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Highway-Rail Intersection Crash Taxonomy For Connected Vehicle Safety Research

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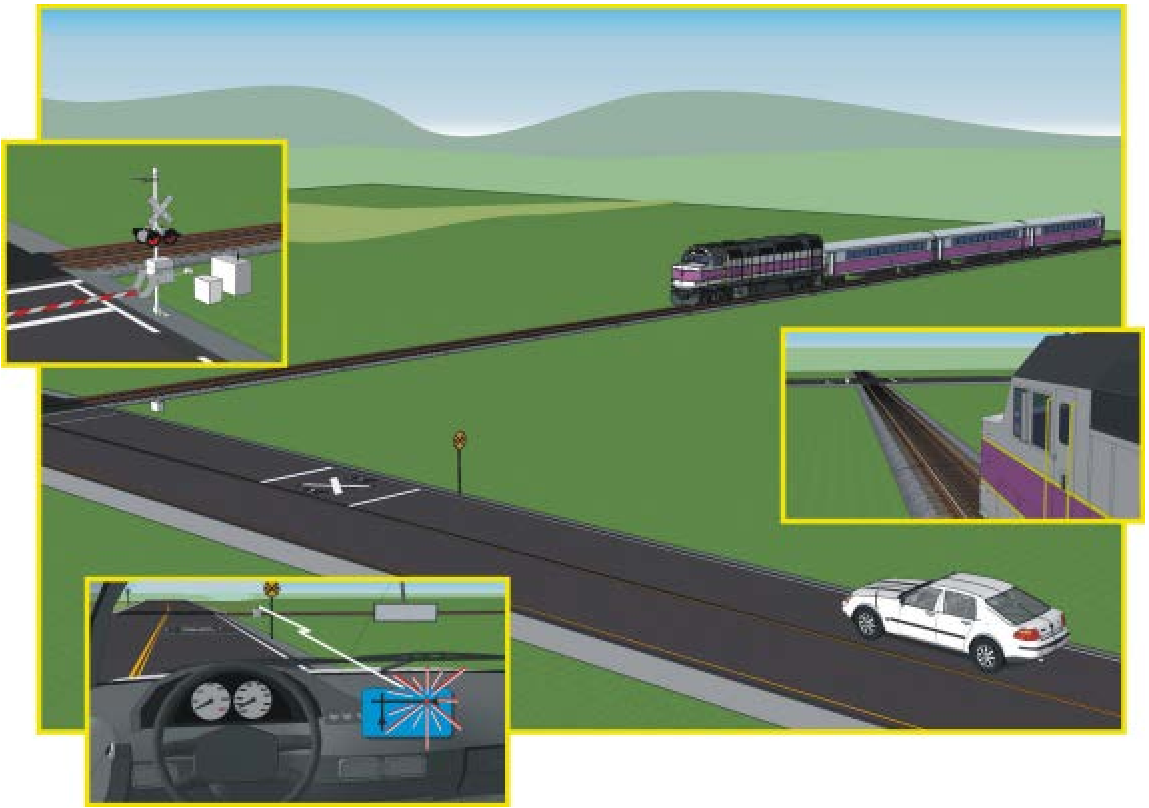

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13. ABSTRACT (Maximum 200 words)

This report characterizes the frequency, severity, and costs of highway-rail intersection (HRI) collisions, and the estimated potential reductions in these metrics resulting from the implementation of Connected Vehicle HRI safety applications. Multiple data sources were accessed with a focus on United States Department of Transportation (US DOT) online databases, which included the Federal Railroad Administration (FRA) Office of Safety Analysis, the National Highway Traffic Safety Administration (NHTSA) National Automotive Sampling System (NASS) and the Federal Transit Administration (FTA) National Transit Database (NTD).

FRA data from the 2008-2012 study period showed that annual combined rail infrastructure and equipment costs due to HRI accidents were between $20 million and $35 million. An alternative method developed by the US DOT National Highway Traffic Safety Administration (NHSTA) provides for the economic losses associated with medical and legal costs, lost productivity, and travel delay. Using this alternative method, the annual costs to society were estimated at $650 million.

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1 pint (pt)	=	0.47 liter (l)			
1 quart (qt)	=	0.96 liter (l)			
1 gallon (gal)	=	3.8 liters (l)			
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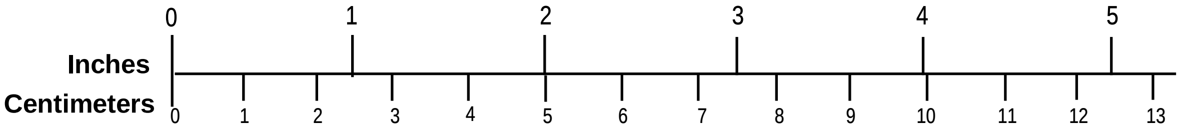

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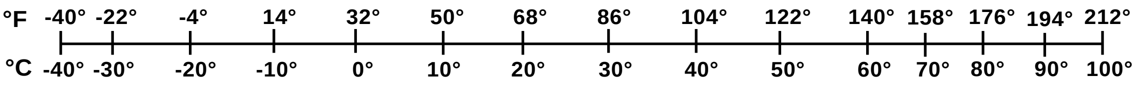

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Executive Summary

This report characterizes the frequency, severity, and costs of highway-rail intersection (HRI) crashes and estimates the potential reductions in these values resulting from the implementation of Connected Vehicle HRI safety applications. Multiple data sources were accessed with a focus on the United States Department of Transportation (US DOT) online databases, which included the Federal Railroad Administration (FRA) Office of Safety Analysis, the National Highway Traffic Safety Administration (NHTSA) National Automotive Sampling System (NASS) and the National Transit Database (NTD).

In the 2008-2012 dataset used for this study, FRA accident records registered 9775 incidents, 969 fatalities, and 4336 injuries; 80 percent of the incidents and 88 percent of all fatalities involved a train striking a motor vehicle (Figure ES-1). Most significantly, the probability of a fatality was twice as high for the "train striking motor vehicle" scenario rather than the "motor vehicle striking train" scenario. While commercial vehicles caused only 20-25 percent of all HRI incidents, they were responsible for 45-55 percent of the annual motor vehicle damage costs. On a per accident basis, commercial vehicle damage costs exceeded those of light vehicles by three to four times.

FRA accident data from the 2008-2012 study period showed that annual combined HRI and rail infrastructure accident costs were between $20 million and $35 million dollars. An alternative method, developed by the US DOT National Highway Traffic Safety Administration (NHTSA), includes the economic losses associated with medical and legal costs, lost productivity, and travel delay. Using this alternative method, the annual costs to society were estimated at $650 million and 18,000 functional years lost, as shown in Table ES-1.

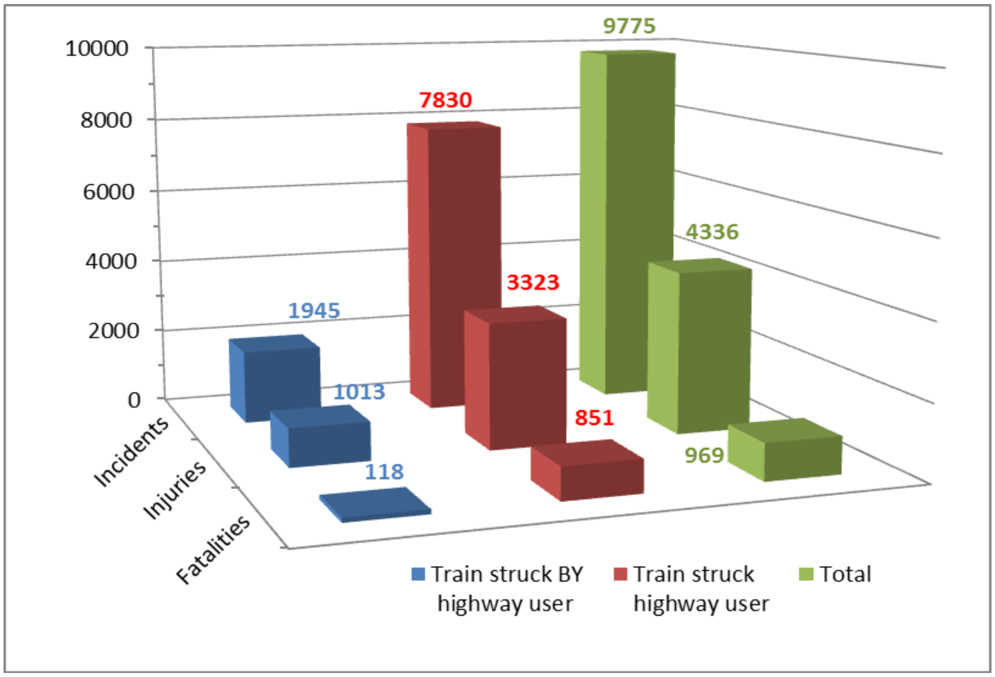

Figure ES-1. HRI Incident and Casualty Statistics from 2008-2012 for all HRIs, excluding pedestrians

Table ES-1. FRA HRI Incident and Casualty Estimated Average Damage Costs and Functional Years Lost

Year	Property Damage Only Accidents	No Vehicle Occupants Injured	Vehicle Occupant Injuries	Fatalities	Cost*	Functional Years Lost
2008	314	1595	935	227	$728,311,254	20,402
2009	252	1226	703	190	$572,618,073	16,165
2010	249	1248	802	178	$602,811,176	16,787
2011	244	1244	993	188	$703,668,112	19,401
2012	277	1050	871	186	$644,502,307	17,919
5- Year Average	**268**	**1,273**	**861**	**194**	**$650,382,184**	**18,135**

*Calculated using MAIS Costs in 2010 Dollars

1. Introduction and Objectives

Connected vehicle safety applications are designed to increase situational awareness and reduce or eliminate crashes through vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) data transmission. It has been estimated that these technologies may prevent up to 81 percent of crash scenarios involving unimpaired drivers, preventing tens of thousands of automobile and truck crashes every year (Najm, Koopmann, Smith, & Brewer, 2010).

This research explores the design of V2I and V2V applications with a focus on enhancing the safety of commuter, heavy and freight rail systems, specifically at highway-rail intersections (HRIs) where rail intersects with other traffic, such as light vehicle, commercial vehicle, and transit vehicles. This research is part of a larger effort to:

1) Quantify the human and economic impacts of HRI accidents that may be prevented by the implementation of Connected Vehicle (V2X) technologies and
2) Identify potentially enabling V2X technologies.

The report characterizes the severity of HRI accidents and estimates the safety benefits resulting from the implementation of V2I and V2V safety applications.

1.1 Background

The Federal Highway Administration (FHWA) Railroad-Highway Grade Crossing Handbook (2007) defines a highway-rail grade crossing (HRI) as:

> *"The general area where a highway and a railroad cross at the same level, within which are included the railroad, roadway, and roadside facilities for traffic traversing that area."*

To define the magnitude of the problem, consider the following information from calendar year 2012, which as of this writing is the most recent year that FRA has published complete safety statistics (FRA, 2013):

- 210,043 non-pedestrian HRIs were in service
  - 129,563 were public and 80,480 were private
  - The public HRIs consisted of 67,036 equipped with active warning devices and 62,527 equipped with passive warning devices
- 1,840 HRI incidents involving motor vehicles and trains occurred at all HRIs (public and private)
  - These incidents involved 174 fatalities and 904 injuries
  - HRIs equipped with active warning devices accounted for 991 (53.5%) of the incidents, 87 (50%) of the fatalities, and 513 (56.7%) of injuries
- The majority of incidents, 1,565, (85%) occurred at public HRIs
  - Likewise, the majority of fatalities and injuries, 144 (82.8%) and 777 (86%) respectively, occurred at public HRIs

- Public HRIs equipped with active warning devices accounted for 969 (61.9%) of the incidents, 85 (59%) of the fatalities, and 500 (64.4%) of the injuries

1.2 Overall Approach

Multiple data sources were accessed for this research with a focus on US DOT online databases, including the following:

- Federal Railroad Administration (FRA) Office of Safety Analysis Railroad Accident/Incident Reporting System (RAIRS)
- National Highway Traffic Safety Administration (NHSTA) National Automotive Sampling System (NASS)
- National Transit Database (NTD)

All relevant literature was reviewed in order to understand the frameworks used in analyzing crash scenarios and acquire the skillset needed for 1) identification of potentially preventable HRI accidents using V2X technologies, 2) quantification of the economic and human costs of these accidents and 3) estimation of the benefit that V2X safety applications may offer.

The most comprehensive research found on this topic was performed by the Volpe Center in support of NHTSA. Since the mid-1990s, the Volpe Center has been analyzing crash data from the NHTSA NASS GES database and one result of this research initiative was the creation of the crash scenario taxonomy and cost model, which is now considered the industry standard. Other relevant research has been performed by General Motors Corporation and the Crash Avoidance Metrics Partnership - Vehicle Safety Communications Consortium (CAMP-VSCC). The information gathered from these research efforts and others constitutes a foundation for the analysis presented in this report.

1.3 Organization of the Report

- Chapter 2 presents a review of the relevant previous research.
- Chapter 3 describes the methodology employed in this research.
- Chapters 4 and 5 provide the results of the FRA crash and cost data analyses.
- Chapter 6 contains the results of the NHTSA crash and cost data analyses and discussion. of the data analysis
- Chapters 7 and 8 present the conclusions and recommendations.

2. Review and Analysis of Previous Research

In 1997, General Motors (GM) developed the “44 crashes” typology, which incorporated vehicle dynamics, vehicle movements, critical events, crash causes, and crash contributing factors from the 1991 National Automotive Sampling System (NASS) General Estimates System (GES) crash database. This classification system is the foundation for much of the research into pre-crash scenarios and vehicle safety applications that is being performed.

The 44 crash scenarios are shown in Table 1 and for the most part are self-explanatory. Although most scenarios can be mapped to a GES crash variable or crash sequence, some, such as pedal miss, cannot. The “44 crashes” typology was sufficient to characterize all highway collision scenarios in the GES crash database. In addition, the “44 crashes” typology could be a tool for researching crash scenario causality.

