type showed the potential for this application area to be better targeted to rural areas; nearly 60 percent of crashes at two-way stop-controlled intersections in California occurred in rural areas. Similarly, 61.2 percent of crashes at two-way stop-controlled intersections in Minnesota occurred in rural areas.

Heavy vehicles and motorcycles should be considered in the design of this application. More than 9 percent of the crashes at two-way stop-controlled intersections from the California HSIS data involved at least one heavy vehicle, more than a quarter of which were broadside crashes. Similarly, approximately 4 percent of the two-way stop-controlled crashes involved at least one motorcycle, more than 30 percent of which were broadside crashes. These heavy vehicle and motorcycle crashes were more likely to result in a fatality than other crashes at two-way stop-controlled intersections. Similar distributions were also identified in the Minnesota data for heavy vehicles and motorcycles.

CHAPTER 5. SPEED APPLICATIONS

5.1 CURVE SPEED WARNING

The curve speed warning application area is intended to target crashes approaching horizontal curves on segments or interchange ramps that are speed-related. The application will provide a warning to drivers approaching a curve or ramp at an unsafe speed.

5.1.1 Associated Pre-Crash Scenarios

The curve speed warning application area targets several pre-crash scenarios including the following single-vehicle scenarios:

- Control loss/no vehicle action.
- Control loss/vehicle action when the vehicle action is not an intersection maneuver such as turning right or left.
- Road edge departure/no maneuver.
- Road edge departure/maneuver when the vehicle maneuver is not an intersection maneuver.
- Opposite direction/no maneuver.
- Rollover.
- Object contacted/no maneuver.

It also targets the following multi-vehicle pre-crash scenarios:

- Control loss/no vehicle action.
- Control loss/vehicle action when the vehicle action is not an intersection maneuver.
- Road edge departure/no maneuver.
- Opposite direction/no maneuver.

For both single-vehicle and multi-vehicle scenarios, speed-related crashes that occurred on a curve or an interchange ramp are targeted for this application.

5.1.2 Magnitude of Problem

There were an estimated 168,993 annual national target crashes based on weighted NASS GES data, and the estimated total annual cost of these crashes was more than $29 billion. This included 146,906 crashes at curve locations and 22,086 crashes at interchange ramps. Additionally, 44 percent of the target crashes resulted in fatalities or injuries.

5.1.3 Relevant Distributions

The distributions of target crashes by the six vehicle-type categories were considered for both single-vehicle and multi-vehicle crashes, with the latter referring to the first two vehicles involved. The overwhelming majority of the crashes involved light vehicles as expected. Vehicles in the "other vehicles" category represented 6 percent of the single-vehicle crashes, while trucks (single-unit and combination-unit) represented 12 percent of the multi-vehicle crashes. Additionally, 5 percent of the target single-vehicle crashes involved motorcycles, which was approximately twice the occurrence of motorcycles in all single-vehicle crashes (2.7 percent). Motorcycles were also overrepresented in multi-vehicle crashes, accounting for 4.3 percent of the target crashes but only 1.4 percent of all multi-vehicle crashes.

The distribution of target curve crashes by area type was considered for both single-vehicle and multi-vehicle crashes. The number of curve crashes was greater in urban areas for both crash types when compared to rural areas. This was somewhat unexpected because single-vehicle crashes are generally a greater concern in rural areas.

The distribution of crashes by number of lanes and land use indicated that two-lane roadways represented the majority of crashes for single-vehicle urban crashes (70 percent), single-vehicle rural crashes (85 percent), multi-vehicle urban crashes (63 percent), and multi-vehicle rural crashes (74 percent).

5.1.4 Relationships in HSIS Data

HSIS data were explored from 2005 through 2007 in Illinois and Washington to develop measures of exposure for curves by area type. While there were generally more curves and miles of curves in rural areas (possibly due to the rural sampling bias), the vehicle-miles traveled on curves were greater in urban areas. Traditionally, single-vehicle lane-departure crashes, often associated with curves, are a concern in rural areas. However, this concern is usually based on comparisons of this crash type to other crash types on rural roads (not in comparison to urban areas). While intersection crashes are traditionally thought of as the major urban safety concern, these results indicated that curve crashes in urban areas can also benefit from the curve speed warning application area.

HSIS data were also investigated to determine the distribution of curves by degree of curve and severity. While the GES data indicated the magnitude of potential crashes impacted by speed advisory and warning approaching horizontal curves, the HSIS data were used to help identify the curves where most of the crashes occurred.

Although the frequency of crashes is greater for tangents when compared to curves, an analysis of HSIS curve data revealed that crashes on curves tend to be more severe than those on tangent segments of the roadway. In Washington, there were 31,419 crashes identified on curves and 113,303 crashes identified on tangents from the HSIS data from 2005 through 2007. Approximately 0.9 percent of the curve crashes resulted in a fatality, 2.3 percent resulted in an incapacitating injury, and 10.9 percent resulted in a non-incapacitating injury. These percentages were higher than the respective percentages for crashes on tangents: 0.4 percent fatal crashes, 1.7 percent incapacitating injury crashes, and 8.9 percent non-incapacitating injury crashes by comparison.

Degree of curve measures the sharpness of the curve and is inversely related to curve radius (the higher the degree, the sharper the curve). The degree of curvature category with the most severe injury crashes was 10.01 to 20.0 degrees. For this category, 1.2 percent of crashes resulted in a fatality, 3.4 percent resulted in an incapacitating injury, and 13.9 percent resulted in a non-incapacitating injury.

5.2 WORK ZONE WARNING FOR REDUCED SPEED IN WORK ZONES

The work zone warning for reduced speed in work zones application area is intended to target speed-related crashes in work zones. Speeding drivers will be provided with a warning in active work zones.

5.2.1 Associated Pre-Crash Scenarios

Speed-related crashes are not specific to any particular pre-crash scenario but are found in multiple scenarios. All pre-crash scenarios were considered targets for this application. Work zones were the only speed zones that could be explicitly identified in the NASS GES data.

5.2.2 Magnitude of Problem

There were an estimated 16,364 annual national target crashes based on weighted NASS GES data, and the estimated total annual cost of these crashes was more than $1.3 billion. Additionally, 33 percent of the target crashes resulted in fatalities or injuries.

5.2.3 Relevant Distributions

Considering only the first two vehicles involved, the distribution of target crashes by the six vehicle-type categories indicated that crashes only involving light vehicles represented 86 percent of the total crashes. Additionally, 7 percent of single-vehicle target crashes involved combination-unit trucks, and 5 percent involved motorcycles. This was an overrepresentation of motorcycles by almost double because motorcycles only accounted for 2.7 percent of all single-vehicle crashes. All other vehicle types represented only a small portion (2 percent or less each) of the involved vehicles.

The distribution of target crashes by area type indicated that the majority of the crashes (55 percent) occurred in urban areas. Roadways with two lanes represented 46 percent of the crashes.

5.3 SPOT TREATMENT/WEATHER CONDITIONS

The spot treatment/weather conditions application area is intended to warn drivers to slow down for rain, ice, snow, or other adverse weather conditions that impact the roadway environment. These applications are envisioned to be applied to areas with a known history of weather-related crashes such as icy bridges or tangents in low-lying areas that flood during heavy rain.

5.3.1 Associated Pre-Crash Scenarios

The spot treatment/weather conditions application area targets crashes related to speeding during adverse weather conditions (based on both the surface conditions and the reported weather) for the single-vehicle and multi-vehicle pre-crash scenarios control loss/vehicle action and control loss/no vehicle action.

5.3.2 Magnitude of Problem

Based on weighted NASS GES data, there were an estimated 211,304 annual national target crashes, with an estimated total annual cost of $13.0 billion. Additionally, 28 percent of all the target crashes resulted in fatalities or injuries. (Note that these estimates include all locations, and targeting only selected locations decreases the estimates.)

5.3.3 Relevant Distributions

The distributions of target crashes by the six vehicle-type categories were considered for both single-vehicle and multi-vehicle crashes, with the latter referring to the first two vehicles involved. Vehicles in the "other vehicles" category represented 11 percent of the multi-vehicle crashes, while trucks (single- and combination-unit) represented 9 percent of the multi-vehicle crashes.

The distribution of target crashes by area type was considered for both single-vehicle and multi-vehicle crashes. The number of adverse weather crashes related to speeding was greater in urban areas for both single vehicle crashes (61 percent for urban) and multi-vehicle crashes (72 percent for urban) when compared to those in rural areas.

5.4 SPEED ZONE WARNING

The speed zone warning application area is intended to warn drivers of reduced speed limits on tangents (e.g., on the approaches to small towns).

5.4.1 Associated Pre-Crash Scenarios

Speed-related crashes are not specific to any particular pre-crash scenario but are found in multiple scenarios. All pre-crash scenarios were considered targets for this application, and specific speed zones were used to identify target crashes. The NASS GES database does not explicitly identify speed zones. As a result, posted speed limits were analyzed for urban and rural locations based on statutory speed limits in the United States in section 11-802 of the *Uniform Vehicle Code* (UVC).[17] UVC establishes a statutory speed limit of 55 mi/h in locations other than urban districts and 35 mi/h in urban districts. Roadways with posted speed limits lower than these statutory speed limits may have been established as "speed zones." In this study, posted speed limits of 30 mi/h and under and 50 mi/h and under were considered speed zones for urban and rural areas, respectively, excluding interstate highway locations. It is likely that using this method for identifying speed zones overestimates the number of speed zones, therefore overestimating the target crashes.

