

# **SERIOUS AND FATAL INJURY RISK IN ROAD DEPARTURE CRASHES WITH GUARDRAIL**

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Dissertation submitted to the faculty of the  
Virginia Polytechnic Institute and State University  
in partial fulfillment of the requirements for the degree of

Doctor of Philosophy

in

Biomedical Engineering

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May 6, 2015

Blacksburg, VA

**KEYWORDS:** Guardrail, End Terminals, Roadside Barrier, Roadside Object, Injury

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(ABSTRACT)

Guardrails are a key safety feature of modern roadways. Collisions with many roadside hazards, e.g. trees, poles and culverts, can be dangerous and guardrail prevents many crashes with such hazards. However, using guardrail safely and effectively is a challenging problem in itself. This research examined two aspects of the problem: 1) assessment of the injury risks posed by guardrail itself; 2) determination of appropriate guardrail length.

When controlling for other factors, light truck / van / sport utility vehicles (LTVs) showed injury odds 3.9 times greater in end terminal crashes compared to guardrail face crashes, while cars showed no significant increase in injury odds. Additionally, the odds of injury in frontal end terminal crashes appeared to be between 3.9 and 5.0 times lower when the terminal design was compliant with the National Cooperative Highway Research Program (NCHRP) 350 crash testing protocol, compared to non-compliant designs. Rollover occurred in 10 % of all frontal guardrail crashes, and was initiated by the guardrail in roughly 46 % of instances. The evidence indicates that end terminal contact increases rollover odds by 6.9 times compared to guardrail face contact for LTVs, but not for cars. NCHRP 350 compliance of end terminals was not observed to have any significant effect on rollover propensity.

In side-impact crashes with guardrail, end terminal crashes represented only about 25% of crashes but accounted for more than 70 % of the injuries sustained. End terminals compliant with NCHRP-350 may be about five times as safe as non-compliant designs, but the difference appears to be overshadowed by the high degree of risk involved in striking any narrow fixed object with the side of the vehicle. A somewhat larger sample appears necessary to make this finding significant at the 95 % confidence level. Only about 20 % of rollovers in non-tracking guardrail side crashes are initiated by contact with the rail; 80 % are

initiated by some subsequent contact. Those rollovers which are rail-initiated appear to be about twice as likely to be initiated by a terminal as by the guardrail face.

Cars showed odds of minor to severe injury 3.6 times greater than LTVs in end terminal crashes. End terminal designs compliant with NCHRP 350 were not observed to carry significantly different odds of minor to severe injury than non-compliant end terminals. The findings control for driver seat belt use, rollover occurrence, terminal orientation (leading/trailing), control-loss and the number of impact events. Rollover and non-use of seatbelts were observed to carry much larger increases in risk than end terminal type.

For cars, electronic stability control (ESC) reduces odds of fatal crashes with roadside barriers by about 50 %. For LTVs, ESC reduces barrier fatality odds by about 40 %. Based on the effectiveness levels observed in this research, it is estimated that ESC could prevent about 410 out of 1180 possible barrier-related fatalities per year by 2028, when 75 % of the fleet is estimated to be equipped with ESC. The study findings suggest that ESC significantly reduces road departures into roadside barriers, and/or that ESC changes departure conditions so that barrier crashes have less severe outcomes.

This research has compared the current standard procedure for computing guardrail length of need (LON) with “departure corridors” based on real-world road departure trajectories. Due to the current procedure’s simplified treatment of road departure geometry, LON recommended by the current procedure becomes very conservative for hazards located closer to the roadside, and less conservative for hazards located further away. By contrast, the departure corridor technique developed in this research provides a known, precisely defined level of protection which remains the same for different hazard offsets. Departure corridors can be made for any desired level of protection, and the technique provides flexibility in how protection may be defined. Most importantly, the departure corridor technique is fundamentally more realistic than the current standard procedure and gives LON recommendations which provide protection levels that can be easily communicated to policy makers and other stakeholders.

## ACKNOWLEDGEMENTS

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There are many people to whom I am indebted for their guidance and support during my research. First and foremost is my advisor, Dr. Hampton Clay Gabler. Any hard work or talent on my part would have come to nothing without a kind, understanding and – particularly in my case – very patient advisor. Dr. Gabler is one of those people who brings out the best in his students; people like him are the salt of the earth. I am privileged to have known and worked with him.

I would like to thank the members of my committee – Dr. Stefan Duma, Dr. Warren Hardy, Dr. Andrew Kemper and Dr. Pamela VandeVord – and Dr. Rob Thomson, who was not on my committee, for their input and advice on my research, and elsewhere. It takes a village to raise a grad student, and I couldn't ask for a better village. My village would not be complete without the other faculty and staff of the School of Biomedical Engineering and Science as well. Thank you all.

Throughout my time as a graduate student, my parents and brother have always been there, ready to lend whatever support they could. What can I possibly say about my family that would adequately convey the depth of my gratitude?

I am grateful to all my labmates, past and present, for putting up with me, helping me with my research every now and again and above all, being my friends. Kris and Stephanie Kusano, Jackey Chen, Ada Tsoi, John Scanlon, Tom Gorman, Stan Gregory, and all the others both old and new who there just isn't space to name. You know who you are. I would also like to extend my gratitude to my friends elsewhere whom I get to see all too rarely: Thomas and Adele Budroe, who are like a second family to me, Matthew Lombardi and Brittany Curtis, Paul Kohler and all the others.

Finally, I would like to thank the Transportation Research Board of the National Academies of Science for funding the research in this dissertation.

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# 1 INTRODUCTION

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## 1.1 ROAD DEPARTURE CRASHES AND GUARDRAIL

Guardrails are a key safety feature of modern roadways. Collisions with many roadside hazards, e.g. trees, poles and culverts, can be dangerous and guardrail prevents many crashes with such hazards. Even so, in an average U.S. year (2006-2009) there were still about 940,000 police-reported passenger-vehicle crashes with fixed objects, resulting in about 8,700 fatalities and 66,000 incapacitating injuries. The cost of these crashes in terms of lost productivity, medical costs and property damages totaled about \$110 billion in 2000 dollars (Council et al. 2005). These fixed object crashes accounted for about 43 % of all fatalities, 32 % of all incapacitating injuries and 21 % of the total economic cost due to U.S. passenger vehicle crashes annually. Guardrail can be effective in helping to reduce this toll, but it can be challenging to use effectively. How much guardrail is needed to protect a given hazard? How much is prudent? These are critical questions for any road safety engineer, particularly as funds for installing and maintaining roadside safety hardware become ever more scarce, even as the roads are used more and more.

Although guardrail can be an effective means of preventing crashes with roadside hazards, the risks associated with guardrail crashes must be understood and accounted for in order to provide a safety benefit. Figure 1.1 shows an example of a road departure crash with guardrail that resulted in fatality. The 1999 Volkswagen Passat in the photograph lost control after exiting a turn, entered a lateral skid, and struck the guardrail end treatment shown lodged in the vehicle. The 18 year old driver was fatally injured, sustaining multiple head trauma and a transected aorta. The 20 year old right front passenger survived, but was admitted to a trauma center for open lower right leg fractures. How much guardrail can be installed before the guardrail becomes a greater hazard than the danger being shielded? In an average U.S. year (2006-2009), passenger vehicle crashes where guardrail was the most harmful event account for approximately 99,000 towed vehicles, 13,000 incapacitating injuries and 1,600 fatalities. The average yearly economic

cost associated with these crashes is approximately \$7.2 billion, or about 7 % of the total for fixed-object crashes.

This dissertation will examine two aspects of roadside guardrail use: assessment of the injury risks associated with guardrail crashes, and determination of the appropriate length of guardrail to shield a hazard.

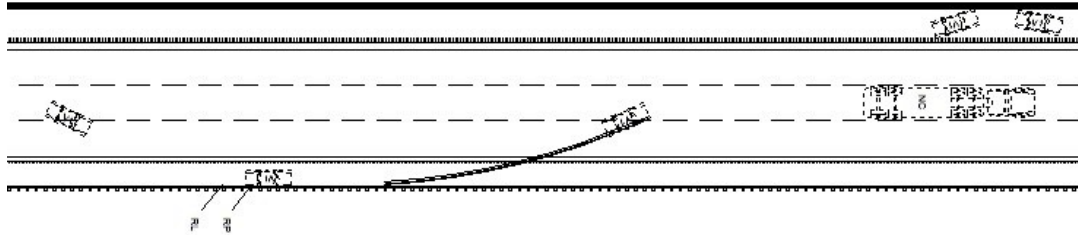


**Figure 1.1. Although guardrail is a safety feature, it still has the potential to cause injury in crashes.**

### *1.1.1 GUARDRAIL FUNDAMENTALS*

Guardrail is longitudinal roadside safety barrier consisting of a (relatively) flexible to semi-rigid rail element supported by posts. Guardrail is used to contain errant vehicles and redirect them back into the roadway, and thereby prevent more hazardous impacts with objects on the roadside (AASHTO 2011). Figure 1.2 shows a crash scene diagram for a typical guardrail crash. Ideally, all hazards would be removed from the roadside so that errant vehicles would be able to regain control before striking any hazards whatsoever (AASHTO 2011). However, this is often not practical to achieve, so guardrail is therefore designed to be as forgiving as possible to strike, while still redirecting errant vehicles. More flexible

guardrail systems are more forgiving to strike but allow greater barrier deflection, whereas more rigid guardrails are less forgiving but can be used in locations where very little deflection is permissible.



**Figure 1.2. Crash scene diagram of a typical guardrail crash. The errant vehicle departed the road, but was redirected back into the lane of travel by the guardrail.**

There are a number of different types of rail used in guardrail. The most common types are shown in Figure 1.3, and are called (from left) “W-beam”, “Thrie-beam” and “box-beam”. W-beam gets its name from the W-shape of its cross section, and is by far the most common type of rail (AASHTO 2011). The etymology of “thrie-beam” is uncertain, but seems like it might be a corruption of “three-beam”. It is similar to W-beam, but has three peaks and two valleys, as opposed to two peaks with a single valley. Box beam is a closed beam with a square (box-shaped) cross section.



**Figure 1.3. Common types of rail used in guardrail. From left: W-beam, thrie-beam, box-beam.**

Guardrail posts are broadly classified into two types: “strong posts” and “weak posts”. Guardrail systems that use strong posts are often called “strong post guardrail”, and systems that use weak posts are frequently labeled “weak post guardrail”. Strong posts are designed to deflect relatively little during crashes, and thereby provide more positive containment. Strong post guardrail uses the strength of the posts

to provide containment (AASHTO 2011). Standard strong posts are either W6x9 wide-channel steel I-beams, or 6” by 8” solid wood posts. The W-beam guardrail shown in Figure 1.3 uses standard wood strong posts; the damaged W-beam guardrail in Figure 1.4 uses standard steel strong posts. Both are called strong-post W-beam guardrail.

By contrast, weak posts are designed to deflect a great deal during crashes, and thereby make the barrier more forgiving to strike at the expense of greater lateral deflection. Standard weak posts are S3x5.7 steel I-beams. Weak post guardrail systems rely heavily on tension in the rail to provide containment (AASHTO 2011). The right panel in Figure 1.4 shows damaged weak-post W-beam guardrail. Posts may also be designed to break off at the base during an impact. These are called “breakaway posts”, and are typically used in the ends of guardrail. Breakaway posts are discussed in Appendix A.



**Figure 1.4. Left: damaged strong-post W-beam guardrail. Right: damaged weak-post W-beam guardrail.**

Many guardrail systems use spacers between the rail element and the posts. These spacers are called “blockouts”. The purpose of blockouts is to minimize vehicle snagging on the posts and to help maintain rail height early in an impact (AASHTO 2011). Blockouts can be made of wood (Figure 1.3), plastic (Figure 1.4) or steel (Appendix A).

The ends of a guardrail are an area of special concern. Impacts to unprotected guardrail ends may result in the rail penetrating into the occupant compartment, possibly striking the occupant. “End

treatments”, or “end terminals”, are therefore applied to the ends of guardrail spans in order to prevent this from happening. Appendix A discusses end treatments in detail, outlines the different components typically used to make end treatments, and provides a field guide to different end treatment systems.

The “length of need”, or LON, is the nominal length of guardrail installed to protect against a particular roadside hazard. LON is distinct from the end terminal, which is always added in addition to the LON required to shield a hazard. With only a few notable exceptions, end terminals are not designed to redirect vehicles, so the distinction between the end terminal and the LON is important. In nearly all cases, guardrail is designed to be redirective starting 3 posts in from the ends. Thus, the 3<sup>rd</sup> post in a system is normally taken to separate the end terminal and the LON.

### *1.1.2 DETERMINING APPROPRIATE GUARDRAIL LENGTH*

Determining how much guardrail to install and where to place it is an important task for road designers. Traditionally, procedures for determination of appropriate LON, have involved a degree of “engineering judgment” and therefore uncertainty as to the level of protection actually afforded (Wolford and Sicking 1996; Coon, Sicking and Mak 2006). This is in large part due to the historic paucity of data regarding what vehicles do when they leave the roadway. There have been a total of three (3) major studies of road departures in the U.S. and Canada: the Hutchinson and Kennedy study from 1966; the Cooper study from 1980; and NCHRP project 17-22 (Mak, Sicking and Coon 2010).

#### **1.1.2.1 Existing Road Departure Data**

Hutchinson and Kennedy (1966) recorded the frequency and length of median encroachments on a 25-mile section of U.S. Interstate 74 and a much smaller portion of Interstate 57 in Illinois. Data was collected on Interstate 74 from its opening in 1960 through April 1964, and on Interstate 57 during the winters of 1957-1960. Survey teams drove the monitored sections of highway weekly at low speeds, looking for any new tire tracks on the median. Data collection was purposely biased towards periods of snow cover in order to more easily detect signs of encroachment. For many years, this was the only data available

describing vehicle trajectory in road departures, even though the study recorded very little information describing vehicle paths other than the length traveled parallel to the roadway. This dataset is thought to have a number of serious limitations, which are described in depth by McGinnis (1999) and Davis and Morris (2006). Bias towards encroachments occurring at times of snow cover may have resulted in overly long departure lengths and possibly shallower departure angles. Departure lengths seem to have been measured along the vehicle path and not parallel to the roadway (which is the way the data was used by subsequent studies). Interstate highways were a new road design at the time, and it has been hypothesized that drivers may have been more prone to driving long distances on the median than now (Davis and Morris 2006). Actual travel speeds may possibly have been much higher as well, for similar reasons. This last point raises a more fundamental issue; the study methodology used by Hutchinson and Kennedy cannot distinguish controlled, intentional departures from uncontrolled departures.

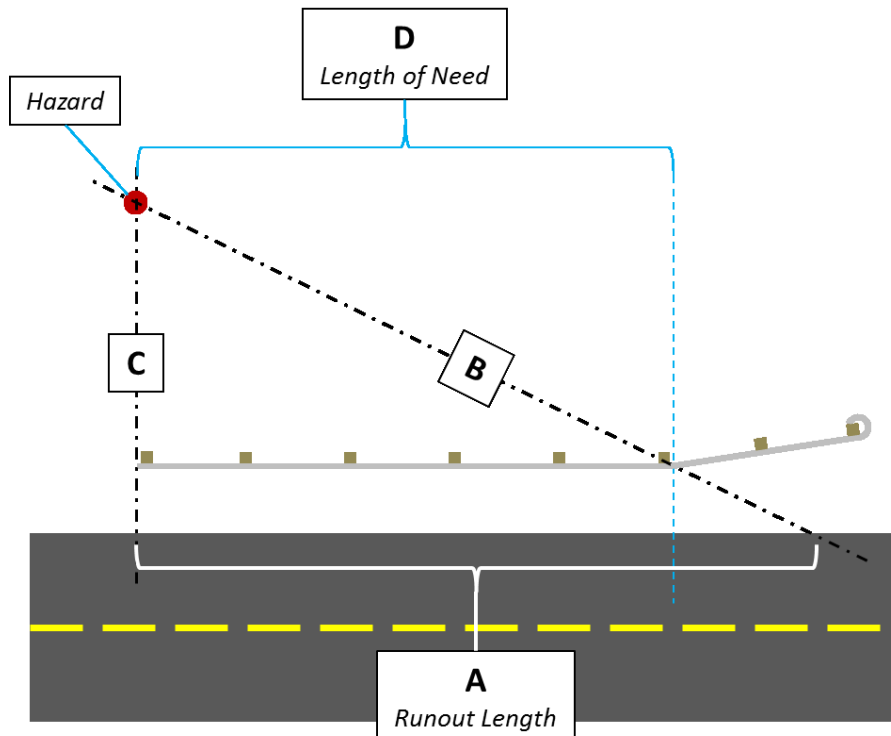
Cooper (1980) collected data on roadside departures from a variety of Canadian highways during 5 summer months in 1979, using surveillance techniques similar to Hutchinson and Kennedy (1966). Because Cooper collected data only during summer months, concerns about overly long departures due to icy conditions do not apply. Departure lengths were actually measured parallel to the travel way (again, this is how the data was used in subsequent research). By 1980, drivers were familiar with large, interstate-style highways, so extended, intentional travel off the road or of excessive travel speeds are much less likely in this dataset as well. While there has been some heated debate over the reliability of the Cooper data (see McGinnis 1999), the general consensus is that the data is a vast improvement over the Hutchinson and Kennedy study. The departure lengths reported by Cooper are overall about 30 % shorter than those reported by Hutchinson and Kennedy (Wolford and Sicking 1996). However, like the Hutchinson and Kennedy data, the Cooper data also reported very little information on road departure trajectories besides travel distance parallel to the road. The Cooper data, like the Hutchinson and Kennedy data, cannot distinguish between controlled and uncontrolled departures.



NCHRP project 17-22 (Mak, Sicking and Coon 2010) was an in-depth study of 890 U.S. road departure crashes spanning the years 1997-2004, conducted with the objective of improving upon the Cooper data, which was nearly 20 years old at the start of the project. Data gathered by the 17-22 study was extremely detailed, and included fully reconstructed vehicle trajectory, impact speeds for all impacts, departure conditions and detailed measurements of the roadside. All cases in the 17-22 sample were collected as part of the National Highway Traffic Safety Administration (NHTSA) routine data collection activities, so the 17-22 sample is nominally nationally representative. However, due to requirements for inclusion in the study, and the fact that the sample is partly composed of samples from two prior, smaller studies of rollover that happened to record some of the needed data, the 17-22 sample is biased towards severe injury outcomes and rollover occurrence (Mak, Sicking and Coon 2010). However, the data is newer than Cooper (1980) by more than 18 years and reflects a vehicle fleet very similar to the present fleet. Furthermore, unlike Cooper (1980) and Hutchinson and Kennedy (1966), project 17-22 actually reports fully-described vehicle trajectories. Chapter 2 contains additional information on NCHRP project 17-22. A follow-on to project 17-22, NCHRP project 17-43, will provide roughly 1,000 additional cases, but the data collection phase of this project has not yet begun.

### **1.1.2.2 Existing Procedure for Determining Guardrail Length**

For many years, the recommended procedure to determine guardrail length of need (LON) has been the one described by the American Association of State Highway and Transportation Officials (AASHTO) Roadside Design Guide, or RDG (AASHTO 2011). This procedure is shown in Figure 1.5. First, the designer chooses a longitudinal runout length to shield a hazard from (line [A]). Table 5-10 in the 2011 edition of the RDG contains suggested runout lengths for different traffic volumes and design speeds. A line is then drawn from the roadside one runout length upstream of the hazard to the hazard itself (line [B]). According to the RDG, any barrier that spans the distance between this line and another line between the hazard and the road edge perpendicular to the road (line [C]) provides adequate shielding. LON (line [D]) is the distance between line [B] and the intersection of the barrier with line [C].



**Figure 1.5. Roadside Design Guide barrier length computation procedure. This is perhaps the most widely used procedure for determining guardrail length.**

The different editions of the RDG have all provided a table of recommended runout lengths versus design speed and expected traffic volume for use with this procedure. In the first three RDG editions, these runout lengths were based on the departure lengths observed by Hutchinson and Kennedy (1966) (AASHTO 2011). The section of Interstate 74 observed by Hutchinson and Kennedy had a speed limit of 70 mph. In the RDG runout length table, the different traffic volumes levels corresponded directly to different percentiles of the Hutchinson and Kennedy data for a design speed of 70 mph. For speeds other than 70 mph, new values were extrapolated based on a braking distance and perception time relationship originally presented in an unpublished FHWA report (see Wolford and Sicking 1996). Table 1.1 reproduces the runout length table from the 3<sup>rd</sup> edition of the RDG (AASHTO 2006), and is annotated with the origins of all values.

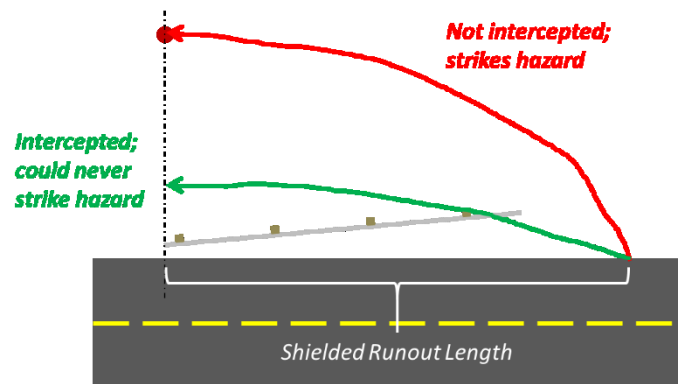
**Table 1.1. Table of recommended runout lengths for the RDG (2006) barrier length computation procedure.**

Design Speed [mi/h]	Traffic Volume [vehicles/day]				
	> 6000	2000-6000	800-2000	< 800	
	<i>Runout Length [ft]</i>				
70	475	445	395	360	<b>85<sup>th</sup>, 80<sup>th</sup>, 75<sup>th</sup>, 70<sup>th</sup> percentile Hutchinson and Kennedy runout lengths</b>
60	425	400	345	330	
55	360	345	315	280	<i>Values extrapolated for lower speeds</i>
50	330	300	260	245	
45	260	245	215	200	
40	230	200	180	165	
30	165	165	150	130	

For the first three editions of the RDG, the recommended runout lengths were derived from the Hutchinson and Kennedy data, despite wide belief (Wolford D and Sicking DL 1996; Coon BA, Sicking DL and Mak KK 2006; AASHTO 2011) that the shorter Cooper runout lengths were more accurate. Only in the 4<sup>th</sup> edition (AASHTO 2011) were the recommended runout lengths updated to use the Cooper (1980) data. Most of the Cooper data also corresponded to a single speed limit, so the different percentile runout lengths of the Cooper data were extrapolated to other speeds in the same way as in previous RDG editions.

The best available data on road departure trajectory were, for many years, the Hutchinson and Kennedy (1966) and Cooper (1980) studies. Other than runout lengths, substantial data did not exist with which to model vehicle behavior while off the road. Consequently the RDG procedure protects against departures only on the basis of runout length, not of their actual potential to strike a hazard. Not every departure with a specified runout length will make contact with a given hazard, so fully shielding against a specified percentage of runout lengths will give conservative values for barrier length. However, by assuming vehicles travel in straight lines while off the road, the RDG procedure neglects the possibility of errant vehicles that travel around the end of a barrier. The RDG procedure does not *fully* protect against all crashes of the specified departure length, i.e., the RDG procedure intercepts some departures that would not be hazardous and fails to intercept some departures that would be hazardous. Figure 1.6 illustrates both

of these contingencies. Hence, the percentage of otherwise potentially hazardous crashes intercepted is not precisely known with the RDG procedure.



**Figure 1.6. By modeling road departures solely on the basis of runout length, the RDG barrier length procedure neglects several variations in vehicle trajectory that can affect the hazard presented by a departure.**

### *1.1.3 ASSESSING SAFETY PERFORMANCE OF GUARDRAIL*

#### **1.1.3.1 Guardrail Crash Testing Standards**

Crash testing has been used perhaps more than any other method to evaluate the safety of roadside barriers. Motivated by the need for consistent barrier systems across all states, there has been a strong push for standardization of testing procedures. The first standardized testing protocol for U.S. guardrail was published in 1962 in *Highway Research Correlation Services Circular 482* (HRB 1962). In 1974, National Cooperative Highway Research Council (NCHRP) Report 153 (Mitchie and Bronstad 1974) provided a more complete set of testing procedures (AASHTO 2009) which gained wide acceptance even though portions were still understood to be based on outdated or inadequate information (Ross et al. 1993). *Transportation Research Circular 191* (TRB 1978) made minor refinements to the NCHRP 153 testing protocols and injury metrics (AASHTO 2009). NCHRP Report 230 (Mitchie 1981) made major revisions to NCHRP 153 and Circular 191, including new test protocols for additional hardware types (e.g. construction barriers) and for a wider range of vehicle types (e.g. busses, heavy trucks), as well as updated performance metrics to reflect advances in barrier technology and design practices. NCHRP 230 became a

standard reference for crash testing of roadside barriers in the U.S. and many other countries (Ross et al. 1993). NCHRP Report 350 (Ross et al. 1993) was a comprehensive update to and replacement of NCHRP 230, first published in 1993, formally accepted by the American Association of State Highway and Transportation Officials (AASHTO) and the Federal Highway Administration (FHWA) later that year, and fully implemented by 1998 (Bullard et al. 2010). NCHRP 350 contains completely revised testing criteria meant to reflect the large changes in vehicle design since NCHRP 230. The Manual for Assessing Safety Hardware, or MASH (AASHTO 2009) was published in 2009 and supersedes NCHRP 350. MASH contains a number of updates to NCHRP 350, most notably incrementally more severe test conditions (AASHTO 2011). As of the beginning of 2011, all roadside barrier systems installed on the U.S. National Highway System must be compliant with either NCHRP 350 or MASH. Systems that were accepted under NCHRP 350 prior to the adoption of MASH may still be installed and maintained even though MASH supersedes NCHRP 350 (AASHTO 2011).