Table 1. “44 Crashes” Scenario Typology

Struck Human	Inattentive, Ran Stop	Avoidance, Rear	Lane Change, Rear
Struck Animal	View Obstruction	Pedal Miss	Back Track
Drowsy	Looked but Didn’t See	Inattentive, Rear	U-Turn
Aggressive, Departure	Sirens	Stutter Stop	Inexperience, Departure
Slick Road Departure	Left Turn Clip	Aggressive, Rear	Impaired, Head-on
Rough Road Departure	Wrong Driveway	Maintenance	Slick Road, head-on
Avoidance, Departure	Wave to Go	Slick Road, Rear	Run Red Into Left Turner
Impaired, Departure	Turn into Passer	Passing Clip	Misjudgment, Left Turn
Back Into Object	Back into Roadway	Lane Change, Right	View Obstructed Left Turn
Ran Red “T-Bone”	Tail gate	Visibility, Rear	Miscellaneous
Slick Road, Ran Stop	Distracted, Rear	Lane Change, Left	New

In 2002, a consortium of domestic and foreign automobile manufacturers founded the Crash Avoidance Metrics Partnership-Vehicle Safety Communications Consortium (CAMP-VSCC) to further this research (in conjunction with US DOT). One of CAMP-VSCC’s research projects was the Vehicle Safety Communications (VSC) Project and one of its objectives was the identification of V2I and V2V communications-based vehicle safety and non-safety application scenarios.

CAMP-VSCC compiled an initial list of more than 75 application scenarios. From that list, the consortium used the “44 crashes” typology to select a core set of 34 safety application scenarios that had the highest estimated safety benefits (NHTSA, 2005). Table 2 contains the results of the selection process, with each scenario categorized as either V2I- or V2V-based. The eight highlighted applications, divided evenly between V2I and V2V technologies, represent the near-term and medium-term applications that are the highest-ranked in estimated benefits (NHTSA, 2005).

Table 2. Highest Ranking Communications-Based Safety Applications

V2I (Communications Between Vehicle and Infrastructure)	**V2V (Communications Between Vehicles)**
Blind Merge Warning	Approaching Emergency Vehicle Warning
Curve Speed Warning	Blind Spot Warning
Emergency Vehicle Signal Preemption	Cooperative Adaptive Cruise Control
Highway/Rail Collision Warning	Cooperative Collision Warning
Intersection Collision Warning	*Cooperative Forward Collision Warning*
In Vehicle Amber Alert	Cooperative Vehicle-Highway Automation System
In-Vehicle Signage	**Emergency Electronic Brake Lights**
Just-In-Time Repair Notification	Highway Merge Assistant
Left Turn Assistant	*Lane Change Warning*
Low Bridge Warning	Post-Crash Warning
Low Parking Structure Warning	*Pre-Crash Sensing*
Pedestrian Crossing Information at Intersection	Vehicle-Based Road Condition Warning
Road Condition Warning	Vehicle-to-Vehicle Road Feature Notification
Safety Recall Notice	Visibility Enhancer
SOS Services	Wrong Way Driver Warning
Stop Sign Movement Assistance	Approaching Emergency Vehicle Warning
Stop Sign Violation Warning	Blind Spot Warning
Traffic Signal Violation Warning	Cooperative Adaptive Cruise Control
Work Zone Warning	Cooperative Collision Warning

Bold = High Priority Near Term

Italics = High Priority Medium Term

Although the “44 crashes” typology was derived from the GES database, it did not employ GES crash variables to describe the scenarios. This trait limits the usefulness of the typology beyond the 1991 GES database and prevents any analysis of crash data from other years (Najm et al., 2007).

Najm, Sen, Smith, & Campbell (2003) found that light vehicle crashes at HRIs represented about 0.2 percent, or 14,000, of the 6.1 million vehicle crashes in the 2000 GES database. Table 3 shows the analysis of vehicle crashes in relation to junction. Although this data reveals the number of motor vehicle crashes at HRIs, we cannot draw any conclusions as to the nature of the accidents – that is, how many involved a train and how many were vehicle-to-vehicle.

Table 3. Distribution of Light Vehicle Crashes by Relation to Junction from 2000 GES (Najm et al., 2003)

Relation to Junction	Number of Crashes	Share by Relation to Junction
Non-Junction	2,426,000	39.6%
Intersection	1,503,000	24.5%
Intersection-Related	1,249,000	20.4%
Driveway/Alley	663,000	10.8%
Entrance/Exit Ramp	156,000	2.5%
Rail Grade Crossing	14,000	0.2%
On a Bridge	53,000	0.9%
Crossover Related	19,000	0.3%
Other	50,000	0.8%
Total	**6,133,000**	**100.0%**

Analyzing the different crash types can shed more light on the nature of the HRI accidents. In the 2003 research mentioned above, Najm et al. identified the 9 crash types (Table 4), that accounted for 96 percent of all police reported (PR) light vehicle accidents that were found in the 2000 GES data. The last column in Table 4 provides the number of crashes that occurred at or near a highway-rail grade crossing. Notably, 50 percent of the crashes that occurred at or near a HRI were the result of a rear-end collision while 36 percent were not attributed to a particular crash type.

Table 4. Crash Types representing 96 percent of all light vehicle crashes in 2000 GES (Najm et al., 2003)

Crash Type	Number of Crashes	Share of Crashes by Type	Share at Highway-rail
Rear-End	1,806,000	29.4%	7,000
Crossing Paths	1,590,000	25.9%	0
Off Roadway	1,280,000	20.9%	2,000
Lane Change	565,000	9.2%	0
Animal	247,000	4.0%	0
Opposite	163,000	2.7%	0
Backing	129,000	2.1%	0
Pedestrian	66,000	1.1%	200
Pedalcyclist	47,000	0.8%	0
Other	240,000	3.9%	4,800
Total	**6,133,000**	**100.0%**	**14,000**

Najm et al. (2003) were able to map each crash type to a sequence of vehicle movements and critical events that transpired just before each collision. These sequences, called pre-crash scenarios, were derived from three variables in the GES crash database: *Accident Type* {*Movement Prior to Critical Event* : *Critical Event}*. The variables are defined as follows:

- *Accident Type* categorizes the pre-crash situation in terms of rear-end, off-road, lane change, crossing paths, opposite direction, backing, pedestrian, pedal-cyclist, and animal crashes.
- *Movement Prior to Critical Event* describes vehicle activity prior to recognition by a motorist of an impending critical event or just prior to impact if the motorist took no action or had no time to attempt any evasive maneuver.
- *Critical Event* variable identifies the circumstances that made the crash imminent.

An example of such a pre-crash scenario is *Animal* {*vehicle negotiating a curve*: *animal in road*}.

The *rear-end* crash type for collisions between two light vehicles contains the six pre-crash scenarios shown in Table 5. A breakdown of the crashes at or near an HRI is listed in the second row. A similar breakdown of pre-crash scenarios for *off-roadway* crashes of light vehicles is presented in Table 6, which shows that all of the accidents involved single vehicles.

Table 5. Rear-End Pre-Crash Scenarios Involving Two Light Vehicles - from 2000 GES (Najm et al., 2003)

	Lead Vehicle Changing Lanes	Following Vehicle Changing Lanes	Lead Vehicle Decelerating	Lead Vehicle Accelerating	Lead Vehicle Stopped	Lead Vehicle Moving at Constant Speed	Total, all scenarios
All	25,000	30,000	401,000	17,000	895,000	144,000	**1,513,000**
Highway-rail (HRI)	0	0	3,000	0	3,000	1,000	**7,000**

Table 6. Off-Roadway Pre-Crash Scenarios of Light Vehicles from 2000 GES (Najm et al., 2003)

	Single Vehicle	Backing	No Impact	Multi-Vehicle	Total, all scenarios
All	1,126,000	70,000	3,000	81,000	**1,280,000**
Highway-rail (HRI)	2,000	0	0	0	**2,000**

Building upon this research, in 2007 Najm et al. defined 65 pre-crash scenarios that were responsible for 99 percent of all vehicle crashes. This “65 pre-crash” scenario typology synthesized the crash information from the GM “44 crashes” typology and the pre-crash scenarios that were identified previously in 2003. The sequences used to describe the pre-crash scenarios, known as coding schemes, were more complex and contained more than the three variables described above. These new variables included *traffic control devices; violations charged; first harmful event; crash event sequence number; vehicle number; vehicle role; rollover type; hit-and-run;* and *number of vehicles involved*. The complete coding sequences included additional variables, with the full list provided by Najm et al. in their report.

Eventually the 65 pre-crash scenarios were simplified into the “36 pre-crash” scenario typology that is listed in Table 7. The “36 pre-crash” scenario typology is now the accepted standard for researchers to estimate the safety benefits that are associated with Connected Vehicle Safety applications. The top 5 scenarios - *Vehicle Failure, Control Loss With Prior Vehicle Action, Control Loss Without Prior Vehicle Action, Running Red Light and Running Stop Sign* represent 45 percent of all light vehicle crashes, as based on GES statistics.

Table 7. Pre-crash Scenarios listed in alphabetical order (Najm et al., 2007)

No.	Scenario	No.	Scenario
1	Animal Crash With Prior Vehicle	**19**	Pedalcyclist Crash Without Prior Vehicle
2	Animal Crash Without Prior Vehicle	**20**	Pedestrian Crash With Prior Vehicle
3	Backing Up Into Another Vehicle	**21**	Pedestrian Crash Without Prior Vehicle
4	Control Loss With Prior Vehicle Action	**22**	Road Edge Departure While Backing Up
5	Control Loss Without Prior Vehicle	**23**	Road Edge Departure With Prior Vehicle
6	Evasive Action With Prior Vehicle	**24**	Road Edge Departure Without Prior
7	Evasive Action Without Prior Vehicle	**25**	Running Red Light
8	Following Vehicle Making a Maneuver	**26**	Running Stop Sign
9	Lead Vehicle Accelerating	**27**	Straight Crossing Paths at Non-Signalized
10	Lead Vehicle Decelerating	**28**	Vehicle Failure
11	Lead Vehicle Moving at Lower Constant	**29**	Vehicle Turning Right at Signalized
12	Lead Vehicle Stopped	**30**	Vehicle(s) Changing Lanes – Same
13	LTAP/OD at Non-Signalized Junctions	**31**	Vehicle(s) Drifting – Same Direction
14	LTAP/OD at Signalized Junctions	**32**	Vehicle(s) Making a Maneuver – Opposite
15	Non-Collision Incident	**33**	Vehicle(s) Not Making a Maneuver –
16	Object Crash With Prior Vehicle	**34**	Vehicle(s) Parking – Same Direction
17	Object Crash Without Prior Vehicle	**35**	Vehicle(s) Turning – Same Direction
18	Pedalcyclist Crash With Prior Vehicle	**36**	Vehicle(s) Turning at Non-Signalized

Using statistics from the 2004 GES database, Najm et al. (2007) employed the "36 pre-crash" scenario typology to estimate the number of crashes, vehicles involved, and people involved for each pre-crash scenario. Then these results were employed to calculate the crash severity for each scenario in terms of direct economic cost and functional years lost.

The National Highway Traffic Safety Administration (NHTSA) has worked closely with the medical community to evaluate these crash severity metrics. This research is based on a coding scheme developed by the Association for the Advancement of Automotive Medicine (AAAM), which is known as the Abbreviated Injury Scale (AIS). This scheme classifies and describes the severity of specific individual injuries. Najm et al. wished to quantify the worst-case severity associated with the pre-crash scenarios and employed the Maximum Abbreviated Injury Scale (MAIS), a variant of the AIS, to estimate overall maximum injury severity.

Table 8 shows the MAIS levels, Direct Costs, and the functional years lost that are associated with highway crashes for the calendar year 2000. Direct Costs are the economic value of medical care, emergency services, lost market and household activity, insurance administration, legal and court services, travel delay losses, and property damage. Pain, suffering, and loss of life costs, so-called "willingness-to-pay" costs, are difficult to quantify and not included in the direct cost approach; these values are contained in Comprehensive Cost, which is the total of all costs associated with a crash. An alternative approach, called Years Lost Plus Direct, combines Functional Years Lost (FYL), shown in the last column of Table 8, and the direct cost total (Miller, et al., 1991). FYL is a non-monetary approximation of life lost resulting from a fatal injury and the years of functional capacity lost caused by a nonfatal injury. In this sense, FYL may be used as a proxy for the willingness-to-pay costs described previously.

Table 8. MAIS Severity Scale (Najm et al. 2007)

MAIS	Severity	2000 $	Functional Years Lost
0	Uninjured	1,962	0
1	Minor	10,562	0.07
2	Moderate	66,820	1.1
3	Serious	186,097	6.5
4	Severe	348,133	16.5
5	Critical	1,096,161	33.1
6	Fatal	977,208	42.7

Table 9 details the five highest-ranking pre-crash scenarios involving at least one light vehicle for the year 2004. The combined direct economic cost for the two pre-crash scenarios, *lead vehicle decelerating* and *lead vehicle stopped*, was approximately $21.8 billion, as calculated on a national basis in the year 2004. Referring back to Table 5, these two scenarios accounted for 6,000 incidents at HRIs in the year 2000. Assuming that HRI crashes as a fraction of total highway crashes is relatively constant at 0.2 percent for the year 2000 (Najm, Sen, Smith, & Campbell, 2003) allows for an approximation of the annual direct economic cost of HRI accidents. Application of the 0.2 percent value to the 2004 cost data in Table 9 yields a direct economic cost of HRI accidents related to the two scenarios of $43.6 million. Given the catastrophic nature of many highway-rail accidents, we can safely assume that this value represents the low end of the cost spectrum.

Table 9. Top Five Pre-Crash Scenarios for Frequency, Functional Years Lost, and Economic Cost for the Year 2004 (Najm et al. 2007)

Scenario	Occurrence		Functional Years Lost		Direct Economic Cost	
	Rank	**Frequency**	**Rank**	**Years**	**Rank**	**Cost ($)**
Control Loss Without Prior Vehicle Action	**2**	529,000	**1**	478,000	**1**	15,796,000,000
Lead Vehicle Stopped	**1**	975,000	**3**	240,000	**2**	15,388,000,000
Road Edge Departure Without Prior Vehicle Maneuver	**5**	334,000	**2**	270,000	**3**	9,005,000,000
Vehicle(s) Turning at Non-Signalized Junctions	**3**	435,000			**4**	7,343,000,000
Straight Crossing Paths at Non-Signalized Junctions			**5**	174,000	**5**	7,290,000,000
Lead Vehicle Decelerating	**4**	428,000		100,000		6,390,000,000
Vehicle(s) Not Making a Maneuver– Opposite Direction			**4**	206,000		

Najm et al. (2010) furthered the pre-crash scenario research with an analysis of 2005-2008 GES statistics. The goal of this research was to map V2V and V2I Connected Vehicle technologies onto the pre-crash scenarios that were previously identified in their research. Since V2V technology requires at least two vehicles with V2V equipment installed, this technology is most appropriate for vehicle-to-vehicle pre-crash scenarios. Likewise, V2I technology leverages vehicle communications with roadside infrastructure and it is best applied to intersections equipped with active traffic signaling technology.