5.4.2 Magnitude of Problem

There were an estimated 360,694 annual national target crashes based on weighted NASS GES data, and the estimated total annual cost of these crashes was more than $28.5 billion. Additionally, 38 percent of the target crashes resulted in fatalities or injuries.

5.4.3 Relevant Distributions

Considering only the first two vehicles involved, the distribution of target crashes by the six vehicle-type categories indicated that crashes involving light vehicles represented 92 percent of single-vehicle crashes and 99 percent of multi-vehicle crashes. More than 4 percent of single-vehicle target crashes were motorcycles, which was an overrepresentation of motorcycles by almost double because they only accounted for 2.7 percent of all single-vehicle crashes. All other vehicle types represented only a small portion (2 percent or less each) of the involved vehicles.

The distribution of target crashes by area type indicated that the majority of the crashes (62 percent) occurred in rural areas. Roadways with two lanes represented more than half (56 percent) of the crashes.

CHAPTER 6. VULNERABLE ROAD USERS

6.1 WORK ZONE ALERTS

The work zone alerts application area is intended to warn drivers of changes in traffic patterns due to construction (e.g., lane closures). It would be targeted to crashes in and approaching work zones. The application area is similar to the work zone warning for reduced speed in work zones but would not be limited to crashes involving speeding.

6.1.1 Associated Pre-Crash Scenarios

The work zone alerts application area targets crashes in and approaching work zones, including any crash occurring in or related to a work zone as identified by a work zone variable in the NASS GES database. The distribution of pre-crash scenarios indicates that several pre-crash scenarios are common in work zone related crashes. The pre-crash scenarios road edge departure/no maneuver (28 percent), control loss/no vehicle action (19 percent), and object contacted/no maneuver (14 percent) represented the largest proportions of single-vehicle work zone crashes. For multi-vehicle crashes, the leading pre-crash scenarios were rear-end/LVS (25 percent), changing lanes/same direction (16 percent), and rear-end/LVD (14 percent).

6.1.2 Magnitude of Problem

Based on weighted NASS GES data, there were an estimated 86,611 annual national target crashes, with an estimated total annual cost of more than $4.5 billion. Additionally, 29 percent of all the target crashes resulted in fatalities or injuries.

6.1.3 Relevant Distributions

The NASS GES database provides information on the relation of the crash location to the work zone. According to the data, the majority of single-vehicle and multi-vehicle work zone crashes occurred in work or construction zones. Only 2 percent of the single-vehicle crashes and 5 percent of the multi-vehicle crashes did not occur in the work zone, but the first harmful event was related to the work zone. However, the location of a large proportion (43 percent) of work zone-related crashes (i.e., crashes in the work zone or on the approach) was not identified in the database.

The distribution of target crashes by the six vehicle-type categories was considered for both single-vehicle and multi-vehicle crashes, with the latter referring to the first two vehicles involved. While the majority of the crashes (86 percent) involved light vehicles, trucks (single- and combination-unit) represented 8 percent of both single-vehicle and multi-vehicle crashes. Motorcycles accounted for more than 3 percent of single-vehicle target crashes, which was higher than the percentage of motorcycle crashes for all single-vehicle crashes (1.4 percent), indicating that motorcycles were overrepresented in work zone crashes.

The distribution of target crashes by area type was considered for both single-vehicle and multi-vehicle crashes. The number of work zone crashes was greater in urban areas for both single-vehicle crashes (54 percent) and multi-vehicle crashes (63 percent) when compared to those in rural areas.

The distribution of target crashes by posted speed limit was considered for both single-vehicle and multi-vehicle crashes. It is unknown whether the data indicate the normal posted speed limits or the reduced work zone speed limits. A greater proportion of single-vehicle crashes occurred on higher speed limit roads (55 mi/h or greater) and low speed limit roads (25 mi/h or less) when compared to multi-vehicle crashes. At moderate speed limits (30–50 mi/h), multi-vehicle crashes represented a larger proportion of work zone crashes than single-vehicle crashes.

The distribution of target crashes by the number of lanes was considered for both single-vehicle and multi-vehicle crashes. The majority of work zone-related crashes occurred on roadways with three lanes or less (79 percent). Single-vehicle crashes represented a larger proportion of crashes on roadways with fewer lanes compared with multi-vehicle crashes.

6.2 INFRASTRUCTURE PEDESTRIAN DETECTION

The infrastructure pedestrian detection application area is intended to detect pedestrians and allows for changes in the walk phase of a signal (e.g., to allow more time for those with mobility impairments to cross). This application targets pedestrian crashes at signalized crossings including intersections and midblock crossings.

6.2.1 Associated Pre-Crash Scenarios

This application area targets single-vehicle and multi-vehicle pedestrian/maneuver and pedestrian/no maneuver pre-crash scenarios. Target crashes were limited to crashes that occurred at intersections and midblock locations with signalized control.

6.2.2 Magnitude of Problem

Based on weighted NASS GES data, there were an estimated 17,811 annual national target crashes, with an estimated total annual cost of more than $3.3 billion. Additionally, 99 percent of all the target crashes resulted in fatalities or injuries. Note that the estimated target is based on 506 observed crashes. As a result, it is less reliable than other estimates due to the small sample size.

6.2.3 Relevant Distributions

The relevant distribution of the single-vehicle target crashes is presented in this section. Only single-vehicle target crashes are included because they constitute the majority of the target crashes. The majority of single-vehicle target crashes occurred in urban areas (86 percent) compared to rural areas (14 percent).

According to the relationship to junction description in NASS GES, the target crashes mainly occurred at intersections (48 percent) or were intersection-related (51 percent).[1] According to non-motorist location description in NASS GES, almost half of pedestrian crashes occurred in a crosswalk (49 percent) or in the roadway (43 percent) at the intersection.[1] Crashes at mid-block crossings, (i.e., not located at intersections) represented less than 7 percent of target crashes. It is likely that some of the crashes described as occurring in the intersection or intersection-related may have been signalized midblock crossings that were considered intersections. As a result, midblock crashes may be an underrepresented crash typology.

The distribution of crash types shows that more than half (53 percent) occurred between a pedestrian and a turning or merging vehicle. Light vehicles were involved in the majority (92 percent) of crashes. Only 2 percent of crashes involved transit vehicles, less than 2 percent involved trucks, and 4 percent of crashes involved other vehicles.

The distribution of lighting conditions for target crashes shows that although the majority of crashes occurred during daylight (65 percent), approximately 30 percent occurred during dark conditions (both dark (3 percent) and dark but lighted conditions (27 percent)).

Target crashes occurred most often on moderate speed limit roadways. A total of 20 percent were on roadways posted at 25 mi/h or less, more than 60 percent of crashes were roadways posted 30–35 mi/h, and 19 percent were roadways posted 40–45 mi/h.

Almost half of target crashes (48 percent) occurred on roads with six or more lanes, while less than one-fourth of the crashes were on one- or two-lane roads. This distribution reflects the increased potential for pedestrian crashes along wider, more vehicle-oriented roadways.

6.3 AT-GRADE RAIL CROSSING

This application area is intended to warn drivers of approaching trains, including light and heavy rail trains, for at-grade crossings.

6.3.1 Associated Pre-Crash Scenarios

The at-grade rail crossing application area targets single-vehicle and multi-vehicle crashes involving rail vehicles by providing warning of an approaching rail vehicle. This application is not limited by pre-crash scenario. Target crashes for this application include any crashes involving one or more vehicles and a train.

6.3.2 Magnitude of Problem

Based on weighted NASS GES data, there were an estimated 1,314 annual national target crashes, with an estimated total annual cost of more than $653 million. Additionally, 41 percent of all the target crashes resulted in fatalities or injuries. Note that the estimated target is based on 23 observed crashes. As a result, it is less reliable than other estimates. All but one of the observed crashes was a single-vehicle crash with a train.

6.3.3 Relevant Distributions

The distribution of traffic control type indicates that single-vehicle target crashes were split nearly evenly between active traffic control devices with gates, flashing lights, or traffic signals (50 percent) and passive devices including stop signs and crossbucks (46 percent). Few target crashes (less than 4 percent total) occurred at rail crossings without control or with other traffic control types.

The distribution of the six vehicle-type categories was considered for single-vehicle target crashes. While the majority of target crashes involved single vehicles (79 percent), 21 percent of crashes involved trucks, including single- and combination-unit trucks.

The distribution of the number of lanes for single-vehicle target crashes indicated that more than 80 percent of target crashes occurred on roadways with two or less lanes. Additionally, almost 90 percent of crashes occurred during favorable weather, while 8 percent of crashes occurred during rainy conditions. Finally, the distribution of land showed that the majority of single-vehicle crashes were in urban areas (80 percent), while only 20 percent occurred in rural areas.