### **1.1.3.2 Real-World Studies of Guardrail Safety Performance**

While crash testing is necessary to establish the safe crash performance of a guardrail system, it is not by itself sufficient. Actual guardrail installations experience impacts outside the range for which they are designed, they are installed in locations that may be less than optimal, they are subject to weathering and damage (Gabauer and Gabler 2009b; Gabler, Gabauer and Hampton 2010), and they may be installed incorrectly (Ray, Weir and Hopp 2003; Hampton and Gabler 2013; Hampton, Gabauer and Gabler 2010; Hampton and Gabler 2012). Studies of real-world guardrail safety performance are therefore necessary to detect unanticipated problems and to verify the theoretical safety performance observed in crash tests (Figure 1.7). To this end, a number of studies have been done in the past to assess the real-world performance of guardrails. Some notable examples include: a study by Bryden and Fortuniewicz (1986) that examined the effects of vehicle, barrier type and other highway features on guardrail crash severity using 1982-1983 New York state data; the Longitudinal Barrier Special Study which used nationally representative crash data from the mid-1980s to examine differences in injury rate between different barrier

systems and different vehicle types; Viner, Council and Stewart (1994) used Michigan and North Carolina state data from 1985-1990 to reexamine some of the same issues; and Bligh and Mak (1999) who also revisited the issue using nationally representative data from 1987-1995. NCHRP Report 490 (Ray, Weir and Hopp 2003) also incorporated three different, high-quality studies of various roadside barriers from 1997-1999, as well as a comprehensive literature review of roadside barrier safety assessments.



**Figure 1.7. A guardrail end terminal embedded in the front of a crashed vehicle.**

Most existing studies of injury risk in guardrail crashes use data collected during the first half of the 1990s, or earlier. Substantial changes have taken place in the intervening twenty years. Federal regulations made driver airbags mandatory on passenger cars in 1997, and on light trucks a year later in 1998; airbags were rare during the 1980s (Gabauer and Gabler 2010). Seatbelt use has increased from approximately 11 % during the 1980s to over 80 % by 2008 (Derrig, Segui-Gomez and Abtahi 2000; Pickrell and Ye 2008). Stringent crash testing standards adopted by the Insurance Institute for Highway Safety (IIHS) and the National Highway Traffic Safety Administration (NHTSA) have spurred dramatic

improvements in vehicle crashworthiness as well. In 1995, the National Maximum Speed Limit Law was repealed and speed limits on many high-speed facilities increased almost immediately (NHTSA and FHWA 1998). Active safety technologies, particularly electronic stability control, are now commonplace in the vehicle fleet and may change both the incidence and the characteristics of road departures (Kahane 2014; Høye 2011; Gorman, Kusano and Gabler 2013; Kusano and Gabler 2012; Kusano and Gabler 2014; Kusano, Gabler and Gorman 2014). NCHRP 350 was adopted as the testing standard for roadside safety hardware in 1993 and was fully implemented by 1998, meaning the guardrail designs present on roadways have been changing since 1993 as well. Because many older vehicles remain in use and because it can take many years before obsolete roadside appurtenances are updated with hardware meeting new standards, even data collected soon after mandated changes in vehicle or roadside design may not completely capture the effects of those changes. In light of this, studies of injury risk in guardrail crashes that use data from the 1990s or earlier cannot safely be assumed to represent the injury risks currently faced.

## 1.2 RESEARCH OBJECTIVES

Road departure crashes are a major road safety problem. Guardrail can be an effective means of addressing this problem, but using guardrail safely and effectively is a challenging problem in itself. This dissertation will examine two aspects of the problem: 1) assessment of the injury risks posed by guardrail itself; 2) determination of appropriate guardrail length.

### *1.2.1 WHAT ARE THE INJURY RISKS ASSOCIATED WITH GUARDRAIL IN THE REAL WORLD?*

Chapters 3 and 4 will address this by providing studies of injury outcomes in real-world guardrail crashes. These studies will use nationally representative crash data that reflects current vehicle safety technology and guardrail designs.

Chapter 5 will present an analysis of injury outcome in crashes with different types of guardrail end treatment. Guardrail ends are particularly hazardous compared to guardrail face, so protection of guardrail ends is an area of special concern.

Chapter 6 will study the effect of electronic stability control, or ESC, on crashes with roadside barriers such as guardrail. ESC is an active safety technology whose purpose is to prevent loss of vehicle control, which is a factor in many road departure crashes. As ESC becomes common, it may change the incidence of crashes with guardrail, as well as impact conditions and injury outcomes in such crashes.

### *1.2.2 WHAT IS THE LENGTH OF GUARDRAIL NECESSARY TO PROTECT A GIVEN HAZARD?*

This question will be addressed in Chapter 7 with the development of an improved technique for computing the length of barrier needed to shield a hazard. This technique will be used to evaluate the data and assumptions of the current standard procedure.



## 2 DATA SOURCES

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The research presented in the chapters that follow is based on a diverse set of crash databases. This chapter provides an overview of the different data sources used in this dissertation.

### 2.1 THE NATIONAL AUTOMOTIVE SAMPLING SYSTEM (NASS)

The National Automotive Sampling System (NASS) is the U.S. national crash surveillance effort operated by the National Highway Traffic Safety Administration (NHTSA). NASS provides nationally-representative estimates of crash occurrence and injury outcomes and is responsible for informing U.S. national road safety policy and regulations. Data collection began in 1979 and, starting in 1988, the program was split into two parts: the General Estimates System and the Crashworthiness Data System (NHTSA 2009).

#### 2.1.1 NASS GENERAL ESTIMATES SYSTEM (NASS-GES)

The NASS-GES is a nationally representative sample of all police-reported crashes where (1) the result was property damage, injury or death and (2) where at least one vehicle was in a traffic way at the time of the crash. GES does not limit the types of vehicles that may be sampled; crashes involving all vehicle types are included so long as the crash meets the aforementioned requirements. GES is a clustered, stratified and weighted sample of Police Accident Reports, or PARs. GES cases are collected from a group of 60 geographic regions, called Primary Sampling Units (PSUs – the sample clusters), that were selected to provide a representative sample of national geography. Within each PSU, police-reports of crashes meeting the GES requirements are assigned to one of several strata based on outcome severity and other factors. Reports may be selected from all police jurisdictions within a PSU or from a representative sample of jurisdictions in larger PSUs. A fraction of the reports in each stratum are then sent to trained technicians who code the PAR information into the GES database format. GES therefore does not contain any information beyond that found in PARs; it effectively aggregates and homogenizes PARs from different

jurisdictions. The weight assigned to each GES case is effectively the number of actual police-reported crashes represented by that case nationally in the year it was sampled (NHTSA 2012a).

GES contains a much larger number of cases than the NASS Crashworthiness Data System as well as a wider variety of cases, but the information gathered is less detailed. GES cases are essentially homogenized police reports and while the data is extremely valuable, the limitations of police-collected crash data still apply. Because it samples all crash types, GES is useful for estimating how many crashes of different kinds occur and roughly what happens when they do occur – hence the name “General Estimates System”.

### *2.1.2 NASS CRASHWORTHINESS DATA SYSTEM (NASS-CDS)*

Whereas the GES is primarily intended to monitor the number and type of crashes occurring in the U.S., the NASS-CDS is designed to provide detailed information on occupants, injuries, vehicle safety performance and the sequence of events in crashes. Unlike GES which samples crashes involving all vehicle types, CDS only samples police-reported tow-away crashes involving passenger vehicles. This includes cars, light trucks and vans. CDS is a clustered, stratified and weighed sample collected in much the same way as GES. Police accident reports are collected from 24 of the 60 PSUs used by GES and are assigned to one of 10 strata based on injury outcome, vehicle damage and a number of other factors. A certain number of the cases from each stratum are then selected for inclusion in CDS; crashes with severe outcomes, late model vehicles or other occurrences of research interest are oversampled. Each case is weighted according to the number of crashes it represents nationally in that sample year, so CDS estimates are still nationally representative despite not being a random sample.

There are fewer cases in CDS than in GES, but these cases are investigated much more thoroughly. Whenever possible, investigators conduct interviews with vehicle occupants and obtain medical records to determine the nature of any injuries sustained during a crash. This is done discretely and confidentially and only with the consent of the vehicle occupants. No personally identifiable information is included in any

NASS case. Vehicles are inspected to obtain detailed measurements of crash damage and to determine if and where occupants contacted the vehicle interior. Detailed photographs are taken of involved vehicles and very often, the crash site is inspected and photographed as well. When the available evidence and the nature of a crash permit, CDS investigators will attempt to reconstruct the change in velocity, or delta-V ( $\Delta V$ ) experienced by the vehicle during each impact event. A crash reconstruction program called WinSMASH is used for this purpose; WinSMASH estimates  $\Delta V$  directly from vehicle damage without any estimates of initial or final velocity (Sharma et al. 2007; NHTSA 2009; Hampton and Gabler 2009a; Hampton and Gabler 2009b; Hampton and Gabler 2010; Johnson and Gabler 2014). Investigators will also attempt to obtain event data recorder data for NASS-CDS vehicles whenever possible to do so with the consent of the vehicle owner, as this can provide additional crash data not obtainable through other means (Gabler, Hampton and Hinch 2004; Gabler, Hampton and Roston 2003; Gabler, Gabauer, Newell and O'Neill 2004), as well as higher-quality  $\Delta V$  data (Tsoi et al. 2013; Tsoi, Johnson and Gabler 2014).

## 2.2 MICHIGAN STATE CRASH DATABASE

The Michigan State Crash Database contains a record of every police-reported motor vehicle crash in the state of Michigan involving a vehicle in transport, on a roadway, where the crash resulted in death, injury or property damage in excess of \$1,000 (Michigan Dept. of State Police 2014). Unlike the NASS databases, Michigan State crash data is not sampled in any way – it is a census of every police-reported crash in Michigan. As a result, the Michigan State crash data can sometimes be useful for examining very specific crash modes that NASS databases might not have sufficient case counts to study. However, Michigan crash data is much less detailed than NASS crash data, so it can be difficult to positively identify crashes with the characteristics sought. The only data available in the Michigan crash database is the information coded on the Michigan UD-10 Traffic Crash Report (Michigan Dept. of State Police 2014). For example, Michigan crash data does not provide scene diagrams or crash site photographs. One notable advantage of the Michigan State Crash Database over NASS databases is that the Michigan data reports the latitude and longitude of the crash, as well as a description of the crash location. With the availability and

wide coverage of Google Street View, it is often possible to inspect crash locations both before and after the crash date.

### 2.3 FATAL ACCIDENT REPORTING SYSTEM (FARS)

FARS is a census of all crashes resulting in the death of one of the involved persons. To qualify, crashes must take place on a traffic way customarily open to the public and the death must occur within 30 days of the crash and must be the result of injuries sustained during the crash. Because fatalities are rare events, GES estimates of fatalities may not have the precision desired, and CDS is known to underestimate fatalities. FARS is therefore the ideal dataset to use when studying crashes with fatal outcomes. One agency in every state collects PARs and other documents for all fatal crashes. Highly trained FARS analysts within these agencies process the documents, code and check the information, and forward the processed case information to the NHTSA. FARS data essentially consists of PAR data, like GES data. In fact, from 2011 forward, GES cases have comprised a subset of the FARS data elements; the two databases were standardized and henceforth have used the same database schema (NHTSA 2012b).

### 2.4 NCHRP PROJECT 17-22

The NASS-CDS provides a great deal of information on vehicles, their occupants and the injuries they sustained, as well as the sequence of crash events that caused those injuries. However, NASS-CDS contains very little information on roadside objects, the roadway or the roadside itself. NCHRP project 17-22 collected very detailed information for 890 road departure crashes, including reconstructed off-road vehicle trajectory, departure speed, impact speeds for contacted objects and measurements of the road and roadside. 17-22 cases were all collected as part of the NHTSA NASS-CDS effort but added supplementary data on the roadside. A detailed discussion of NCHRP project 17-22 and the data collection protocol used for the study is given by Mak, Sicking and Coon (2010). Although 17-22 cases are all NASS cases, because of the eligibility requirements for 17-22 cases, the 17-22 sample is known to be biased towards cases with rollover and severe injury outcomes, even when CDS sampling weights are applied (Mak, Sicking and

Coon 2010). However, there is presently no other source of comparable U.S. road departure crash data available. NCHRP project 17-43 will provide roughly 1,000 additional road departure cases with similar levels of information, but this study has not yet begun data collection.

## 2.5 NATIONAL HIGHWAY TRAFFIC SAFETY ADMINISTRATION (NHTSA) CRASH

### TEST DATABASE

The NHTSA conducts many vehicle crash tests each year for a number of reasons: to verify regulatory compliance of new vehicles; to provide New Car Assessment Program (NCAP) ratings for vehicles; and to serve their own internal research needs. Records and test data for these crash tests are made publically available in the NHTSA Vehicle Crash Test Database. Available data elements include high-speed video (when recorded), raw data from test sensors such as accelerometers and load cells, measurements of actual impact conditions (to verify compliance with testing protocols), post-test damage measurements, computed values of relevant injury metrics, and written test reports (NHTSA 2013). The WinSMASH program used by NASS-CDS investigators to reconstruct  $\Delta V$  uses this crash test data to characterize energy absorption by different vehicle models, a process that is central to its operation (Sharma et al. 2007). Because they are so highly controlled and well documented, these crash tests are also useful for checking the accuracy of WinSMASH  $\Delta V$  reconstructions (Johnson and Gabler 2011). Crash tests can be reconstructed using WinSMASH, and the WinSMASH  $\Delta V$  compared to the actual  $\Delta V$  as determined from crash test instrumentation, high-speed video or in some cases, the specified test conditions.

## 2.6 INJURY CODING

In all of the crash databases just described, injury is coded using the “KABCO” scale and/or the Abbreviated Injury Scale (AIS). The KABCO injury scale is used by law enforcement to describe the apparent condition of vehicle occupants or other parties involved in a crash, and is recorded on PARs (Gabler et al. 2015). Possible values on the KABCO scale include:

- K – killed. Indicates that the subject was fatally injured.

- A – incapacitating injury. Used when a subject was incapacitated by their injuries, but not killed at the scene.
- B – non-incapacitating injury. The subject sustained evident injuries, but was not incapacitated.
- C – possible injury. Used when a subject may have been injured, but injuries were not immediately evident.
- O – no injury. The subject was not injured.

KABCO is a standard part of police accident reports, so KABCO injury data is nearly always available. However, because it is coded by law enforcement and not medical professionals, it is less accurate than injury data coded using AIS (Farmer 2003).

The Abbreviated Injury Scale rates individual injuries according to their clinical importance, i.e. threat to life and potential for permanent disability (Gabler et al. 2015). AIS injury data is coded by medical professionals, typically physicians working in trauma centers, in contrast to KABCO which is coded in the field by law enforcement. AIS rates injuries on a scale from 1 to 6, where 1 is a relatively minor injury such as a small, shallow laceration, and 6 is a currently untreatable injury such as aortic rupture or decapitation. Injuries rated 3 or higher on the AIS scale are typically considered serious. The AIS scale divides the body into a number of different regions (e.g. torso, head, arms, legs), and treats injuries differently in different regions. For example, a deep laceration located distally on a limb may not be as serious as a deep laceration located on the neck. Because AIS only applies to individual injuries, most crash databases that use AIS typically record the maximum AIS value for a subject, or MAIS. The MAIS value is typically used to determine a subject's injury level when analyzing crash data that includes AIS injury codes.

## 3 INJURY RISK IN FRONTAL CRASHES WITH GUARDRAIL

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### 3.1 INTRODUCTION

According to the National Automotive Sampling System – Crashworthiness Data System (NASS-CDS), each year in the United States from 1997 to 2008 there were on average about 51,000 police-reported tow-away crashes of passenger vehicles where the most severe impact was with guardrail. These crashes comprised about 8 % of all single-vehicle crashes (on the basis of most severe impact) in an average year. Approximately 3 out of every 4 guardrail crashes were frontal impacts. About 75 % of all of seriously injured drivers and 60 % of fatally injured drivers in guardrail crashes were due to frontal crashes. Annually, this corresponds to an average of approximately 800 seriously-to-fatally injured drivers and 100 fatally injured drivers.

Bryden and Fortuniewicz (1986) examined the effects of vehicle, barrier type and other highway features on guardrail crash severity using New York state data from 1982-1983. Fatalities were less frequent in crashes with roadside barriers than with all roadside objects taken together. Amongst roadside barriers, fatalities were less common when the impact was within the design envelope of the barrier and when the barrier was a “current [*sic*]” system at the time of the study. About 58 % of designed-for barrier impacts resulted in some level of injury or fatality. Twenty-six percent of barrier crashes had a secondary event (including rollover), and this 26 % of crashes accounted for nearly 90 % of fatalities and half of A-level injuries. Light trucks, vans and SUVs (LTVs) were observed to have higher injury rates in roadside crashes than cars.

Hunter, Stewart and Council (1993) extensively studied differences in injury rates between different guardrail and end terminal types, between vehicle types and between length-of-need and end terminals. They used the Longitudinal Barrier Special Study (LBSS) file, a highly detailed set of about 1200 longitudinal barrier crashes collected from 1982 to 1986 as part of the NHTSA’s NASS activities. Their

main findings were that weak post guardrail carried less risk of injury than other types; that blunt and turndown end terminals carried greater risk of serious injury than length-of-need sections; and that end terminal impacts were more likely to produce injury than impacts to length-of-need sections because of higher inherent injury risk as well as a greater association with rollovers.

Viner, Council and Stewart (1994) examined injury outcomes by vehicle type in roadside safety appurtenance crashes from 1985-1990, using Michigan and North Carolina state data. They found that, for cars, serious injury occurred in 19 % of reported guardrail end crashes and 6 % of guardrail face crashes while for pickup trucks, the respective percentages were 13 % and 8 %. They also found that pickup trucks were three times more likely to roll over than cars when striking a guardrail face but that, in rollovers, pickup trucks had less than half the serious injury rate of cars. They concluded that the higher serious injury rate for pickup trucks in guardrail face crashes was due to the higher rollover rate and decreased belt use relative to cars.

Bligh and Mak (1999) examined the crashworthiness of different roadside hardware including guardrail using nationally representative data from 1987-1995. Based on NASS General Estimates System (NASS-GES) data, crashes with guardrail resulted in some level of injury for 31.5 % of passenger cars and 39.1 % of LTVs and in serious injury or fatality (A or K) for 5.3 % of cars and 11.4 % of LTVs. LTVs rolled over in 11.2 % of guardrail crashes while cars rolled over in 4.7 % of guardrail crashes.

NCHRP Report 490 (Ray, Weir and Hopp 2003) included a comprehensive literature review of roadside hardware safety evaluations up to 2003. Out of 115 reported crashes with Breakaway Cable Terminals (BCTs) or Modified Eccentric Loader Terminals (MELTs), 60 % resulted in property damage only and only 5 involved serious or fatal (A or K) injury. Seventy-five percent of the 400 police-reported guardrail crashes in the sample were property-damage-only; 13 involved A or K outcomes. Injury was found to be less common with G1 guardrail than with G4 guardrail, and guardrail damage was less severe with G1 than with G4 guardrail.



The majority of the literature concerning injury risk in guardrail crashes uses data from the first half of the 1990s, or earlier. Substantial changes to the U.S. vehicle fleet have happened in the intervening 20 years: airbags became mandatory on new vehicles only in 1997-1998; seatbelt use rates have risen since the early 1990s; crashworthiness of the average fleet vehicle has improved drastically thanks to stringent crash tests run by the Insurance Institute for Highway Safety (IIHS) and NHTSA. Roads and roadside hardware have changed as well. In 1995, the national maximum speed limit law was repealed and in late 1998, NCHRP Report 350 (Ross et al. 1993) was adopted by the FHWA as the standard for roadside safety appurtenances on the National Highway System. In light of these changes, studies based on data from the 1990s or earlier cannot safely be assumed to represent injury risks posed to the current vehicle fleet.

### 3.2 OBJECTIVE

The goal of this study was to determine the injury risks of frontal crashes with guardrail using data representative of the current vehicle fleet and roadside hardware. Particular subjects of interest included the risk of guardrail end terminal impacts relative to the guardrail face, the influence of vehicle type and the effect of compliance with NCHRP 350 safety criteria.

### 3.3 METHODS

Data for this analysis were obtained from the NASS-CDS. The NASS-CDS is a nationally representative database of police-reported tow-away crashes which is maintained by the US Department of Transportation (NHTSA 2014a). NASS-CDS cases are investigated by trained crash investigators and contain information well beyond that found in police accident reports. Cases were selected based on the following criteria:

- Sample year between 1997 and 2008 (inclusive);
- The vehicle was physically inspected by the case investigator;
- The highest-severity impact in the crash was either an impact with guardrail or a rollover that was initiated by an impact with guardrail;

- The damage plane corresponding to the highest-severity impact (or guardrail impact that initiated rollover) was coded by the investigator as ‘Front’.

For each vehicle that met these criteria, the injury level of the driver was recorded. The Abbreviated Injury Scale (AIS) is an anatomically-based injury severity scale created and maintained by the Association for the Advancement of Automotive Medicine (AAAM). Injuries are separated into different body regions and are graded from 1 (minor) to 6 (unsurvivable) based on threat to life (AAAM 2008). Drivers were classed as “seriously injured” if their maximum AIS score was 3 or greater. This includes any fatalities due to crash injuries occurring within 30 days of the crash. A crash was considered to be an injury crash if the driver was seriously injured. Any drivers with an unknown injury level were excluded from the analysis.

Vehicles were classified as either cars or light trucks/vans (LTVs). LTVs included pickup trucks, sport utility vehicles, full-size vans and minivans. Cars included coupes, hatchbacks, sedans, station wagons and convertibles. Large limousines (i.e. stretched-frame limousines) and 3-wheeled vehicles, while sometimes considered cars, were excluded from the analysis.

Guardrail crashes were identified using the highest-severity event and the rollover-initiation event coded in NASS-CDS. Prior studies (Bryden and Fortuniewicz, 1986; Mitchie and Bronstad 1994; Viner 1993) have observed that in about half of all cases where guardrail is struck, it is *not* the most harmful event. Our approach was therefore to select only cases where the highest-severity impact was with guardrail, or was a rollover initiated by guardrail. This ensured that any injuries in the sample were likely to be the result of guardrail contact, and not contact with other hazards. While proper vehicle containment and redirection are important aspects of guardrail function, the focus of this analysis is on injury risk directly resulting from guardrail contact or guardrail-initiated rollover. Injuries caused by non-guardrail roadside objects which were struck due to containment failure are not considered in this analysis.

NASS-CDS codes very limited information pertaining to roadside barrier systems, but generally has extensive crash site photographs. Crash site photos were therefore manually inspected to determine:

- If the impact was with the end terminal or the guardrail face;
- What type of guardrail was contacted (if any);
- What type of end terminal was contacted (if any);
- If the struck portion of the guardrail had been replaced prior to crash site investigation.

In this analysis, a crash was considered to have engaged the end terminal if the vehicle made any direct contact with the end of the guardrail system. By corollary, “guardrail face crashes” in this analysis refer to any crashes where the vehicle did not make direct contact with the end of the guardrail. Crashes to the guardrail face not making contact with the guardrail end but still impacting before the 3<sup>rd</sup> post were coded as face crashes. If it could not be determined whether a crash involved the guardrail face or the guardrail end, that crash was excluded from the sample. Crashes at concrete barrier – metal guardrail junctions were excluded from the analysis, as these are complex regions which bear separate analysis from normal length-of-need and end terminals.

Impact attenuators (“crash cushions”) and concrete barriers were sometimes coded as guardrail in NASS-CDS. Any crashes with impact attenuators or concrete barriers were excluded. One of the NASS-CDS codes used for guardrail was also used for improvised or non-standard barriers. Cases involving improvised or non-standard barriers were excluded from the analysis.

Determining the specific end terminal system involved in a crash from NASS scene photos can be very difficult, as some differences between terminal systems are very subtle. Terminals were therefore only divided into two groups: designs that have successfully met some level of the NCHRP Report 350 safety requirements, and those that have not. Although the Manual for Assessing Safety Hardware (MASH) supplanted NCHRP 350 in 2009, “compliant” hardware in this study refers specifically to NCHRP-350 compliant hardware, since the sample period ends prior to the adoption of MASH. In addition, end treatments designed exclusively against MASH are not yet in widespread use on US roadways, so NCHRP-350 is arguably the more relevant standard.

All NCHRP-350-compliant energy-absorbing end terminal designs were straightforward to identify since they all use a conspicuous impact head of some kind. Non-energy-absorbing, compliant designs can be more difficult to tell apart from non-compliant designs, requiring knowledge of specific differences, but there are only a few such designs in common use. They include: Eccentric Loader Terminal, Modified Eccentric Loader Terminal, Slotted Rail Terminal, Vermont Low-Speed End Treatment, burial-in-backslope. Non-compliant terminals include turndowns, Breakaway Cable Terminals (BCTs), blunt ends and other non-energy-absorbing, non-NCHRP-350-compliant end treatments. BCTs have a cable and only two breakaway posts, with no strut connecting the first two posts at ground level. Turndowns are straightforward to identify, and other non-compliant end treatments lack cables, breakaway posts and ground struts.