The results showed that V2V and V2I systems may apply to 79 percent and 26 percent of all police reported crashes, respectively, at the 95 percent confidence level. However, not all pre-crash scenarios were covered by either one of the two systems and required either a joint V2V/V2I approach or some kind of Autonomous Vehicle (AV) onboard sensor technology such as radar, lidar, or camera.

In 2010, Vanasse, Hangen, Brustlin, Inc. (VHB), under contract with FHWA, analyzed V2I safety applications. In the draft report to FHWA, VHB examined the trends in transit crashes during the 2008-2009 timeframe. This exercise was designed to determine the modes of transit with the highest accident rates, including “drilling” for information down to the crash taxonomy level. Table 10 (below) summarizes light rail and heavy rail crashes from the two years of data that were evaluated by VHB. Of the 8,095 transit crashes in 2008-2009, light rail and heavy rail accounted for 4 percent and 2 percent respectively.

Table 10. Heavy Rail and Light Rail Totals for Collisions with Motor Vehicles, 2008-2009 (FHWA, 2010)

Mode	2008	2009	Total	Percent of All Transit	TWM[a,d] (miles)	PMT[b,d] (miles)	VRM[c,d] (miles)
Heavy Rail	62	78	140	2%	2,277	16.45×10^9	637×10^6
Light Rail	162	169	331	4%	1,538	2.050×10^9	85×10^6

[a] TWM = Trackway Miles
[b] PMT = Passenger Miles Traveled
[c] VRM = Vehicle Revenue Miles
[d] All miles are for calendar year 2008

We can draw several inferences from this data. First, light rail vehicle crashes (in absolute terms) occurred at almost two and one-half times the rate of heavy rail vehicles. Second, the exposure values show that light rail crashes were approximately 20 times more frequent than heavy rail, when normalized for passenger miles traveled (PMT).

A further analysis of the NTD by VHB showed that 172 (52 percent) of the 331 light rail crashes involved motor vehicles. Two locations, grade crossings, and right-of-way accounted for 165 (96 percent) of all the light rail crashes involving motor vehicles. Of that total, 148 (86 percent) occurred at grade crossings. Interestingly enough, since a lot of light rail track is at-grade, about 10 percent of collisions occurred at non-HRI locations. Given the nature of light rail environments, connected vehicle safety technologies have multiple opportunities to reduce collision risks.

Table 11 (see below) breaks down HRI and non-HRI light rail-vehicle collisions as a function of train collision type. The VHB report did not analyze heavy rail collisions with motor vehicles.

Table 11. Classification of HRI and non-HRI Crashes for Light Rail Collisions with Motor Vehicles, 2008-2009 (FHWA, 2010)

Crash Type	Grade Crossing	Right-of-Way (ROW)	Total	Percent	
				Grade Crossing	ROW
Angle	61	6	67	37%	4%
Head-On	24	4	28	15%	2%
Other	3	0	3	2%	0%
Other front impact	42	5	47	25%	3%
Rear-ended	7	1	8	4%	1%
Rear-ending	3	0	3	2%	0%
Sideswipe	8	1	9	5%	1%
Total	**148**	**17**	**165**	**90%**	**10%**

3. Methodology

The FRA and NHTSA crash databases were the primary sources of information for this research. The repository for FRA accident data (RAIRS) provides grade crossing accident data and statistics for all railroads, including commuter lines. It spans from 1975 to the present and provides data for all HRI accidents that meet the FRA reporting threshold. This requirement is quite broad because it includes accidents and incidents of "any impact, regardless of severity, between railroad on-track equipment and a highway user at a highway-rail grade crossing site" (FRA, 2011).

The RAIRS database is an excellent source of grade crossing incident, fatality, and injury data, as well as other secondary variables including protective equipment installed at grade crossings, types of motor vehicles involved in collisions, motorist actions immediately prior to a collision with a train, and whether a motorist struck a train or a train struck a motorist. However, the RAIRS database only stores accidents that involve collisions with trains and does not record incidents in the general vicinity of grade crossings that may precipitate an accident.

Of the estimated 16 million crashes that occur annually, approximately 6 million are police-reported (NHTSA, 2010a). The remaining 10 million are thought to result in minimal property damage and injuries. Analyzing this data is complicated since the process of diagnosing accident and injury severity is subjective, and the threshold for police-reported crashes may vary by state and year. To minimize the impact of these uncontrollable variables, NHTSA has developed a uniform scale for reporting injury severity. Although this scale has been adopted by nearly every state, there has been no real reduction in the variability of accident and injury severity reporting in police accident reports (Blincoe, et al, 2002).

NHTSA maintains multiple databases that analyze police-reported traffic crashes. These databases are updated yearly and traffic safety researchers use them to analyze overall accident trends as well as specific factors (including crashworthiness and crash causation). Two databases that are relevant to this research are the Fatality Analysis Reporting System (FARS) and he National Automotive Sampling System (NASS), which are both used in exploring accident trend analysis.

FARS, which dates back to 1975, contains detailed records of all police-reported accidents in which at least one fatality occurred. These records use information that was culled from police accident reports, medical service reports, vehicle registrations, and driver licenses. Each individual record includes over 100 coded data elements that describe the crash, the vehicles involved, and the vehicles' occupants (NHTSA, 2010b). In 2010, 30,000 fatal crashes accounted for 0.6 percent of the 6 million police-reported crashes (NHTSA, 2010a).

The NASS General Estimates System (GES) was established in 1988 by NHTSA as a way for researchers to study crash mechanisms. The database contains a representative random national sample of 50,000 - 55,000 police-reported motor vehicle crashes of the total that occur annually (NHTSA, 2010a). This equates to approximately 1 percent of the total police-reported crashes and is subject to a high degree of sampling error. However, the data is useful in helping to characterize and estimate V2V and V2I preventable crashes.

The Federal Transit Administration (FTA) maintains the National Transit Database (NTD), a database of transit system information and statistics, including accident data. It is the main source of light rail (LR) and heavy rail (HR) grade crossing accident, fatality, and injury data. The NTD defines a reportable incident as (FTA, n.d., p. 41):

> "…an event that is related to or affects revenue service and meets one or more of the following reporting thresholds:
>
> - Fatality - includes suicides
> - Immediate transport away from the scene for medical attention (1 or more persons). Each person immediately transported away from the scene for medical attention, whether or not they appear to be injured, should be reported as an injury
> - Estimated property damage equal to or exceeding $25,000 - includes ALL property involved
> - An evacuation for life safety reasons. A life safety event is one that presents an imminent danger to ALL people in or on transit property."

4. Results of Crash Data Analysis

FRA Accident Data (2008-2012)

An analysis was conducted with two available online databases hosted by the FRA Office of Safety:

- Highway-Rail Grade Crossing Accident/Incident Reporting System – This database provides a comprehensive look at all incidents occurring at HRIs.
- Rail Equipment Accident/Incident Reporting System – This database provides information with which to more effectively quantify the costs associated with HRI accidents.

FRA notes that the completeness and accuracy of the data used in these analyses is dependent upon the data collection and reporting processes of the nation's railroads as well as state and local highway agencies. While the FRA conducts routine audits of these procedures, it does not have sufficient resources to perform comprehensive reviews of each railroad's reporting procedures.

Despite increases in traffic and rail volume, a number of prior studies and analyses confirm that the number of incidents and fatalities occurring at HRIs in the United States has declined over the past two decades. While factors such as improved vehicle safety and medical response have played very important roles in reducing HRI incidents, Mok and Savage (2005) attributed approximately 20 percent of the reduction to the installation of gates and/or flashing lights.

During the 2008-2012 study period for this research, there were an average of 213,850 HRIs in the United States. Of this total, approximately 132,000 HRIs were public and 81,850 HRIs were private. The FRA RAIRS database file structure categorizes HRI warning devices and this analysis classifies them in terms of five levels of protection, from highest to lowest:

- Gates
- Active devices (other than gates)
  - flashing light signals
  - wig-wags
  - highway traffic signals
  - bells
- Passive
  - crossbucks
  - stop signs
- Other
  - watchman/flagman
  - flagged by crew
- None

Only public HRI inventory data was complete enough to be analyzed, since private HRI inventory records are frequently incomplete. Using categories that are defined above, the public HRI records were classified as either active or passive. Analysis (see Table 12) shows that the number of active public HRIs has exceeded the number of passive HRIs by the start of 2010.

This analysis is supported by the general trends during the past two decades (1992-2012): a 0.60 percent annual increase in the number of public active HRIs and a 2.07 percent annual decrease in the number of public passive HRIs. Overall, the total number of active and passive HRIs decreased at a rate of approximately 1.14 percent annually.

Table 12. Active and Passive Public Grade Crossing Totals, 2008-2012

Year	Active	Passive	Total
2008	65,257	70,783	136,040
2009	66,261	67,900	134,161
2010	66,572	63,994	130,566
2011	66,502	63,092	129,594
2012	67,036	62,527	129,563

4.1 Historical Accident Trends

Figure 1 shows incident, injury and casualty trends for public HRIs from 1997-2012 as published in FRA's reports of annual railroad safety statistics. The incident values and the ancillary injury and fatality data in this figure include all reported occurrences at the HRIs and are not limited to motor vehicles. From 1997-2009, there is an almost linear decrease in the number of incidents. After 2009, the incident data behaves in a similar manner to the injury and fatality data. This broadest measure of public HRI safety shows a marked decrease of 50.4 percent 44.3 percent and 39 percent in incidents, injuries, and fatalities, respectively, despite increased rail traffic.

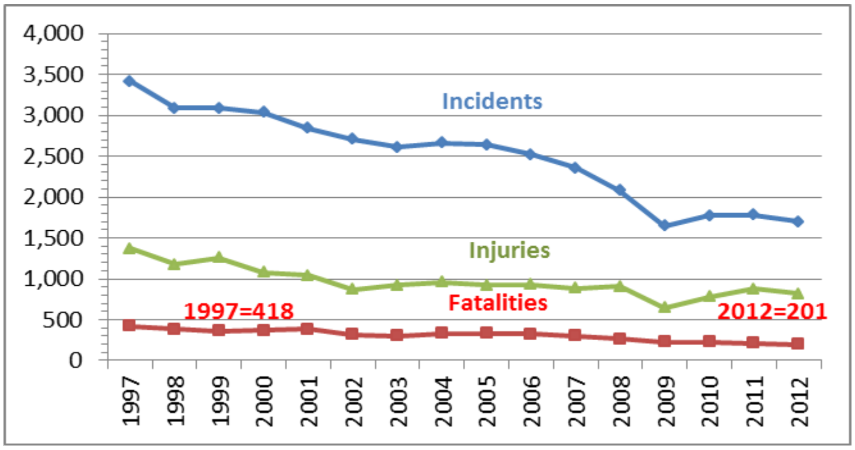

Figure 1. Public HRI Incident and Casualty Statistics from 1997-2012

This data is for public HRIs only. Although local and state agencies and railroads submit inventory updates for both public and private HRIs on a voluntary basis, there is an economic incentive for these organizations to submit public HRI inventory updates because the federal government uses the FRA inventory to rank HRI risk and provide funding for improvements. Since the majority of risk is confined to public HRIs, there is little motivation for private entities to submit timely HRI data updates. As a result, private HRI records in the FRA inventory are, on average, updated less than half as frequently as public HRI data records (Peck, Carroll, & Kloeppel, 2010).

These values, regardless of their quality, are a measure of relative HRI risk. Absolute risk is a better metric since it includes yearly variations in highway vehicle and train traffic (exposure), the HRI inventory, and the composition of active and passive HRIs. Absolute risk is expressed as a function of train miles traveled (TMT), but does not incorporate a measure of highway vehicle traffic. The Traffic Moment (TM) concept used in this report encapsulates both of these parameters as part of the risk calculation. As used in the report, TM is a convenient tool to normalize HRI casualty data. In a given year, the TM for a single HRI is the product of the HRI annual average daily traffic (AADT) and the number of daily trains using the HRI. In this report, all analyses used the total annual TM for all public HRIs in the FRA inventory, which is expressed by the following equation (Ngamdung, 2009):

$$TM = \left(\frac{TotalAADTofXingType}{NumberofXingType} \right) \times \left(\frac{TotalTrainofXingType}{NumberofXingType} \right) \qquad (1)$$

Where

TotalAADTofXingType = the total AADT for all public HRIs in the FRA inventory

TotalTrainofXingType = the total number of trains for all public HRIs in the FRA inventory

NumberofXingType = the total annual number of public HRIs in the FRA inventory

Figure 2 shows the incident and casualty data normalized for TM. As in Figure 1, there is a sharp decrease in the incident rate from 1997-2009, which is almost linear in nature. After 2009, the incident rate behavior follows the injury and fatality rates, which led to associated decreases in incidents, injuries, and fatalities of 64.2 percent, 57.0 percent, and 65.4 percent respectively.

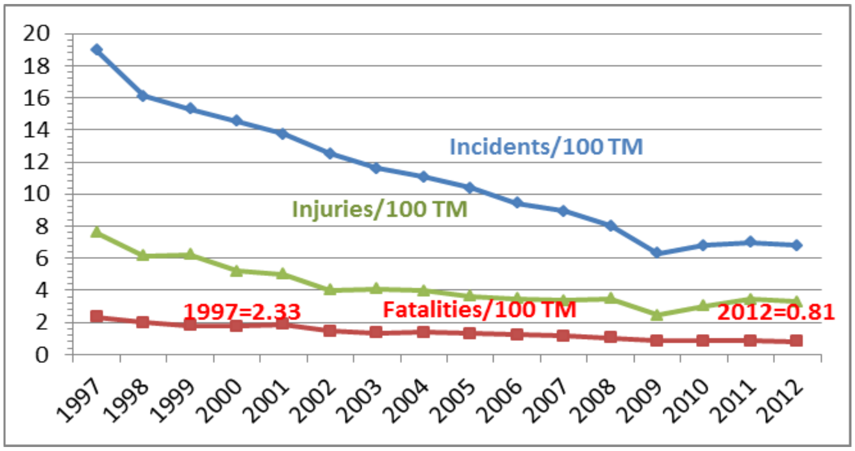

Figure 2. Normalized Public HRI Incident and Casualty Statistics from 1997-2012

4.2 Data Analysis (2008-2012)

The focus of this report is on a five-year set of data that spans from calendar year 2008 to 2012. Figure 3, which was prepared with this data, shows the annual number of HRI incidents, injuries, and fatalities from 2008 through 2012 at all HRIs, public and private[1]. Although there is a general decrease in incidents for this period, the number of injuries and fatalities (excluding those involving pedestrian and other non-motor vehicle users) remains relatively stable. The five-year totals for these categories are 9,775 incidents, 4336 injuries, and 969 fatalities.