CHAPTER 7. OTHER APPLICATION AREAS

Currently, there are two identified V2I for safety applications in the other application area category: secondary accident warning and lane departure warning. This section only describes the lane departure warning application. The secondary accident warning application could not be analyzed with NASS GES data because it is only a sample of crashes and not a comprehensive set in the database.

7.1 LANE DEPARTURE CRASHES

The lane departure crashes application area is intended to warn drivers that they are about to unintentionally leave their lane or that they have unintentionally left their lane.

7.1.1 Associated Pre-Crash Scenarios

The application area targets single-vehicle and multi-vehicle pre-crash scenarios involving lane departure. It targets the same pre-crash scenarios as the speed curve warning application area; however, it is not limited to curve locations or speed-related crashes.

7.1.2 Magnitude of Problem

Based on weighted NASS GES data, there were an estimated 1,236,647 annual national target crashes, including more than 1 million single-vehicle crashes. The estimated cost of these crashes was more than $145 billion. Additionally, 35 percent of all the lane departure crashes resulted in fatalities or injuries.

7.1.3 Relevant Distributions

The majority of target crashes (92 percent) occurred on segments (62 percent occurred on tangent segments, and 30 percent occurred on curve segments). This is notable because lane departure crashes are not limited to curve locations.

While the majority of lane departure crashes occurred in urban areas (57 percent), more than 500,000 lane departure crashes occurred in rural areas, comprising the remaining 43 percent. Speed was a factor in more urban area crashes (18 percent) in comparison to rural areas (14 percent).

In total, 64 percent of all target crashes occurred on two-lane roads. Single vehicles had a slightly higher crash frequency (65 percent) than multi-vehicle crashes (59 percent).

CHAPTER 8. UNADDRESSED CRASHES

Crashes identified in the NASS GES data that are not targeted by one or more of the current V2I application areas mentioned previously are considered unaddressed crashes. These crashes can be explored to identify other potential applications. This chapter provides information on these crashes.

8.1 DISTRIBUTION BY PRE-CRASH SCENARIOS

Table 9 and table 10 present the distribution and cost information of total and unaddressed crashes from NASS GES data sorted by pre-crash scenario for single-vehicle and multi-vehicle crashes, which are presented separately. The second row of table 9 indicates that for vehicle failure, unaddressed crashes represent 8 percent of total unaddressed crash costs, and 98 percent of the total crash cost for this scenario remains unaddressed. Pedestrian/no maneuver is the leading unaddressed single-vehicle pre-crash scenario, followed by cyclist/no maneuver and animal/no maneuver. Collectively, these three pre-crash scenarios represent 56 percent of the costs of unaddressed single-vehicle crashes. Unaddressed pedestrian, bicyclist, and animal pre-crash scenarios represent 67 percent of the unaddressed crash costs for single-vehicle crashes.

The distribution of unaddressed multi-vehicle crashes differed from the distribution of unaddressed single-vehicle crashes. Rear-end/LVS was the leading multi-vehicle pre-crash scenario followed by straight crossing path at non-signal and left turn across path/opposite direction at non-signal. Collectively, these three pre-crash scenarios represented 50 percent of the costs of unaddressed multi-vehicle crashes. The five rear-end pre-crash scenarios represented nearly 50 percent of the unaddressed multi-vehicle crashes and 44 percent of the unaddressed multi-vehicle crash costs. The Volpe report on frequency of target crashes suggests V2V and AV applications as the primary strategies for rear-end crashes.[9]

The annual cost of unaddressed crashes was $136.9 billion, which includes all single-vehicle and multi-vehicle crashes. The leading unaddressed pre-crash scenarios are discussed in detail in the following sections.

Table 9. Single-vehicle unaddressed crashes by pre-crash scenario.

Pre-Crash Scenario	Total Crash Frequency	Unaddressed Crash Frequency	Unaddressed Cost (in millions of dollars)	Percent of Unaddressed Total Cost	Percent of Scenario Total Cost Unaddressed
1. No driver present	602	598	41	0	99
2. Vehicle failure	38,894	37,419	3,540	8	98
3. Control loss/vehicle action	77,173	24,145	1,446	3	23
4. Control loss/no vehicle action	457,714	0	0	0	0
5. Running red light	868	0	0	0	0
6. Running stop sign	3,586	0	0	0	0
7. Road edge departure/maneuver	85,141	56,215	1,718	4	51
8. Road edge departure/no maneuver	417,076	0	0	0	0
9. Road edge departure/backing	85,540	83,596	1,093	2	96
10. Animal/maneuver	17,844	17,735	172	0	99
11. Animal/no maneuver	295,063	291,390	3,936	9	95
12. Pedestrian/ maneuver	20,629	10,184	2,363	5	63
13. Pedestrian/ no maneuver	40,603	31,858	15,525	35	86
14. Cyclist/maneuver	21,022	20,629	2,222	5	99
15. Cyclist/ no maneuver	28,757	28,288	5,330	12	99
16. Backing into vehicle	371	371	4	0	100
18. Parking/same direction	163	147	10	0	83
19. Changing lanes/same direction	30,751	29,489	1,345	3	94
21. Opposite direction/maneuver	1,920	1,875	67	0	43
22. Opposite direction/no maneuver	25,593	0	0	0	0
23. Rear-end/striking maneuver	2,736	2,493	204	0	96
25. Rear-end/lead vehicle moving at lower constant speed (LVM)	2,131	1,746	201	0	92

Pre-Crash Scenario	Total Crash Frequency	Unaddressed Crash Frequency	Unaddressed Cost (in millions of dollars)	Percent of Unaddressed Total Cost	Percent of Scenario Total Cost Unaddressed
26. Rear-end/LVD	7,771	6,828	674	2	92
27. Rear-end/LVS	8,057	7,498	284	1	90
31. SCP at non-signal	3,773	3,642	127	0	98
32. Turn at non-signal	7,572	7,193	315	1	94
33. Evasive maneuver/maneuver	3,624	3,486	148	0	97
34. Evasive maneuver/no maneuver	18,363	17,268	790	2	94
35. Rollover	6,126	0	0	0	0
36. Non-collision no impact	21,171	20,030	1,569	4	97
37. Object contacted/maneuver	68,220	66,574	930	2	92
38. Object contacted/no maneuver	78,808	0	0	0	0
Total	1,877,663	770,697	44,054	100	27

Note: Pre-crash scenarios for which there were no annual observed crashes were omitted from this table.

Table 10. Multi-vehicle unaddressed crashes by pre-crash scenario.

Pre-Crash Scenario	Total Crash Frequency	Unaddressed Crash Frequency	Unaddressed Cost (in millions of dollars)	Percent of Unaddressed Total Cost	Percent of Scenario Total Cost Unaddressed
1. No driver present	0	0	0	0	N/A
2. Vehicle failure	11,881	11,613	1,210	1	98
3. Control loss/vehicle action	31,332	534	8	0	1
4. Control loss/no vehicle action	63,080	0	0	0	0
5. Running red light	234,013	0	0	0	0
6. Running stop sign	40,838	0	0	0	0
7. Road edge departure/maneuver	1,479	1,394	162	0	97
8. Road edge departure/no maneuver	4,299	0	0	0	0
9. Road edge departure/backing	0	0	0	0	N/A
10. Animal/maneuver	404	404	8	0	100
11. Animal/no maneuver	6,065	5,645	344	0	93
12. Pedestrian/maneuver	646	641	22	0	98
13. Pedestrian/no maneuver	2,861	2,406	862	1	94
14. Cyclist/ maneuver	155	89	7	0	73
15. Cyclist/ no maneuver	500	438	96	0	99
16. Backing into vehicle	130,865	126,724	1,315	1	97
17. Turning/same direction	199,311	191,328	5,565	6	96
18. Parking/same direction	38,088	37,017	928	1	98
19. Changing lanes/same direction	309,933	295,994	6,189	7	96
20. Drifting/same lane	110,959	106,690	2,932	3	93
21. Opposite direction/maneuver	8,384	7,961	1,923	2	84

Pre-Crash Scenario	Total Crash Frequency	Unaddressed Crash Frequency	Unaddressed Cost (in millions of dollars)	Percent of Unaddressed Total Cost	Percent of Scenario Total Cost Unaddressed
22. Opposite direction/no maneuver	97,565	0	0	0	0
23. Rear-end/striking maneuver	80,087	74,510	1,872	2	93
24. Rear-end/lead vehicle accelerating (LVA)	22,049	19,658	619	1	89
25. Rear-end/LVM	199,714	180,858	8,445	9	93
26. Rear-end/LVD	386,480	346,492	8,911	10	91
27. Rear-end/LVS	930,045	819,513	21,094	23	88
28. LTAP/OD at signal	200,212	0	0	0	0
29. Turn right at signal	30,980	30,251	957	1	97
30. Left turn across path/opposite direction at non-signal	182,574	178,663	11,260	12	95
31. SCP at non-signal	641,880	360,234	14,037	15	43
32. Turn at non-signal	38,788	29,229	570	1	81
33. Evasive maneuver/maneuver	8,936	8,317	269	0	93
34. Evasive maneuver/no maneuver	28,408	26,508	1,504	2	96
35. Rollover	450	443	409	0	100
36. Non-collision no impact	15,318	14,962	262	0	96
37. Object contacted/maneuver	595	507	29	0	92
38. Object contacted/no maneuver	9,220	8,755	369	0	96
39. Hit and run	3,551	3,547	64	0	91
40. Other—rear-end	1,516	1,427	19	0	98
41. Other—sideswipe	1,875	1,860	31	0	89

Pre-Crash Scenario	Total Crash Frequency	Unaddressed Crash Frequency	Unaddressed Cost (in millions of dollars)	Percent of Unaddressed Total Cost	Percent of Scenario Total Cost Unaddressed
43. Other—turn across path	836	836	4	0	100
44. Other—turn into path	1,417	1,417	21	0	100
46. Other	22,347	22,016	527	1	97
Total	4,099,936	2,918,881	92,846	100	53

N/A = Not applicable.
Note: Pre-crash scenarios for which there were no annual observed crashes were omitted from this table.