For some cases, the terminal shown in the scene photographs was a replacement for the terminal that was involved in the crash. In practice, damaged guardrails and end terminals are frequently replaced with the same system as the original. However, older systems that are not compliant with current testing criteria are sometimes upgraded to newer systems that are compliant. Whenever a replacement terminal was of a non-compliant design, it was assumed that the original was non-compliant as well. When a replacement terminal was of a compliant design, no assumption could safely be made as to the compliance of the original. Analyses involving end terminal type were therefore conducted in three ways: 1) assuming that all questionable terminals were non-compliant, 2) assuming that questionable terminals were compliant and 3) excluding questionable terminals from the sample. In a very small number of cases, terminals could not be positively classified from the case photos. E.g., damaged terminals buried in snow, cases where the terminal had simply been removed without any type of replacement, or photos taken from a moving vehicle or at great distance. These cases were treated the same as cases where the ambiguity stemmed from terminal replacement.

While NASS-CDS scene photographs are often sufficient to identify different end terminals, determining the NCHRP-350 compliance of longitudinal barrier systems was substantially more

challenging. CDS scene photographs frequently do not capture sufficient detail to definitively identify specific systems, or may not depict all features necessary to definitively establish compliance. Additionally, estimation of site grade or rail height is not possible without detailed photo analysis. As a result, this analysis only considers NCHRP 350 compliance for end terminals.

### *3.3.1 STATISTICAL ANALYSIS*

All statistical analysis was performed in SAS v9.3. The complex sampling structure of NASS-CDS was taken into account to produce nationally representative estimates. Multiple logistic regression was used to test the effects of different variables while controlling for one another. Logistic regression was performed using PROC SURVEYLOGISTIC. Model coefficients provided odds ratios for different model effects. Statistical significance of individual model effects (p-values) were evaluated using the Wald Chi-Square test, which is part of the standard SURVEYLOGISTIC output. “Statistical significance” henceforth refers to a 95% confidence level. Contingency table analyses were performed using PROC SURVEYFREQ. Both the Rao-Scott Chi-Square test and the Rao-Scott Likelihood Ratio test were used to evaluate the statistical significance of results. These tests are equivalent to the Pearson’s Chi-Square test and the Likelihood Ratio Chi-Square test respectively, but both include the Rao-Scott correction for complex sample designs. For contingency table analyses in this manuscript, the Rao-Scott p-value is referred to as “p-value”, while the Rao-Scott Likelihood Ratio p-value is denoted by “LR p-value”.

## 3.4 RESULTS

### *3.4.1 SAMPLE COMPOSITION*

Table 3.1 presents the composition of the sampled crashes by the area of the guardrail system struck and body style of the vehicle. The final sample used in the analysis contained 693 crashes. A total of 111 entire vehicles were excluded from the sample. These included 32 cases where concrete barrier was miscoded as guardrail, 18 cases where the object struck was a crash cushion, 14 cases where the struck

object was a cable barrier, 13 cases where miscellaneous non-barrier objects were contacted, 5 cases where contact was with a junction between guardrail and concrete barrier, 9 cases whose impact location could not be determined, 6 cases coded as guardrail-initiated rollovers where the rollover initiation object was not actually a guardrail, 5 guardrail-initiated rollovers where the guardrail impact was not sufficiently damaging to be coded as an impact event in NASS-CDS, 1 guardrail-initiated rollover where the coded rollover object was highly questionable (case 1997-8-15), 1 case where there appears to have been no guardrail contact at all and 7 cases with case weights of zero. A case weight of zero in NASS indicates a crash that was not part of the standard NASS-CDS sampling plan and hence cannot be used to compute national estimates.

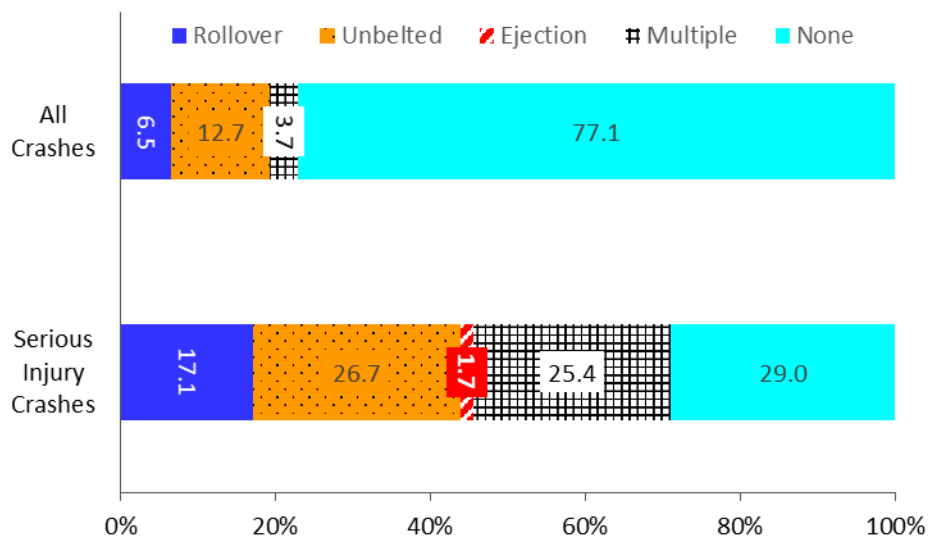
**Table 3.1. Composition of sampled crashes by area of guardrail impacted, vehicle body style and lateral area of vehicle sustaining damage.**

	<i>n</i> Sample Crashes (unweighted)	% Population Crashes (weighted)
<i>Object Struck</i>		
<b>Guardrail Face</b>	551	86.8 %
<b>Compliant Terminal</b>	<i>Replaced</i>	21
	<i>Unknown</i>	2
	<i>Original</i>	30
<b>Non-Compliant Terminal</b>	82	7.1 %
<b>Unknown Terminal</b>	7	0.07 %
<b>Total</b>	693	100 %
<i>Body style of Occupied Vehicle</i>		
<b>Car</b>	454	76.3 %
<b>LTV</b>	239	23.7 %
<b>Total</b>	693	100 %
<i>Primary Lateral Area of Vehicle Face Damaged</i>		
<b>Left</b>	84	11.5 %
<b>Center</b>	5	0.1 %
<b>Right</b>	105	16.1 %
<b>Left + Center</b>	78	6.8 %
<b>Center + Right</b>	37	4.0 %
<b>Left + Center + Right</b>	324	54.4 %
<b>Unknown</b>	60	7.1 %
<b>Total</b>	693	100 %

### 3.4.2 INJURY AND HIGH-RISK COFACTORS

This analysis examined crashes where the high-severity event was an impact with guardrail or a rollover initiated by guardrail. Rollover is a high-risk crash mode in and of itself, and non-guardrail-initiated

rollovers also occurred in the crashes sampled here, so it was useful to control for rollover occurrence in this analysis. Similarly, non-use of seatbelts and ejection from the vehicle also greatly increase injury risk when present in crashes. Figure 3.1 shows the distribution of all guardrail crashes and of guardrail crashes resulting in injury, broken down by the occurrence of rollover and/or non-use of seatbelts. In 77 % of crashes, drivers wore their seatbelts and were not involved in rollovers, but these accounted for just 29 % of the crashes resulting in driver injury. The remaining 23 % of crashes that involve rollover or have drivers that were unbelted or ejected, or some combination thereof accounted for the remaining 71 % of injurious crashes. Contingency table analysis found that injury odds increased by a factor of 8.7 when any of these high-risk cofactors was present, and the result was statistically significant (p-value < 0.0001; LR p-value 0.0002). Note that drivers were belted in about 84-87 % of crashes, which is consistent with the national average belt use rate of 83 % (Gabauer and Gabler 2010) for airbag-equipped vehicles (most of vehicles in this sample were airbag-equipped).



**Figure 3.1. Injury versus high-risk cofactor presence.  $n_{\text{crash}} = 693$ ,  $n_{\text{injury}} = 109$ .**

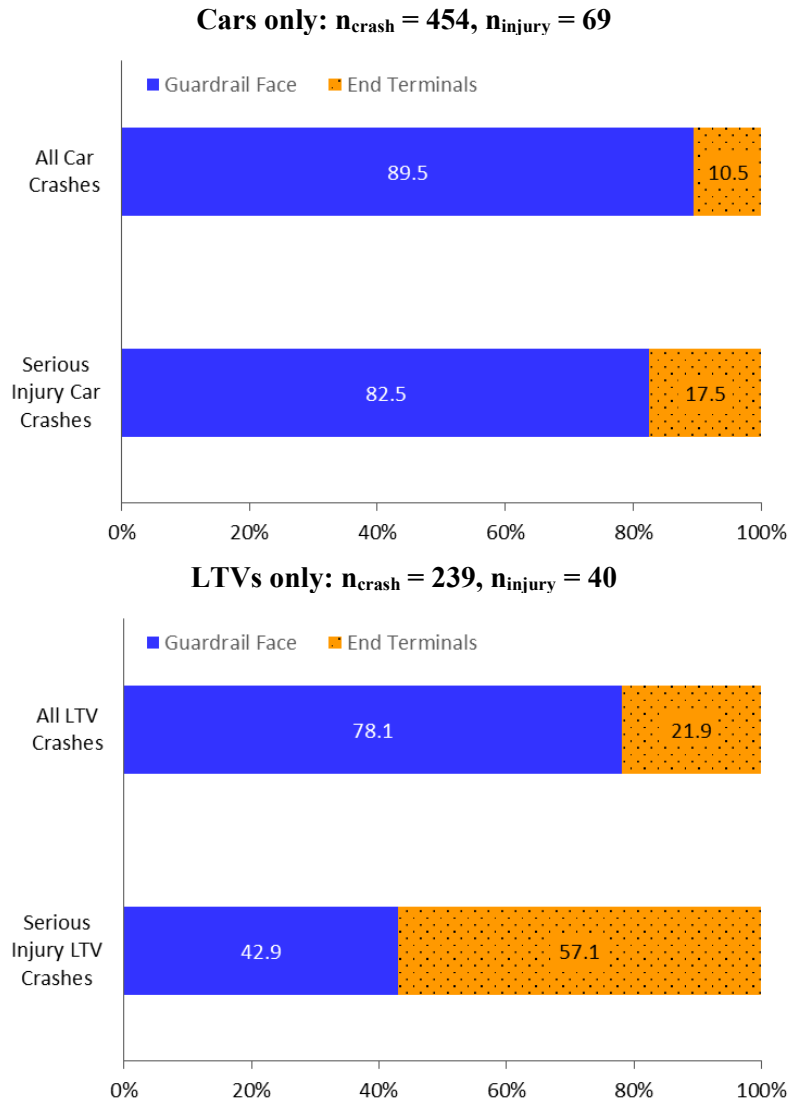
### 3.4.3 INJURY AND GUARDRAIL

#### 3.4.3.1 End Terminal vs. Guardrail Face

For cars, injury occurred in 1.6 % of all guardrail face crashes and 2.8 % of all end terminal crashes. For LTVs, injury occurred in 1.7 % of all guardrail face crashes and 8.3 % of all end terminal crashes. NCHRP Report 490 found that approximately 90 % of crashes with BCT end terminals are non-injury crashes that are not reported to the police (Ray, Weir and Hopp 2003). Unreported crashes are an intractable limitation of NASS-CDS as well as many other crash databases. If rates of unreported property-damage-only (PDO) crashes were similar for other end terminal designs, then the absolute percentages of guardrail end terminal crashes resulting in injury reported above overstate the real injury risk in an end terminal crash. The same is also true for guardrail face crashes, if rates of unreported PDO crashes were similar for guardrail face.

Figure 3.2 shows the distribution of guardrail crashes and of injuries by the area of the rail system contacted, for cars and LTVs separately. In end terminal crashes involving LTVs, injuries were noticeably over-represented, but for cars, the effect was less pronounced. Multiple logistic regressions on area struck (terminal vs. face) and high-risk cofactor presence (rollover, unbelted driver or ejection) were used to test for differences in injury outcome between end terminals and guardrail face, while accounting for the effects of high-risk cofactors. One model was fit for cars and another was fit for LTVs. Table 3.2 gives odds ratios and Wald chi-square p-values (statistical significance) for each model effect.





**Figure 3.2. Crashes and serious injuries by area of guardrail contacted, cars and LTVs.**

**Table 3.2. Injury vs. area struck and high-risk cofactor presence, for cars and LTVs.**

Outcome	Model Effect	Parameter Estimate	Odds Ratio (for injury)	Wald Chi-Square p-value	Significant?
<i>~ Cars ~</i>					
<b>Driver Injured</b> <i>Yes = 69</i> <i>No = 385</i>	Intercept	-4.6843	-	< 0.0441	Yes
	<b>Area Struck</b>	-0.0944	<b>0.910</b> (terminal vs face)	<b>0.8572</b>	<b>No</b>
	Cofactor Present	1.9025	6.703 (yes vs no)	0.0146	Yes
<i>~ LTVs ~</i>					
<b>Driver Injured</b> <i>Yes = 40</i> <i>No = 199</i>	Intercept	-6.8358	-	< 0.0001	Yes
	<b>Area Struck</b>	1.3621	<b>3.905</b> (terminal vs face)	<b>0.0807</b>	<b>Marginal</b>
	Cofactor Present	3.7393	42.069 (yes vs no)	< 0.0001	Yes

For cars, injury does not appear to be significantly more likely in end terminal contact than in guardrail face contact when high-risk cofactors are accounted for. In Table 3.2, the odds ratio for area struck (for cars) is very close to 1 and has a Wald p-value of 0.8572 – not significantly associated with injury outcome. The effect of high-risk cofactors, as well as the overall model, were both significant.

For LTVs, when high-risk cofactors are accounted for, end terminal contact *may* carry an increased likelihood of injury compared to guardrail face contact. Table 3.2 gives end terminal contact by LTVs 3.9 times greater injury odds than guardrail face contact, but with two important caveats. First, the area-struck effect has a Wald p-value of 0.0807, which is approaching statistical significance. Second, the significance of the model effects for this regression must be interpreted with caution, since there is only one (1) observation involving an LTV without high-risk cofactors, with injury and end terminal contact. I.e., that particular corner of the parameter space is not well represented in this data.

If the rate of unreported PDO crashes with LON was similar to that of end terminals, then these findings should not be strongly distorted. However; it is possible that the rate of unreported PDO crashes with LON is higher than the unreported PDO crash rate for end terminals. If this was the case, then the

regressions in Table 3.2 may underestimate the difference in injury risk between crashes to the guardrail face and crashes to guardrail ends.

### **3.4.3.2 Injury by Vehicle Body Style**

No evidence was found for any difference in injury odds between cars and LTVs in guardrail face crashes. Multiple logistic regression on both body style and cofactor presence within guardrail face crashes gave cars only 1.8 times greater odds of injury than LTVs, and the result was not statistically significant (Wald p-value 0.1616).

The data also gave no evidence for any difference in injury odds between cars and LTVs in end terminal crashes. Multiple logistic regression on body style and cofactor presence gave LTVs injury odds 2.7 times greater than cars, once again with no statistical significance (Wald p-value 0.2035). The fact that LTVs showed a (nearly) statistically significant increase in injury risk from end terminal contact while cars did not, but the difference in injury between cars and LTVs in terminal crashes was not itself significant, suggests an apparent contradiction. This may be explained by an increased risk of guardrail-induced rollover for LTVs in end terminal crashes, a finding that is discussed later.

Gabler and Gabauer (2007) observed that LTVs presented an elevated risk of fatality compared to cars when all guardrail crashes (not just frontal) were considered in aggregate. Bryden and Fortuniewicz (1986) also found that LTVs had higher rates of all injury levels than other vehicle types in their analysis of 1982-1983 New York state data. However, they did not comment on this finding or discuss its statistical significance. In contrast, Johnson and Gabler (2013) examined side crashes with guardrail and found that cars presented greater injury risk than LTVs. However, that finding was not statistically significant either. Viner, Council and Stewart (1994) found that serious injury in guardrail face crashes occurred more often for LTVs than for cars, but that cars experienced injury more often than LTVs in end terminal crashes. The differences they observed were also not statistically significant.

### **3.4.3.3 Difference in End Terminal Crash Proportion between Cars and LTVs**

Figure 3.2 shows that 10.5 % of all car crashes involved end terminals, but 21.9 % of all LTV crashes involved end terminals. The odds of an LTV striking an end terminal appear to be 2.4 times higher than the odds of a car doing the same. Contingency table analysis of area struck vs. body style found this difference to be approaching significance (p-value 0.0640; LR p-value 0.0776). Assuming this difference is a real effect, there are a number of possible explanations.

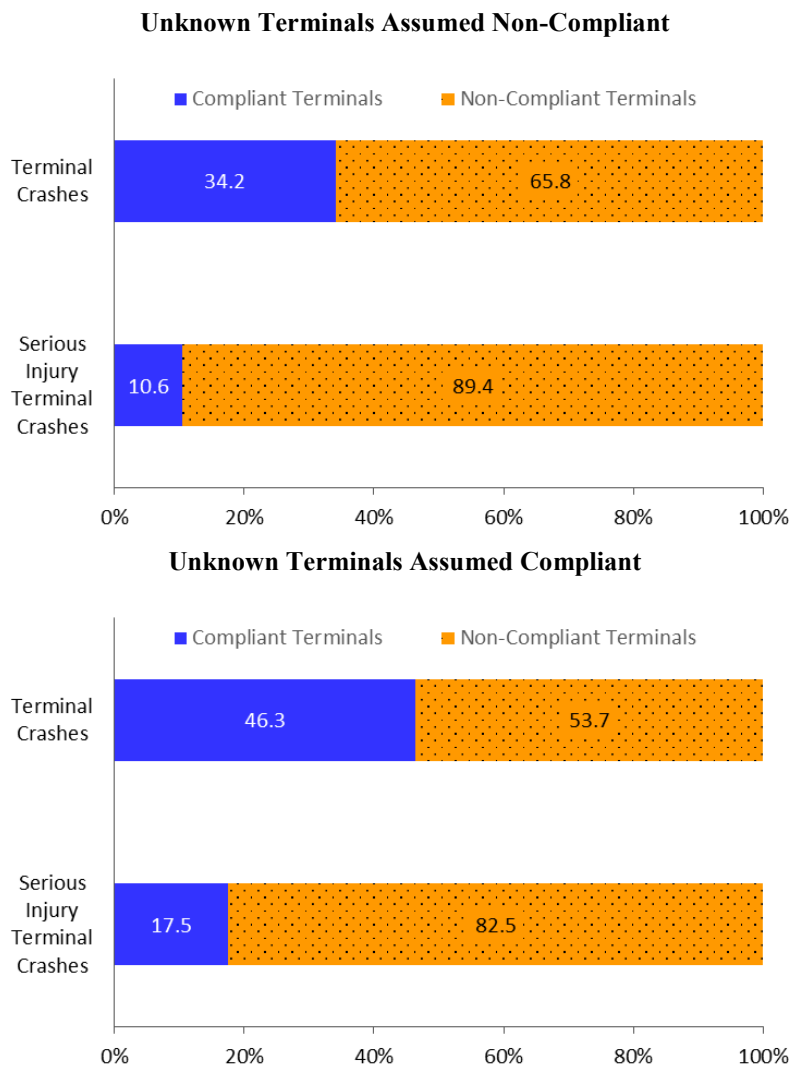
One possibility is that LTVs, particularly pickup trucks, are more common in rural areas. If rural areas contain more end terminals per length of guardrail on average, it could explain the increased proportion of LTVs striking end terminals. However, the sample examined here contained no statistically significant difference in LTV crash proportion between different primary sampling unit (PSU) types (rural, suburban, urban). The proportion of end terminal crashes of all body styles *was* significantly different between PSU types, but end terminals were most common in suburban areas, followed by rural areas and then urban areas.

A second, more likely possibility is that LTVs were less likely than cars to require towing after striking the guardrail face. NASS-CDS only samples tow-away crashes, so if LTVs were less likely than cars to require towing after striking the guardrail face, it could explain the seemingly elevated incidence of end terminal crashes when only LTVs are considered. Unfortunately, NASS-CDS does not include reports of non-tow-away crashes, which does not allow this hypotheses to be tested.

#### **3.4.3.4 NCHRP-350 Compliance of End Terminals**

Table 3.3 shows an analysis of injury risk in crashes with end terminals, with high-risk cofactors controlled for. Three models of driver injury were fit using NCHRP-350 compliance and cofactor presence as model parameters. As discussed in the Methods section, one model assumed all ambiguous end terminals were non-compliant, one assumed ambiguous terminals were compliant, and one excluded them entirely. Non-compliant terminals were observed to carry between 3.9 and 5.0 times greater odds of injury than compliant designs when high-risk cofactors were controlled for. Wald p-values for the terminal compliance

effect ranged between 0.0563 and 0.0732, which is very close to statistical significance. There were only 3 injury crashes involving compliant end terminals in the sample where high-risk cofactors were not present, which could account for the marginal statistical significance. That limitation also means that the same caveats discussed for the effect of area struck also apply to end terminal compliance as well.



**Figure 3.3. Crashes and injuries in frontal end terminal crashes.  $n_{\text{crash}} = 142$ ,  $n_{\text{injury}} = 29$ .**

**Table 3.3. Injury vs. end terminal type, controlling for the presence of high-risk cofactors.**

Outcome	Model Effect	Parameter Estimate	Odds Ratio (for injury)	Wald Chi-Square p-value	Significant?
<i>~ Unknown Terminals Assumed Non-Compliant ~</i>					
<b>Driver Injured</b> <i>Yes = 29</i> <i>No = 113</i>	Intercept	-5.6516	-	< 0.0001	Yes
	<b>Terminal Compliance</b>	-1.5248	<b>4.594</b> <i>(non-compliant vs compliant)</i>	<b>0.0627</b>	<b>Marginal</b>
	Cofactor Present	2.1411	8.509 <i>(yes vs no)</i>	0.0027	Yes
<i>~ Unknown Terminals Assumed Compliant ~</i>					
<b>Driver Injured</b> <i>Yes = 29</i> <i>No = 113</i>	Intercept	-5.3519	-	< 0.0001	Yes
	<b>Terminal Compliance</b>	1.3717	<b>3.942</b> <i>(non-compliant vs compliant)</i>	<b>0.0732</b>	<b>Marginal</b>
	Cofactor Present	2.0798	8.003 <i>(yes vs no)</i>	0.0032	Yes
<i>~ Unknown Terminals Excluded ~</i>					
<b>Driver Injured</b> <i>Yes = 24</i> <i>No = 88</i>	Intercept	-5.5284	-	< 0.0001	Yes
	<b>Terminal Compliance</b>	1.6182	<b>5.044</b> <i>(non-compliant vs compliant)</i>	<b>0.0563</b>	<b>Marginal</b>
	Cofactor Present	1.9992	7.383 <i>(yes vs no)</i>	0.0080	Yes

#### 3.4.4 AIRBAG DEPLOYMENT

NASS CDS records information on vehicle airbags from case years 2000 through 2008. Airbag deployment and its effects on injury risk were analyzed using this subset of the main sample, which contains 553 vehicles, four-hundred sixty (460) of which were airbag-equipped.

86 % of all vehicles in frontal guardrail crashes had one or more airbags equipped. Airbag presence in a vehicle indicates a newer vehicle and a better overall safety design than non-equipped vehicles. However, the data do not give significant evidence that drivers in airbag-equipped vehicles have lesser odds of injury than in non-equipped vehicles. Table 3.4 shows the results of a multiple logistic regression on driver airbag presence, driver belt use, vehicle body style and area struck. Airbag presence actually

increased the odds of injury in the presence of the other effects, but the result was not at all statistically significant. The only statistically significant effect in the model was cofactor presence, which includes belt use; odds of injury were over 8 times lower when the driver was belted (and not ejected, and the vehicle did not roll over). Gabauer and Gabler (2010) examined the effect of airbag presence and belt use on injury outcome in frontal barrier crashes. They concluded that airbag presence had at most a small, incremental effect on injury risk in frontal barrier crashes. The results of this study would seem to confirm that finding.

**Table 3.4. Injury vs. airbag presence, controlling for high-risk cofactors, vehicle body style and area struck.**

Outcome	Model Effect	Parameter Estimate	Odds Ratio (for injury)	Wald Chi-Square p-value	Significant?
<i>~ Injury vs. Airbag Presence ~</i>					
<b>Driver Injured</b> <i>Yes = 76</i> <i>No = 466</i>	Intercept	-5.0095	-	< 0.0001	Yes
	Cofactor Present	2.1143	8.284 (yes vs no)	0.0029	Yes
	<b>Airbags Present</b>	0.3122	<b>1.366</b> (yes vs no)	<b>0.6653</b>	<b>No</b>
	Body Style	-0.6872	0.503 (LTV vs car)	0.1437	No
	Area Struck	0.3490	1.418 (terminal vs face)	0.5760	No

Out of the 86 % of vehicles with driver airbags equipped, one or more of them deployed in 38 % of crashed vehicles. Gabauer and Gabler (2010) found that airbags deployed in 61 % of all non-concrete longitudinal barrier crashes involving airbag-equipped vehicles, which is substantially more frequent than this. However, they examined only single-event crashes, while this study included crashes with multiple events. When only single-event, airbag-equipped crashes are considered (n=142), airbags are observed to deploy in 60.0 % of instances which is almost identical to (Gabauer and Gabler 2013). In airbag-equipped guardrail crashes with two events (n=177), airbags deploy in 38.2 % of crashes. With three or more events (n=136), airbags deploy in 18.3 % of crashes. It is possible that, on average, multiple-event crashes have multiple events because the departure speed was higher, or possibly because each individual impact was less severe, dissipating a smaller portion of the vehicle speed and thus less likely to deploy airbags. Also,

the analysis sample was partly composed of guardrail crashes where rollover was coded as the most severe event. Guardrail-tripped rollover crashes necessarily include at least two events, and rollovers do not typically deploy airbags (rollover curtain airbags were not common during the sampled years).