The data shows a significant decline from 2008-2009 in the frequency of incidents, injuries, and casualties (20.71 percent, 24.73 percent, and 16.74 percent respectively). After the decline, the yearly totals remain relatively constant and, in the case of injuries, actually show an increase above the 2008 values. Similarly, the number of train miles traveled (TMT) decreased by 13.7 percent between 2008 and 2009.

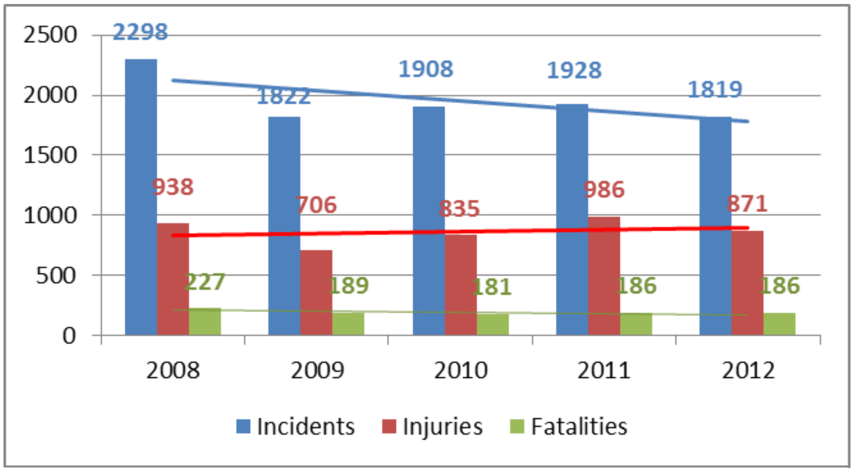

Figure 3. Public and Private HRI Incident and Casualty Statistics from 2008-2012, excluding pedestrians

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[1] Data for 2012 is preliminary as of December 31, 2013. Accident file downloaded from safetydata.fra.dot.gov on March 19, 2014.

A plausible explanation for this decrease is that the recession of 2008-2009 and the accompanying reduction in economic activity caused a significant decline in rail freight traffic, which is borne out by the 15.9 percent reduction of rail freight TMT and the 1 percent increase in passenger train TMT. The majority of HRIs are located on freight lines, which reinforces the theory that a significant percentage of the decrease in HRI incidents is a result of economic conditions.

Figure 4 shows the trends for HRI incidents, injuries, and fatalities normalized with respect to 100 TM for the 2008-2012 accident data set. The data mirrors the trajectory in Figure 3; a significant decrease between 2008 and 2009, followed by a leveling off from 2009-2012. These values are contingent on accurate HRI AADT data.

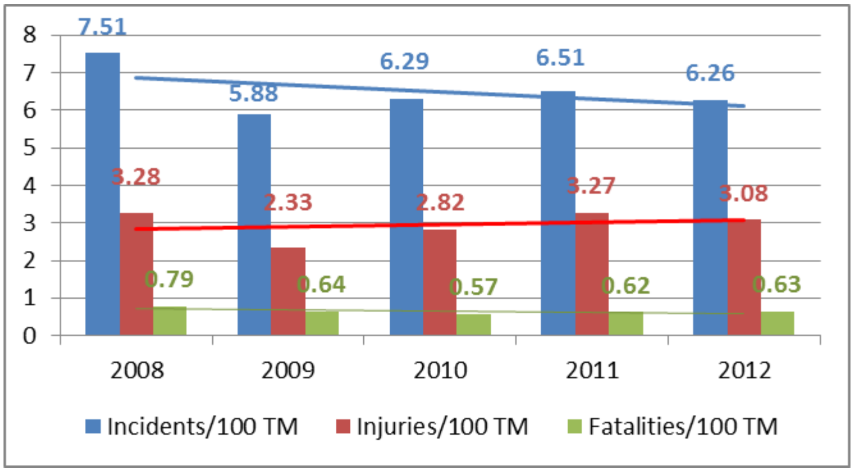

Figure 4. Normalized Public HRI Incident and Casualty Rates from 2008-2012, Excluding Pedestrians

Since accurate AADT data is not available for private HRIs, it is not possible to calculate TM for private HRIs. An alternative method is needed to incorporate private HRI incident, injury, and fatality data into the normalization process. One possible approach to normalizing both public and private HRI data is depicting it in terms of the annual TMT. Although TMT is not explicitly used in the TM equation, it is a proxy measure for the *TotalTrains* variable. Figure 5 (see below) displays public and private HRI incidents and casualties normalized with respect to 100 million TMT and unsurprisingly, this metric for expressing incident and casualty data (which is frequently employed by FRA) behaves similarly to the metrics employed in Figures 3-4.

Another approach to normalizing private and public HRI data is to express incident and casualty rates as a function of the total HRIs in the US DOT inventory. The HRI total is represented in the TM equation by the *NumberofXings* variable. The incident and casualty rates for the 2008-2012 dataset (see Figure 6), confirm the trends observed in Figures 3-5.

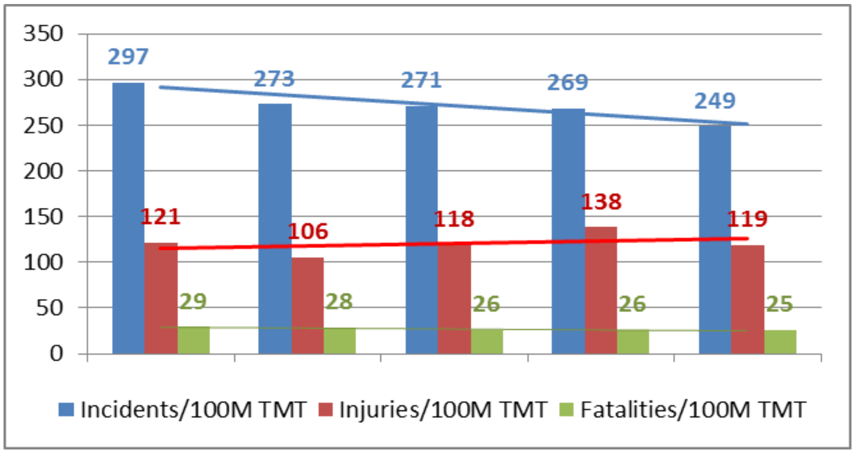

Figure 5. Public and Private HRI Incident and Casualty Rates per 100 million TMT, from 2008-2012, Excluding Pedestrians

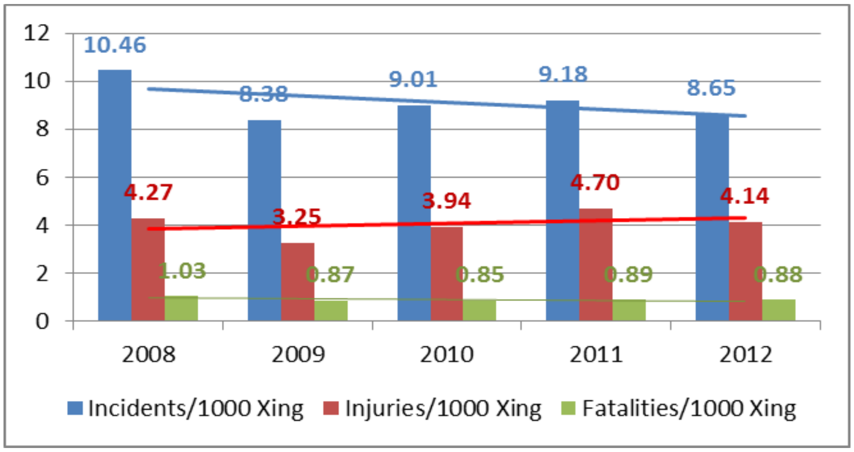

Figure 6. Public and Private HRI Incident and Casualty Rates per 1000 HRIs, from 2008-2012, Excluding Pedestrians

All HRI incidents fit in one of two categories: either a train is struck by a highway user (Type I) or a train strikes a highway user (Type II). Figure 7 (see below) displays the incidents, injuries and fatalities for both scenarios.

It is worth noting that the 2008-2012 dataset includes injuries and fatalities for HRI users, railroad employees, and railroad passengers. Although HRI users account for an average of 98.7 percent of all fatalities, they account for only an average of 75.8 percent of all injuries. However, any reduction in highway user injuries and fatalities as a result of connected vehicle technology will produce an accompanying reduction in railroad employee and passenger casualties. Therefore, the entire HRI injury and fatality dataset was employed in these calculations.

As shown in Table 13, 80 percent of all incidents and 88 percent of all fatalities were Type II. However, given the occurrence of either incident type, a Type II incident was 80 percent more likely to result in a fatality than a Type I incident. There are multiple reasons for this disparity, including collision dynamics, the distribution of light and commercial vehicles, and the number and location of passengers in highway vehicles.

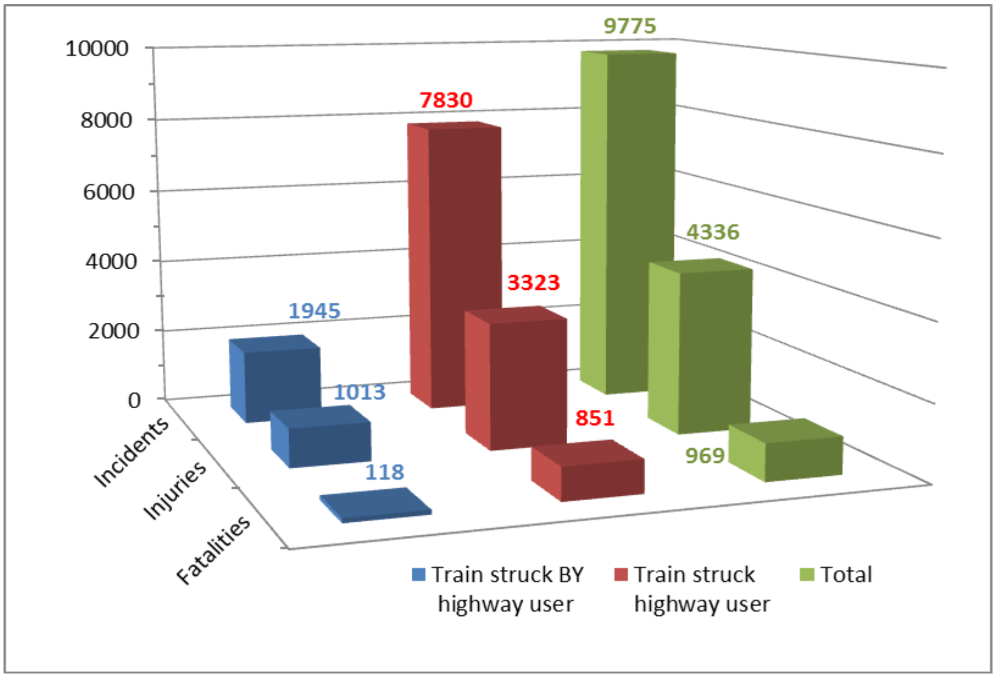

Figure 7. HRI Incident and Casualty Statistics from 2008-2012 for all HRIs, Excluding Pedestrians

Table 13. Distribution of Type I and Type II HRI Incidents and Casualties from 2008-2012 for all HRIs, Excluding Pedestrians

	Incidents (%)	**Injuries (%)**	**Fatalities (%)**	**Casualties (%)**	**Pr(Fatality)**
Train struck BY highway user (Type I)	1945 (19.90%)	1013 (23.36%)	118 (12.18%)	1131 (21.32%)	6.07%
Train struck highway user (Type II)	7830 (80.10%)	3323 (76.64%)	851 (87.82%)	4174 (78.68%)	10.87%
Totals	**9775**	**4336**	**969**	**5305**	

4.3 Highway User Demographics

Figures 8 through 13 (see below) present 2008-2012 HRI incident and casualty data in terms of light, commercial, and motor vehicle types. Light vehicles include autos, pick-up trucks and vans. Commercial vehicles consist of trucks, truck-trailers, buses, and school buses. Other motor vehicles include motorcycles. Figures 8 through 10 show the unprocessed HRI incident and casualty statistics, and Figures 11-13 show the statistics normalized with respect to 100 million TMT.

For both metrics, there is a significant decrease in incidents involving light vehicles between 2008 and 2012. The unprocessed data exhibited a decrease of 24.2 percent, and the normalized data shows a decline of 20.7%. The light vehicle category also exhibited a decrease of 26.1 percent in fatalities for the unprocessed data and 21.7 percent for the normalized set. However, light vehicle injury statistics, after experiencing a marked decrease from 2008-2009, were relatively flat between 2009 and 2012, for both metrics.

Commercial vehicle incident and casualty data trends diverged significantly from that of light vehicles. There was essentially no change in the absolute number of incidents or the normalized incident rate. Injuries actually increased by 24.9 percent and 30.3 percent, respectively, for both the unprocessed and normalized data. Likewise commercial vehicle fatalities increased by 27.8 percent and 33.5 percent for the unprocessed and normalized data. For both injuries and fatalities, the commercial vehicle share of the commercial vehicle/light vehicle total increased by more than 50%.