8.2 CHARACTERISTICS OF LEADING UNADDRESSED CRASHES BY PRE-CRASH SCENARIO

8.2.1 Single-Vehicle Pedestrian Crashes

A total of 40 percent of unaddressed costs for single-vehicle crashes were represented by two pedestrian pre-crash scenarios, pedestrian/maneuver and pedestrian/no maneuver, with the latter being the more prevalent of the two. The estimated total annual cost of unaddressed single-vehicle pedestrian crashes was more than $17.8 billion. As stated in the Volpe report, these two crash scenarios are primarily targeted by AV applications, with the V2I applications only addressing crashes that occur at crosswalks.[9]

The locations of these unaddressed pedestrian crashes are presented in table 11. There were no unaddressed pedestrian crashes at signalized intersections because those crashes are targeted by one of the currently identified applications and were previously discussed in this report. Intersections represented 35 percent of unaddressed single-vehicle pedestrian crashes, while the majority (58 percent) were non-junction crashes. The remaining crashes occurred at driveways/alleys (6 percent) and other locations. Additionally, 10 percent of the unaddressed pedestrian crashes occurred at stop-controlled intersections, which could potentially be targeted through the extension of the driver gap assist at stop-controlled intersections application as discussed in section 4.4 of this report.

Notably, the segment crashes represented the more severe crashes. Although segments represented 58 percent of the crashes, they represented 97 percent of the fatalities.

Table 11. Distribution of crash location for annual national (weighted) unaddressed pedestrian crashes.

Location of Crash		Crashes	Percent
Intersections	Signalized	0	0
	Stop-controlled	4,346	10
	Other Intersections	10,707	25
Segments	Tangents	23,331	55
	Curves	1,092	3
Driveways	Tangents	2,520	6
	Curves	47	0
Total		42,043	100

In total, 77 percent of these crashes occurred in urban areas. The majority of crashes also occurred on moderate speed roadways, with two-thirds of those crashes occurring on roadways with posted speeds limits of 25–35 mi/h. Crashes mainly occurred on two-lane roadways (41 percent).

8.2.2 Single-Vehicle Bicycle Crashes

In total, 17 percent of the total unaddressed costs for single-vehicle crashes were represented by two bicycle pre-crash scenarios, cyclist/maneuver and cyclist/no maneuver, with the latter being the more prevalent of the two. The estimated total annual cost of unaddressed single-vehicle bicycle crashes was more than $7.5 billion. The primary strategies proposed for addressing cyclist crashes are AV applications, as reported in the Volpe study.[9]

Table 12 presents the number and percentage of crashes based on location of unaddressed single-vehicle bicycle crashes. Intersection-related crashes represented 64 percent of unaddressed single-vehicle bicycle crashes, 21 percent of crashes were non-junction crashes, and 15 percent occurred at driveways/alleys.

Table 12. Distribution of crash location for annual national (weighted) unaddressed bicycle crashes.

Location of Crash		Crashes	Percent
Intersections	Signalized	12,520	26
	Stop-controlled	10,870	22
	Other Intersections	7,810	16
Segments	Tangents	9,429	19
	Curves	886	2
Driveways	Tangents	7,221	15
	Curves	181	0
Total		48,917	100

Over 70 percent of the unaddressed bicycle crashes occurred in urban areas. The majority of crashes also occurred on moderate-speed roadways, with 70 percent of the crashes occurring on roadways with posted speeds limits of 25–35 mi/h. Additionally, 40 percent of the crashes occurred on two-lane roadways.

8.2.3 Single-Vehicle Animal Crashes

A total of 9 percent of the total unaddressed single-vehicle crashes were represented by two animal pre-crash scenarios, animal/maneuver and animal/no maneuver, with the latter being the more prevalent of the two. While 91 percent of the unaddressed animal crashes resulted in no injury, the estimated total annual cost of unaddressed animal crashes was more than $4.1 billion due to the large frequency of these crashes. Similar to cyclist crashes, AV applications are proposed as strategies for targeting animal crashes.(9)

Over half of the unaddressed animal crashes (57 percent) occurred in rural areas, while the remaining 43 percent occurred in urban areas, indicating that animal crashes do not occur in just one area type (see table 13). The distribution of animal crashes by location (tangent and curve) and area type indicated that the crashes predominately occurred on tangent sections for both urban and rural locations (88 and 90 percent, respectively).

Table 13. Distribution of area type for annual national (weighted) unaddressed animal crashes.

Area Type	Crashes	Percent
Urban	133,695	43
Rural	175,430	57
Total	309,125	100

The distribution of vehicle type for single-vehicle animal crashes indicated that light vehicles were involved in 95 percent of the crashes. Other vehicles accounted for 2 percent of the crashes. Each of the remaining vehicle types accounted for 1 percent or less of the total animal crashes.

8.2.4 Rear-End Crashes

A total of 44 percent of the total unaddressed multi-vehicle crashes were represented by five multi-vehicle rear-end pre-crash scenarios: rear-end/striking maneuver, rear-end/LVA, rear-end/ LVM, rear-end/LVD, and rear-end/LVS. The latter pre-crash scenario was the most prevalent of the five. The estimated total annual cost of unaddressed rear-end crashes was more than $40.9 billion. As previously mentioned, the majority of rear-end crashes are addressed by V2V and AV applications, which was a main cause for the high number of unaddressed read-end crashes in the Volpe report.(9) However, there were a substantial number of rear-end crashes targeted by the speed zone, work zone, and speed work zone V2I applications.

Table 14 presents the distribution of location for unaddressed crashes with urban and rural locations combined. Approximately half of the crashes occurred at intersection locations, and half occurred on roadway segments. The distribution by area type, shown in table 15, indicates that 76 percent of the crashes occurred in urban areas.

Table 14. Distribution of crash location for annual national (weighted) unaddressed rear-end crashes.

Location of Crash		Crashes	Percent
Intersections	Signalized	442,037	31
	Stop-controlled	50,377	3
	Other intersections	199,728	14
Segments	Tangents	679,041	47
	Curves	69,848	5
Total		1,441,030	100

Table 15. Distribution of area type for annual national (weighted) unaddressed rear-end crashes.

Area Type	Crashes	Percent
Urban	1,094,013	76
Rural	346,936	24
Unknown	81	0
Total	1,441,030	100

The distribution of vehicle type for multi-vehicle rear-end crashes indicated that crashes involving only light vehicles represented 93 percent of the crashes. Trucks, including single-unit and combination-unit vehicles, constituted 4 percent of rear-end crashes.

8.2.5 Straight Crossing Path Crashes at Non-Signals

A total of 15 percent of the total unaddressed multi-vehicle crashes were represented by the pre-crash scenario straight crossing path crashes at non-signals. The estimated total annual cost of these target crashes was more than $14 billion.

Table 16 presents the distribution of locations of unaddressed crashes. Notably, 53 percent of unaddressed straight crossing path at non-signal crashes occurred at driveways/alleys. The Volpe report proposes V2I applications for straight crossing path crashes at intersections and V2V applications for the straight crossing path crashes at non-intersections such as driveways.[9] Table 17 shows the distribution of these crashes by area type.

Table 16. Distribution of crash location for annual national (weighted) straight crossing path crashes at non-signals.

Location of Crash		Crashes	Percent
Intersections	Flashing signals	13,901	4
	Stop-controlled	61,258	17
	Other intersections	80,276	22
Segments	Tangents	10,162	3
	Curves	1,731	0
Driveways	Tangents	184,152	51
	Curves	8,754	2
Total		360,234	100

Table 17. Distribution of area type for annual national (weighted) straight crossing path crashes at non-signals.

Area Type	Crashes	Percent
Urban	265,686	74
Rural	94,548	26
Total	360,234	100

The distribution of vehicle type for multi-vehicle, straight crossing path crashes at non-signals indicated that crashes only involving light vehicles represented 91 percent of crashes. Trucks, including single-unit and combination-unit vehicles, were involved in 4 percent of the crashes.