The data also shows that the odds of injury when driver airbags deploy is 2.7 times greater than when no deployment occurs (Table 3.5). The effect was just short of statistical significance. Multiple logistic regression was used to control for high-risk cofactor presence, vehicle body style and guardrail area struck. This finding is to be expected, as airbag deployment occurs in higher severity crashes with a higher chance of injury.

**Table 3.5. Injury vs. airbag deployment, controlling for high-risk cofactors, vehicle body style and area struck.**

Outcome	Model Effect	Parameter Estimate	Odds Ratio (for injury)	Wald Chi-Square p-value	Significant?
<i>~ Injury vs. Airbag Deployment, Where Airbags Present ~</i>					
<b>Driver Injured</b> <i>Yes = 76</i> <i>No = 466</i>	Intercept	-5.1911	-	< 0.0001	Yes
	Cofactor Present	1.8044	6.076 (yes vs no)	0.0143	Yes
	<b>Airbags Deployed</b>	1.0077	<b>2.739</b> (yes vs no)	<b>0.0529</b>	<b>Marginal</b>
	Body Style	-0.5184	0.595 (LTV vs car)	0.3305	No
	Area Struck	0.6164	1.852 (terminal vs face)	0.3650	No

#### 3.4.4.1 Airbag Deployment versus Vehicle Body Style, Area of Guardrail Contacted

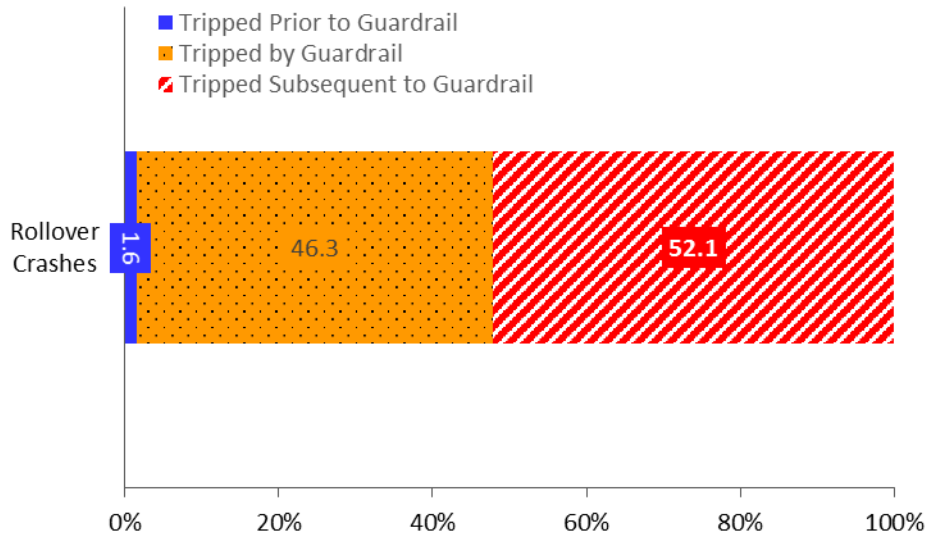
Multiple logistic regression of airbag deployment on vehicle body style and area struck was used to test for differences in airbag deployment rate. For airbag-equipped vehicles, the data gave no significant evidence for any difference in the likelihood of airbag deployment between end terminal crashes and guardrail face crashes. The data also provided no significant evidence for any difference in airbag deployment rate between cars and LTVs in frontal guardrail crashes.



In end terminal crashes, the data also gives no indication of a significant difference in deployment between compliant and non-compliant end terminals. This may simply indicate that crashes with any narrow, fixed object are highly likely to deploy airbags, or that any difference in deployment rate between compliant and non-compliant terminals is too small to be discerned in this sample.

### 3.4.5 ROLLOVER INITIATION

Rollover, guardrail-initiated or otherwise, was observed in 10 % of all frontal guardrail crashes. When rollover does occur, Figure 3.4 shows the breakdown of initiation mechanism. NASS-CDS investigators code the object that, in their best judgment, was responsible for initiating a rollover when one occurs. For cases where guardrail was coded as the highest-severity event, any rollovers that occurred were considered “tripped by guardrail” if the rollover-initiating object was coded as a guardrail, and no other guardrail impacts occurred between the high-severity guardrail impact and the rollover event. I.e., the rollover had to be tripped by the *highest-severity* impact (which was always guardrail). For cases where rollover was coded as the high-severity event, the roll-initiation object was always coded as guardrail. Forty-six percent (46 %) of rollovers in frontal guardrail crashes were initiated by the guardrail itself, while most of the remainder were tripped by objects contacted after the high-severity guardrail.



**Figure 3.4. Distribution of investigator-coded rollover initiation object.  $n_{\text{rollover}} = 156$ .**

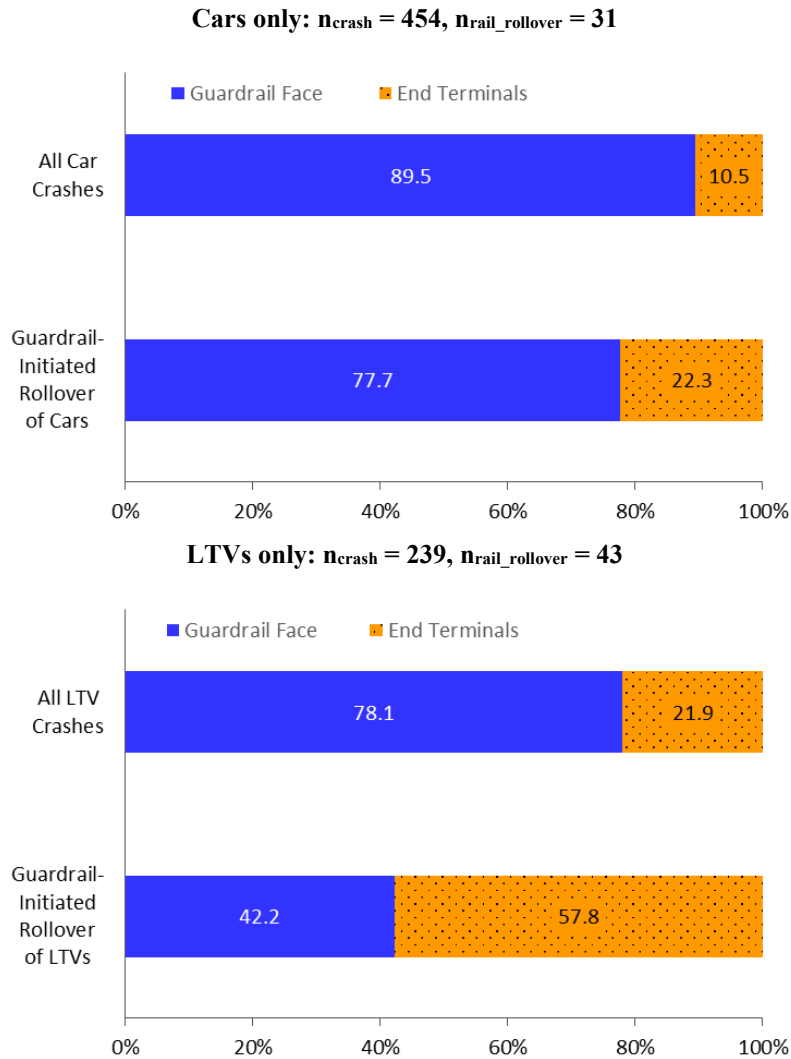
### 3.4.5.1 Rollover Initiation by Area of Guardrail Contacted and Vehicle Body Style

The odds of guardrail-initiated rollover were observed to be 7.7 times higher for LTVs than for cars. Contingency table analysis found this result to be highly statistically significant ( $p\text{-value} < 0.0001$ ; LR  $p\text{-value} < 0.0001$ ). This finding is consistent with the fact that LTVs generally have higher centers of gravity. Gabler and Gabauer (2007) found that LTVs had 3 times the rollover probability of cars, which corresponds to 3.7-times greater odds of rollover. While this is consistent with our findings, it is a much smaller effect than was observed here. The sample in Gabler and Gabauer (2007) was not restricted to frontal crashes, which may explain the difference. Bligh and Mak (1999) found that roughly half of all fatal crashes with guardrail involved rollover, and conjectured that this high rollover rate might be due to contact with end terminals (their sample did not distinguish guardrail face crashes from end terminal crashes). They also found that LTVs had higher rollover rates than cars for most roadside objects, including guardrail. Viner, Council and Stewart (1994) also found that pickup trucks were three times more likely to roll over than cars when striking a guardrail face.

When all body styles were considered together, end terminal contact was observed to have 6.6 times greater odds of initiating rollover than guardrail face contact. This result is highly significant ( $p\text{-value}$

0.0008; LR p-value 0.0051). However, when this same contingency table was conducted for cars and LTVs separately, only LTVs showed significant evidence of an increased rollover likelihood in end terminal crashes. Cars did not show any statistically significant increase in rollover odds in end terminal crashes. Figure 3.5 shows guardrail-initiated rollover broken down by area of the guardrail system contacted, for cars and LTVs separately. For cars, the odds of guardrail-induced rollover in end terminal crashes were 2.5 times greater than in guardrail face crashes, with a p-value of 0.1929 / LR p-value of 0.2475. LTVs, by contrast, show rollover odds 6.9 times greater in end terminal crashes with a p-value of 0.0017 / LR p-value 0.0040. This finding is also consistent with the higher centers of gravity of LTVs. NCHRP 350 compliance of end terminals was not observed to have any statistically significant effect on rollover risk, either with all vehicles lumped or when cars and LTVs were considered separately.

When high-risk cofactors, including rollovers, were controlled for, LTVs were observed to carry a marginally statistically significant increase in injury risk in end terminal crashes. This finding was discussed earlier. Even if end terminals actually carried no real increase in injury risk for LTVs and the observed effect of end terminal contact for LTVs was a false positive, end terminal crashes would still appear to pose an increased hazard to LTVs because of the elevated risk of initiating rollover. Cars, by contrast, showed no change in injury risk in end terminal crashes, nor did they show any increased risk of rollover from end terminal crashes.



**Figure 3.5. Guardrail-initiated rollover by area of rail system contacted, cars and LTVs considered separately.**

### 3.4.6 OCCURRENCE OF SPEARING

Spearing, or penetration of the guardrail into the vehicle, sometimes occurs in guardrail impacts and can result in very severe injuries when it does happen. But how frequently does spearing actually occur with current end treatments? Out of the 693 crashes examined in this study, only three were found that involved spearing. These cases are shown in Figure 3.6: NASS-CDS cases 2005-45-104 (case 1, top), 2006-47-34 (case 2, middle) and 2003-73-34 (case 3, bottom). In total, these three cases represent 0.087 % of all frontal guardrail crashes and about 0.63 % of all frontal end terminal crashes; spearing appears to be a very rare occurrence. In cases 1 and 2, the guardrail penetrated the occupant compartment and caused serious

injury, while in case 3 the guardrail only penetrated the engine bay and no serious injury occurred. Cases 1 and 3 both involved end terminals that were not compliant with NCHRP 350. In case 2, the compliance of the end terminal could not be determined.

**NASS-CDS Case 2005 – 45 – 104**



**NASS-CDS Case 2006 – 47 – 34**



**NASS-Case 2003 – 73 – 34**



**Figure 3.6. Out of 693 cases in the sample, only three were found where spearing had occurred.**

### 3.5 CONCLUSIONS

This analysis examined the effect of a number of factors on injury risk in frontal guardrail crashes. High-risk cofactors including rollover, ejection and non-use of seatbelts were associated with 22 % of all frontal guardrail crashes, yet were associated with 71 % of the resulting serious injuries. Odds of an injury crash were significantly elevated when one or more high-risk cofactors are present. When high-risk cofactors were controlled for, vehicle body style was not observed to have a statistically significant influence on injury risk in this crash mode, although the differences that were observed were consistent with prior studies using recent data (Gabler and Gabauer 2007). When controlling for other variables, car crashes with end terminals were not observed to carry statistically significantly greater odds of injury than crashes with the guardrail face. For LTVs however, end terminal crashes showed injury odds 3.9 times greater than guardrail face crashes. This finding came very close to statistical significance and it is likely that contact with the end terminal itself increases the risk of injury in LTV crashes at least somewhat, compared to contact with the guardrail face.

In end terminal crashes, terminals compliant with NCHRP 350 carried injury odds between 3.9 and 5.0 times lower than non-compliant end terminals when other factors were controlled for. Bryden and Fortuniewicz (1986) studied crashes with guardrail in New York State during 1982-1983. They observed that fatalities and A-injuries (on the KABCO scale) occurred in 15.4 % of crashes with guardrail considered “obsolete [*sic*]”, but in only 10.5 % of crashes with guardrail considered “current [*sic*]”. This equates to an odds ratio of about 1.5 for serious injury, comparing then-obsolete hardware to then-current hardware. This difference is much smaller than the 4.3 to 5.2 odds ratio observed here. This may suggest that advances in end terminal design have made greater strides in the recent past.

Airbags were present in about 86 % of vehicles in frontal guardrail crashes, and deployed in about 38 % of equipped vehicles. Airbag deployment in frontal guardrail crashes appears to be a strong function of the number of total impact events. Airbag deployments are correlated with high crash severity and consequently increased injury risk. The data gives no significant evidence that end terminal crashes are more likely to result in airbag deployment than guardrail face crashes. Neither does end terminal compliance with NCHRP 350 appear to have any significant effect on airbag deployment.

Rollover occurred in 10.0% of all frontal guardrail crashes. Forty-six point three percent (46.3 %) of those rollovers were initiated by the high-severity guardrail impact itself; the remainder was initiated prior to guardrail impact or by objects subsequent to the high-severity guardrail. Overall, LTVs were observed to have odds of guardrail-initiated rollover 7.7 times higher than cars in frontal guardrail crashes. This difference was significantly higher than what Gabler and Gabauer (2007) found, but their comparison was not restricted to only frontal-mode guardrail crashes. End terminals were observed to carry 6.9-times greater odds of initiating rollover than guardrail face when the striking vehicle was an LTV. When the striking vehicle was a car, there was no statistically significant evidence that end terminals were more likely than guardrail face to initiate rollover. In end terminal crashes, NCHRP 350 compliance was not observed to have any significant effect on the likelihood of rollover initiation.

Even if striking an end terminal in an LTV is not, in reality, any more dangerous than striking the guardrail face, the risk of injury in an LTV-end-terminal crash is still elevated due to the increased likelihood that the end terminal will initiate a rollover. Viner, Council and Stewart (1994) observed that pickup trucks (which are a large proportion of LTVs) were over-represented in fatal crashes with roadside safety appurtenances. They attributed this to pickup trucks being more likely to roll over, and to their drivers being less likely to use seatbelts and therefore more likely to be ejected. In this analysis, LTVs were observed to be more likely than cars to roll over, but no statistically significant difference was observed in belt use between car and LTV drivers. Additionally, rollover, unbelted drivers and ejection were all controlled for in this analysis. End terminal contact itself may be inherently somewhat more dangerous for LTVs than guardrail face contact, but even if it is not, the increased likelihood of end-terminal-initiated rollover for LTVs still increases the risk of injury that end terminals pose for LTVs.

Out of 639 frontal guardrail crashes studied in this analysis, spearing was only observed in 3 crashes. Nationally, these 3 cases represent 0.087 % of all frontal guardrail crashes and 0.63 % of all frontal crashes with end terminals. In the 2 spearing cases where the end terminal could be identified, both end terminal designs were not compliant with NCHRP-350.



## 4 INJURY RISK IN SIDE CRASHES WITH GUARDRAIL

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### 4.1 INTRODUCTION

Side crashes are one of the most dangerous types of guardrail crash. Of particular concern is when a non-tracking vehicle slides sideways into a guardrail end treatment. Modern guardrail end treatments are designed to break away or absorb energy under the loads that are typical of a frontal impact. Because the side of a vehicle, unlike the front, has so little structure to protect an occupant, side impacts to end treatments carry a higher injury risk than frontal impacts to end treatments. The concentrated load on the side door structure seen in end treatment side impacts can result in deep intrusion of door structure into the occupant compartment. In extreme cases, the guardrail itself may even penetrate the occupant compartment directly, resulting in a very high probability of serious occupant injury or death.

Stolle et al. (2011) examined the database of roadside crashes compiled under National Cooperative Highway Research Program (NCHRP) projects 17-11, 17-22 and the Federal Highways Administration (FHWA) rollover studies. They found that side impacts with narrow roadside objects carried a 19% higher risk of critical injury when the occupant compartment was struck. The 85<sup>th</sup> percentile impact speed for such impacts was found to be 40 mph.

Gabler and Gabauer (2007) showed that side impacts account for 22% of fatalities in passenger vehicle-guardrail crashes and 14% of all guardrail crash fatalities. They also found that the car occupants have 30% higher probability of fatal injury in side impacts to guardrail compared to frontal impacts to guardrail, while light truck / van (LTV) occupants have 30% *lower* probability of fatal injury in side guardrail impacts compared to frontal impacts. A possible explanation is that since LTV occupants tend to be seated higher than car occupants, guardrail would tend to impact lower on LTV passenger compartments – possibly below the level of the occupant – resulting in less intrusion and thus less injury risk.

Ray (1999) examined 1983 National Automotive Sampling System / Continuous Sampling System (NASS/CSS) data and 1983 Fatal Accident Reporting System (FARS) data. He found that vehicle mass had no discernible effect on fatality rates in roadside object crashes, but did not examine occupant seating height or body type. Ray and Carney (1994) examined crash data from 1982 to 1985. They found that in side-impact collisions with narrow roadside objects, the fatality rate was more than 20% higher for passenger compartment impacts than for any other vehicle region. This is consistent with the findings of Stolle et al. (2011).

Guardrail end treatments also appear to be a potential rollover hazard (Gabler and Gabauer 2007; Gabauer and Gabler 2009a). Gabler and Gabauer (2007) found that approximately one in every three fatal passenger vehicle-guardrail crashes resulting in a rollover also struck the ends of the guardrail. As guardrail end treatments comprise only a tiny portion of the length of a typical guardrail system, this suggests that collisions with guardrail end treatments are overrepresented in terms of fatality.

## 4.2 OBJECTIVE

This chapter aims to describe the nature of real-world guardrail side impacts, and the injury risks posed by these impacts. Of particular interest are direct side impacts with guardrail end terminals, as opposed to conventional redirection crashes.

## 4.3 METHODS

The analysis examined National Automotive Sampling System / Crashworthiness Data System (NASS/CDS) data from case years 1997 to 2008 (inclusive). A NASS case can contain multiple vehicles, each one of which may be involved in any number of impact events. Only CDS vehicles for which the highest- $\Delta V$  (delta-V; i.e., highest-severity) impact was a non-oblique side impact with a guardrail were included in the analysis. Vehicle occupants were considered “injured” if their maximum Abbreviated Injury Scale (MAIS) score was 3 or greater, or if they died within one month of the crash date due to crash-related injuries. In the discussion that follows, the acronym “MAIS3+F” will be used to indicate “MAIS 3 or

greater, including fatality as a result of crash injuries”. The Abbreviated Injury Scale is a medically based measure of threat to life (AAAM 2008). AIS 3, 4, 5 and 6 correspond to serious, severe, critical and unsurvivable injuries respectively. In order to simplify the analysis, only drivers were considered, as drivers comprise approximately 70% of all occupants in vehicles that strike guardrail. All analysis was performed in SAS 9.2 using NASS case weights and, if necessary, clustering and stratification variables to obtain results representative of all U.S. crashes. All cases with statistical weights of zero or less were excluded prior to analysis (7 in total). Odds ratios comparing relative injury risk between different categories (and associated confidence intervals) were computed using PROC SURVEYLOGISTIC.

#### *4.3.1 IDENTIFYING SIDE CRASHES*

Side crashes were identified based on the coded General Area of Damage (GAD) for the highest- $\Delta V$  event. As the name suggests, GAD describes the side of the vehicle predominantly damaged by an impact event. Any crash where highest- $\Delta V$  event damage was predominantly to the left or right side of the vehicle was considered a side crash. Side crashes as defined here can thus include oblique corner impacts and sideswipes typical of tracking, redirection-type crashes as well as non-tracking, end terminal crashes. However, oblique corner impacts were removed from the dataset prior to analysis (discussed below).

#### *4.3.2 IDENTIFYING GUARDRAIL CRASHES*

A set of probable guardrail side crashes were first identified using GAD and the object-contacted variable for the high- $\Delta V$  event. Guardrail crashes are coded in NASS as “Metal Guardrail”, “Cable Guardrail” or “Other Barrier”. The “Metal Guardrail” and “Cable Guardrail” codes were introduced in NASS case year 2008. Prior to 2008, all metal guardrail impacts were coded using “Other Barrier”. Infrequently, “Other Barrier” may also include non-guardrail barriers.

NASS did not record any additional detail about struck objects besides the object contacted code. Hence, likely guardrail side crashes were manually inspected to confirm that they were actually guardrail

crashes, and to obtain information that was not coded in NASS. NASS scene diagrams, case summaries and case photographs for each of the preliminary cases were used to ascertain:

- That the struck object was in fact guardrail or a guardrail end terminal. Crash cushions, concrete barriers and junctions between rail systems and concrete barriers were excluded.
- Whether the vehicle interacted with an end terminal, or with the Length-of-Need (LON). Only crashes where the vehicle directly contacted the physical end of the rail were classified as end terminal crashes. Crashes where a collision point was near the end of the rail but not directly on it were classified as LON.
- The type of rail or terminal contacted. NASS object-contacted codes do not differentiate between LON and terminals, nor do they identify individual rail or terminal systems.
- Vehicle tracking state for the high- $\Delta V$  impact. This was judged from NASS scene diagrams and case photographs. This was necessary to facilitate the exclusion of oblique corner impacts and redirection crashes from the sample.
- If the terminal had been replaced prior to the investigation. Older terminal designs are being phased out in favor of newer designs tested according to NCHRP Report 350 criteria. Hence, terminals that were repaired with NCHRP-350-compliant designs may not have been compliant at the time of the crash.

#### *4.3.3 TERMINAL CLASSIFICATION*

Determining the exact end terminal system involved in a crash from NASS scene photos can be very difficult, as some differences between terminal systems are very subtle. Terminals were therefore only divided into designs that had successfully met some level of the NCHRP Report 350 safety requirements (AASHTO 2011; Ross et al. 1993) and those that had not. All NCHRP-350-compliant energy-absorbing designs were straightforward to identify, as they all use a conspicuous impact head of some kind.

Compliant, non-energy-absorbing designs can be more difficult to tell apart from non-compliant designs, requiring knowledge of specific differences, but there are only a few such designs in common use (Eccentric Loader Terminal, Modified Eccentric Loader Terminal, Slotted Rail Terminal, Vermont Low-Speed End Treatment, burial-in-backslope, and three-strand cable terminal). Non-compliant terminals include turndowns, Breakaway Cable Terminals (BCTs) and other non-energy-absorbing, non-compliant end treatments. BCTs have a cable and breakaway posts but lack a strut connecting the first two posts at ground level. Turndowns are obvious, and other non-energy-absorbing, non-compliant end treatments lack cables, breakaway posts and ground struts. For some cases, the terminal shown in the scene photographs was a replacement for the terminal that had been impacted. When a replacement terminal was of a non-compliant design, it was assumed that the original was non-compliant as well. When a replacement terminal was of a compliant design, the compliance of the original terminal was listed in the sample as unknown.

#### *4.3.4 IDENTIFYING OBLIQUE CRASHES*

The focus of this analysis was on direct side crashes involving guardrail and guardrail end terminals. As such, oblique tracking crashes and conventional redirections were identified and excluded from the sample prior to analysis. Oblique tracking crashes initially engage the corner of the vehicle, and can progress to a sideswipe if the vehicle is redirected by the LON. Most such crashes are coded in NASS as frontal crashes, but sometimes they are coded as side crashes. NASS directly codes the Principal Direction of Force (PDOF) for impact events, or the direction of the crash impulse relative to the vehicle body. PDOF allowed us to identify oblique crashes directly. Any crashes where the PDOF coded for the event of interest was less than 20 degrees from the vehicle longitudinal axis were excluded from the analysis. PDOF was occasionally not coded for impacts in NASS. In cases where PDOF was not coded, the vehicle tracking state at impact, as determined from careful examination of NASS scene diagrams and evidence of vehicle trajectory in case photos, was used to judge whether the impact was tracking or oblique.