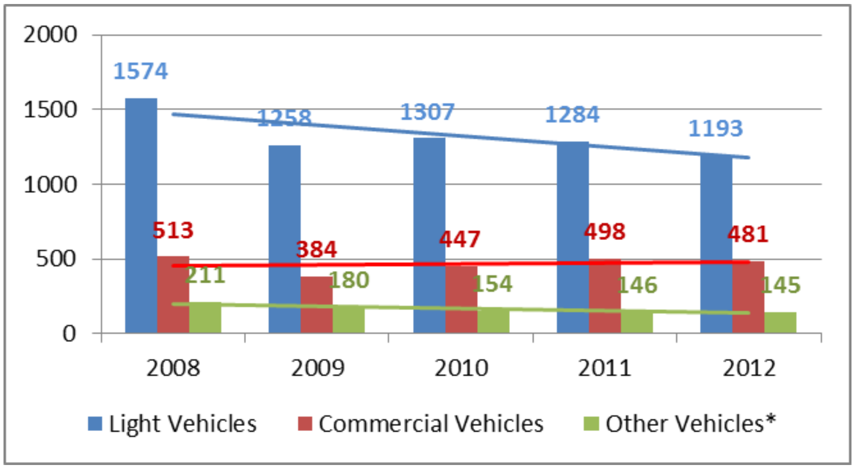

Figure 8. Public and Private HRI Incident Statistics by Motor Vehicle Type from 2008-2012, Excluding Pedestrians

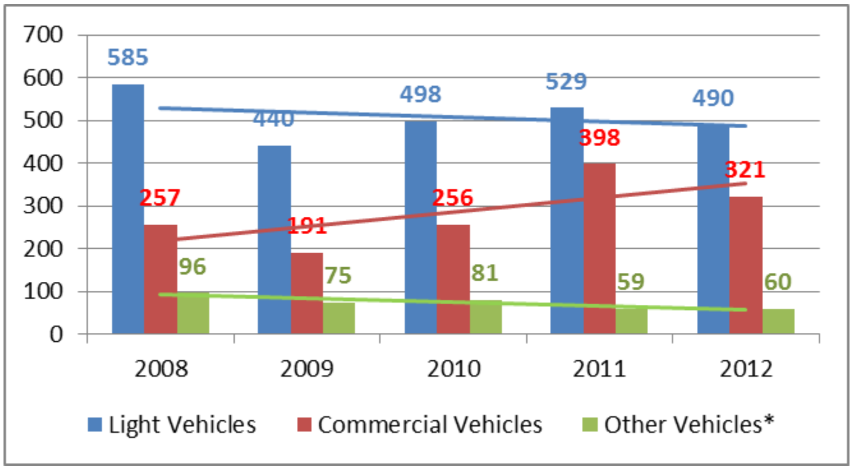

Figure 9. Public and Private HRI Injury Statistics by Motor Vehicle Type from 2008-2012, Excluding Pedestrians

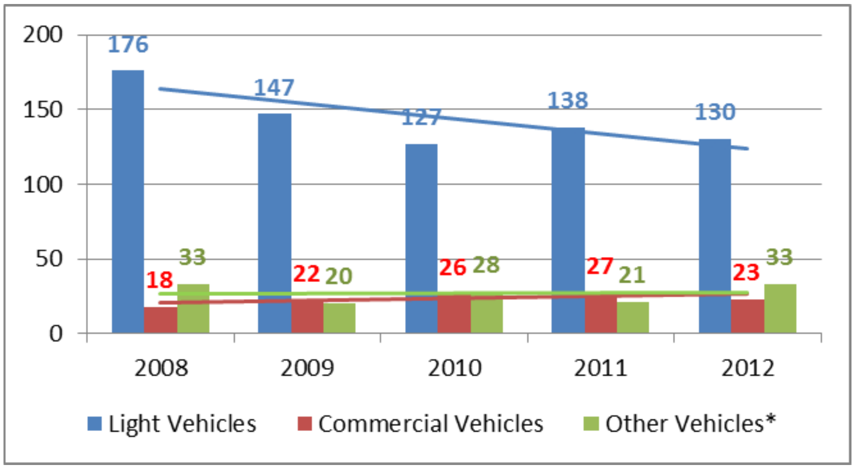

Figure 10. Public and Private HRI Fatality Statistics by Motor Vehicle Type from 2008-2012, Excluding Pedestrians

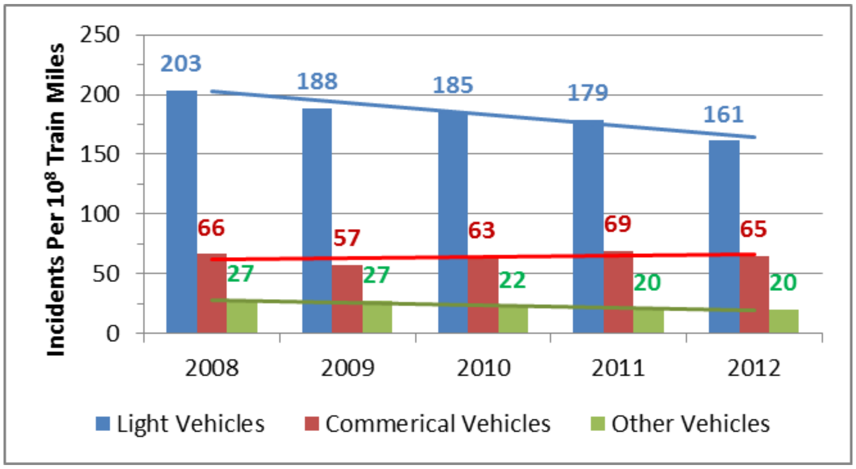

Figure 11. Public and Private HRI Incident Rates per 100 Million TMT by Motor Vehicle Type, from 2008-2012, Excluding Pedestrians

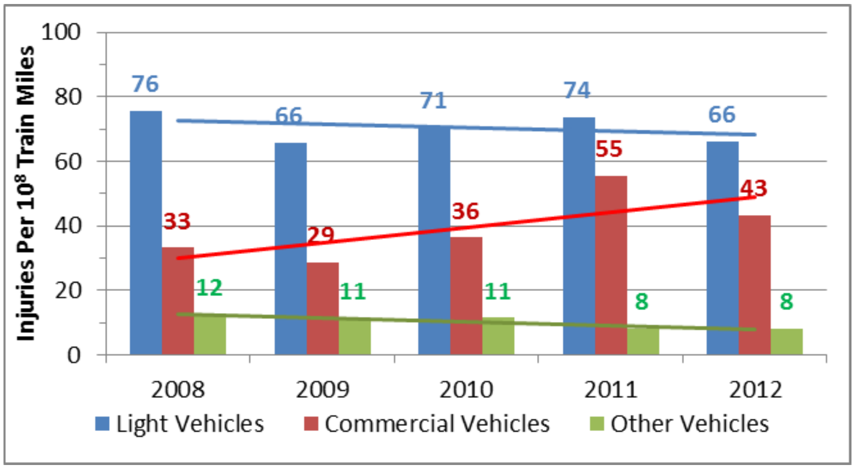

Figure 12. Public and Private HRI Injury Rates per 100 Million TMT by Motor Vehicle Type, from 2008-2012, Excluding Pedestrians

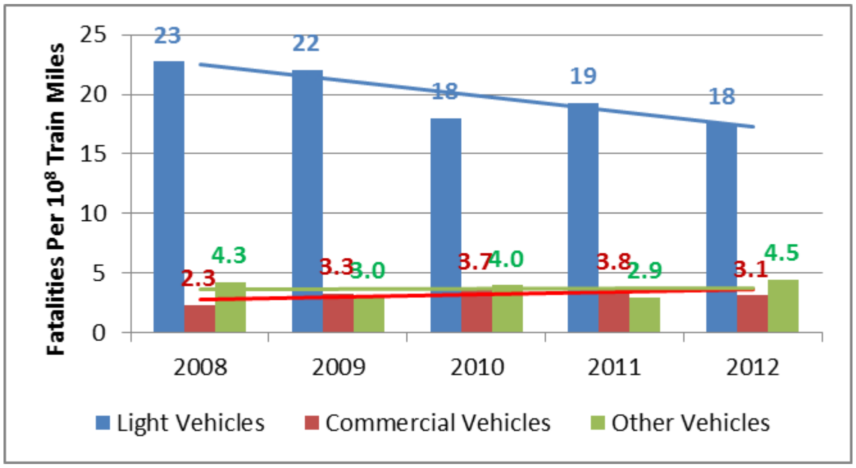

Figure 13. Public and Private HRI Fatality Rates per 100 Million TMT by Motor Vehicle Type, from 2008-2012, Excluding Pedestrians

4.4 Crash Mechanisms

Table 14 displays the distribution of HRI incidents as a function of the warning device type and the action taken by the motorist immediately prior to an incident. The number of incidents at active HRIs and passive HRIs was 5,248 (54%) and 4,095 (42%), respectively. HRIs equipped with gates exhibit the highest motor vehicle and rail traffic and 3,676 (38%) incidents were reported at those locations.

Table 14. Distribution of HRI Incidents as a Function of Motorist Action and Warning Device, 2008-2012

Warning Device	**Motorist Action**					
	Went Around/Thru Gates	Stopped and Proceeded	Did not Stop	Stopped on HRI	Other*	**Totals**
Gates	1317	67	95	1251	946	3676
Active (FLS, WW, HTS, Bells)	0	171	1049	311	41	1572
Passive (CB, SS)	0	422	2647	913	113	4095
Other (Watchman, Crew)	0	15	44	17	5	81
Unknown	0	33	196	104	18	351
Totals	1317	708	4031	2596	1123	9775

*Other = other, went around/thru temporary barricade, suicide/attempted suicide.

Figure 14 illustrates the distribution of motorist action regardless of warning device. Motorists who failed to stop at the HRI were the largest demographic (4031 or 41%), while motorists who stopped on the HRI followed (2596 or 27%). Motorists driving around gates were responsible for 1231 (13%) HRI incidents, while 708 (7%) stopped at an HRI and then proceeded to drive through.

Any highway traffic signal that is within 200 feet of HRIs and is equipped with active warning devices must be interconnected with HRI train detection circuitry. When a train is detected by the HRI, the HRI controller will transmit a preemption message to the highway traffic signal controller. This will result in the highway traffic signal cycling to green so that motor vehicles that may be queued up over the crossing may safely clear.

Around 4850 (2.3 percent) of all HRIs are interconnected with highway traffic signals, and an even smaller number of these, approximately 3550 or 1.68 percent, are equipped with gates[2]. As depicted in Table 15, the majority of HRI incidents, 6996 (72 percent), occurred at locations with no traffic signal interconnection. The 951 incidents that occurred at HRIs with a highway traffic signal interconnection represent 9.7 percent of all HRI incidents. This is a relatively large frequency compared to the total number of interconnected HRIs, which indicates that many HRI crashes occur at locations with the highest amounts of rail and highway traffic. As further confirmation, 833 of the accidents occurred at HRIs equipped with gates.

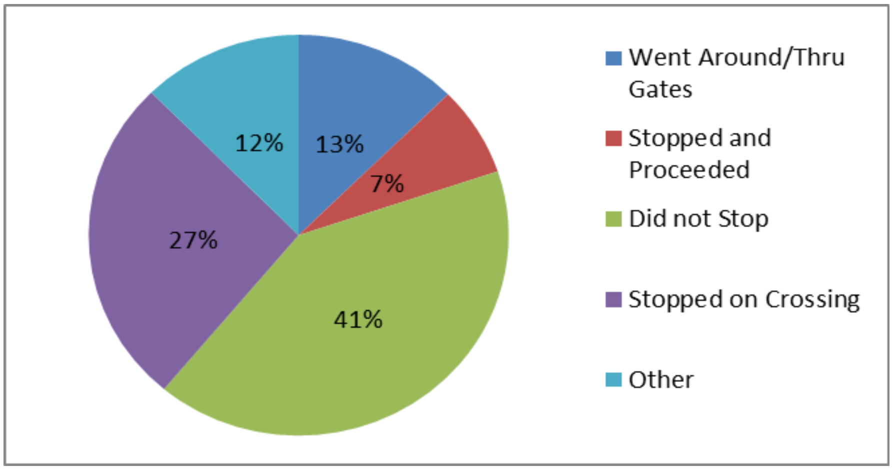

Figure 14. Distribution of HRI Incidents as a Function of Motorist Action, 2008-2012

Table 15. Distribution of HRI Incidents as a Function of Motorist Action and Highway Traffic Signal Interconnection, 2008-2012

Highway Traffic Signal Interconnection?	Motorist Action					
	Went Around/Thru Gates	Stopped and Proceeded	Did not Stop	Stopped on Crossing	Other*	Grand Total
Yes	206	38	147	353	207	951
No	882	522	3085	1824	683	6996
Unknown	44	17	148	97	31	337
(blank)	185	131	651	322	202	1491
Grand Total	1317	708	4031	2596	1123	9775

*Other = other, went around/thru temporary barricade, suicide/attempted suicide.

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[2] FRA public and private HRI inventory data current through December 7, 2012. HRI inventory files were downloaded from safetydata.fra.dot.gov on January 3, 2013.

5. FRA Accident Cost and Functional Years Lost

5.1 Motor Vehicle Damage Cost Analysis

The FRA Railroad Accident and Incident Reporting System is the source of the cost data in Table 16. All vehicle damage costs were based on self-reported repair estimates by the motor vehicle drivers. Table 16 shows the distribution of HRI incidents, casualties, and vehicle damage costs as a function of the total number of fatalities per incident for the 2008-2012 dataset. The majority of the 9,775 HRI incidents recorded, 8,961 (91.67 percent), did not involve any fatalities. The zero fatality accidents accounted for 3,874 (89.2 percent) of injuries and $63,504,318 (89.3 percent) of the vehicle damages incurred. The average vehicle damage costs equaled $7,276 (on a per accident basis).

Table 16. Distribution of HRI Incidents, Injuries, Fatalities and Motor Vehicle Damage Cost as a function of total fatalities per incident, 2008-2012

Total Fatalities per Incident	Incidents	Injuries	Fatalities	Vehicle Damage
0	8961	3874	0	$63,504,318
1	695	268	695	$6,324,914
2	92	46	184	$714,725
3	20	30	60	$453,500
4	4	24	16	$25,000
5	2	0	10	$16,000
6	1	101	6	$80,000
Totals	**9775**	**4343**	**971**	**$71,118,457**

Figure 15 shows motor vehicle damage costs resulting from train crashes at HRIs for the years 2008-2012. These costs are categorized in terms of light, commercial, and other types of motor vehicles. For every year, commercial vehicle damage costs equal or exceed the costs incurred by the other categories. The same data, normalized for cost, is shown as a function of vehicle damage per incident in Figure 16. Unlike Figure 15, the normalized cost associated with light vehicle HRI incidents is no longer approximately equivalent to the commercial vehicle damage costs. The data shows that normalized commercial vehicle damage cost is greater than normalized light vehicle damage cost by a factor of 3 to 4.

5.2 Railroad Infrastructure Costs

The data in Figure 17 was obtained from FRA's Railroad Accident and Incident Reporting System. The histograms in Figure 17 illustrate annual damage to railroad equipment and track assets. Damage to railroad equipment is strictly limited to the train consist involved in the accident. Track asset damages include damages to the track itself, signals, roadbed, track structures, and so on.