8.2.6 Left Turn Across Path/Opposite Direction Crashes at Non-Signals

The pre-crash scenario left turn across path/opposite direction at non-signals represented a total of 12 percent of the total unaddressed multi-vehicle crashes. The estimated total annual cost of these target crashes was more than $11.2 billion. The Volpe report proposes V2I applications only address intersection crashes for this pre-crash scenario, while V2V applications address all remaining crashes.(9)

Table 18 presents the distribution of locations of unaddressed crashes. While the majority (60 percent) of the unaddressed left turn across path/opposite direction at non-signal crashes occurred at intersection or intersection related locations, 37 percent occurred at driveways/alleys.

Table 18. Distribution of crash location for annual national (weighted) unaddressed left turn across path/opposite direction crashes at non-signals.

Location of Crash		Crashes	Percent
Intersections	Flashing signals	6,200	3
	Stop-controlled	16,554	9
	Other intersections	86,236	48
Segments	Tangents	3,932	2
	Curves	154	0
Driveways	Tangents	62,171	35
	Curves	3,415	2
Total		178,663	100

A total of 18 percent of the crashes occurred on non-level roadways (i.e., on a grade, hillcrest, or sag). Over two-thirds (71 percent) of these unaddressed crashes occurred in urban areas, and two-thirds of the crashes occurred on roadways with a speed limit between 35 and 45 mi/h. The distribution of vehicle type for unaddressed multi-vehicle left turn across path/opposite direction crashes at non-signals indicated that crashes only involving light vehicles represented 96 percent of the crashes. Trucks, including single- and combination-unit vehicles, were involved in less than 3 percent of the crashes.

8.3 CHARACTERISTICS OF UNADDRESSED CRASHES BY VEHICLE, AREA, AND LOCATION TYPE

8.3.1 Vehicle Type

The distribution of unaddressed single-vehicle and multi-vehicle crashes by vehicle type is presented in table 19. For single-vehicle crashes, single-unit and combination-unit trucks appear to be overrepresented, accounting for 8 percent of the vehicles. Other vehicles also are overrepresented when compared to multi-vehicle crashes, representing another 6 percent of the unaddressed crashes.

Table 19. Distribution of vehicle type for unaddressed crashes.

	Single-Vehicle Crashes		Multi-Vehicle Crashes		Total	
Vehicle Type	Number of Vehicles Involved	Percent	Number of Vehicles Involved	Percent	Number of Vehicles Involved	Percent
Light vehicles	666,118	86	5,430,129	93	6,096,247	92
Transit vehicles	2,334	0	24,471	0	26,805	0
Special vehicles	3,466	0	15,965	0	19,431	0
Single-unit trucks	35,057	5	112,382	2	147,439	2
Combination-unit trucks	20,101	3	106,979	2	127,080	2
Other vehicles	44,457	6	100,619	2	145,076	2
Not reported	0	0	47,216	1	47,216	1
Total	771,533	100	5,837,761	100	6,609,294	100

8.3.2 Area Type

Table 20 presents the distribution of unaddressed crashes by area type for single-vehicle and multi-vehicle crashes. More than 70 percent of the unaddressed crashes were in urban areas. Urban locations represented a greater proportion of the unaddressed crashes for multi-vehicle crashes than for single-vehicle crashes.

Table 20. Distribution of area type for unaddressed crashes.

Area	Single-Vehicle		Multi-Vehicle		Total	
Type	Crashes	Percent	Crashes	Percent	Crashes	Percent
Urban	454,274	59	2,171,556	74	2,625,829	71
Rural	317,164	41	747,152	26	1,064,316	29
Unknown	95	0	173	0	268	0
Total	771,533	100	2,918,881	100	3,690,413	100

8.3.3 Location Type

Table 21 presents the distribution of unaddressed crashes by intersection and segment locations. For both single-vehicle and multi-vehicle crashes, the majority of the unaddressed crashes were on tangent segments. This was expected because many of the current applications target intersections and curved segments. Specifically, 75 percent of single-vehicle crashes compared to 51 percent of multi-vehicle crashes occurred on tangents. Furthermore, the difference in percentage between single-vehicle and multi-vehicle crashes for crashes at intersections and segments was expected because multi-vehicle crashes are generally more prevalent at intersections. Additionally, 21 percent of the unaddressed multi-vehicle crashes were at signalized intersections. Signalized intersections could be a target for new applications or extensions to existing application areas.

Table 21. Distribution of crash location for unaddressed crashes.

Location of Crash		Single-Vehicle		Multi-Vehicle		Total	
		Crashes	Percent	Crashes	Percent	Crashes	Percent
Intersections	Signalized	31,800	4	613,532	21	645,332	17
	Stop-controlled	27,835	4	163,404	6	191,239	5
	Other intersections	73,829	10	512,332	18	586,161	16
Segments	Tangents	575,672	75	1,500,622	51	2,076,294	56
	Curves	62,397	8	128,990	4	191,387	5
Total		771,533	100	2,918,881	100	3,690,413	100

CHAPTER 9. CONCLUSIONS

This report documents the annual national frequencies and costs of crashes that could be targeted for 12 of the currently identified V2I for safety application areas. These analyses also provide information on crash scenarios and the associated costs that are unaddressed by these 12 safety applications. These unaddressed crashes can be explored to identify other potential applications.

Table 22 summarizes the estimated annual crashes and associated costs that could be targeted by the 12 V2I for safety application areas. These application areas could potentially target a significant number of crashes and their associated crash costs (more than $200 billion annually). When combined, the costs would total more than $200 billion, and the overlap among some of the application areas is accounted for in the total. The lane departure application represents the greatest potential to improve safety with respect to crash frequency and the potential crash cost. This finding is expected because the targets for this application are several pre-crash scenarios with significant crashes resulting from vehicles leaving their lanes.

Table 22. Overview of annual target crashes and associated costs identified in NASS GES for currently identified application areas.

Application Area		Estimated Annual Crashes Targeted	Annual Cost of Crashes Targeted (millions of dollars)
Intersection applications	Running red light	234,881	13,152
	Running stop sign	44,424	2,034
	Driver gap assist at signalized intersections	200,212	10,252
	Driver gap assist at stop-controlled intersections	278,886	18,273
Speed applications	Curve speed warning	168,993	29,080
	Work zone warning for reduced speed	16,364	1,335
	Spot treatment/weather conditions	211,304	13,019
	Speed zone warning	360,695	28,500
Vulnerable road users applications	Work zone alerts	86,611	4,563
	Infrastructure pedestrian detection	17,812	3,333
	At-grade rail crossing	1,314	653
Other applications	Lane departure warning	1,236,647	145,347
Total (accounting for overlaps)		2,288,021	202,344

Some caution is necessary because these results represent all potential target crashes for each application area. Targeted crashes are those that could potentially be eliminated through the deployment of a specific V2I application or set of applications (assuming 100 percent effectiveness and 100 percent deployment). The actual number of crashes addressed depends on the effectiveness of the application and the extent to which it is deployed.

The 12 analyzed application areas have the potential to cover approximately 73 percent of the single-vehicle total crash costs and 47 percent of the multi-vehicle total crash costs (see table 1 and table 2). The remaining crashes are considered unaddressed crashes, which are crashes that would not be eliminated even if the analyzed V2I applications were 100 percent effective and fully deployed. Unaddressed crashes might be covered through the development of new application areas or by other V2I technologies. They account for $44.0 billion in single-vehicle crash costs and $92.8 billion in multi-vehicle crash costs.

The following currently identified V2I for safety application areas could not be explored due to small samples or limitations of the NASS GES data:

- School zone speed warning.
- Priority assignment for emergency vehicle preemption.
- Bridge clearance warning.
- Secondary accident warning.

Other datasets and methods would be needed to identify the target populations for these application areas and estimate costs associated with these crash types.

Based on the percentage of crash costs targeted, current application areas appear to be well conceived in that they target major crash scenarios, particularly for single-vehicle crashes. In addition, a relatively large percentage of unaddressed crash costs are related to rear-end collisions. While V2I application areas could be conceived to target these scenarios, the Volpe report suggests V2V and AV as the primary applications areas for addressing rear-end crashes.[(12)]

More detailed crash data analysis is necessary to help target the deployment of V2I applications to identify the maximum benefit per dollar spent. For example, the benefits of the pre-crash scenario driver gap assist at signalized intersections would be expected to be greater at intersections with permissive left-turn phases and high numbers of potential conflicts (e.g., high volume of left-turn and opposing through vehicles).

This report identifies the magnitude, characteristics, and cost of crashes that would be targeted with currently proposed V2I safety application areas. It also identifies the magnitude, characteristics, and cost of the remaining crashes that are not targeted by a currently proposed V2I for safety application area (unaddressed crashes) to help identify potential new applications or modifications to proposed applications. The results indicate that the currently identified V2I application areas are well conceived and can potentially reduce crashes and crash costs. However, many crashes are not addressed in this report, and characteristics of unaddressed crashes are presented in this report provide a starting point for identifying either new applications or modifications to current applications.

ADDENDIX A: RELEVANT DISTRIBUTIONS

Table 23. Frequency of annual observed and annual weighted single-vehicle and multi-vehicle crashes by pre-crash scenario.