## 4.4 RESULTS

The analyzed dataset contained 142 side guardrail crashes. 55 cases were identified as tracking impacts and were excluded. 12 cases were excluded because the struck object was a concrete barrier, rail junction with a concrete barrier or crash cushion, 4 were excluded for having unknown driver injury levels and another 7 were excluded for having NASS weights of zero or less. Almost all of the cases were judged as non-tracking on the basis of PDOF. Manually coded tracking state was only applied to 15 vehicles out of 197 considered. Table 4.1 gives the composition of the analyzed dataset. Left and right (driver and passenger) side crashes were split about 40%-60%. Cars made up about 80% of all side guardrail crashes, with the remaining 20% being LTVs. The majority of studied crashes had less than 4 total impacts, and about 60% were LON crashes. Although not shown, each examined NASS case year was well represented in the sample.

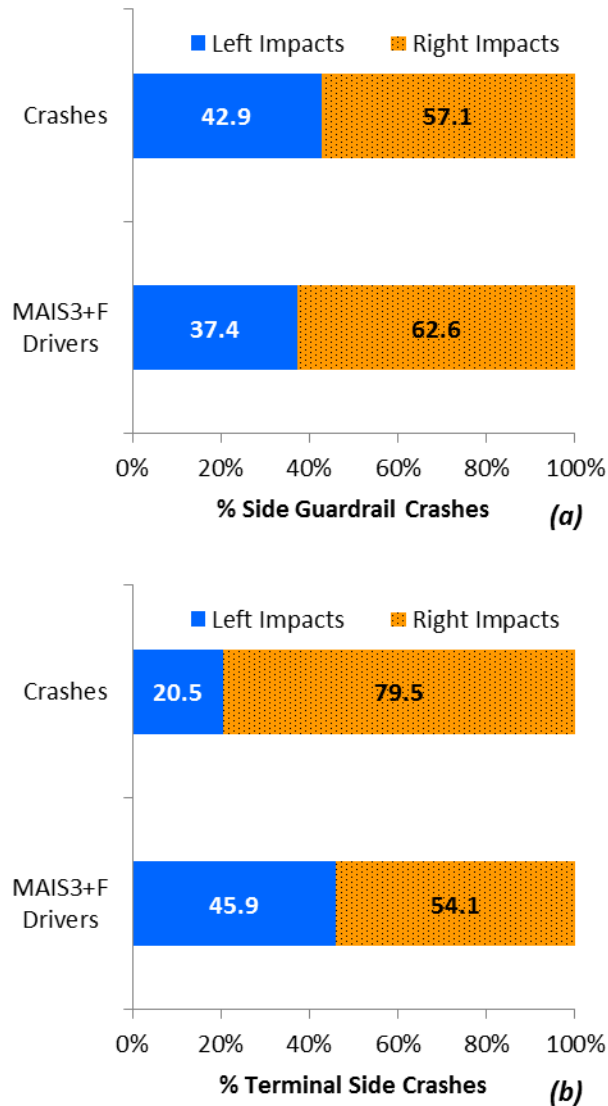
**Table 4.1. Sample composition, all guardrail side crashes**

	# Cases	% Cases	# Crashes (Weighted)	% Crashes (Weighted)
<b>General Area of Damage (GAD)</b>				
Right Side (R)	79	55.6%	26861	57.1%
Left Side (L)	63	44.4%	20155	42.9%
<i>Total</i>	<i>142</i>	<i>100.0%</i>	<i>47016</i>	<i>100.0%</i>
<b>Specific Horizontal Location (SHL)</b>				
Front (F)	21	14.8%	5051	10.7%
Passenger (P)	18	12.7%	1345	2.9%
Back (B)	21	14.8%	12731	27.1%
Y (F+P)	17	12.0%	2634	5.6%
Z (P+B)	23	16.2%	12256	26.1%
Distributed (D, F+P+Y)	36	25.4%	12502	26.6%
Unknown	6	4.2%	497	1.6%
<i>Total</i>	<i>142</i>	<i>100.0%</i>	<i>47016</i>	<i>100.0%</i>
<b>Vehicle Type</b>				
Car	115	81.0%	34537	73.5%
LTV	27	19.0%	12479	26.5%
<i>Total</i>	<i>142</i>	<i>100.0%</i>	<i>47016</i>	<i>100.0%</i>
<b>Total Number of Events in Crash</b>				
1	33	23.2%	15266	32.5%
2	50	35.2%	17540	37.3%
3	38	26.8%	8769	18.6%
4 - 7	21	14.8%	5441	11.6%
<i>Total</i>	<i>142</i>	<i>100.0%</i>	<i>47016</i>	<i>100.0%</i>
<b>Object Struck</b>				
Length of Need	81	57.0%	35478	75.5%
Compliant Terminal	14	9.9%	3927	8.3%
Non-Compliant Terminal	22	15.5%	4261	9.1%
Unknown Terminal	25	17.6%	3350	7.1%
<i>Total</i>	<i>142</i>	<i>100.0%</i>	<i>47016</i>	<i>100.0%</i>
<b>Driver Side Airbags (Case Years 2000 – 2008 only)</b>				
Equipped	19	17.1%	2099	5.0%
Non-Equipped	92	82.9%	39555	95.0%
<i>Total</i>	<i>111</i>	<i>100.0%</i>	<i>41655</i>	<i>100.0%</i>

#### 4.4.1 INJURY DISTRIBUTIONS BY DAMAGED SIDE AND DAMAGED AREA

Figure 4.1 shows crash and injury distributions by GAD for all guardrail side crashes and for terminal side crashes only. When all guardrail side crashes were considered together, there was no statistically significant difference in injury odds between near- and far-side impacts. Left side crashes were observed to be 0.788 times as likely as right side crashes to result in injury (95% CI: 0.306 – 2.03). However,

when only terminal side impacts are considered, near-side crashes are 3.98 times more likely than far-side crashes to cause injury (95% CI: 1.03 – 15.4).

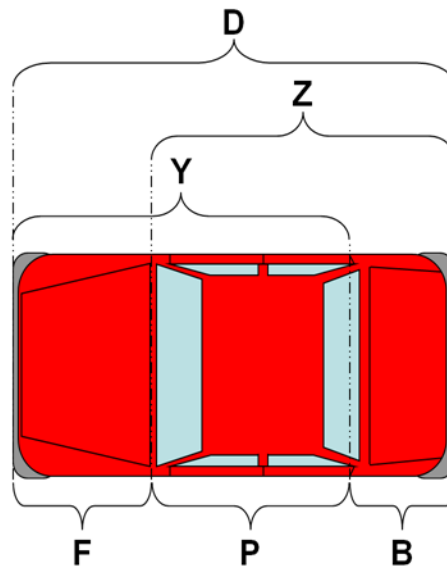
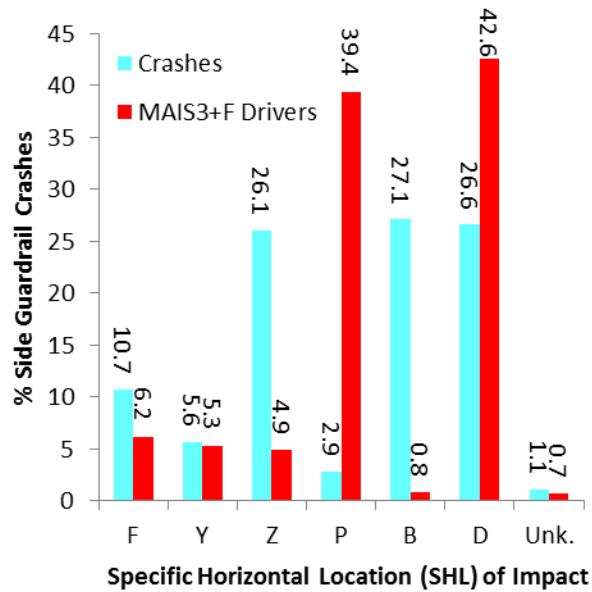


**Figure 4.1. Crash and injury distribution by damaged side, all guardrail side crashes together (a) and terminal side impacts only (b).**

Specific Horizontal Location (SHL) is part of the Collision Deformation Classification standard (SAE J224). As shown in Figure 4.2, SHL describes the specific region of the vehicle plane that was damaged. “P” refers to the passenger compartment, “F” and “B” to the front and back, “Y” to a combination of P and F, “Z” to a combination of B and P, and “D” to damage distributed over the entire side (F, P and



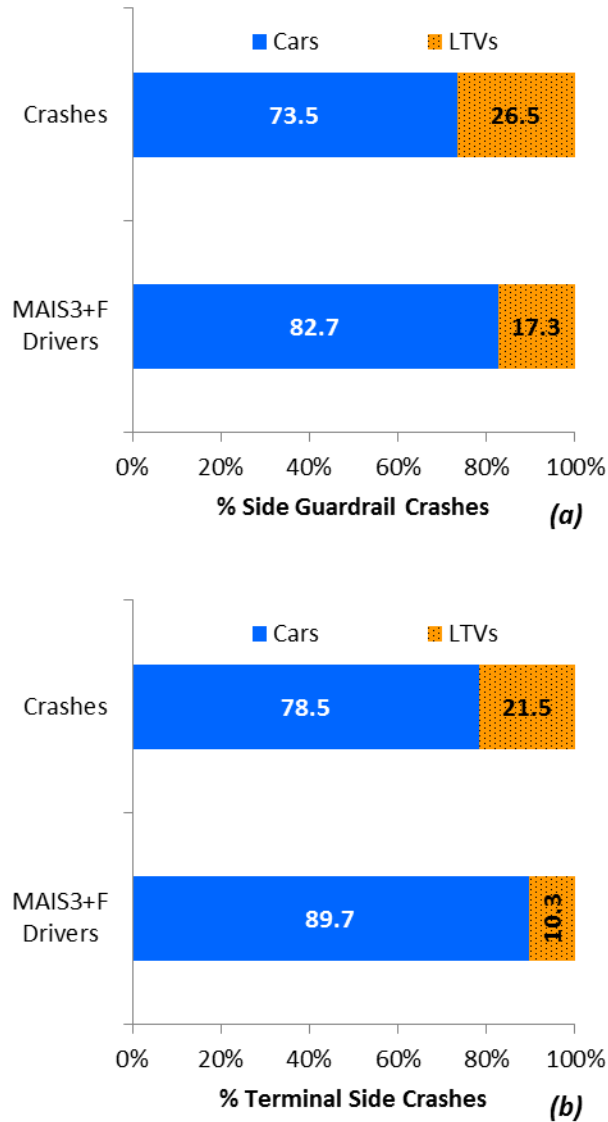
B). Figure 4.2 shows that P crashes were grossly overrepresented in driver injuries. The odds of injury in P crashes were 15.9 times greater than in D crashes (95% CI: 3.56 – 70.9). This was consistent with the findings of Ray and Carney (1994) and Stolle et al. (2011). B and Z crashes were also observed to be only 0.018 and 0.112 times as risky as D crashes, respectively (B 95% CI: 0.002 – 0.197; Z 95% CI: 0.017 – 0.722). Taken together Figure 4.1 and Figure 4.2 seem to imply that occupant compartment intrusion was responsible for much of the injury risk presented by guardrail side crashes, particularly end terminal side crashes.



**Figure 4.2. Crash and injury distribution by specific horizontal location (SHL) of impact.**

Figure 4.3 shows the distribution of crashes and driver injuries by vehicle type. When all guardrail side crashes are considered together, LTVs present only 0.570 times the injury risk of cars, but the difference is statistically insignificant (95% CI: 0.152 – 2.13). When only terminal side crashes are considered, LTVs become only 0.388 times as risky as cars, and the difference remains statistically insignificant (95% CI: 0.037 – 4.02). The latter finding is consistent with Gabler and Gabauer (2007) and

could suggest that taller vehicles are somewhat less threatened by side impacts with short, narrow objects such as end terminals. However, a much larger sample appears to be necessary to confirm this if true.

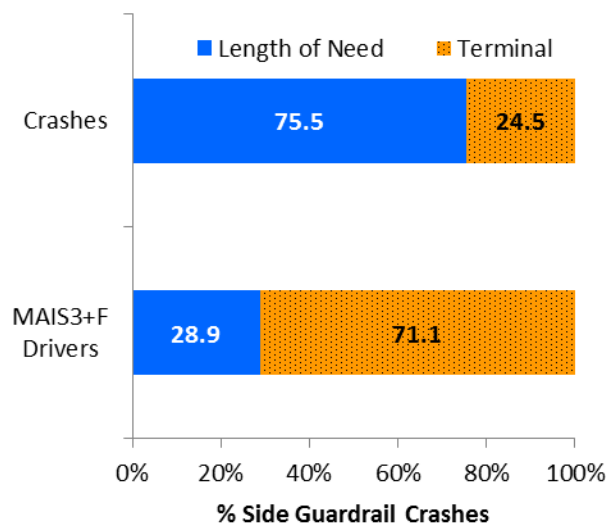


**Figure 4.3. Crashes, injuries by vehicle type for all guardrail side crashes together (a) and end terminal side impacts only (b).**

Figure 4.4 divides cases by guardrail area impacted. It appears that contact with the end terminal is substantially more hazardous than LON contact. Terminal side crashes are observed to be 8.33 times more likely than LON side crashes to produce injury (95% CI: 2.96 – 23.4). LON impacts represent 75.5% of all

non-tracking guardrail side crashes, yet only 28.9% of the resulting injuries; the remaining 24.5% of crashes with end terminals causes 71.1% of the injuries.

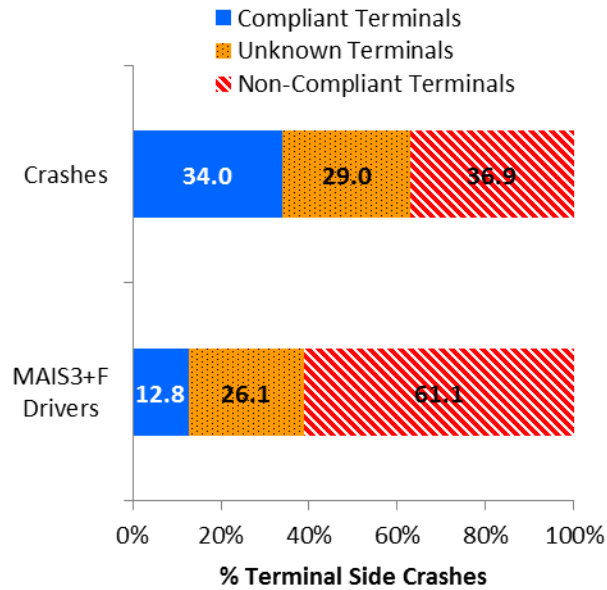
It is very difficult to hit the passenger compartment in a non-tracking LON side crash. Contact tends to be with one vehicle corner (SHL of “F” or “B”) which Figure 4.2 has shown to be relatively safe. When the passenger compartment is involved in part of a “D” impact (unlike in redirection crashes, the crash forces are directed more normally to the vehicle surface). By contrast, crashes that engage the end of the rail – a discrete prominence – can readily engage the passenger compartment. These impacts can result in the deeper intrusion and larger forces directed into the occupant compartment that are thought to make side impacts so dangerous.



**Figure 4.4. Crashes and injuries by area of rail system contacted.**

Figure 4.5 breaks down terminal crashes and associated injuries by the type of the terminal system. Designs not compliant with NCHRP Report 350 criteria were observed to pose an injury risk 5.11 times as great as compliant designs, but the difference was not statistically significant (95% CI: 0.629 – 41.5). The p-value for this difference is only 0.171; it is very likely that a larger sample would yield a statistically significant difference between compliant and non-compliant terminals. Striking any narrow fixed object with the side of a vehicle is inherently very dangerous, so the difference between terminal types may appear

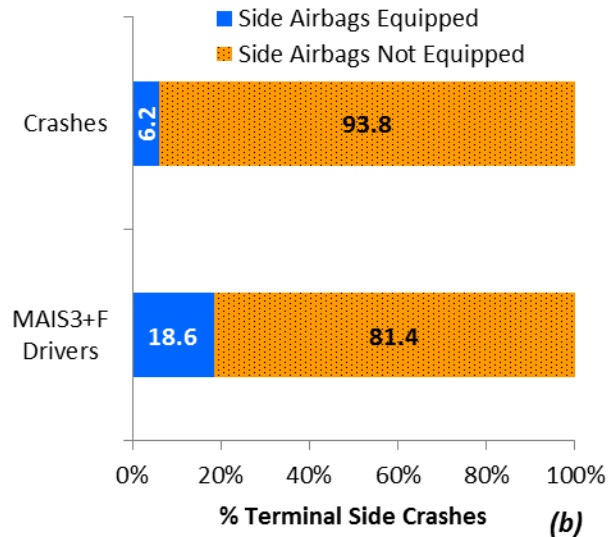
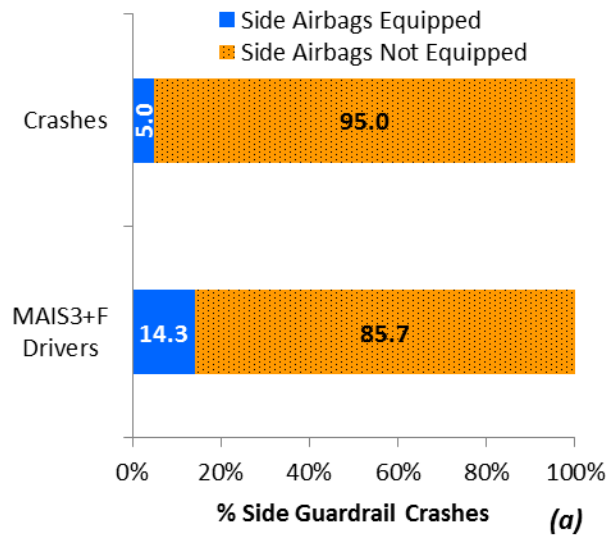
somewhat subdued as a result. Note that this assessment does not qualitatively change even if all terminals of unknown type are assumed to be non-compliant.



**Figure 4.5. Effect of terminal crashworthiness on injury risk (terminal side crashes only).**

#### 4.4.2 EFFECT OF SIDE AIRBAGS

NASS records of side airbag presence in vehicles only go back to case year 2000, so the subsample used to assess the effect of side airbags contains 111 crashes as opposed to 142. Figure 4.6 indicates that vehicles equipped with side airbags do not exhibit injury risk significantly different from non-equipped vehicles. This finding does not change when only terminal side crashes are considered. This section is intended to provide an early look at side airbag effectiveness in side guardrail crashes. This issue should be revisited with a larger sample when one becomes available.



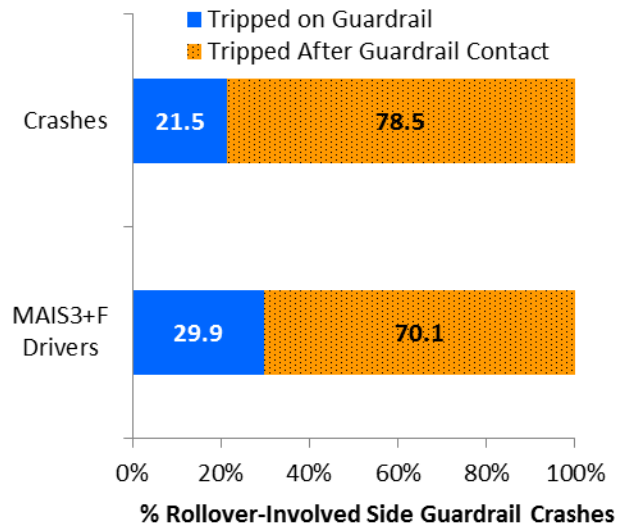
**Figure 4.6. Crashes and injuries by side airbag presence, all guardrail side crashes (a) and terminal side crashes only (b).**

#### 4.4.3 ROLLOVER INVOLVEMENT BY IMPACT TYPE

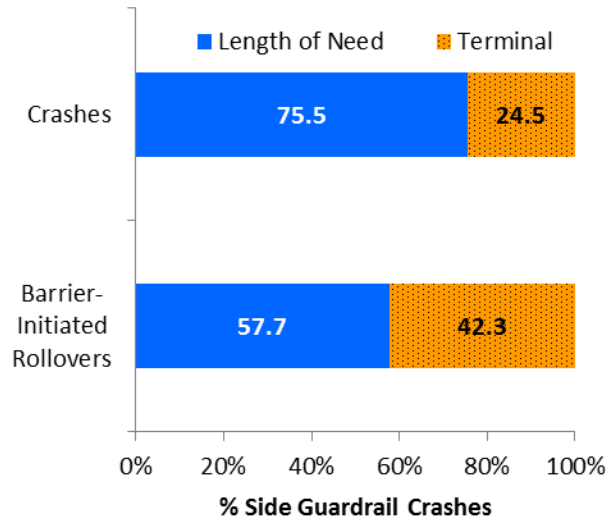
Several studies (Gabler and Gabauer 2007; Gabauer and Gabler 2009) have reported that guardrail end treatments may present a rollover hazard for certain vehicles. NASS crash investigators code the object that initiated vehicle trip for each rollover event in NASS. Determination of the causative factors in rollover can be complex, however for our analysis we used the following definitions: every side guardrail crash in the sample where a) the object initiating the trip was coded as guardrail and b) there were no other guardrail

impacts between the high- $\Delta V$  event and the rollover event were assumed to have tripped as a result of the high- $\Delta V$  guardrail impact.

Figure 4.7 shows the distribution of rollover-involved guardrail side crashes and resulting injuries by the rollover initiation object, for all 30 crashes where rollover occurred. For the majority of rollover-involved guardrail side crashes, roll was initiated by something subsequent to the guardrail impact. Only about 20% of all rollovers that do occur are initiated by contact with the guardrail. Figure 4.8 shows that these rail-initiated crashes are 2.30 times more likely to be initiated by a terminal than by the LON, but the finding is not statistically significant (95% CI: 0.409 – 12.9). The apparently increased likelihood of rollover in terminal impacts might be explained at least in part by the fact that vehicles have somewhere to roll in terminal impacts – the vehicle is much better contained when striking the LON than it is when striking the terminal.



**Figure 4.7. Rollover occurrence relative to guardrail impact in rollover crashes.**

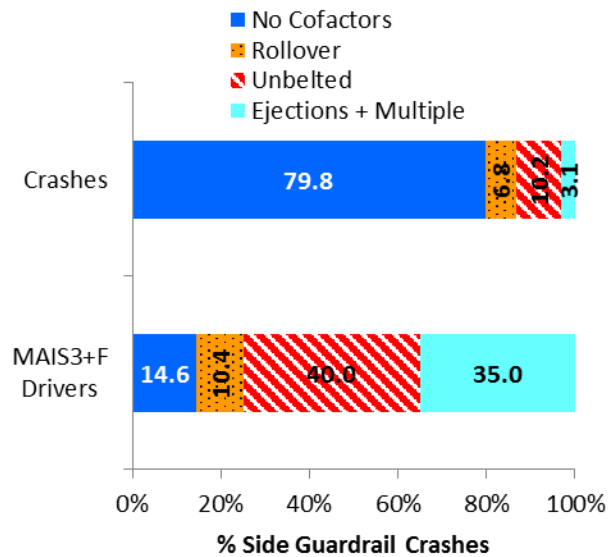


**Figure 4.8. Rail-tripped rollovers by area struck.**

#### 4.4.4 EFFECT OF HIGH-RISK COFACTORS

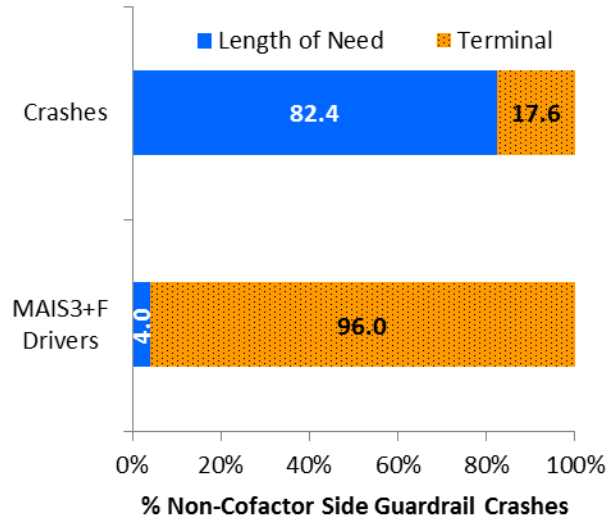
Whether or not guardrail impacts cause rollovers, it is a fact that rollovers as well as other high-risk events do sometimes occur in the same crashes as guardrail side impacts. To what degree do such high-risk cofactors affect the distribution of injuries in guardrail side crashes? By extension, what is the direct hazard presented by side impact with guardrail? To attempt to shed light on this, the effects of three high-risk cofactors were examined: rollover, driver ejection and non-use of seatbelts. Figure 4.9 shows crash and injury distribution versus the presence of these high-risk cofactors. Only about 20% of side guardrail crashes involve high-risk cofactors, yet these cases account for about 85% of all side guardrail injuries. All three cofactors individually increase injury risk by a significant amount. Rollovers are 8.79 times more likely to result in injury than non-cofactor crashes (95% CI: 1.44 – 53.8); belt non-use, 24.7 times (95% CI: 4.30 – 142); multiple cofactors (including ejections), 101 times (95% CI: 21.7 – 471). Not surprisingly, crashes involving multiple cofactors are by far the most hazardous – although whether multiple cofactors cause injury or crash severity causes multiple cofactors and injury cannot be determined.