During the years that were studied, damages to railroad equipment greatly exceeded those incurred to track infrastructure. There is a gradual reduction in damage-related costs between 2008 and 2010, followed by a large increase in 2011. The data for 2012 shows a slight reduction in damage-related costs from the previous year.

Since most HRI accidents involve a collision between a light vehicle and a train, damage-related costs involving railroad infrastructure fall within a tight range. Therefore, rare high-consequence accidents with significant damages can significantly distort the total for a particular year. For example, when an Amtrak train was struck by a semitrailer in Reno, Nevada in June 2011, the accident resulted in $8,554,000 and $214,682 of equipment and track damages, respectively. In contrast, there were only three accidents in 2008 and one in 2009 in which the total damage exceeded $1 million. In 2010, one accident occurred with total damages of $3.3 million, while none of the remaining accidents was greater than $650,000.

The data in Figure 18 depicts the motor vehicle and rail infrastructure damage costs incurred annually from 2008-2012 and includes a combined total for each year. From 2008-2010, motor vehicle and rail infrastructure damages are roughly equal. In 2011 and 2012, infrastructure damages significantly outweigh those incurred by motor vehicles, which reflects the impact of outlier accidents. Although a five-year sample size is far too small to speculate if infrastructure damages will become the primary driver, annual accident costs are bounded between $20 million and $35 million.

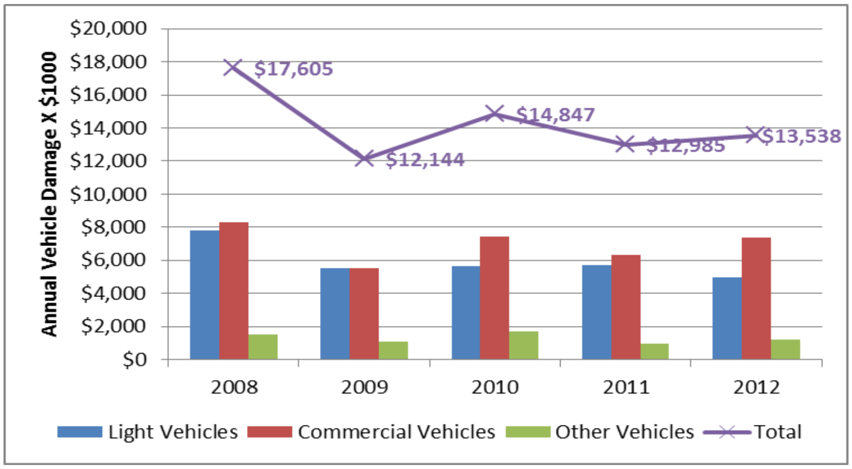

Figure 15. Annual Motor Vehicle HRI Incident Damage Costs for Light, Commercial and Other Motor Vehicles, from 2008-2012

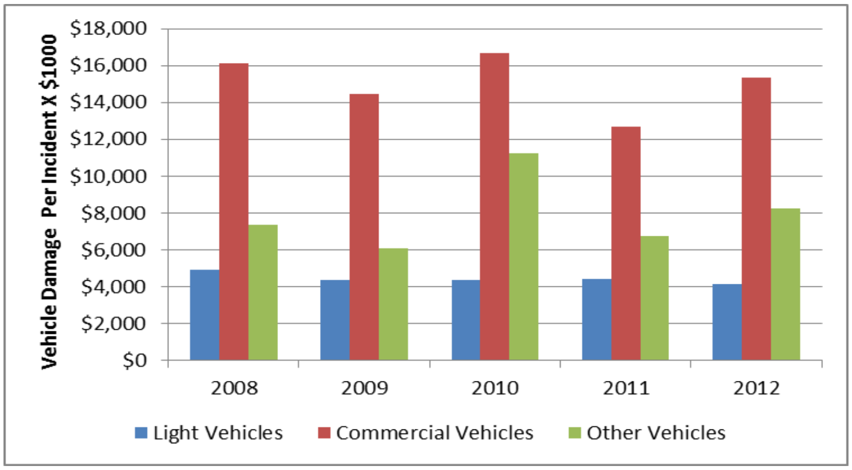

Figure 17. Annual Motor Vehicle HRI Incident Damage Costs for Light, Commercial and Other Motor Vehicles, from 2008-2012, Normalized Per Incident

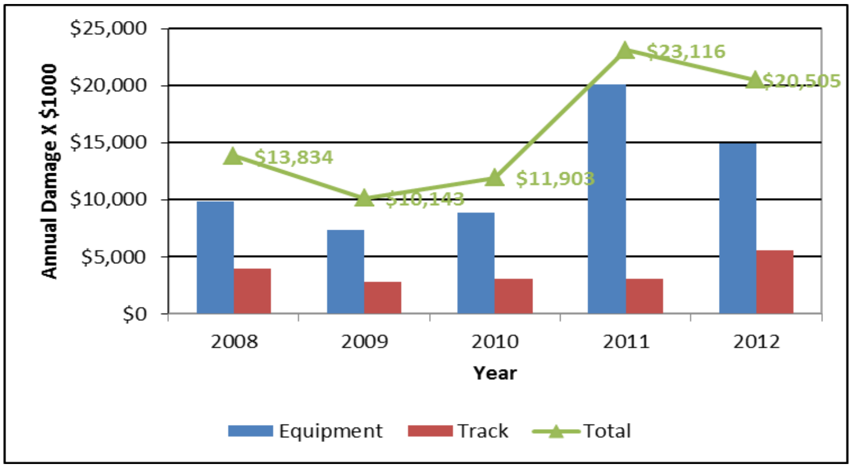

Figure 16. Annual Rail Infrastructure Damage Costs resulting from HRI Incidents, from 2008-2012

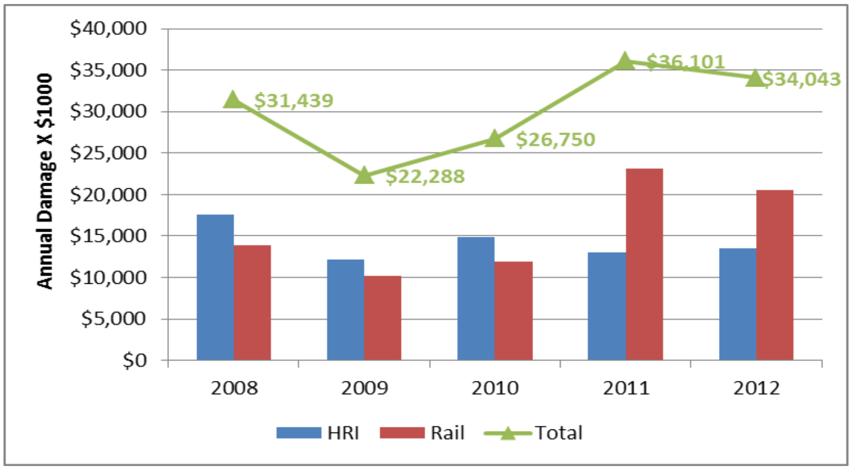

Figure 18. Combined Annual Highway and Rail Infrastructure Damage Costs resulting from HRI Incidents, from 2008-2012

5.3 Accident Costs Related To Vehicle Violations

The primary y-axis in Figure 19 displays the light and commercial vehicle damage costs as a function of the highway user actions or violations that precipitated the incidents. The secondary y-axis is a plot of light and commercial vehicle incident counts. Most of the light commercial vehicle accident-related costs and incidents were associated with the “Did not Stop” violation type. Of the approximately $71 million in motor vehicle accidents costs incurred between 2008 and 2012 (Table 17), the action “Did not Stop” accounted for approximately $28 million or almost 40 percent of the total. The damages from the combined actions “Did not Stop” and “Stopped on Crossing” totaled $46 million, equivalent to almost two-thirds of the entirety.

On a per incident basis, the significance of commercial vehicle incidents is more apparent. The average incident cost for commercial vehicles involved in “Went Around/Thru Gates” violations was $13,680 compared to an average of $4,500 for light vehicles. Likewise, the average incident cost for commercial vehicles linked to “Did not Stop” violations was $14,900 and the average cost for light vehicles was $4,385. This supports Figure 16, which shows that commercial vehicle incidents are, on average, 3-4 times more costly than light vehicle incidents.

Figure 20 is similar to Figure 19, but it displays incident cost and incident totals in terms of the warning system at the HRI (active or passive). The vehicle damage costs at both active and passive warning device sites that were assigned to the “Did not Stop” violation type totaled $31.2 million or roughly 44 percent of the $71 million in motor vehicle damage costs, and damage costs at passive warning device-equipped HRIs for this violation type equaled $23.8 million or almost $8,600 per incident. The “Stopped on Crossing” violation type showed the highest number of active HRI incidents as well as damage costs of $13 million or approximately $8,240 per incident.

Taken together, Figure 19 and Figure 20 imply that the most common cause of crashes with trains (and the most costly) is motor vehicles who fail to stop at HRIs. The majority of these crashes occurred at passive HRIs, which seems to validate the effectiveness of active HRI technology.

There are many reasons that drivers do not stop at HRIs when trains are approaching, including driver distraction, lighting, and weather conditions. However, commercial vehicle users appear to be disproportionally involved.

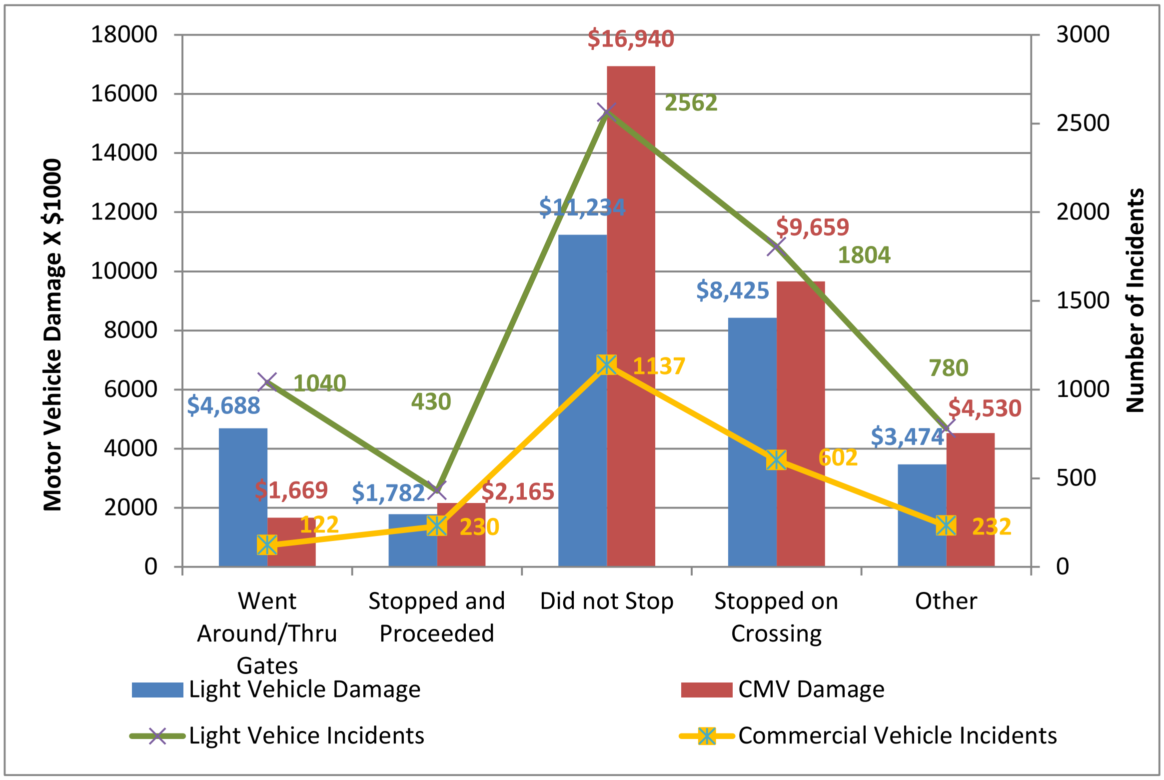

Figure 19. HRI Incident Cost by Crash Mechanism for Light and Commercial Vehicles and the Number of Incidents at All Crossing Type as a Function of Vehicle Type, from 2008-2012

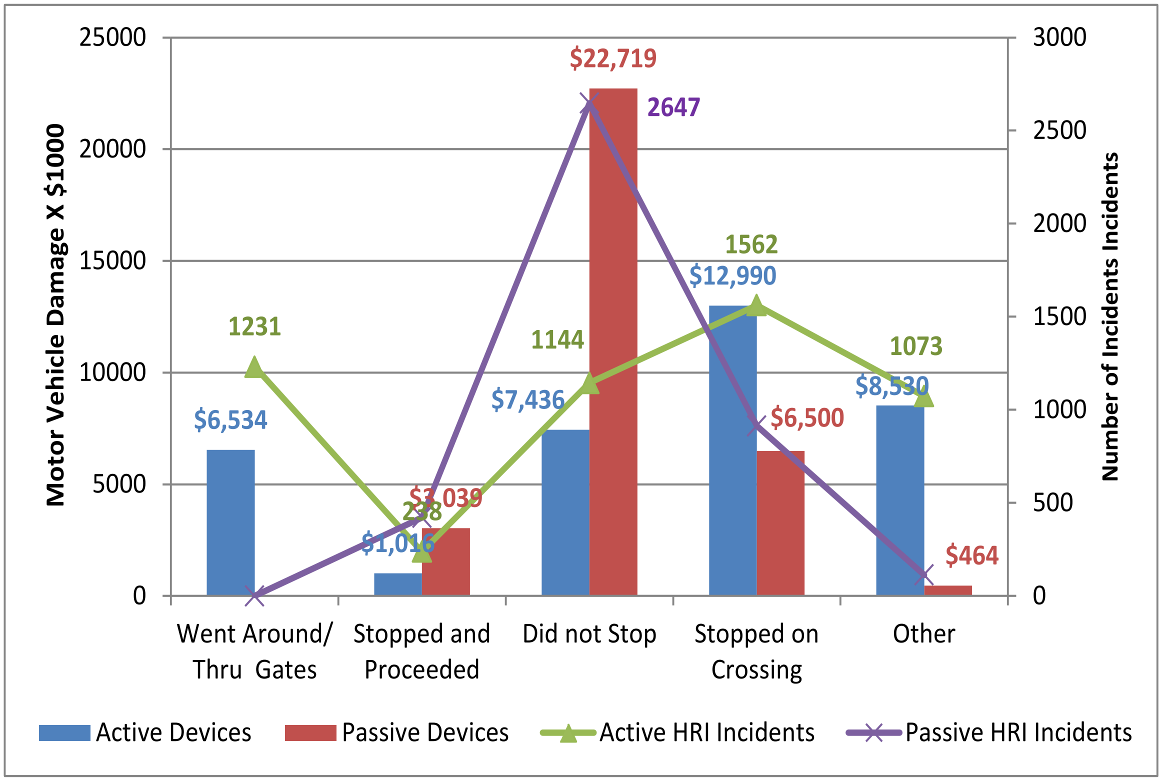

Figure 20. HRI Incident Cost by Crash Mechanism for Active and Passive Warning Devices and the Number of Incidents as a Function of Warning Device from 2008-2012

5.4 RAIRS Accident Costs and Functional Years Lost Using MAIS

FRA accident databases are very accurate sources for costs incurred from physical damage and statistics for HRI injuries and fatalities. However, FRA does not track HRI incident-related injury and travel delay costs. Additionally, FRA does not rate injury severity or cost.