	Single-Vehicle Crashes		Multi-Vehicle Crashes	
Pre-crash Scenario	**Annual Observed Crashes**	**Annual Weighted Crashes**	**Annual Observed Crashes**	**Annual Weighted Crashes**
1. No driver present	7	602	0	0
2. Vehicle failure	467	38,894	184	11,881
3. Control loss/vehicle action	893	77,173	350	31,332
4. Control loss/no vehicle action	5,620	457,714	984	63,080
5. Running red light	18	868	2,932	234,013
6. Running stop sign	41	3,586	478	40,838
7. Road edge departure/maneuver	656	85,141	30	1,479
8. Road edge departure/no maneuver	4,693	417,076	90	4,299
9. Road edge departure/backing	404	85,540	0	0
10. Animal/maneuver	101	17,844	3	404
11. Animal/no maneuver	1,686	295,063	52	6,065
12. Pedestrian/maneuver	562	20,629	7	646
13. Pedestrian/no maneuver	1,226	40,603	40	2,861
14. Cyclist/maneuver	564	21,022	3	155
15. Cyclist/no maneuver	716	28,757	9	500
16. Backing into vehicle	3	371	679	130,865
17. Turning/same direction	0	0	1,562	199,311
18. Parking/same direction	4	163	256	38,088
19. Changing lanes/same direction	392	30,751	2,750	309,933
20. Drifting/same lane	0	0	1,055	110,959
21. Opposite direction/maneuver	18	1,920	118	8,384
22. Opposite direction/no maneuver	248	25,593	1,228	97,565
23. Rear-end/striking maneuver	26	2,736	577	80,087
24. Rear-end/LVA	0	0	151	22,049
25. Rear-end/LVM	34	2,131	1,861	199,714
26. Rear-end/LVD	119	7,771	3,078	386,480
27. Rear-end/LVS	97	8,057	6,853	930,045
28. LTAP/OD at signal	0	0	2,359	200,212
29. Turn right at signal	0	0	228	30,980
30. Left turn across path/opposite direction at non-signal	0	0	1,903	182,574
31. SCP at non-signal	39	3,773	5,783	641,880
32. Turn at non-signal	97	7,572	242	38,788
33. Evasive maneuver/maneuver	38	3,624	71	8,936
34. Evasive maneuver/no maneuver	217	18,363	291	28,408
35. Rollover	149	6,126	13	450

36. Non-collision no impact	191	21,171	133	15,318
37. Object contacted/maneuver	326	68,220	9	595
38. Object contacted/no maneuver	615	78,808	100	9,220
39. Hit and run	0	0	26	3,551
40. Other—rear-end	0	0	13	1,516
41. Other—sideswipe	0	0	13	1,875
43. Other—turn across path	0	0	5	836
44. Other—turn into path	0	0	9	1,417
46. Other	0	0	145	22,347
Total	20,265	1,877,663	36,668	4,099,936

Note: Pre-crash scenarios for which there were no annual observed crashes were omitted from this table.

Table 24. Cost of annual single-vehicle crashes by pre-crash scenario and injury type.

Pre-Crash Scenario	Cost by Injury Type (millions of dollars)						
	No Injury	Possible Injury	Non-Incapacitating	Incapacitating	Fatal	Injured, Unknown Severity	Total
1. No driver present	1	3	11	15	0	11	41
2. Vehicle failure	119	199	447	690	2,143	24	3,622
3. Control loss/vehicle action	247	358	847	1,102	3,730	39	6,323
4. Control loss/no vehicle action	1,299	2,667	5,511	10,277	39,240	362	59,356
5. Running red light	2	5	22	22	0	0	51
6. Running stop sign	11	16	61	49	18	0	155
7. Road edge departure/maneuver	323	281	469	571	1,677	37	3,358
8. Road edge departure/no maneuver	1,261	2,177	4,603	7,834	25,768	478	42,121
9. Road edge departure/backing	375	76	109	141	396	36	1,135
10. Animal/maneuver	76	42	24	29	0	4	174
11. Animal/no maneuver	1,230	528	896	1,116	333	28	4,131
12. Pedestrian/maneuver	3	354	586	973	1,737	87	3,740
13. Pedestrian/no maneuver	6	515	1,155	2,797	13,348	149	17,969
14. Cyclist/maneuver	9	283	782	571	507	97	2,249
15. Cyclist/no maneuver	13	419	923	1,183	2,808	34	5,379
16. Backing into vehicle	2	0.04	2	0	0	0	4
18. Parking/same direction	0.25	2	3	7	0	0	12
19. Changing lanes/same direction	91	222	343	420	340	14	1,429
21. Opposite direction/maneuver	5	17	24	18	91	0	155
22. Opposite direction/no maneuver	80	153	224	476	498	3	1,434
23. Rear-end/striking maneuver	10	11	25	17	149	0	212

Pre-Crash Scenario	Cost by Injury Type (millions of dollars)						
	No Injury	Possible Injury	Non-Incapacitating	Incapacitating	Fatal	Injured, Unknown Severity	Total
25. Rear-end/LVM	6	10	37	57	108	0	218
26. Rear-end/LVD	22	37	118	150	400	7	734
27. Rear-end/LVS	25	51	85	121	25	9	315
31. SCP at non-signal	11	30	41	48	0	0	129
32. Turn at non-signal	23	32	107	173	0	2	336
33. Evasive maneuver/maneuver	12	16	31	56	35	1	152
34. Evasive maneuver/no maneuver	56	112	202	300	163	10	843
35. Rollover	8	51	148	324	921	3	1,455
36. Non-collision no impact	77	55	165	275	1,031	9	1,611
37. Object contacted/maneuver	297	82	86	91	437	19	1,012
38. Object contacted/no maneuver	315	173	288	554	2,913	36	4,279
Total	6,013	8,973	18,375	30,455	98,817	1,499	164,132

Note: Pre-crash scenarios for which there were no annual observed crashes were omitted from this table.

Table 25. Cost of annual multi-vehicle crashes by pre-crash scenario and injury type.

Pre-Crash Scenario	Cost by Injury Type (millions of dollars)						
	No Injury	Possible Injury	Non-Incapacitating	Incapacitating	Fatal	Injured, Unknown Severity	Total
2. Vehicle failure	37	74	90	215	810	9	1,235
3. Control loss/vehicle action	104	212	213	249	660	10	1,448
4. Control loss/no vehicle action	172	533	648	1,133	4,755	45	7,286
5. Running red light	593	2,556	2,473	3,373	3,835	270	13,099
6. Running stop sign	102	414	519	543	223	80	1,882
7. Road edge departure/maneuver	4	11	14	17	118	3	168
8. Road edge departure/no maneuver	11	25	59	125	604	3	828
10. Animal/maneuver	1	1	4	1	0	0	8
11. Animal/no maneuver	21	36	39	53	216	5	369
12. Pedestrian/maneuver	3	1	3	10	6	0	23
13. Pedestrian/no maneuver	9	10	22	63	798	11	913
14. Cyclist/maneuver	0	3	4	3	0	0	10
15. Cyclist/no maneuver	1	1	5	35	53	$1	$96
16. Backing into vehicle	556	316	146	117	202	25	1,362
17. Turning/same direction	747	971	753	1,026	2,202	102	5,800
18. Parking/same direction	148	157	110	173	349	10	948
19. Changing lanes/same direction	1,225	1,205	816	1,180	1,957	62	6,446
20. Drifting/same lane	426	470	410	499	1,314	29	3,148
21. Opposite direction/maneuver	19	65	100	299	1,794	9	2,286
22. Opposite direction/no maneuver	263	619	1,126	2,473	17,403	84	21,967
23. Rear-end/striking maneuver	288	530	263	354	537	52	2,023
24. Rear-end/LVA	73	183	84	161	180	15	697

Pre-Crash Scenario	Cost by Injury Type (millions of dollars)						
	No Injury	Possible Injury	Non-Incapacitating	Incapacitating	Fatal	Injured, Unknown Severity	Total
25. Rear-end/LVM	640	1,692	1,117	1,405	4,060	161	9,076
26. Rear-end/LVD	1,297	3,230	1,550	2,026	1,503	221	9,827
27. Rear-end/LVS	3,028	8,529	4,005	4,765	3,177	446	23,951
28. LTAP/OD at signal	518	1,960	2,404	2,787	2,360	222	10,252
29. Turn right at signal	121	129	92	75	556	19	991
30. Left turn across path/opposite direction at non-signal	503	1,672	1,861	2,618	5,052	134	11,840
31. SCP at non-signal	1,991	5,044	4,934	6,872	13,504	430	32,776
32. Turn at non-signal	153	151	122	95	177	3	701
33. Evasive maneuver/maneuver	30	76	37	44	93	9	290
34. Evasive maneuver/no maneuver	93	179	235	220	829	13	1,569
35. Rollover	0	3	13	22	369	1	410
36. Non-collision no impact	62	41	43	69	55	1	273
37. Object contacted/maneuver	2	1	6	6	17	0	32
38. Object contacted/no maneuver	36	36	32	43	239	1	386
39. Hit and run	14	8	11	20	18	0	71
40. Other—rear-end	6	3	8	2	0	0	19
41. Other—sideswipe	8	4	0	6	16	0	35
43. Other—turn across path	4	0	0	0	0	0	4
44. Other—turn into path	5	7	5	3	0	1	21
46. Other	89	74	67	86	211	17	544
Total	13,407	31,233	24,446	33,266	70,252	2,508	175,111

Note: Pre-crash scenarios for which there were no annual observed crashes were omitted from this table.