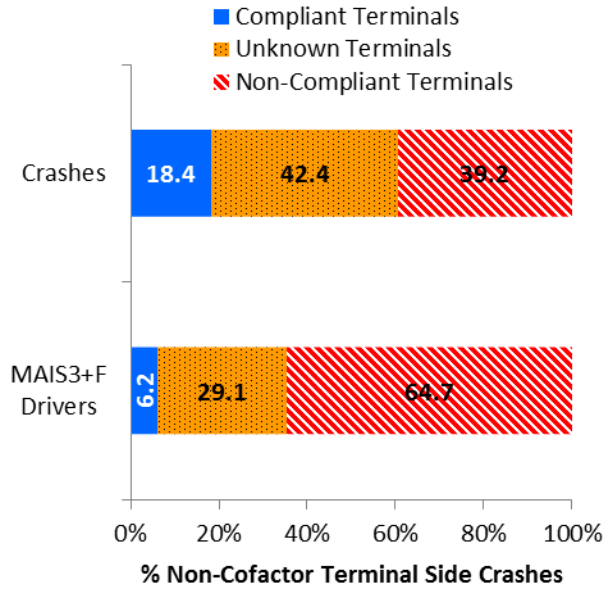
**Figure 4.9. Crashes, injuries by high-risk cofactor presence. All cases where ejection occurred also involved at least one other cofactor.**

In order to more directly quantify the injury risk inherent in side guardrail impacts, the subset of 78 cases without any ejection, rollover or unbelted drivers was analyzed separately. Figure 4.10 gives the distribution of crashes and driver injuries by area struck for side guardrail crashes without any high-risk cofactors. Out of 25 LON crashes, only one was injurious (there were 8 total injury crashes involving terminals). This makes terminal impacts 116 times more likely to result in injury than LON impacts in this sample (95% CI: 9.33 – >1000). The extreme magnitude of this odds ratio is clearly due to the small number of injury crashes in the sample without high-risk cofactors. However, it does seem clear that removing high-risk cofactors accentuates the injury risk posed by end terminal contact even further. A larger sample with a sufficient number of injury crashes is required to arrive at a more realistic value for the increase in risk over LON side crashes.



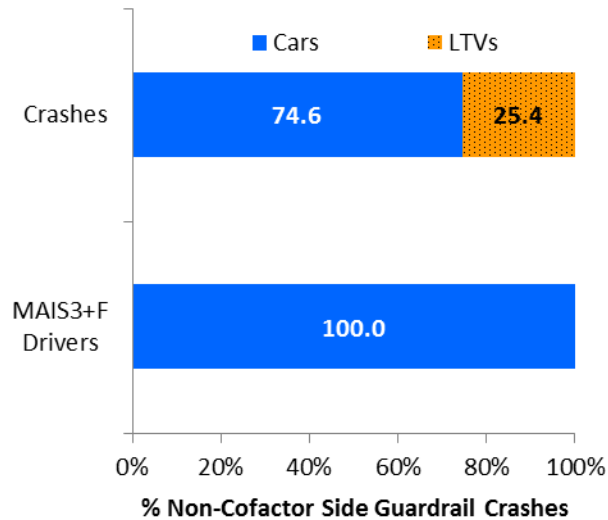
**Figure 4.10. Crashes and injuries by area of rail system contacted, non-cofactor crashes only.**

Figure 4.11 suggests that when cofactors are removed, the difference in injury risk between NCHRP-350-compliant and non-compliant terminals is similar to that of Figure 4.5 (with cofactors). The observed difference of 5.16 (non-compliant compared to compliant) is still however statistically insignificant (95% CI: 0.376 – 70.8). This is again almost certainly an artifact of the highly reduced sample under consideration. Since in all examined cases the guardrail impact is the highest- $\Delta V$  event, the lack of difference with cofactors removed is unsurprising – only those cases where most of the harm was done by the guardrail were selected for.



**Figure 4.11. Effect of terminal type on injury risk for non-cofactor terminal side crashes.**

Figure 4.12 shows the re-assessed distribution of crashes and injuries by vehicle type. With non-side-impact factors removed, all observed injuries in the sample are now accounted for by cars. The non-cofactor sample contains 63 cars, 15 LTVs and 8 cases where driver injury occurred. While an odds ratio comparing injury risk between cars and LTVs cannot be calculated for this subsample, it seems likely that cars may carry a greater risk of injury than do LTVs in side guardrail impact, which fits with the findings of Gabler and Gabauer (2007).



**Figure 4.12. Crashes and injuries by vehicle type, non-cofactor crashes.**

#### 4.5 CONCLUSIONS

This study has investigated the issue of non-tracking side impact using a dataset of 142 guardrail side crashes extracted from the NASS/CDS. Any impact with an end terminal, tracking or not, is highly over-represented in terms of driver injury. Although terminal crashes represented only about 25% of guardrail side crashes, they accounted for more than 70% of the injuries sustained in such crashes. When terminal side crashes were considered separately from LON crashes, cars were observed to be roughly 2.5 times as likely to sustain driver injury. This result was consistent with other studies, but it was not statistically significant. Terminals compliant with NCHRP-350 may be about five times as safe as non-compliant designs, but the difference appears to be overshadowed by the high degree of risk involved in striking any narrow fixed object with the side of the vehicle. A somewhat larger sample appears necessary to make this finding significant at the 95% confidence level.

Intrusion appears to be a major risk factor in guardrail side crashes, particularly terminal crashes. Crashes directly involving the occupant compartment (SHL of “P”) were the most dangerous, accounting for only 3% of all non-tracking side guardrail crashes yet almost 40% of the total injuries. For terminal side crashes, driver-side impacts significantly greater injury risk compared to passenger-side impacts.

Only about 20% of rollovers in non-tracking guardrail side crashes are initiated by contact with the rail; 80% are initiated by some subsequent contact (none of the sampled cases were rolling prior to contact). Those rollovers that are rail-initiated appear to be about twice as likely to be initiated by a terminal as by LON.

Most observed injuries occurred in crashes involving some combination of rollover, unbelted drivers and ejection. When these high-risk cofactors were removed from the sample, the risk presented by terminal contact was accentuated, as was the disparity in injury risk between cars and LTVs for terminal side crashes. The difference between NCHRP-350-compliant terminals and non-compliant terminals remained relatively unchanged.

## 5 INJURY IN CRASHES WITH GUARDRAIL END TERMINALS

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### 5.1 INTRODUCTION

Guardrail is flexible or semi-rigid roadside safety barrier designed to intercept and redirect vehicles departing the roadway before they can strike roadside hazards such as trees or buildings. According to the U.S. National Automotive Sampling System – Crashworthiness Data System (NASS-CDS), between 1997 and 2008, there were on average about 51,000 police-reported, tow-away crashes with guardrails each year on United States roads. About 13% of those crashes, or about 6,600 per year, involved the ends of the guardrail. The ends of a guardrail are an area of special concern in a crash, since a bare guardrail end can penetrate, or “spear”, into the occupant compartment of a vehicle and strike occupants directly. In practice, guardrail end terminals are installed at the ends of nearly all guardrails to prevent the rail from spearing in an end-on collision. Even so, the 13% of crashes involving guardrail ends still account for about 32% of the total serious injuries and fatalities observed in guardrail crashes (NHTSA 2009).

Recently, there has been a great deal of controversy (Nadeau 2014; FHWA 2015) over the safety of certain widely used end terminal designs. Concerns have been raised that some of these systems can penetrate through vehicles, causing amputations and in some cases death of vehicle occupants, despite being designed specifically to prevent this outcome. This controversy exists partly because there is surprisingly little real-world crash data for end terminals specifically. Most existing studies of injury in end terminal crashes use data from prior to the mid-1990s (Ross et al. 1993; Hunter, Stewart and Council 1993; Viner, Council and Stewart 1994; Ray, Weir and Hopp 1994; Gattis, Varghese and Toothaker 1993). Since then, there have been large improvements to vehicle crashworthiness and seatbelt usage rates, as well as new roadside safety hardware tested to the requirements of National Cooperative Highway Research Program NCHRP Report 350 (Ross et al. 1993). Additionally, most existing studies of injury risk in end terminal crashes do not control for seatbelt use or the occurrence of rollover.

Hunter, Stewart and Council (1993) studied differences in injury rates between different guardrail and end terminal types, between vehicle types and between length-of-need and end terminals. Their study used the Longitudinal Barrier Special Study (LBSS) file, a detailed set of about 1200 longitudinal barrier crashes collected from 1982 to 1986 as part of the NASS crash investigation activities. Blunt ends and turndowns had a higher proportion of serious and fatal injury crashes in their sample than breakaway-cable, non-breakaway-cable, buried-in-backslope end treatments and junctions with bridge parapets. However, while blunt ends and turndowns were significantly more dangerous than impacts with barrier face, the study found no statistically significant differences between these terminal designs and the other terminals in their sample.

Viner, Council and Stewart (1994) examined injury outcomes by vehicle type in roadside safety appurtenance crashes from 1985-1990. Using North Carolina state data, the study found that serious injury occurred in 19% of police-reported guardrail end crashes involving cars, and 13% involving pickup trucks. The study also found that, in rollovers, pickup trucks had less than half the serious injury rate of cars. However, their analysis primarily focused on differences between vehicle types, and did not explore differences between different kinds of guardrail end treatment.

NCHRP Report 490 (Ray, Weir and Hopp 2003) included in-service performance analyses for several end terminal systems during 1997-1999. Sixty percent of crashes with Modified Eccentric Loader Terminals (MELTs) or Breakaway Cable Terminals (BCTs) resulted in property damage only. Out of 115 such crashes observed, only 5 cases resulted in injuries rated as K or A on the KABCO scale. Gattis, Varghese and Toothaker (1993) performed an in-service performance evaluation comparing different guardrail end treatments in Oklahoma from 1987 – 1991. The study obtained useful numbers of crashes with “exposed” guardrail ends (presumably a spade-shaped or rounded end cap on the end of the guardrail, with no cable present) and turndowns. The analysis found that rollover was significantly more likely in crashes with turndowns than exposed ends. However, no statistically significant difference in K+A injuries

among rollover crashes was observed between the two systems. In addition, no statistically significant difference was observed between the two systems in terms of overall K+A crashes.

The majority of the literature concerning injury risk in guardrail crashes uses data from the mid-1990s or earlier. Substantial changes to the U.S. vehicle fleet have happened in the intervening 20 years. Airbags became mandatory on new vehicles only in 1997-1998. Seatbelt use rates have risen since the early 1990s. Crashworthiness of the average fleet vehicle has improved drastically thanks to demanding crash tests performed by the Insurance Institute for Highway Safety (IIHS) and the National Highway Traffic Safety Administration (NHTSA). Roads and roadside hardware have changed as well. In 1995, the national maximum speed limit law was repealed. In late 1998, NCHRP Report 350 (1993) was adopted by the Federal Highway Administration as the standard for roadside safety appurtenances on the National Highway System.

The adoption of NCHRP 350 is very important, as there is very little data comparing end terminal designs developed subsequent to the adoption of this crash test protocol. End terminals designed to pass the NCHRP 350 crash tests are intended to be more forgiving objects to strike than non-compliant end terminals. Many designs incorporate special energy-absorbing impact heads that dissipate crash energy in a controlled manner by deforming the guardrail. Others prevent spearing by incorporating specially weakened guardrail segments that allow for controlled, predictable buckling of the guardrail. All designs use special posts designed to break away in an impact. In light of these changes, studies based on data from the 1990s or earlier cannot safely be assumed to represent injury risks posed to occupants of the current vehicle fleet.

## 5.2 RESEARCH OBJECTIVE

The objective of this study is to determine the risk of injury in crashes with guardrail end terminal systems.

## 5.3 METHODS



Potential crashes for this analysis were drawn from the Michigan State UD-10 crash database, sample years 2011 and 2012. This database includes all police-reported crashes in the state of Michigan. Cases in this database are submitted via the UD-10 crash report form, which is filled out by police responding to the crash. Information is collected on the crash location, involved vehicles, vehicle occupants, involved pedestrians and damaged property. Crashes were selected which met the following criteria:

- Vehicle was either a car or a light truck, van or sport utility vehicle (LTV)
- Most harmful event (MHE) for the vehicle was coded as an impact with a guardrail end, or MHE was coded as a rollover that was directly preceded by impact with a guardrail end
- Any crashes coded as “backing-up” or “sideswipe” were excluded
- Latitude and longitude of the crash location were coded
- Driver was present during the crash
- Known injury outcome (KABCO) was coded for the driver

Michigan crash data coding distinguishes impacts to the guardrail face from impacts to the guardrail end. Even so, there was still some uncertainty as to whether vehicles actually engaged the end of the guardrail, or simply struck the guardrail face very near the end. It is likely that at least some crashes coded as striking the guardrail end were in fact impacts to the guardrail face very near the end. However, there are two factors which should mitigate any effects this might have. First, crashes to the guardrail face are frequently sideswipes, and the sample specifically excluded crashes coded as sideswipes. Second, most end terminal systems actually comprise the first 3 posts in an installation, so impacts to the guardrail face very near the end are still, in fact, impacts to what is commonly considered part of the end terminal.

Michigan crash data codes occupant injury level using the KABCO scale. This injury coding scale describes the overall state of an occupant at the scene of the crash, and is coded by police. On this scale, “K” denotes a fatality; “A” denotes an incapacitated occupant; “B” denotes an occupant with injuries that

are apparent but not incapacitating; “C” denotes an occupant that may be injured, but whose (possible) injuries are not apparent; and “O” denotes an uninjured occupant (Gabler, Weaver and Stitzel 2015).

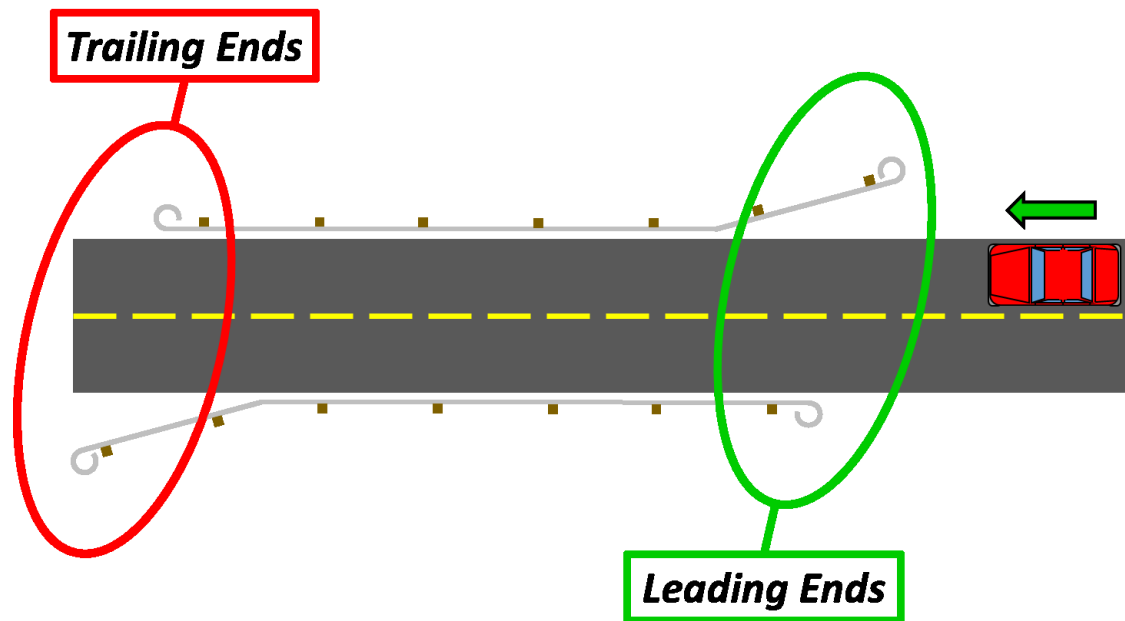
This analysis examined only drivers and their injuries. Occupants in different seating locations can have different restraints and experience different loads during the same crash. Different vehicle types may also possibly have different occupancy rates (e.g., cars typically have more seats than pickup trucks), which could in turn distort findings if not handled carefully. By examining only drivers, these issues are avoided entirely.

### *5.3.1 IDENTIFICATION OF VEHICLE TYPE*

In this analysis, vehicles were divided into passenger cars and light trucks, vans and sport utility vehicles (LTVs). While the Michigan crash data does uniquely code pickup trucks and vans, Michigan uses the same body style code for passenger cars and sport utility vehicles. When the vehicle was not coded as a van or pickup truck, it was therefore necessary to decode the Vehicle Identification Numbers (VINs) to distinguish passenger vehicles from sport utility vehicles. The VIN is a standardized 17 digit number that uniquely identifies every passenger vehicle in the world. Michigan crash data includes the first 12 digits of the VIN, which is sufficient to determine many vehicle attributes, including vehicle type. The last 5 digits are not reported in the public data, as these would allow identification of specific vehicles. Using a publically available VIN-decoding code produced by the NHTSA (Kahane 2014), the partial VINs were decoded and the vehicle body type information used to separate cars from sport utility vehicles. The VIN decoder used in this analysis was valid for model years 1980-2011. For the handful of vehicles from model years prior to 1980 and subsequent to 2011, VINs were decoded manually when necessary to assign vehicle type. Any vehicles for which the body type could not be determined, for any reason, were excluded from the analysis.

### *5.3.2 IDENTIFICATION OF END TERMINALS*

Crash sites were manually inspected using Google Street View to determine what kind of end terminal was present prior to the crash. Google Street View has recently made street view imagery from previous years available. When imagery from multiple dates was available for a crash site, the imagery nearest to the crash date but still preceding it was used for identification of the system. In many cases, imagery was also available subsequent to the crash date as well. This sometimes helped positively identify the end terminal that was involved in the crash, as the replaced terminal was often visibly newer than the rest of the guardrail. As shown in Figure 5.1, impacts where the vehicle struck the trailing terminal for the lane of travel, or the leading terminal on an oncoming lane, were coded as impacts with trailing ends in the analysis sample.



**Figure 5.1. Trailing terminals were identified in the analysis sample.**

Any crashes for which Street View imagery was not available, or was not available prior to the crash date, were excluded from the analysis. The latitude and longitude coded as the crash location were occasionally somewhat imprecise, or were some distance from the nearest guardrail. In these cases, the written description of the crash location given on the police accident report was also used to help locate the struck end terminal. Even with this approach, it was frequently not possible to identify the crash location

with reasonable certainty. Cases where a plausible candidate for the struck end terminal could not be found were excluded from the analysis. In other cases, the crash location was relatively certain, but there were multiple end terminals near that location, and it was unclear which one had been struck. It was sometimes possible to determine which end terminal had been replaced using post-crash imagery. In others, all possible end terminals were of the same type, so there was no problem identifying the design of the struck terminal. When the contacted terminal could not be identified with certainty, the crash was excluded from the analysis sample.

Identification of energy-absorbing end terminal designs was generally straightforward, since all energy-absorbing designs use a conspicuous crash head of some kind. Examples of commonly installed energy-absorbing end terminals include the SKT-350, the ET-2000 and the ET-Plus (Figure 5.2). Non-energy-absorbing end terminal designs can be more difficult to distinguish, as the distinguishing features are often more subtle than for energy-absorbing systems. Compared to energy-absorbing terminals, higher-quality images are generally needed to successfully identify non-energy-absorbing terminals. Examples of common non-energy-absorbing end terminals include the SRT-350, the Modified Eccentric Loader Terminal (MELT), and the Breakaway Cable Terminal (BCT). Guardrails may also be terminated by simply placing blunt end caps or spade-shaped end caps on the end of the rail, with no anchor cables or ground struts. Such end treatments were distinguished from other end terminal designs. Although technically an end treatment, impacts to guardrail ends buried in backslope were excluded from the sample as well. Since the end of the guardrail is not exposed when this treatment is used, vehicles cannot really be said to impact the end of the guardrail.



**Figure 5.2. Examples of common energy-absorbing (left) and non-energy-absorbing (right) guardrail end terminals.**

In rare instances, pre-crash imagery showed that the struck end terminal with unrepaired crash damage prior to the date of the sampled crash. While it was likely that, in many such cases, the end terminal in question would have been repaired prior to the crash date, there was no way to confirm that this happened. Furthermore, in a very few cases, the same unrepaired crash damage was shown in pre-crash images going back multiple years, or unrepaired damage was shown in pre-crash images from very close to the crash date. When an end terminal showed unrepaired crash damage, and no pre-crash photos closer to the crash date showed that the damage had been repaired, the case was excluded from the sample. Additionally, pre-crash images for several cases showed end terminals that were obviously incorrectly assembled or installed – e.g., an SRT-350 end terminal constructed using a section of standard un-slotted W-beam for the first rail segment. Any cases where the end terminal was clearly assembled in such a way that it would not function as intended were excluded from the sample as well.

### *5.3.3 STATISTICAL ANALYSIS*

All statistical analysis was performed using SAS v9.3. The final sample was analyzed using multiple logistic regression (SAS PROC LOGISTIC), in order to test the effects of different variables on driver injury outcome while controlling for one another. Model coefficients in a logistic regression model provide odds ratios for model effects, and the p-values of those model coefficients provide a measure of the statistical significance of that effect within the model being fit. Henceforth, “statistical significance” refers to a 95% confidence level. Variables examined in this analysis included reported driver belt use and rollover occurrence, both of which are known high-risk cofactors, vehicle type (car/LTV), and end terminal type. Regressions were performed using all crashes in the sample, and also using subsets of the sample containing crashes on roads of the same access control level, posted speed limit and road class.

Since state crash data do not oversample crashes with severe outcomes, it can be difficult to obtain large numbers of crashes with severe outcomes. This analysis therefore examined the incidence of crashes

including any level of confirmed injury to the driver, i.e. crashes were considered to be injury crashes if the driver injury level was coded as K, A or B. Crashes where the driver sustained a C injury – where injury was possible but not confirmed – were not counted as injuries in this study.

## 5.4 RESULTS

A total of 1001 police-reported guardrail end crashes selected from the 2011-2012 Michigan State crash data were manually inspected to identify the end terminal that had been struck. Table 5.1 shows a breakdown of both the excluded cases and the final analysis sample on the analysis variables. By definition of the sample, the excluded cases contain primarily unidentified or unknown end terminals, while the analysis sample contains none. The only identified end terminals among the excluded cases were those observed with unrepaired crash damage, those that were incorrectly built prior to the crash, or were end terminals for which no pre-crash imagery was available.

Table 5.2 presents the composition of the dataset. A total of 550 cases were excluded from the analysis, leaving 451 in the final analysis sample. Table 5.2 shows the 550 cases which were excluded with reason for exclusion. The most common reason for excluding cases was a lack of plausibly-struck end terminals in pre-crash Street View imagery. Other significant reasons for case exclusion were uncertainty about the crash location, a lack of Street View imagery for the crash site or a lack of Street View imagery prior to the crash date, and miscoded impacts with objects other than guardrail end terminals.

**Table 5.1. Composition of dataset (excluded cases and retained cases).**

	<b># of Analyzed Cases</b>	<b>% of Analyzed Cases</b>	<b># of Excluded Cases</b>	<b>% of Excluded Cases</b>
<u>Driver Injury Outcome</u>				
K	3	0.67 %	2	0.36 %
A	14	3.10 %	14	2.55 %
B	36	7.98 %	36	6.55 %
C	72	15.96 %	70	12.73 %
O	326	72.28 %	413	75.09 %
Unknown	-	-	15	2.73 %
<b>Total</b>	<b>451</b>	<b>100.00 %</b>	<b>550</b>	<b>100.00 %</b>
<u>Rollover</u>				
Yes	43	9.53 %	35	6.36 %
No	408	90.47 %	515	93.64 %
<b>Total</b>	<b>451</b>	<b>100.00 %</b>	<b>550</b>	<b>100.00 %</b>
<u>Driver Unbelted</u>				
Yes	10	2.22 %	14	5.64 %
No	422	93.57 %	505	91.82 %
Unknown	19	4.21 %	31	2.55 %
<b>Total</b>	<b>451</b>	<b>100.00 %</b>	<b>550</b>	<b>100.00 %</b>
<u>Vehicle Bodystyle</u>				
Car	252	55.88 %	298	54.18 %
LTV	199	44.12 %	230	41.82 %
Unknown	-	-	22	4.00 %
<b>Total</b>	<b>451</b>	<b>100.00 %</b>	<b>550</b>	<b>100.00 %</b>
<u>End Terminal Type</u>				
BCT	67	14.86 %	6	1.09 %
End Anchor	66	14.63 %	2	0.36 %
ET-2000	10	2.22 %	2	0.36 %
ET-Plus	43	9.53 %	7	1.27 %
FLEAT	58	12.86 %	7	1.27 %
Modified Eccentric Loader Terminal	-	-	1	0.18 %
SKT-350	57	12.64 %	10	1.82 %
SRT-350	81	17.96 %	4	0.73 %
Spade End/Blunt End	69	15.30 %	10	1.82 %
Concrete-Guardrail Junction	-	-	59	10.73 %
Other	-	-	52	9.46 %
Unknown	-	-	390	70.91 %
<b>Total</b>	<b>451</b>	<b>100.00 %</b>	<b>550</b>	<b>100.00 %</b>
<u>NCHRP 350 Compliant End Terminal</u>				
Compliant	249	55.21 %	34	6.18 %
Not Compliant	202	44.79 %	19	3.45 %
Neither/Unknown	-	-	497	90.36 %
<b>Total</b>	<b>451</b>	<b>100.00 %</b>	<b>550</b>	<b>100.00 %</b>



The proportions of serious injuries (K+A), minor to serious injuries (K+A+B), drivers reported as unbelted and vehicle types appear to be similar between the excluded cases and the analyzed cases. Contingency table analysis found no statistically significant evidence for any difference in K+A+B injury, K+A+B+C injury, rollover, belt use or vehicle type between the excluded and included groups. By definition of the sample, the excluded cases contain primarily unidentified or unknown end terminals, while the analysis sample contains none. The only identified end terminals among the excluded cases were either damaged or incorrectly built prior to the crash, were terminals for which no pre-crash imagery was available, or were cases with unknown injury outcomes.