NHTSA employs a tool known as the Maximum Abbreviate Injury Scale (MAIS) to quantify the overall harm to society resulting from motor vehicle crashes. The tool, described in the literature review section of this report, was developed by the Association for the Advancement of Automotive Medicine (AAAM). All injuries on the MAIS scale are ranked in terms of increasing severity from 0 (no injury) to 6 (fatal). There is also a cost associated with each injury severity level that is updated annually.

Table 17 provides a breakdown of the MAIS costs for each severity level. All values are in constant 2007 dollars. The table elements describe the direct economic costs associated with each of the injury levels, with a fatality equating to a total loss. The elements highlighted in blue and orange represent the injury related and non-injury related components of the direct economic costs[3].

Table 17. Summary of MAIS Unit Costs for 2009 (NHTSA, n.d.)

Factor	**PDO**	**MAIS 0**	**MAIS 1**	**MAIS 2**	**MAIS 3**	**MAIS 4**	**MAIS 5**	**Fatal**
Severity	Property Damage Only	No Injuries	Minor	Moderate	Serious	Severe	Critical	Fatal
Medical	$0	$1	$3,427	$22,504	$66,964	$189,111	$478,816	$31,822
EMS	$39	$27	$121	$264	$458	$1,034	$1,061	$1,038
Market Productivity	$0	$0	$2,324	$33,246	$94,959	$141,452	$583,016	$791,199
Household Productivity	$62	$44	$760	$9,730	$28,007	$37,222	$198,423	$254,548
Ins. Admin	$145	$100	$923	$8,607	$23,538	$40,285	$84,964	$46,246
Workplace	$68	$45	$335	$2,595	$5,670	$6,243	$10,886	$11,565
Legal	$0	$0	$187	$6,206	$19,695	$41,967	$99,490	$127,250
Travel Delay	$1,067	$1,027	$1,033	$1,124	$1,249	$1,327	$12,157	$12,157
Property Damage	$1,849	$1,269	$4,789	$4,926	$8,471	$12,250	$11,768	$12,798
Total	$3,230	$2,514	$13,899	$89,202	$249,011	$470,891	$1,480,581	$1,288,623

🟦 **Injury Elements**

🟧 **Non-injury Elements**

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[3] Toward the conclusion of the crash taxonomy research, the National Cooperative Highway Research Program issued Report 755, *Comprehensive Costs of Highway-Rail Grade Crossing Crashes*. The methodology presented in the report employs a single casualty cost metric that is the total of the injury and willingness to pay costs and does not explicitly differentiate between the two.

Table 18 shows the results of processing FRA HRI accident incident and casualty data with the MAIS tool. Since there is currently no method to record MAIS injury severity within the FRA HRI accident reporting system, *low-cost* and *high-cost* estimates are used to range-bound damage costs. The low-cost estimate assumes that all injuries are MAIS level 0, or the lowest severity level, while the high-cost estimate assumes that all injuries are MAIS level 5. Since the distribution of injury severity from FRA HRI accident data is unknown, the arithmetic mean of MAIS level 1-5 costs is a proxy for *average cost*. The values in column six of Table 18 are calculated using the 2009 average cost MAIS level 1-5 cost of $460,717, with the 5-year average damage costs of $650 million per year. The low-cost and high-cost estimates are found in Appendix A. The average Functional Years Lost (FYL) are shown in the last column of Table 18.

Despite the gradual decline in fatalities during the study period, there is no discernible change in damage costs (Table 18). Weighting of the injuries and fatalities in the MAIS cost matrix is partially responsible for this lack of change in damage costs. The values in Table 18 provide a contrast with the damage costs maintained in the FRA HRI and Rail Equipment accident databases. As illustrated in Figure 21, the economic costs calculated using the MAIS tool are roughly 20-25 times the combined motor vehicle and rail infrastructure damage costs.

Table 18. FRA HRI Incident and Casualty Estimated Average Damage Costs and Functional Years Lost

Year	Property Damage Only Accidents	No Vehicle Occupants Injured	Vehicle Occupant Injuries	Fatalities	Cost*	Functional Years Lost
2008	314	1595	935	227	$728,311,254	20,402
2009	252	1226	703	190	$572,618,073	16,165
2010	249	1248	802	178	$602,811,176	16,787
2011	244	1244	993	188	$703,668,112	19,401
2012	277	1050	871	186	$644,502,307	17,919
5- Year Average	**268**	**1,273**	**861**	**194**	**$650,382,184**	**18,135**

*Calculated using MAIS Costs in 2009 Dollars

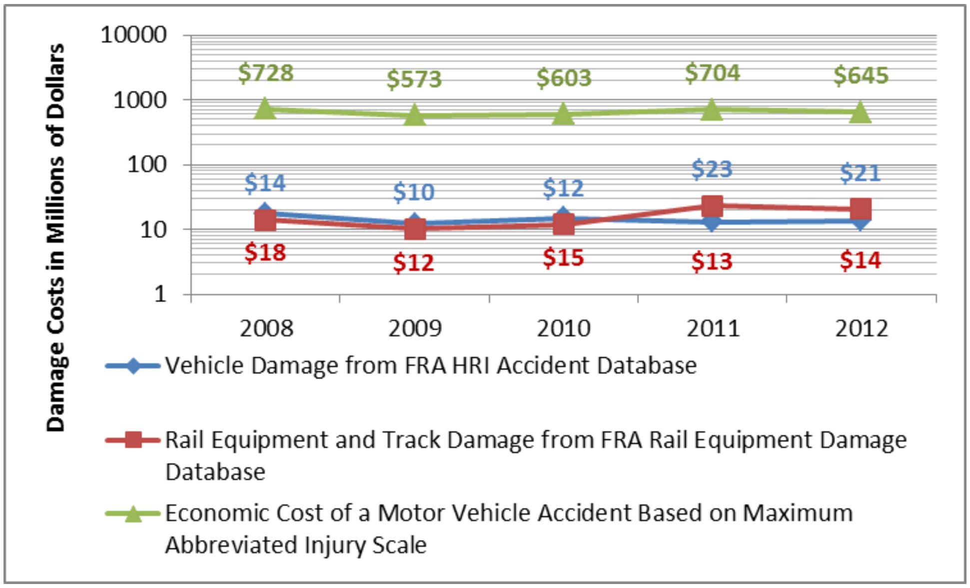

Figure 21. Comparison of Motor Vehicle, Rail Infrastructure, and MAIS Costs, from 2008-2012

6. NASS GES Crash and Cost Analysis

In the GES dictionary, an HRI is a specific type of junction consisting of the area formed by the at-grade connection of a railroad and a roadway. If the first harmful event occurs within this area, a crash is considered to occur at an HRI. According to the GES definition, it is not necessary that a train be involved in every crash at an HRI junction. A highway vehicle may strike another highway vehicle or a highway vehicle may strike an object, and the GES would define those incidents as occurring at an HRI.

The all-vehicle GES crash data for the years 2005-2008, which was taken from research by Najm et. al. (2010), was used to estimate the number of HRI crashes. Figure 22 shows the total number of estimated average annual crashes of unimpaired drivers by vehicle type over the years 2005-2008. GES data is a statistical sample of the true population of crashes and represents a national estimate, subject to sampling error. The error bars in Figure 22 and all the other figures in this section denote uncertainty at the 95 percent confidence levels. Finally, since light vehicle and heavy vehicle crashes are not mutually exclusive, the sum of these two categories does not equal the total number of crashes.

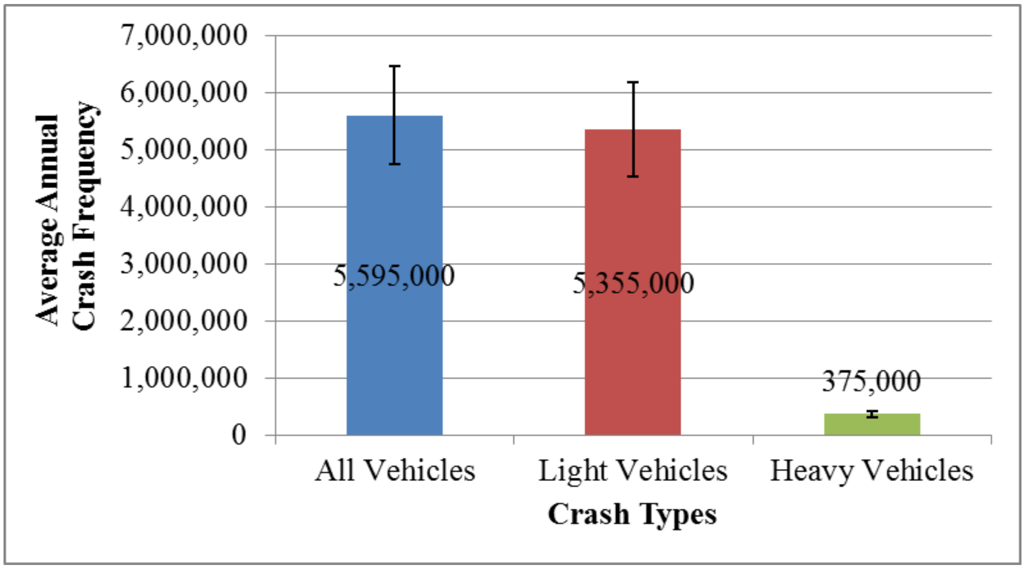

Figure 22. Estimated Annual Crashes of Unimpaired Drivers by Vehicle Involvement from 2005-2008 GES (Najm et al., 2010)

A complete analysis of the GES crashes within the 36 pre-crash scenario framework is found in Najm et. al. (2010). For each pre-crash scenario category, the number of HRI junction crashes was approximated by calculating the product of the total number of crashes of unimpaired drivers and the probability of a crash occurring at an HRI junction (which was derived from the GES dataset and varied for each pre-crash scenario). Referring to the 2005-2008 GES data, 14,800 (0.26 percent) of the roughly 5,595,000 total annual vehicle crashes were estimated to occur within the HRI junction, as defined in this report.

Table 19 lists the 20 scenarios where HRI junction crashes were concentrated and illustrates how the HRI junction crashes involving unimpaired drivers were distributed between light and heavy vehicles. The 95 percent confidence level bars denote the large uncertainty associated with this approach.

Consequently, the method discussed above may not be suitable for estimating the actual number of HRI junction crashes and the resultant economic costs for any given year. However, it is an efficient approach for capturing information about vehicle crashes at HRI junctions that involve trains, other vehicles, or objects. Since not all HRI junction crashes involve trains, it is important to identify and quantify crashes that result from the presence of HRI and HRI equipment. The result of this process is an estimate of the overall number of HRI junction accidents, both train and non-train involved accidents, which may be addressed by connected vehicle technology.

The next step was to estimate the economic cost to society with NHTSA's societal harm measures. Using the 2004 GES crash database and the 2000 MAIS economic cost matrix, Najm et. al. (2007) estimated the economic societal harm associated with each of the 36 pre-crash scenarios. While this report covers both light and heavy vehicle crashes, Najm et. al. (2007) only released information on light-vehicle crashes. Since most crashes involve light-vehicles, these costs are a good first-order approximation of all vehicle crash costs.

For each of the 36 pre-crash scenarios, Najm et. al (2007) were able to estimate the fraction of each scenario's crashes that occurred at each junction type (e.g. HRI), from the GES crash database. Of the seven possible junction types, HRI was present in the 20 HRI pre-crash scenarios listed in Table 19. The fraction of accidents at an HRI (also called HRI factors) is shown in the third column of Table 20. The HRI economic costs in the last column of Table 20 are the product of the HRI factors distributed across the GES economic costs, and these values represent 2004 GES crash estimates applied to 2005-2008 data in 2000 economic costs.

Typical use cases for pre-crash scenarios are in Appendix B. The descriptions are general in nature and little insight is offered into how they apply to the variables in the FRA accident databases. The GES dataset provides a means to filter for the type of vehicles involved in a crash (i.e. motor vehicles, railway vehicles, etc.), but the pre-crash scenario research in this report is focused on collision dynamics at the junction (intersection) level. Since GES is a statistical sample of the true population of HRI crashes, the values in Tables 19-20 are representative of the actual number of HRI crashes and associated economic costs.

At this level of granularity, any analysis of the significance or meaning of the economic costs would be pure speculation. Figure 23 and Table 20 present an upper bound for the number of incidents that occur within the limits of HRIs and the associated costs. What is revealing about the data is how frequent motor vehicle-motor vehicle crashes occur at or near HRIs. These crashes are not captured by the FRA accident databases because no train is involved. The GES data also captures crashes that may precipitate a motor-vehicle collision with a train. In either case, V2X HRI technology, if deployed, may potentially reduce the frequency of more than just HRI crashes.