Table 26. Single-vehicle pre-crash scenarios by vehicle type—annual crashes (observed).

Single-Vehicle Pre-Crash Scenario	Light Vehicles	Transit Vehicles	Special Vehicles	Single-Unit Trucks	Combined-Unit Trucks	Other Vehicles	Total
1. No driver present	6	0	0	1	0	1	7
2. Vehicle failure	364	1	1	33	39	30	467
3. Control loss/vehicle action	690	1	1	21	41	141	893
4. Control loss/no vehicle action	4,803	4	4	87	200	522	5,620
5. Running red light	16	0	0	1	1	0	18
6. Running stop sign	39	0	0	0	1	1	41
7. Road edge departure/maneuver	509	5	4	34	51	54	656
8. Road edge departure/no maneuver	4,141	8	8	112	134	291	4,693
9. Road edge departure/backing	339	2	4	30	8	22	404
10. Animal/maneuver	87	0	0	7	1	7	101
11. Animal/no maneuver	1,548	2	2	11	30	94	1,686
12. Pedestrian/maneuver	505	10	2	16	4	25	562
13. Pedestrian/no maneuver	1,109	12	4	24	10	68	1,226
14. Cyclist/maneuver	534	2	2	11	3	14	564
15. Cyclist/no maneuver	658	8	2	10	4	36	716
16. Backing into vehicle	3	0	0	1	0	0	3
18. Parking/same direction	2	0	0	0	0	2	4
19. Changing lanes/same direction	299	0	0	12	25	57	392
21. Opposite direction/maneuver	14	0	0	1	0	4	18
22. Opposite direction/no maneuver	184	0	0	12	8	44	248
23. Rear-end/striking maneuver	18	0	0	2	2	5	26
25. Rear-end/lead vehicle constant speed	25	0	0	2	2	5	34
26. Rear-end/LVD	60	0	0	10	10	39	119
27. Rear-end/LVS	61	0	0	5	9	23	97
31. Straight crossing path at non-signal	23	0	0	0	1	14	39
32. Turn at non-signal	54	1	0	3	1	39	97
33. Evasive maneuver/maneuver	30	0	0	2	1	6	38
34. Evasive maneuver/no maneuver	165	0	0	11	11	31	217

Single-Vehicle Pre-Crash Scenario	Light Vehicles	Transit Vehicles	Special Vehicles	Single-Unit Trucks	Combined-Unit Trucks	Other Vehicles	Total
35. Rollover	41	1	0	11	23	74	149
36. Non-collision no impact	126	2	1	6	36	20	191
37. Object contacted/ maneuver	185	1	4	71	8	57	326
38. Object contacted/no maneuver	436	1	1	57	69	52	615
Total	17,069	59	38	598	730	1,771	20,265

Note: Pre-crash scenarios for which there were no annual observed crashes were omitted from this table.

Table 27. Single-vehicle pre-crash scenarios by vehicle type—annual national crashes (weighted).

Single-Vehicle Pre-Crash Scenario	Light Vehicles	Transit Vehicles	Special Vehicles	Single-Unit Trucks	Combined-Unit Trucks	Other Vehicles	Total
1. No driver present	540	3	0	26	1	32	602
2. Vehicle failure	34,928	18	10	896	1,452	1,588	38,894
3. Control loss/vehicle action	69,501	75	153	589	1,116	5,739	77,173
4. Control loss/no vehicle action	427,253	363	168	2,863	5,335	21,732	457,714
5. Running red light	860	0	0	4	4	1	868
6. Running stop sign	3,459	0	0	0	46	81	3,586
7. Road edge departure/ maneuver	64,416	733	944	5,876	7,932	5,241	85,141
8. Road edge departure/ no maneuver	375,558	1,386	1,588	11,765	6,545	20,234	417,076
9. Road edge departure/backing	71,128	471	830	6,667	1,219	5,225	85,540
10. Animal/maneuver	15,049	0	0	1,705	210	880	17,844
11. Animal/no maneuver	283,464	392	405	1,526	3,272	6,004	295,063
12. Pedestrian/maneuver	18,608	263	72	494	47	1,145	20,629
13. Pedestrian/no maneuver	37,551	326	57	329	193	2,145	40,603
14. Cyclist/maneuver	20,255	88	41	140	29	470	21,022
15. Cyclist/no maneuver	27,160	131	140	116	97	1,112	28,757
16. Backing into vehicle	354	0	0	5	0	12	371
18. Parking/same direction	129	0	0	1	0	33	163
19. Changing lanes/same direction	28,174	0	0	318	580	1,679	30,751
21. Opposite direction/maneuver	1,567	0	0	74	0	279	1,920
22. Opposite direction/no maneuver	21,944	26	0	910	724	1,988	25,593
23. Rear-end/striking maneuver	2,233	0	0	118	105	280	2,736
25. Rear-end/lead vehicle constant speed	1,913	0	0	48	58	112	2,131
26. Rear-end/LVD	6,020	4	0	221	241	1,286	7,771
27. Rear-end/LVS	6,770	0	1	122	280	885	8,057
31. Straight crossing path at non-signal	3,131	5	55	0	97	484	3,773
32. Turn at non-signal	5,795	7	4	221	134	1,410	7,572

Single-Vehicle Pre-Crash Scenario	Light Vehicles	Transit Vehicles	Special Vehicles	Single-Unit Trucks	Combined-Unit Trucks	Other Vehicles	Total
33. Evasive maneuver/maneuver	3,005	0	4	83	137	395	3,624
34. Evasive maneuver/ no maneuver	16,274	9	5	480	377	1,219	18,363
35. Rollover	2,684	6	5	159	624	2,648	6,126
36. Non-collision no impact	16,259	51	9	355	3,256	1,242	21,171
37. Object contacted/maneuver	34,235	190	1,085	17,964	1,218	13,527	68,220
38. Object contacted/ no maneuver	57,493	136	64	8,643	4,610	7,863	78,808
Total	1,657,709	4,684	5,641	62,719	39,938	106,972	1,877,663

Note: Pre-crash scenarios for which there were no annual observed crashes were omitted from this table.

Table 28. Multi-vehicle pre-crash scenarios by vehicle type—annual crashes (observed).

Multi-Vehicle Pre-Crash Scenario	Light Vehicles	Transit Vehicles	Special Vehicles	Single-Unit Trucks	Combined-Unit Trucks	Other Vehicles	Not Reported	Total
2. Vehicle failure	227	1	1	27	56	5	52	367
3. Control loss/vehicle action	524	1	1	25	78	14	56	700
4. Control loss/no vehicle action	1,433	3	6	68	204	40	215	1,967
5. Running red light	5,348	26	9	209	158	113	1	5,864
6. Running stop sign	886	4	3	27	18	18	0	956
7. Road edge departure/ maneuver	27	0	0	2	2	1	30	60
8. Road edge departure/ no maneuver	81	0	0	3	6	2	90	181
10. Animal/maneuver	4	0	0	0	0	2	1	7
11. Animal/no maneuver	74	0	0	3	3	4	20	104
12. Pedestrian/maneuver	8	0	0	1	1	1	4	14
13. Pedestrian/no maneuver	49	0	0	2	2	4	23	80
14. Cyclist/maneuver	4	0	0	0	0	0	2	6
15. Cyclist/no maneuver	10	0	0	0	0	0	7	17
16. Backing into vehicle	1,115	5	8	118	71	31	11	1,358
17. Turning/same direction	2,449	21	11	198	317	128	0	3,124
18. Parking/same direction	433	4	2	25	28	18	2	511
19. Changing lanes/same direction	4,079	28	10	363	848	166	7	5,501
20. Drifting/same lane	1,514	16	4	148	331	73	24	2,109
21. Opposite direction/ maneuver	206	1	2	8	9	9	2	237
22. Opposite direction/ no maneuver	2,149	6	13	108	110	57	13	2,455
23. Rear-end/striking maneuver	987	3	3	51	65	37	9	1,155
24. Rear-end/LVA	266	1	3	12	16	6	0	302
25. Rear-end/LVM	3,073	7	8	189	333	104	8	3,721
26. Rear-end/LVD	5,360	15	10	269	351	125	25	6,155
27. Rear-end/LVS	12,512	45	32	442	392	183	99	13,706
28. Left turn across path/opposite direction at signal	4,423	12	4	80	94	105	0	4,718
29. Turn right at signal	384	4	1	25	28	14	0	456

Multi-Vehicle Pre-Crash Scenario	Light Vehicles	Transit Vehicles	Special Vehicles	Single-Unit Trucks	Combined-Unit Trucks	Other Vehicles	Not Reported	Total
30. Left turn across path/opposite direction at non-signal	3,537	8	6	68	44	145	0	3,807
31. Straight crossing path at non-signal	10,586	31	32	290	235	365	28	11,566
32. Turn at non-signal	415	3	1	22	24	17	3	485
33. Evasive maneuver/maneuver	121	0	1	4	7	3	7	142
34. Evasive maneuver/ no maneuver	431	1	1	19	30	38	62	581
35. Rollover	3	0	0	1	2	8	13	27
36. Non-collision no impact	58	0	0	24	46	5	133	266
37. Object contact/maneuver	8	0	0	1	1	0	9	19
38. Object contact/no maneuver	93	0	0	13	28	6	59	199
39. Hit and run	37	1	0	5	3	5	2	53
40. Other—rear-end	20	0	0	0	1	0	4	26
41. Other—sideswipe	20	0	0	3	3	1	0	26
43. Other—turn across path	7	0	0	1	2	0	0	10
44. Other—turn into path	17	0	0	0	1	0	0	18
Total	62,971	246	170	2,850	3,944	1,847	1,020	73,047

Note: Pre-crash scenarios for which there were no annual observed crashes were omitted from this table.