A total of 1001 police-reported guardrail end crashes selected from the 2011-2012 Michigan State crash data were manually inspected to identify the end terminal that had been struck. Table 5.1 shows a breakdown of both the excluded cases and the final analysis sample on the analysis variables. By definition of the sample, the excluded cases contain primarily unidentified or unknown end terminals, while the analysis sample contains none. The only identified end terminals among the excluded cases were those observed with unrepaired crash damage, those that were incorrectly built prior to the crash, or were end terminals for which no pre-crash imagery was available.

Table 5.2 presents the composition of the dataset. A total of 550 cases were excluded from the analysis, leaving 451 in the final analysis sample. Table 5.2 shows the 550 cases which were excluded with reason for exclusion. The most common reason for excluding cases was a lack of plausibly-struck end terminals in pre-crash Street View imagery. Other significant reasons for case exclusion were uncertainty about the crash location, a lack of Street View imagery for the crash site or a lack of Street View imagery prior to the crash date, and miscoded impacts with objects other than guardrail end terminals.

Table 5.1 shows that there were only 17 serious (K+A) injuries in the entire analysis sample, representing 3.8 % of the sampled end terminal crashes. Most drivers in guardrail end terminal collisions were either uninjured (O – 72 %) or were not confirmed as injured (C – 16 %). Non-incapacitating (B)

injury occurred in 36 end terminal crashes, making the total number of minor-to-seriously injured (K+A+B) drivers 53, or 11.8 % of the total sample.

The number of injury crashes observed for each individual end terminal system was too small to perform meaningful comparisons between them. For this analysis, end terminals were therefore classified into one of two groups: designs which have successfully met at least test level 2 of the NCHRP Report 350 safety requirements, and those which have not. Although the Manual for Assessing Safety Hardware (MASH) (AASHTO 2009) supplanted NCHRP 350 (Ross et al. 1993) in 2009, the MASH regulations allow the use of all existing end terminal designs that were previously approved under NCHRP 350. In addition, end treatments designed exclusively against MASH are not yet in widespread use on US roadways, so NCHRP 350 is arguably the more relevant guideline.

**Table 5.2. Composition of guardrail end terminal crashes excluded from analysis sample, by reason for exclusion.**

<b>Reason for Exclusion</b>	<b># of Excluded Cases</b>	<b>% of Excluded Cases</b>
Could not identify end terminal:	15	2.73 %
End terminal damaged prior to crash:	9	1.64 %
End terminal incorrectly built prior to crash:	5	0.91 %
Crash location uncertain:	74	13.45 %
Multiple possible terminals:	29	5.27 %
No plausible end terminals found:	224	40.73 %
No Street View imagery available prior to crash:	40	7.27 %
No Street View imagery available at all:	51	9.27 %
Struck object miscoded:	87	15.82 %
Burial-in-backslope terminal:	3	0.55 %
Driver injury unknown:	5	0.91 %
Vehicle type unknown:	8	1.45 %
<b>Total:</b>	<b>550</b>	<b>100.00 %</b>

The regression results in Table 5.3 show that, when other factors are controlled for, there is no statistically significant difference in the odds of K+A+B injury between NCHRP-350-compliant end terminals and non-compliant end terminals. However, odds of K+A+B injury for passenger cars were 3.6

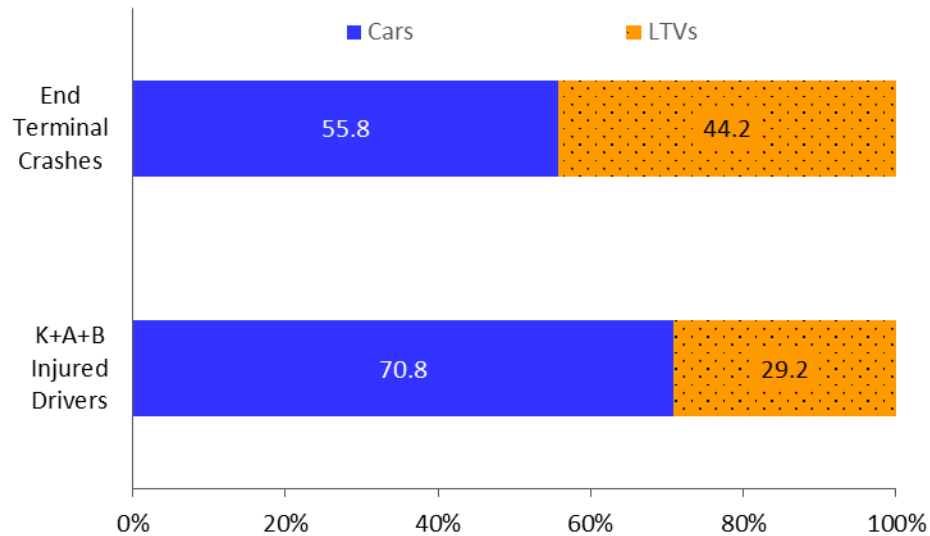
times greater than for LTVs, at greater than 95 % confidence. This regression controls for rollover occurrence, non-use of seatbelts, number of impacts, differences between impacts to leading and trailing ends, and differences in impact conditions in control-loss crashes. As expected, both rollover and non-use of seatbelts result in a large and statistically significant increase in injury odds. Neither control loss, nor terminal orientation (leading/trailing) was observed to have a significant effect on injury outcome. Injury odds almost doubled for every additional impact event coded for a crash, but the finding was just shy of statistical significance.

**Table 5.3. Multiple logistic regression of injury outcome on end terminal type, rollover occurrence, vehicle type, belt use, terminal orientation, occurrence of control loss and number of impacts. Wald Chi-Square p-value for overall model: < 0.0001. Model C-statistic: 0.780. n=432. Nineteen cases were excluded from the regression due to unknown belt use.**

Outcome	Model Effect	Odds Ratio <i>(for injury)</i>	95 % Wald Confidence Interval	Significant?
Driver Injured Yes = 48 No = 384	<b>End Terminal NCHRP 350 Compliance</b>	<b>0.821</b> <i>(non-compliant vs compliant)</i>	<b>0.389 - 1.733</b>	No
	Rollover Involvement	12.748 <i>(yes vs no)</i>	5.533 - 29.375	Yes
	Belt Use	15.144 <i>(unbelted vs. belted)</i>	3.140 - 73.043	Yes
	Terminal Orientation	0.976 <i>(leading vs. trailing)</i>	0.399 - 2.388	No
	<b>Vehicle Type</b>	<b>3.584</b> <i>(car vs LTV)</i>	<b>1.639 - 7.874</b>	<b>Yes</b>
	Crash Involved Control Loss	1.327 <i>(yes vs. no)</i>	0.653 - 2.696	No
	Number of Impacts	1.974 <i>(increases by this factor per additional event)</i>	0.998 - 3.904	Marginal

Figure 5.3 shows the proportion of end terminal crashes and injured drivers in passenger cars and LTVs. Cars account for about 56 % of end terminal crashes and about 71 % of drivers with K+A+B injuries. LTVs account for 44 % of crashes and 29 % of injured drivers. These proportions reflect the increased

injury odds displayed by car drivers in Table 5.3, despite the fact that this plot does not control for any of the cofactors controlled for in Table 5.3.



**Figure 5.3. Percentage of crashes and injuries, by vehicle type. n=432. Nineteen cases with unknown belt use excluded to give identical sample to Table 5.3.**

The regression shown in Table 5.3 does not account for the area of greatest damage on the crashed vehicle. This factor would be expected to have an effect on injury likelihood. Inclusion of this factor in the regression resulted in a separation of variables, a condition where the cases are perfectly separated into positive and negative outcomes (i.e. injuries and non-injuries) by some combination of the explanatory variable values. This causes the model-fitting process used for multiple logistic regression to fail. The effect of damaged vehicle area was therefore examined separately using contingency table analysis. Table 5.4 gives the contingency table for injury outcome versus vehicle area damaged. Damage to the left (driver) side is associated with injury more often than frontal damage (recall that crashes coded as sideswipes were excluded from the sample). Top damage is also more frequently associated with injury than frontal damage, but this is to be expected as top damage is indicative of a rollover crash. The “other” category includes rear damage, undercarriage damage and crashes where the greatest damage involved multiple vehicle surfaces. Disaggregating this analysis by vehicle type resulted in a significant number of table cells with less than 5

observations. Fisher’s Exact test found that damaged area was significantly associated with injury outcome for both cars and LTVs separately. However, odds ratios were not computed for cars and LTVs separately due to the small cell counts.

**Table 5.4. Contingency table analysis of injury outcome and area of greatest vehicle damage. Chi-square p-value: < 0.0001. Likelihood Ratio Chi-square p-value: < 0.0001. Mantel-Haenszel Chi-square p-value: 0.0022.**

	<b>K+A+B Injury</b>	<b>C+O Injury</b>	<b>Total</b>
<b>Front</b>	17	238	255
<b>Left</b>	10	34	44
<b>Right</b>	0	32	32
<b>Top</b>	7	11	18
<b>Other</b>	19	83	102
<b>Total</b>	53	398	451

*Odds Ratio (Left / Front): 4.118*  
*Odds Ratio (Top / Front): 8.909*  
*Odds Ratio (Other / Front): 3.205*

The occurrence of rollover was explicitly controlled for in the analysis. However, it is possible that NCHRP-350-compliant end terminals were more or less associated with rollover than non-compliant end terminals. Table 5.5 shows a multiple logistic regression of rollover occurrence on end terminal type, vehicle bodystyle, leading/trailing end and occurrence of control loss. The only factor significantly associated with rollover in the sample was vehicle bodystyle. LTVs exhibited higher odds of rollover than did cars. End terminal type, terminal orientation and control loss showed no significant association with rollover.

**Table 5.5. Multiple logistic regression of rollover occurrence on end terminal type, vehicle type, terminal orientation relative to direction of travel (leading/trailing). Wald Chi-Square p-value for overall model: 0.0575. Model C-statistic: 0.651. n=451.**

Outcome	Model Effect	Odds Ratio (for rollover)	95 % Wald Confidence Interval	Significant?
Rollover Yes = 43 No = 408	End Terminal NCHRP 350 Compliance	0.761 (non-compliant vs compliant)	0.382 - 1.518	No
	<b>Vehicle Type</b>	<b>2.074</b> (LTV vs car)	<b>1.087 - 3.958</b>	<b>Yes</b>
	Terminal was Trailing End	0.426 (trailing vs. leading)	0.157 - 1.154	No
	Crash Involved Control Loss	0.920 (yes vs. no)	0.483 - 1.750	No

#### 5.4.1 DISCUSSION

In our sample, NCHRP 350 compliance did not appear to have a statistically significant effect on the likelihood of K+A+B injury. End terminals are designed to be as forgiving as possible in crashes, and NCHRP-350-compliant end terminals are designed to be forgiving in extremely severe crashes (Ross et al. 1993; AASHTO 2009). However, as a total of 1001 police-reported guardrail end crashes selected from the 2011-2012 Michigan State crash data were manually inspected to identify the end terminal that had been struck. Table 5.1 shows a breakdown of both the excluded cases and the final analysis sample on the analysis variables. By definition of the sample, the excluded cases contain primarily unidentified or unknown end terminals, while the analysis sample contains none. The only identified end terminals among the excluded cases were those observed with unrepaired crash damage, those that were incorrectly built prior to the crash, or were end terminals for which no pre-crash imagery was available.

Table 5.2 presents the composition of the dataset. A total of 550 cases were excluded from the analysis, leaving 451 in the final analysis sample. Table 5.2 shows the 550 cases which were excluded with reason for exclusion. The most common reason for excluding cases was a lack of plausibly-struck end terminals in pre-crash Street View imagery. Other significant reasons for case exclusion were uncertainty

about the crash location, a lack of Street View imagery for the crash site or a lack of Street View imagery prior to the crash date, and miscoded impacts with objects other than guardrail end terminals.

Table 5.1 shows, the sample in this analysis is dominated by minor injuries, and because the sample did not intentionally select for high-severity crashes in any way, it is likely dominated by crashes of only average severity. NCHRP 350 may very well have a protective effect, but given that NCHRP 350 crash testing conditions represent very severe crashes, any protective effect of end terminals designed to this standard will more likely be most evident in higher severity crashes. Sub-dividing the sample and performing the Table 5.3 regression for end terminal crashes on roads with the same access control level, road class, or posted speed limit did not qualitatively change this finding. The regression results in Table 5.3 clearly show that rollover and non-use of seatbelts are dominant injury risks in end terminal crashes.

The observed difference in injury odds between passenger cars and LTVs is probably a result of LTVs having higher mass and higher ride height on average. LTVs' larger masses result in lower delta-Vs for a given impact speed, end terminal type and impact configuration. Table 5.4 shows that left-side impacts are more strongly associated with driver injury than frontal impacts, while right-side impacts are not associated with any driver injuries in this sample. This suggests that vehicle deformation in proximity to the driver is a key injury risk in end terminal crashes. Since LTVs have higher ride height and larger dimensions than cars on average, end terminal impacts to the side of an LTV will be lower than on cars, more focused toward the door sill and further from the driver H-point and torso.

The results of this study were similar to the NCHRP 490 findings for BCT and MELT terminals. NCHRP Report 490 examined injury in crashes with BCTs and modified eccentric loader terminals (MELTs). The study used crash data from North Carolina and Iowa, years 1997 – 1999. The study found that K+A injury occurred in 5 out of 115, or 4.3 %, of crashes with BCT/MELT end terminals (Ray, Weir and Hopp 2003). The analysis presented here found that K+A injury occurred in 3.8 % of all end terminal crashes, and in 2 out of 67 crashes (3.0 %) involving BCTs only (there were no MELTs in this sample).

NCHRP Report 490 also reported that 60 % of BCT/MELT crashes involved only property damage (i.e. O injury) (Ray, Weir and Hopp 2003). In this analysis, O injury accounted for 72 % of all end terminal crashes together and 69 % of crashes with BCTs only.

Viner, Council and Stewart (1994) examined crashes involving roadside safety hardware using North Carolina state data from years 1985-1990. The study observed that, for crashes where the most harmful event was an impact with a guardrail end, K+A injury occurred in 19 % of car crashes and 13 % of LTV crashes. The analysis did not find any statistically significant difference in injury likelihood between cars and LTVs in guardrail end crashes (Viner, Council and Stewart 1994). In contrast, the analysis presented here found K+A injury in 6.0 % of car crashes and 1.0 % of LTV crashes to guardrail end terminals – substantially less frequent. This analysis also found that K+A+B injury was different between cars and LTVs with 95 % confidence. This difference could easily be due to lower belt use in the 1980s and the much older vehicles examined by Viner, which would have predated current vehicle crash testing requirements. Viner, Council and Stewart (1994) did not report the composition of end terminal designs represented by their sample, but because of the time period presumably all terminals were pre-NCHRP-350 designs.

## 5.5 LIMITATIONS

Impact conditions, e.g. impact speed and angle, are not recorded in the state crash databases. It therefore cannot be determined how the observed crashes compare to NCHRP 350 crash testing conditions. NCHRP 350 crash testing criteria are designed to represent very severe impacts (Ross et al. 1993; AASHTO 2009) while the sample should represent a cross section of the full range of impact conditions. It is therefore likely that most of the crashes in this sample were much less severe than the NCHRP 350 crash testing conditions to which 350-compliant end terminals are designed. However, it should be noted that: 1) sideswipes – a very low-risk crash mode – were excluded from this sample; and 2), the sample is comprised of only those guardrail impacts which were reported to the police. NCHRP Report 490 found that about 90 % of all collisions to BCT end terminals are non-injury crashes that are not reported to the police (Ray,



Weir and Hopp 2003). This sample contains only police-reported crashes and the NCHRP 350 impact conditions were based on only police-reported crashes as well. So, the sample in this analysis is still likely to represent mostly less severe crash conditions.

Many guardrail end terminal crashes may be unreported non-injury crashes (Ray, Weir and Hopp 2003). The absolute percentages of end terminal crashes resulting in injury observed in study therefore are probably overestimates of the percent of injury crashes. However, observed differences in injury odds between different end terminal types or vehicle types would only be distorted if there were substantial differences in the rate of unreported crashes between them. It should also be noted that this limitation is not unique to guardrail end terminal crashes, or to Michigan State crash data.

This analysis has found that NCHRP-350-complaint end terminals do not offer a discernable safety advantage over non-compliant end terminals when less severe injuries are considered. There may very well be a difference between the two categories when severe injury outcomes are considered, but this sample could not test for such an effect. Additionally, less severe injuries are much more common in guardrail crashes, so the findings of this study still hold relevance. It was also not possible to study differences in injury between individual end terminal designs. This is an important and topical question in light of current events. It may be possible to explore this question after collecting a larger sample of crashes.

It is widely accepted that police-reported belt use overestimates actual belt use (Viano and Parenteau 2009). If more accurate belt use data were available for the sampled crashes, the significance of belt use in the regression would in all likelihood become stronger. More accurate belt use data could also possibly enhance the significance of other explanatory variables.

## 5.6 CONCLUSIONS

K+A injury occurred in 3.8 % of end terminal crashes, K+A+B injury occurred in 11.8 %, and 72.3 % of end terminal crashes involved property damage only. Cars are at greater risk of injury in end terminal crashes than LTVs. Cars showed odds of K+A+B injury 3.6 times greater than LTVs in end

terminal crashes. The area of the vehicle damaged in an end terminal crash was also significantly associated with injury outcome, with damage to the driver-side showing higher injury odds than frontal damage. End terminal designs compliant with NCHRP 350 were not observed to carry significantly different odds of K+A+B injury than non-compliant end terminals. The findings control for driver seat belt use, rollover occurrence, terminal orientation (leading/trailing), control-loss and the number of impact events. Rollover and non-use of seatbelts were observed to carry much larger increases in risk than end terminal type. Rollover occurrence was not significantly associated with end terminal type.

## 6 REDUCTION IN FATAL LONGITUDINAL BARRIER CRASHES DUE TO ELECTRONIC STABILITY CONTROL

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### 6.1 INTRODUCTION

Electronic stability control (ESC) is a vehicle safety system designed to keep vehicles moving in the direction commanded by the driver, and thereby prevent loss-of-control crashes. Loss-of-control frequently leads to road departure, which in turn can lead to rollovers and fixed-object crashes. ESC shows great promise to reduce the approximately 12,000 fatalities and 590,000 tow-away crashes that result annually from control loss and road departure in the U.S. (Kusano and Gabler 2014).

ESC systems monitor wheel speeds, steering input, vehicle heading and sideslip angle at each wheel in order to predict losses of lateral stability. When an ESC system detects that lateral sliding at a wheel is imminent, the system modulates brake force and, in some systems, even engine output to prevent any sliding from occurring. When successful, this strategy prevents many types of control loss, including spin-outs, plow-outs and 4-wheel lateral skids.

ESC first appeared in the US on 1998 BMW 7-Series cars (Kahane 2014). At first, ESC was only available on high-end luxury vehicles but as time passed, ESC became more widespread. All new passenger vehicles sold in the US were required to be equipped with ESC as of September 1, 2011 through Federal Motor Vehicle Safety Standard (FMVSS) no. 126, Electronic Stability Control Systems (NHTSA 2007). FMVSS no. 126 defines an ESC system as a system that (NHTSA 2007):

- (1) *“Augments vehicle directional stability by applying and adjusting the vehicle brake torques individually to induce a correcting yaw moment to a vehicle;”*
- (2) *“Is computer-controlled, with the computer using a closed-loop algorithm... to limit vehicle oversteer and to limit vehicle understeer;”*

- (3) *“Has a means to determine vehicle yaw rate... and to estimate its sideslip... or the time derivative of sideslip;”*
- (4) *“Has a means to monitor driver steering input;”*
- (5) *“Has an algorithm to determine the need, and a means to modify engine torque, as necessary, to assist the driver in maintaining control of the vehicle, and”*
- (6) *“Is operational over the full speed range of the vehicle (except at vehicle speeds less than 15 km/h (9.3 mph) or when being driven in reverse).”*

In addition to this definition, FMVSS no. 126 establishes performance requirements for ESC systems and testing requirements to enforce them (NHTSA 2007). Thus, individual manufacturers are free to design ESC systems as they choose, so long as the system satisfies the definition above, meets all other requirements of FMVSS no. 126 and is able to pass the performance tests required by the standard.

FMVSS no. 126 was enacted due to strong evidence that ESC has been very effective at its intended goal of reducing loss-of-control crashes. Farmer (2006) examined the rate of single-vehicle and multi-vehicle crashes per registered vehicle, with and without ESC, using data from ten U.S. states. The study used only vehicle models where ESC went from unavailable to standard equipment in a single model year with minimal additional changes. Adding ESC to these vehicles was observed to reduce single-vehicle crashes by 41 percent overall, with fatal single-vehicle crashes being reduced by 56 percent. Fatal multiple-vehicle crashes were reduced by 25 percent for cars and 32-37 percent for sport utility vehicles. Sivinski (2007) used nationally-representative U.S. crash data to examine changes in the proportion of ESC-applicable crashes relative to a control sample of low-speed and similar crashes where ESC would have no effect. Similar to Farmer (2014), the Sivinski sample consisted of vehicle models that transitioned directly from no ESC availability to standard ESC. Addition of ESC reduced police-reported side impacts with fixed objects by 60 percent for cars and 73 percent for LTVs, and reduced first-event rollovers by 72 percent for cars and 64 percent for LTVs. Kahane (2014) examined fatal crash reduction due to ESC using largely the same method as Sivinski (2007), but with an expanded list of vehicle models. Kahane (2014) also explicitly

controlled for the effect of rollover curtain airbags. ESC was found to reduce fatal first-event rollovers by 60 percent for cars and 74 percent for light trucks and vans and fatal single-vehicle crashes (excluding pedestrian/bike crashes) by 31 percent for cars and 46 percent for light trucks and vans. Extensive reviews of ESC-effectiveness research may be found in Høye (2011) and Ferguson (2007).

With such compelling evidence that ESC reduces loss-of-control crashes, the continued proliferation of ESC raises important questions about current roadside safety practices. If vehicles with ESC run off the roadway less frequently, and all vehicles will soon have ESC, how will that affect benefit-to-cost ratios for roadside barrier? Are the ESC effectiveness values reported for single-vehicle crashes in general accurate for roadside barriers in particular? If ESC-equipped vehicles are allowed to depart the roadway, will they be as likely to roll over? The answers to these questions will bear directly on how roadside barriers, and roadside safety appurtenances of all types, are designed and used.

## 6.2 OBJECTIVE

The objective of this study is to estimate how ESC will affect the number of fatalities in longitudinal barrier crashes in the U.S. The higher purpose of doing this is to highlight the importance of considering modern cars when designing the roadside.

## 6.3 METHODS

### 6.3.1 *SELECTION OF VEHICLES FOR STUDY*

The analysis presented here is based on the approach taken by Kahane (2014), but narrows and extends the analysis of Kahane to look specifically at longitudinal barrier crashes. First, VIN-derived make-model identifiers were assigned to all Fatal Accident Reporting System (FARS) vehicles from case years 1997-2011. FARS is a census of yearly fatal crashes in the U.S. These VIN-based identifiers are much more specific and precise than the standard make-model codes assigned by FARS, and are listed in the documentation provided with the publicly available (NHTSA 2014b) SAS code (a common statistical

analysis software suite). These more precise VIN-based identifiers are necessary to distinguish vehicle variants equipped with ESC from variants that were not.

Next, all crashes involving any of 58 specific car models and 35 light truck / van (LTV) models were selected from the set of all FARS cases from case years 1994-2011. These 93 vehicle models were the models identified by Kahane (2014) to have gone from having almost no ESC to largely having ESC without other substantial vehicle changes that might affect crash risk or fatality risk. Each vehicle model was only included in the pool for a maximum of 6 model years, 3 model years before ESC and 3 after ESC, and frequently less than that. This was done to minimize the effect of possible changes to static stability factor or other vehicle properties due to repeated re-designs over many years. ESC availability for each vehicle model was determined from [www.safercar.gov](http://www.safercar.gov), [www.cars.com](http://www.cars.com), [www.motortrend.com](http://www.motortrend.com) and Ward's Automotive Yearbook (Southfield, MI: Penton Media, Inc.). For domestic vehicles from model years 2004-2011 and imported vehicles from model years 2003-2011, Ward's provides the percentage of vehicles of a given model that were equipped with ESC. In this analysis, non-ESC vehicles included any for which ESC was unavailable, or for which Ward's reported less than 20 percent ESC presence. ESC-equipped vehicles included models for which ESC was standard, or for which Ward's reported greater than 80 percent ESC presence. For some models, ESC presence could be deduced from the VIN itself. A document listing ESC availability for all U.S. passenger vehicles for model years 1998-2011 is publicly available as part of the documentation of the Kahane SAS code (Kahane 2014; NHTSA 2014b).