Table 19. Estimated Annual All-Vehicle Crashes Involving Unimpaired Drivers at HRI Junctions that may be Addressed by Connected Vehicle Technology from 2005-2008 GES

No.	Pre-Crash Scenario	Frequency	Rel. Freq.
1	Lead Vehicle Stopped	3640	24.60%
2	Object Crash Without Prior Vehicle Maneuver	3280	22.16%
3	Backing Up Into Another Vehicle	1290	8.72%
4	Vehicle(s) Drifting - Traveling in Same Direction	1050	7.09%
5	Control Loss Without Prior Vehicle Action	884	5.97%
6	Lead Vehicle Decelerating	776	5.24%
7	Straight Crossing Paths at Non-Signalized Junctions	637	4.30%
8	Lead Vehicle Moving at Lower Constant Speed	576	3.89%
9	Vehicle Failure	500	3.38%
10	Control Loss With Prior Vehicle Action	388	2.62%
11	Vehicle(s) Changing Lanes – Same Direction	334	2.26%
12	Road Edge Departure Without Prior Vehicle Maneuver	277	1.87%
13	Following Vehicle Making a Maneuver	243	1.64%
14	Lead Vehicle Accelerating	220	1.49%
15	Vehicle(s) Not Making a Maneuver - Traveling in Opposite Direction	216	1.46%
16	Road Edge Departure With Prior Vehicle Maneuver	148	1.00%
17	Object Crash With Prior Vehicle Maneuver	132	0.89%
18	Running Red Light	113	0.76%
19	Road Edge Departure While Backing Up	82	0.55%
20	Vehicle(s) Turning at Non-Signalized Junctions	14	0.09%
		14,800	**100%**

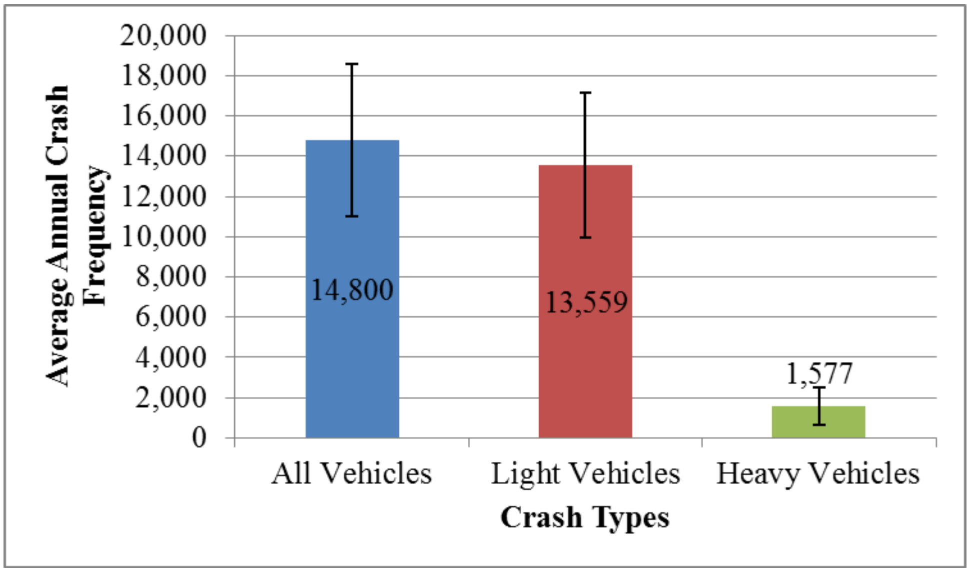

Figure 23. Distribution of Annual Estimated HRI Junction Crashes for Unimpaired Drivers that may be Addressed by Connected Vehicle Technology from 2005-2008 GES

Table 20. Estimated Annual Economic Costs Attributed to All-Vehicle Crashes Involving Unimpaired Drivers at HRI Junctions that may be Addressed by Connected Vehicle Technology, from 2005-2008 GES

Pre-Crash Scenario No.	Frequency	HRI Factor	GES Economic Cost	HRI Economic Cost
1	3640	0.0040	$15,388,000,000	$61,552,000
2	3280	0.0400	$687,000,000	$27,480,000
3	1290	0.0100	$947,000,000	$9,470,000
4	1050	0.0100	$1,383,000,000	$13,830,000
5	884	0.0020	$15,796,000,000	$31,592,000
6	776	0.0020	$6,390,000,000	$12,780,000
7	637	0.0010	$7,290,000,000	$7,290,000
8	576	0.0030	$3,910,000,000	$11,730,000
9	500	0.0100	$1,051,000,000	$10,510,000
10	388	0.0040	$1,970,000,000	$7,880,000
11	334	0.0010	$4,247,000,000	$4,247,000
12	277	0.0010	$9,005,000,000	$9,005,000
13	243	0.0030	$1,212,000,000	$3,636,000
14	220	0.0100	$273,000,000	$2,730,000
15	216	0.0020	$6,407,000,000	$12,814,000
16	148	0.0020	$1,144,000,000	$2,288,000
17	132	0.0020	$155,000,000	$310,000
18	113	0.0005	$6,627,000,000	$3,313,500
19	82	0.0010	$350,000,000	$350,000
20	14	0.0040	$15,388,000,000	$61,552,000
Totals	**14,800**		**$91,575,000,000**	**$235,010,400**

7. Conclusions

The number of HRI incidents declined between 2008 and 2012 by approximately 20 percent, but aside from the years 2008-2009, there was no comparative decrease in injuries and fatalities. This is reflected in the overall trend from 1997-2012, which shows a leveling of injuries and fatalities after 2009.

Of the 9775 incidents and 969 fatalities in the 2008-2012 dataset, 80 percent of all incidents and 88 percent of all fatalities involved a train striking a motor vehicle. Most significantly, the probability of a fatality is twice as high when a train strikes a motor vehicle than when the reverse occurs.

More than one-half of all incidents occurred at HRIs with active warning devices and 37 percent occurred at HRIs with gates. Moreover, 13 percent of incidents at HRIs equipped with gates involved motor vehicles that drove around them. Since most motor vehicle traffic is consentrated at active HRIs, especially those equipped with gates, it is not surprising that more than 50 percent of incidents occurred at active HRIs. However, the number of gate-equipped HRIs, especially those interconnected with highway traffic signals, presents an opportunity for targeting new incident prevention technologies.

While commercial vehicles are involved in only 20-25 percent of all HRI incidents, they are responsible for 45-55 percent of the annual motor vehicle damage costs. On a per accident basis, commercial vehicle damage costs exceed those of light vehicles by three to four times.

The economic cost to railroad infrastructure may vary from year-to-year since a relatively small number of incidents are responsible for a significant amount of the damage. Damage to railroad equipment far outweighs damage to track assets resulting for such events. During the 2008-2012 study period, annual combined HRI and rail infrastructure accident costs were between $20 million and $35 million.

FRA accident databases do not account for the economic losses associated with medical and legal costs, lost productivity, and travel delay. Since these databases do not record the severity of injuries, these measures of societal harm are difficult to estimate. At a minimum, these costs are about $250 million annually, but they could be as high as $1.5 billion.

An alternative approach to characterizing HRI vehicle crashes used NHTSA crash databases. This entailed identifying motor vehicle crashes that occurred within the vicinity of or at HRI junctions. In contrast to the FRA accident database analysis, this approach captured motor vehicle accidents that did not involve a train, but may have precipitated a motor vehicle crash with a train or a motor vehicle crash near an HRI. In either case, these crashes may benefit from Connected Vehicle technology. The results of this analysis showed 14,800 crashes occurred at or near an HRI, costing approximately $230 million per year.

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Appendix A. Expanded FRA Accident Costs and Functional Years Lost

Table A-1. FRA HRI Incident and Casualty Estimated Damage Costs Calculated using MAIS Costs in 2010 Dollars

Year	Property Damage Only Accidents	No Vehicle Occupants Injured	Vehicle Occupant Injuries	Fatalities	Low-Cost	High-Cost	Average Cost
2008	314	1595	935	227	$310,536,611	$1,681,884,281	$728,311,254
2009	252	1226	703	190	$258,505,160	$1,289,582,606	$572,618,073
2010	249	1248	802	178	$244,463,300	$1,420,742,264	$602,811,176
2011	244	1244	993	188	$259,978,036	$1,716,393,262	$703,668,112
2012	277	1050	871	186	$255,324,003	$1,532,804,025	$644,502,307
5- Year Average	**268**	**1,273**	**861**	**194**	**$265,761,422**	**$1,528,281,288**	**$650,382,184**

The low-cost estimate, which is heavily weighted towards MAIS level 0, exhibits a low sensitivity to a change in the number of injuries, and is more dependent on the number of fatalities. Similarly, the high-cost estimate is more sensitive to a change in the injury total and is less dependent on the fatality total. This is borne out in the 18 percent decrease in the low-cost estimate during the study period. By comparison, the high-cost estimate decreased by 9 percent.

Table A-2. Expanded Functional Years Lost

Year	Low	High	Average
2008	9,758	40,641	20,402
2009	8,162	31,382	16,165
2010	7,657	34,147	16,787
2011	8,097	40,896	19,401
2012	8,003	36,772	17,919
5- Year Average	**8,336**	**36,768**	**18,135**

Appendix B. Typical Use-Cases of Pre-Crash Scenarios

Backing Up Into Another Vehicle - Vehicle is backing up in an urban area, in daylight, under clear weather conditions, at a driveway or alley location, with a posted speed limit of 25 mph; and collides with another vehicle.

Control Loss Without Prior Vehicle Action - Vehicle is going straight in a rural area, in daylight, under adverse weather conditions, with a posted speed limit of 55 mph or more, and then loses control due to wet or slippery roads and runs off the road.

Following Vehicle Making a Maneuver - Vehicle is changing lanes or passing in an urban area, in daylight, under clear weather conditions, at a non-junction with a posted speed limit of 55 mph; and closes in on a lead vehicle.

Lead Vehicle Accelerating - Vehicle is going straight in an urban area, in daylight, under clear weather conditions, at an intersection-related location with a posted speed limit of 45 mph; and closes in on an accelerating lead vehicle.

Lead Vehicle Decelerating - Vehicle is going straight and following another lead vehicle in a rural area, in daylight, under clear weather conditions, at a non-junction with a posted speed limit of 55 mph or more; and the lead vehicle suddenly decelerates.

Lead Vehicle Moving at Lower Constant Speed - Vehicle is going straight in an urban area, in daylight, under clear weather conditions, at a non-junction with a posted speed limit of 55 mph or more; and closes in on a lead vehicle moving at lower constant speed.

Object Crash With Prior Vehicle Maneuver - Vehicle is leaving a parked position at night, in an urban area, under clear weather conditions, at a non-junction location with a posted speed limit of 25 mph; and collides with an object on road shoulder or parking lane.

Object Crash Without Prior Vehicle Maneuver - Vehicle is going straight in a rural area at night, under clear weather conditions, at a non-junction location with a posted speed limit of 55 mph or more; and collides with an object on the road.

Object Crash Without Prior Vehicle Maneuver - Vehicle is going straight in a rural area at night, under clear weather conditions, at a non-junction location with a posted speed limit of 55 mph or more; and collides with an object on the road.

Road Edge Departure While Backing Up - Vehicle is backing up in an urban area, in daylight, under clear weather conditions, with a posted speed limit of 25 mph; and then departs the road edge on the shoulder/parking lane in a driveway/alley location.

Road Edge Departure With Prior Vehicle Maneuver - Vehicle is turning left/right at an intersection-related location, in a rural area at night, under clear weather conditions, with a posted speed of 25 mph; and then departs the edge of the road.

Road Edge Departure Without Prior Vehicle Maneuver - Vehicle is going straight in a rural area at night, under clear weather conditions, with a posted speed limit of 55 mph or more, and departs the edge of the road at a non-junction area.

Running Red Light - Vehicle is going straight in an urban area, in daylight, under clear weather conditions, with a posted speed limit of 35 mph; vehicle then runs a red light, crossing an intersection and colliding with another vehicle crossing the intersection from a lateral direction.

Straight Crossing Paths at Non-Signalized Junctions - Vehicle stops at a stop sign in an urban area, in daylight, under clear weather conditions, at an intersection with a posted speed limit of 25 mph; and then proceeds against lateral crossing traffic.

Vehicle(s) Changing Lanes – Same Direction - Vehicle is changing lanes in an urban area, in daylight, under clear weather conditions, at a non-junction with a posted speed limit of 55 mph or more; and then encroaches into another vehicle traveling in the same direction.

Vehicle(s) Drifting - Traveling in Same Direction - Vehicle is going straight in an urban area, in daylight, under clear weather conditions, at a non-junction with a posted speed limit of 55 mph or more; and then drifts into an adjacent vehicle traveling in the same direction.

Vehicle Failure - Vehicle is going straight in a rural area, in daylight, under clear weather conditions, on a dry road with a posted speed limit of 55 mph or more, and then loses control due to catastrophic component failure at a non-junction and runs off the road. Failure of tires, brakes, power train, steering system, and wheels contributed to about 95 percent of these crashes, with tires alone accounting for 62 percent of vehicle failure crashes.

Vehicle(s) Not Making a Maneuver - Traveling in Opposite Direction - Vehicle is going straight in a rural area, in daylight, under clear weather conditions, at a non-junction with a posted speed limit of 55 mph or more; and drifts and encroaches into another vehicle traveling in the opposite direction.

Vehicle(s) Turning at Non-Signalized Junctions - Vehicle stops at a stop sign in a rural area, in daylight, under clear weather conditions, at an intersection with a posted speed limit of 35 mph; and proceeds to turn left against lateral crossing traffic.

Abbreviations and Acronyms

AADT	Annual Average Daily Traffic
AAAM	Association for the Advancement of Automotive Medicine
AIS	Abbreviated Injury Scale
AV	Autonomous Vehicle
CAMP-VSCC	Crash Avoidance Metrics Partnership - Vehicle Safety Communications Consortium
DOT	Department of Transportation
DSRC	Digital Short Range Communications
FARS	Fatality Analysis Reporting System
FHWA	Federal Highway Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
FYL	Functional Years Lost
GES	General Estimates System
GM	General Motors
HR	Heavy Rail
HRI	Highway-Rail Intersection
KABCO	An injury scale that employs the following nomenclature: K for killed, A for incapacitating injury B for non-incapacitating injury C for possible injury O for no apparent injury ISU injury severity unknown
MAIS	Maximum Abbreviated Injury Scale
NASS	National Automotive Sampling System
NHTSA	National Highway Traffic Safety Administration
NTD	National Transit Database
PMT	Passenger Miles Traveled
QALY	Quality-Adjusted Life Year
RAIRS	Railroad Accident and Incident Reporting System

TM	Traffic Moment
TMT	Train Miles Travelled
TWM	Trackway Miles
V2I	Vehicle-to-Infrastructure
V2V	Vehicle-to-Vehicle
V2X	Connected Vehicle
VHB	Vanasse, Hangen, Brustlin, Inc.
VRM	Vehicle Revenue Miles
VSL	Value of a Statistical Life