Table 29. Multi-vehicle pre-crash scenarios by vehicle type—annual national crashes (weighted).

Multi-Vehicle Pre-Crash Scenario	Light Vehicles	Transit Vehicles	Special Vehicles	Single-Unit Trucks	Combined-Unit Trucks	Other Vehicles	Not Reported	Total
2. Vehicle failure	18,108	89	115	549	1,866	244	2,791	23,762
3. Control loss/ vehicle action	55,741	92	125	884	2,153	1,005	2,663	62,664
4. Control loss/no vehicle action	106,048	227	638	2,689	4,518	2,812	9,228	126,160
5. Running red light	447,840	2,307	591	4,891	4,029	8,307	62	468,027
6. Running stop sign	78,673	236	388	828	669	879	4	81,676
7. Road edge departure/ maneuver	1,183	0	0	199	74	22	1,479	2,958
8. Road edge departure/no maneuver	3,998	0	0	85	141	76	4,299	8,599
10. Animal/maneuver	456	5	0	0	0	177	169	807
11. Animal/ no maneuver	9,140	0	0	113	149	193	2,534	12,129
12. Pedestrian/ maneuver	819	71	0	69	71	66	194	1,291
13. Pedestrian/ no maneuver	4,976	0	0	9	18	189	530	5,723
14. Cyclist/maneuver	253	0	0	0	0	0	57	311
15. Cyclist/no maneuver	748	0	0	65	0	3	184	1,000
16. Backing into vehicle	232,283	1,103	1,757	11,781	7,568	4,605	2,633	261,731
17. Turning/same direction	354,003	3,710	1,857	12,116	16,762	10,172	1	398,621
18. Parking/same direction	69,973	808	236	1,898	1,217	1,865	179	76,176
19. Changing lanes/same direction	550,798	4,586	1,839	21,185	27,774	13,059	625	619,866
20. Drifting/same lane	187,281	3,023	772	10,031	11,285	6,653	2,872	221,918
21. Opposite direction/ maneuver	15,015	27	120	278	248	799	281	16,768
22. Opposite direction/ no maneuver	172,669	351	1,722	6,975	6,749	4,930	1,733	195,129
23. Rear-end/striking maneuver	149,967	471	370	2,607	1,558	4,165	1,036	160,174
24. Rear-end/LVA	41,766	25	311	741	561	695	0	44,098
25. Rear-end/LVM	375,424	347	798	6,486	8,081	7,856	438	399,429
26. Rear-end/LVD	742,967	1,254	1,127	9,743	6,754	10,136	979	772,960

Multi-Vehicle Pre-Crash Scenario	Light Vehicles	Transit Vehicles	Special Vehicles	Single-Unit Trucks	Combined-Unit Trucks	Other Vehicles	Not Reported	Total
27. Rear-end/LVS	1,798,898	5,082	3,793	18,028	11,281	17,326	5,682	1,860,090
28. Left turn across path/opposite direction at signal	388,802	942	205	2,316	2,612	5,546	0	400,423
29. Turn right at signal	56,905	646	279	1,877	1,019	1,233	0	61,959
30. Left turn across path/opposite direction at non-signal	351,595	945	453	3,115	2,165	6,873	0	365,148
31. Straight crossing path at non-signal	1,227,427	3,704	4,206	12,625	10,285	24,425	1,088	1,283,759
32. Turn at non-signal	70,503	547	129	2,533	1,939	1,397	529	77,577
33. Evasive maneuver/ maneuver	17,023	5	88	240	141	210	166	17,872
34. Evasive maneuver/ no maneuver	49,420	212	172	994	1,051	1,956	3,010	56,816
35. Rollover	142	0	0	14	81	214	450	901
36. Non-collision no impact	8,358	69	0	2,780	3,596	515	15,318	30,636
37. Object contact/ maneuver	526	0	0	144	43	5	474	1,191
38. Object contact/ no maneuver	10,188	0	77	1,897	1,683	635	3,960	18,440
39. Hit and run	4,960	139	0	867	95	588	454	7,102
40. Other—rear-end	2,741	0	4	1	1	3	283	3,032
41. Other—sideswipe	3,286	63	0	175	154	5	68	3,751
43. Other—turn across path	1,344	0	0	131	196	0	0	1,672
44. Other—turn into path	2,743	0	0	0	74	4	13	2,834
Total	7,614,990	31,085	22,170	141,957	138,662	139,844	66,469	8,155,177

Note: Pre-crash scenarios for which there were no annual observed crashes were omitted from this table.

REFERENCES

1. National Highway Traffic Safety Administration. (2009). *National Automotive Sampling System/General Estimates System (NASS GES)*, Washington, DC. Obtained from: ftp://ftp.nhtsa.dot.gov/GES/.

2. Federal Highway Administration. (2011). *Highway Safety Information System (HSIS)*, Washington, DC. Obtained from: http://www.hsisinfo.org.

3. National Highway Traffic Safety Administration. (2009). *Fatality Analysis Reporting System (FARS)*, Washington, DC. Obtained from: ftp://ftp.nhtsa.dot.gov/FARS/.

4. Shelton, T.S. (1993). *Imputation in the NASS General Estimates System*, Report No. DOT HS 807 985, U.S. Department of Transportation, Washington, DC.

5. National Highway Traffic Safety Administration. (2009). *National Automotive Sampling System (NASS) General Estimates System (GES) Analytical User's Manual 1988–2008*, U.S. Department of Transportation, Washington, DC.

6. Shelton, T.S. (1991). *National Accident Sampling System General Estimates System Technical Note*, Report No. DOT HS 807 796, U.S. Department of Transportation, Washington, DC.

7. Najm, W.G., Smith, J.D., and Yanagisawa, M. (2007). *Pre-Crash Scenario Typology for Crash Avoidance Research*, Report No. DOT HS 810 767, U.S. Department of Transportation, Washington DC.

8. DaSilva, M.P., Smith, J.D., and Najm, W.G. *Heavy Vehicle Pre-Crash Scenario Typology for Crash Avoidance Research*, U.S. Department of Transportation, Washington DC. (Manuscript submitted in 2009 for publication and in-press).

9. National Highway Traffic Safety Administration. (2008). *Preliminary Regulatory Evaluation: FMVSS No. 128 Motorcycle Helmet Labeling*, U.S. Department of Transportation, Washington, DC.

10. North America Operations Crash Avoidance Department. (1997). *44 Crashes*, Version 3.0, General Motors Corporation, Warren, MI.

11. Najm, W.G., Sen, B., Smith, J.D., and Campbell, B.N. (2003). *Analysis of Light Vehicle Crashes and Pre-Crash Scenarios Based on the 2000 General Estimates System*, Report No. DOT HS 809 573, U.S Department of Transportation, Washington, DC.

12. Najm, W.G., Koopmann, J., Smith, J.D., and Brewer, J. (2010). *Frequency of Target Crashes for IntelliDrive Safety Systems*, Report No. DOT HS 811 381, U.S. Department of Transportation, Washington, DC.

13. Chang, J., Cohen, D., Blincoe, L., Subramanian, R., and Lombardo, L. (2007). *CICAS-V Research on Comprehensive Costs of Intersection Crashes*, Report No. 07-0016, U.S. Department of Transportation, Washington, DC.

14. National Highway Traffic Safety Administration. (2009). *National Automotive Sampling System Crashworthiness Data System (NASS CDS)*, Washington, DC. Obtained from http://www.nhtsa.dot.gov/people/ncsa/nass_cds.html.

15. Federal Highway Administration. (2003). *Intersection Collision Avoidance Study Final Report*, Report No. FHWA/TX-03/4027-1, U.S Department of Transportation, Washington, DC.

16. Mitretek Systems Analysis. (2005). *Cooperative Intersection Collision Avoidance System: Distribution of Crashes by Intersections—An Exploratory Analysis*, Draft Version 1.0, Falls Church, VA.

17. NCUTLO. (2000). *Uniform Vehicle Code*, Millennium Ed., National Committee on Uniform Traffic Laws and Ordinances, Alexandria, VA.

HRDS-10/11-12(WEB)E