Model year ranges for each vehicle model were also further tailored so that, for each vehicle model, there were about twice as many vehicles without ESC as with ESC in the fatal crash pool. This ensures that the ESC-sample represents the same relative proportions of vehicle models as the non-ESC-sample. Included model year ranges were also tailored to exclude changes in the availability of rollover curtain airbags. This was done for 2 car models and 11 LTV models.

For some vehicle models, rollover curtains were made available at or near the same time as ESC, but were not universally present. When rollover curtain presence could be determined for specific vehicles within a model, vehicles of that model that were not equipped with rollover curtains were included as well. ESC is designed to prevent rollovers; rollover curtain airbags are designed to prevent injury and fatality resulting from rollovers. It is therefore important to exclude changes in rollover curtain availability from the vehicle sample, as it would confound the effects of ESC.

### *6.3.2 SELECTION OF REFERENCE CRASHES AND ESC-APPLICABLE CRASHES*

Once the pool of all FARS crashes involving one of the chosen vehicles had been assembled, crashes fitting the case and reference group definitions were selected. Reference crashes in this study consisted of crashes where ESC would have no effect on the outcome, or where its effect would be at most very small. The reference sample included multi-vehicle crashes where the sampled vehicle was:

- Stopped, parked, entering or leaving a parking space, backing up, or moving at 10 mph or less prior to the crash;
- Struck in the rear;
- Driving on a dry road and did not engage in any FARS-coded actions that would indicate culpability (see Kahane (2014) for an exact listing)

This is exactly the same reference-group used in Kahane (2014). Some prior studies, e.g. Farmer (2006), have found evidence that ESC may reduce fatal multi-vehicle crashes. However, ESC only appears to significantly affect multi-vehicle crashes occurring on high-speed roads or in wet or slippery conditions (Høye 2011; Ferguson 2007). These types of multi-vehicle crashes are not representative of the reference sample as defined here, which specifically isolates vehicles struck while not moving, or moving too slowly to realistically lose control, vehicles on dry roads, and vehicles for which control loss was likely not a factor in their crash involvement.

The focus of this analysis is crashes with longitudinal roadside barrier. The case-group for this analysis consisted of two different types of longitudinal barrier crashes. They were:

- Rollovers associated with roadside barriers, consisting of single-vehicle crashes where the most harmful event (MHE) was coded as a rollover and the first harmful event (FHE) was coded as a traffic barrier of some kind
- Roadside barrier crashes, consisting of single-vehicle crashes where the MHE was coded as a traffic barrier

This analysis counted the following as longitudinal traffic barriers: “Impact Attenuator/Crash Cushion”, “Bridge Rail”, “Guardrail Face”, “Concrete Traffic Barrier”, “Other Traffic Barrier”, “Guardrail End” and “Cable Barrier” respectively. The number of involved vehicles was determined from the number of vehicle forms submitted for the FARS case, coded by the “VE\_FORMS” field. MHE was determined from the “M\_HARM” field and FHE from the “HARM\_EV” field. Since this analysis uses the reference sample from Kahane (2014), but defines a new case sample, the data was checked to ensure than there was no overlap between cases and references.

### 6.3.3 *STATISTICAL ANALYSIS*

Contingency table analysis was used to compare the number of longitudinal barrier crashes among vehicles equipped with ESC to the number among the same vehicles before ESC was added, relative to the number of reference crashes where ESC would have little to no effect. Differences in the proportion of barrier crashes relative to reference with and without ESC were tested using the classical Pearson’s Chi-Square test, as well as the Likelihood Ratio Chi-Square test, the Continuity-Adjusted Chi-Square test and the Mantel-Haenszel Chi-Square test. Testing significance with several different methods is a useful way to help guard against spurious results caused by sparse or poorly-balanced samples. All four of these tests have the same interpretation, and for reasonably-sized, reasonably-well-balanced samples, their results will usually be similar. Major differences between the test results can indicate that the sample is deficient



somehow, and that conclusions drawn from the data may not be reliable. All statistical analysis was performed using SAS v9.3 (Cary, NC, U.S.A).

## 6.4 RESULTS

As discussed earlier, the non-ESC group in this analysis permits vehicle year-make-models where as many as 20 percent of the vehicles were equipped with ESC, and the ESC-equipped group permits year-make-models with ESC presence as low as 80 percent. Analysis of our sample showed this to be a good assumption. In the final sample used in the analysis, only about 1.4 percent of the vehicles in the non-ESC group would have been equipped with ESC, and only about 0.24 percent of the vehicles in the ESC-equipped group would have been without ESC.

Table 6.1 shows the distribution of case and reference crashes by vehicle type. The final sample contains similar numbers of car and LTV crashes. The relatively small number of fatal barrier crashes in this sample should not be taken as evidence that serious crashes with barrier are a negligible concern. Although this sample covers 18 FARS case years, it is restricted to a specific set of vehicle models and to a very narrow range of model years for each model, and to a specific set of crash criteria within that limited model year range. Including all FARS vehicles, there were an average of 375 barrier-tripped rollover fatalities and 421 MHE-barrier fatalities per year between 1994 and 2011, or about 800 total barrier-related fatalities annually. Although there are certainly crash modes that account for many more yearly road fatalities (e.g. tree/pole crashes), these 800 fatalities occur in crashes with hardware designed to *prevent* harm.

**Table 6.1. Case and Reference Crashes in Final Sample, by Vehicle Type.**

	<b>Cars</b>	<b>LTVs</b>	<b>Total</b>
<b>Barrier-Tripped Rollovers</b>	64	109	173
<b>Most Harmful Event == Barrier</b>	109	73	182
<b>Reference</b>	2421	2930	5351
<b>Total</b>	2594	3112	5706

Table 6.2 gives contingency tables showing ESC’s effect on fatal crashes where roadside barrier is the MHE, for cars and LTVs separately. For cars, equipping ESC reduces the odds of fatal crashes where barrier is the MHE by almost 50 percent, compared to the reference group. For LTVs, MHE barrier fatality odds are reduced by about 40 percent relative to reference. Table 6.3 gives the results of statistical testing for each contingency table shown in Table 6.2. For cars, all four statistical tests found the results to be statistically significant to well past the 95 percent level. For LTVs, the tests were very close to, but just short of, 95 percent significance. This is almost certainly due to the small number of LTV barrier fatalities with ESC. If just one fewer ESC-equipped LTV barrier fatality had occurred in the sample, 3 of the 4 chi-square tests would have been significant at 95 percent. With 2 fewer ESC-equipped barrier fatalities, all 4 chi-square tests would have been significant at 95 percent. The observed reduction in MHE-barrier fatalities for ESC-equipped LTVs is in all likelihood a real effect, and not a false positive.

**Table 6.2. Contingency Tables for Fatal Barrier Crashes vs. ESC.**

	<b>Cars</b>		<b>Total</b>		<b>LTVs</b>		<b>Total</b>
	<b>Reference</b>	<b>Barrier is MHE</b>			<b>Reference</b>	<b>Barrier is MHE</b>	
<b>No ESC</b>	1434	80	1514	<b>No ESC</b>	1999	57	2056
<b>With ESC</b>	987	29	1016	<b>With ESC</b>	931	16	947
<b>Total</b>	2421	109	2530	<b>Total</b>	2930	73	3003

*Odds Ratio (with ESC / no ESC): 0.5267*  
*95 % confidence interval: 0.3418 to 0.8117*

*Odds Ratio (with ESC / no ESC): 0.6027*  
*95 % confidence interval: 0.3443 to 1.0551*

**Table 6.3. Statistical Test Results and P-Values for Fatal Barrier Crashes vs. ESC.**

Test	Cars		LTVs	
	Test Statistic Value	P-Value	Test Statistic Value	P-Value
Pearson's Chi-Square	8.7060	0.0032	3.2052	0.0734
Likelihood Ratio Chi-Square	9.1584	0.0025	3.4204	0.0644
Continuity-Adjusted Chi-Square	8.1266	0.0044	2.7649	0.0964
Mantel-Haenszel Chi-Square	8.7026	0.0032	3.2041	0.0735

Examining only fatal crashes where the MHE was the barrier itself neglects another possible barrier-related crash mode: rollover. Like any other roadside object, traffic barriers have the potential to destabilize vehicles that contact them and cause rollovers. Rollover itself is a very dangerous crash mode – ESC was conceived for the purpose of preventing rollovers. Table 6.4 gives contingency tables for cars and LTVs comparing the incidence of fatal barrier-associated rollovers with and without ESC. Perhaps unsurprisingly, ESC appears to reduce rollovers more for LTVs than for cars. The odds of barrier-associated rollovers are reduced by about 45 percent for cars, and by close to 55 percent for LTVs. Table 6.5 gives the statistical test results for the contingency tables in Table 6.4. All four tests found the results LTVs to be statistically significant to at least 95 percent. Three of the four tests found the results for cars statistically significant. As with the MHE-barrier findings for LTVs discussed earlier, had one fewer barrier-associated rollover occurred with ESC, it would have been enough to make all four tests significant.

Note that “barrier-associated” in this analysis means fatal crashes where the FHE was a roadside barrier and the MHE was a rollover. This definition suggests a reasonable possibility that the rollover was actually initiated by the barrier contact, but it does not actually mean that the FARS investigator linked the barrier contact to the rollover. This limited definition was used because FARS did not code anything more than the FHE and MHE for crashes until 2005. Crashes can have more than two events, so it is likely that some of the barrier-initiated rollovers in this analysis were in fact initiated by other objects. However, crashes tend to have fewer events rather than more, so most of the sampled rollovers will have immediately

followed the barrier contacts. For these reasons, these cases are called “barrier-associated” rather than “barrier-tripped”.

**Table 6.4. Contingency Tables for Fatal Barrier-Associated Rollovers vs. ESC.**

	<u>Cars</u>		Total		<u>LTVs</u>		Total
	Reference	Barrier-Associated Rollover			Reference	Barrier-Associated Rollover	
<b>No ESC</b>	1434	46	1480	<b>No ESC</b>	1999	90	2089
<b>With ESC</b>	987	18	1005	<b>With ESC</b>	931	19	950
<b>Total</b>	2421	64	2485	<b>Total</b>	2930	109	3039

*Odds Ratio (with ESC / no ESC): 0.5685*  
*95 % confidence interval: 0.3277 to 0.9863*

*Odds Ratio (with ESC / no ESC): 0.4533*  
*95 % confidence interval: 0.2747 to 0.7480*

**Table 6.5. Statistical Test Results and P-Values for Fatal Barrier-Associated Rollovers vs. ESC.**

Test	<u>Cars</u>		<u>LTVs</u>	
	Test Statistic Value	P-Value	Test Statistic Value	P-Value
Pearson’s Chi-Square	4.1380	0.0419	10.0618	0.0015
Likelihood Ratio Chi-Square	4.3253	0.0375	11.1594	0.0008
Continuity-Adjusted Chi-Square	3.6298	0.0568	9.4054	0.0022
Mantel-Haenszel Chi-Square	4.1364	0.0420	10.0585	0.0015

## 6.5 DISCUSSION

Many other studies have found that ESC is effective at reducing loss-of-control crashes, or single-vehicle crashes, or fixed-object crashes. Our analysis indicates that ESC reduces fatalities due specifically to roadside barriers and the rollovers associated with them by 40-55 percent. Fatalities due to rollovers are reduced more for vehicles with higher centers of gravity, e.g. LTVs. Fatalities due to direct contact with barriers are reduced more for lower, lighter vehicles, e.g. cars.

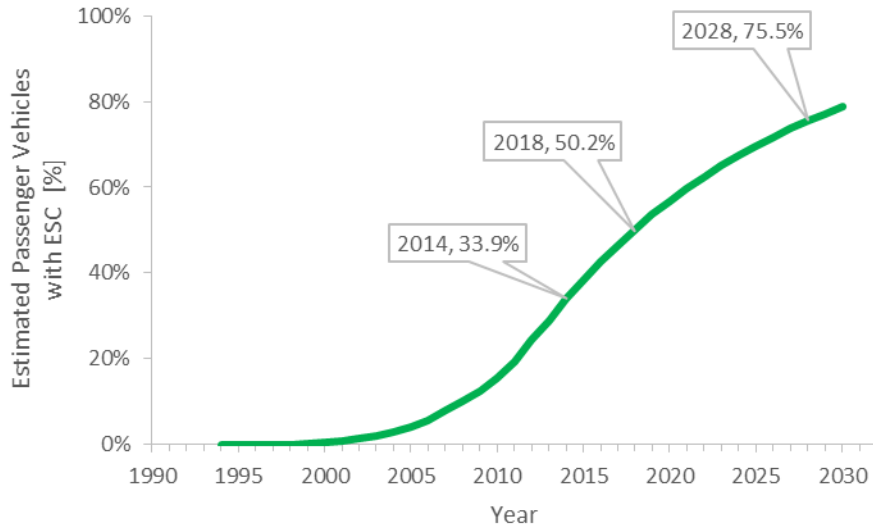
There are three possible ways in which ESC may reduce fatalities in barrier crashes: 1) reducing the overall rate at which vehicles depart the roadway and strike hazards or roadside barriers shielding hazards; 2) changing the distribution of road departure conditions, shifting crashes towards less severe outcomes; or 3) both. FARS does not provide the necessary information to determine which of these

possibilities is the case. Follow-up analyses will require examination of more in-depth databases, e.g. the National Automotive Sampling System – Crashworthiness Data System. Regardless, roadside barriers are only beneficial to install in locations where injuries from road departures are high enough that the costs of barrier installation and maintenance (plus crashes with the barrier itself) are less than the expected cost of crashes with roadside hazards at that location. If ESC reduces the rate at which vehicles depart the roadway or the severity of crashes with barriers, current estimates for road departure rates used by cost-benefit tools will need to be updated to reflect the new balance. Some existing barrier installations on low-volume roads could possibly even become net liabilities, albeit most likely very slight liabilities.

### *6.5.1 ESTIMATED GROWTH OF ESC-EQUIPPED VEHICLE FLEET PROPORTION*

Even though mandated for all passenger vehicles starting in model year 2012, ESC will not appear instantly throughout the fleet. Figure 6.1 is an estimate of the percentage of U.S. passenger vehicles equipped with ESC as a function of year. Figure 6.1 was made using yearly U.S. passenger vehicle sales volume for 1994-2013 (Alliance of Automobile Manufacturers 2014), yearly percentage of new vehicles sold with ESC for 2003-2009 (Sivinski 2007; NHTSA 2011), and the size of the 2012 U.S. passenger vehicle fleet (NHTSA 2014c). ESC was first offered in the U.S. in 1998 (Kahane 2014), and all new passenger vehicles were equipped with ESC as of model year 2012 (NHTSA 2007). To perform this estimate, a constant fleet size of 240 million vehicles was assumed. It was also assumed that each new vehicle sold replaced a vehicle already in the fleet and that every vehicle in the fleet was equally as likely to be replaced in a given year. For years later than 2013, sales volume was not available, so average sales volume from 1994-2007 (16.4 million vehicles) was used for 2014 and later. First, the percentage of the fleet replaced by new vehicles during each year was computed from yearly sales volume and the fixed fleet size of 240 million vehicles. Next, the number of ESC-equipped vehicles accumulated from previous years was reduced by this percentage, to get the number of pre-existing ESC vehicles that were not replaced. Next, the number of new ESC-equipped vehicles added to the fleet in was computed from sales volume and the percentage of new vehicles equipped with ESC, and added to the number of ESC vehicles from prior

years remaining in the fleet. Finally, the percentage of the fleet equipped with ESC was computed as the number of ESC-equipped vehicles divided by the assumed fleet size of 240 million vehicles.



**Figure 6.1. Estimated percentage of U.S. vehicles with ESC, based on yearly passenger vehicle sales volumes (Alliance of Automobile Manufacturers 2014) and yearly percentage of new vehicles sold with ESC (Sivinski 2007; NHTSA 2011). By this estimation, approximately one-third of the vehicles in the U.S. fleet have ESC as of 2014. By 2028, more than 75 percent of passenger vehicles will be equipped with ESC.**

### 6.5.2 ESTIMATED BENEFITS OF ESC IN ROADSIDE BARRIER CRASHES

When all barrier-related fatalities (barrier-associated rollovers and barrier-is-MHE crashes) for cars and LTVs are combined, ESC reduces barrier-related fatality odds by a factor of 0.5376 (95% confidence interval 0.4174 to 0.6924). The reference group in this study was chosen so that ESC would have no effect on fatality risk in those crashes. For any given FARS case year, the number of observed reference fatalities is therefore equivalent to both the number that would have occurred with 100 percent ESC and the number that would have occurred with 0 percent ESC. From the definition of the odds ratio, the number of barrier-related fatalities with 100 percent ESC is therefore equal to the number with 0 percent ESC multiplied by the overall odds ratio of 0.5376:

$$\left(\frac{B}{R}\right)_{Without\ ESC} * R_{With\ ESC} * OR = B_{With\ ESC}$$

$$R_{Without\ ESC} = R_{With\ ESC} = R_{Observed}$$

$$B_{Without\ ESC} * OR = B_{With\ ESC}$$

where:

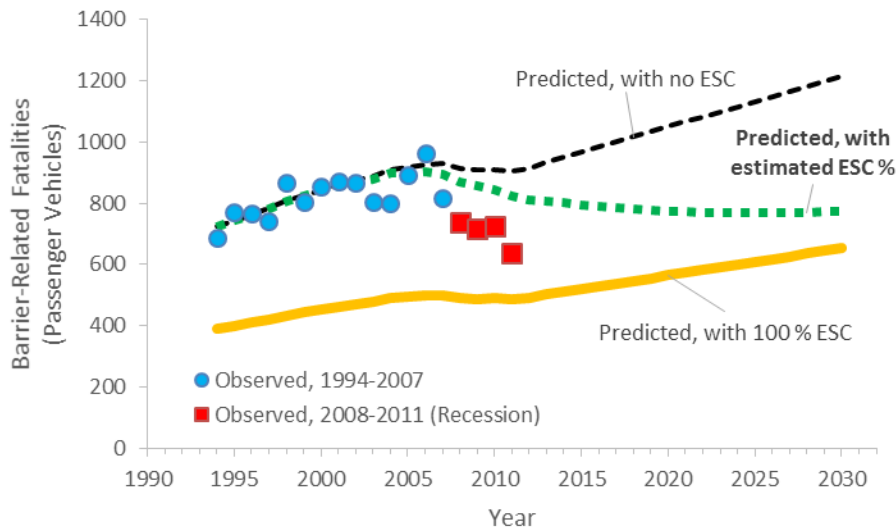
$B$  = fleet-wide number of yearly barrier-related fatalities

$R$  = fleet-wide number of yearly reference-group fatalities

$OR$  = odds ratio for overall ESC effectiveness

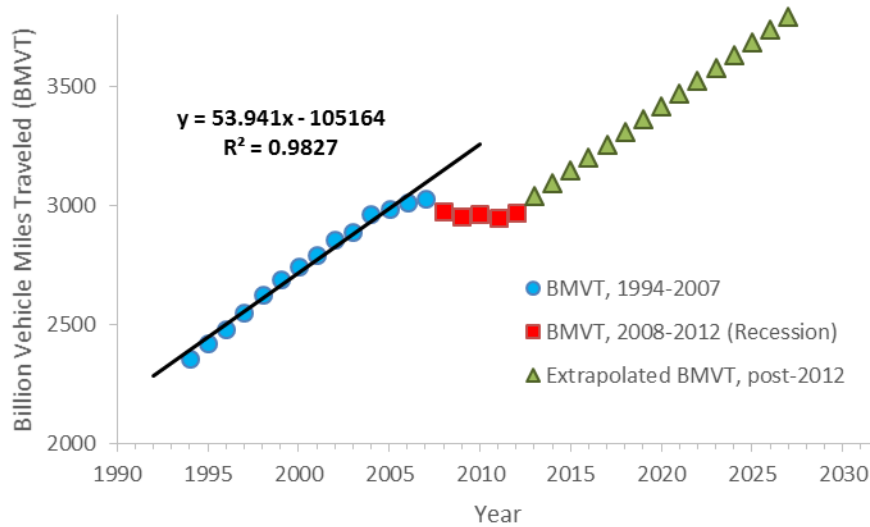
Figure 6.2 produces an estimation of the potential benefits of ESC. First, an extrapolation of trends in annual vehicle miles traveled (VMT) (NHTSA 2014c) was made (Figure 6.3). The effect of the 2008 recession is plainly visible in the data; vehicle mileage from 2008-2012 was not used in extrapolating past 2012. Next, the average barrier-related fatality rate was calculated for FARS case years 1994-2000, before ESC was present in the U.S. fleet in any meaningful amount. Over that period, without any ESC present there were an average of 30.69 barrier-related fatalities per 100 billion vehicle miles traveled. Using this barrier fatality rate and the projected VMT values in Figure 6.3, predicted barrier fatality counts for a fleet without any ESC were made for 1994-2025 (dashed line in Figure 6.2). Observed barrier fatality counts through 2011 are shown in Figure 6.2 for comparison. Scaling the ESC-free predictions by the overall odds ratio for ESC effectiveness gives the solid line in Figure 6.2. This line represents a VMT-adjusted prediction of yearly barrier-related fatalities, if every vehicle in the fleet had been / is in the future equipped with ESC. If every U.S. vehicle had been equipped with ESC in 2014, about 440 barrier-related fatalities out of a possible 950 could have been prevented that year. By 2028, ESC could theoretically prevent about 550 yearly barrier-related fatalities out of a possible 1180.

The dotted line in Figure 6.2 between the upper and lower limits is a projection that uses the estimated percentages of ESC-equipped vehicles shown in Figure 6.1. Vehicles without ESC are subject to the barrier-fatality rate represented by the no-ESC prediction; vehicles with ESC are subject to the fatality rate represented by the full-ESC prediction. The expected fatality rate for a given mixture of ESC and non-ESC vehicles is thus a weighted average of the full-ESC and no-ESC fatality predictions, using the respective percentages of ESC and non-ESC vehicles in the fleet as weights. According to the estimate in Figure 6.1, as of 2014 about 1 in 3 U.S. passenger vehicles had ESC. By approximately 2028, more than 3 out of every 4 passenger vehicles will be ESC-equipped. Note that there are always some number of old vehicles in the fleet, so ESC coverage approaches 100 % asymptotically. Based on this estimation, in 2014 ESC prevented approximately 150 out of 950 possible barrier fatalities. By 2028, ESC may prevent 410 out of a possible 1180 barrier fatalities.



**Figure 6.2. Yearly barrier-related fatalities. Observed values from FARS 1994-2011, predicted values assuming no ESC and assuming 100 percent ESC in the U.S. fleet. Predictions based in part on extrapolated trends in vehicle miles traveled.**





**Figure 6.3. U.S. vehicle miles traveled, by year. Historical values through 2012 obtained from (NHTSA 2014c). Predictions for years 2013 to 2030 assume pre-2008 trend in yearly mileage increase.**

### 6.5.3 LIMITATIONS

Some of the vehicle make-model-year ranges in this analysis include more than one vehicle generation. This could possibly confound the observed effects of ESC by introducing better safety design or different rollover propensity, e.g. different static stability factors, along with the change in ESC presence. However, many vehicle redesigns are not extremely drastic. Most of the vehicles in this study had already been designed to perform well in both front- and side-impact crash tests before the switch to ESC. Furthermore, not all safety improvements will necessarily have a strong effect on fatality risk due to barrier crashes. Also, many of the vehicle models in the sample do not span multiple generations.

Differences in driver characteristics between ESC-equipped and non-equipped vehicles could also possibly influence the findings of this study. However, because the range of model years for each vehicle extended no more than 3 years before or after ESC was introduced, any shifts in average driver characteristics for a given vehicle are likely to be minimal. No statistically significant differences in seat belt use were found between drivers of ESC-equipped and non-ESC-equipped vehicles, for either cars or LTVs. Furthermore, the study design should control for any driver-related differences between ESC-

equipped and non-ESC-equipped vehicles. Any differences in driver populations will presumably affect both the ESC-applicable crash sample and the reference-crash sample. Both the numerator and denominator of the reported odds ratios will be affected, thus cancelling any effect on the results. Driver differences that unequally affect ESC-applicable crashes and reference-group crashes may potentially affect the results, however.

The FARS data used here does not contain reconstructions of impact angle or estimates of impact speed. This information would allow a direct assessment of whether or not ESC alters road departure conditions and hence, injury risk given that a crash has occurred. To the author's knowledge, the literature to date on ESC effectiveness has not directly examined the effect of ESC on road departure or impact conditions for any crash type. Høye (2011) and Ferguson (2007) found in their reviews that ESC appears to reduce both fatal crashes and crashes with less serious outcomes by similar amounts in single-vehicle crashes (which are mostly run-off-road crashes), rollover crashes or run-off-road crashes. This could imply that ESC only reduces the number of road departure crashes and does not change the distribution of impact conditions (i.e. severity). However, the meta-analysis of Høye (2011) found inconclusive evidence that suggested that ESC could possibly affect crashes of different severities differently, and both Høye (2011) and Ferguson (2007) found that when all crash types were considered together, ESC did reduce fatal crashes more than crashes of lesser severity. Other existing national crash data, in particular the National Automotive Sampling System – Crashworthiness Data System (NASS-CDS) contain much more detailed crash information which could potentially help estimate impact conditions. Studies specifically focused on road departure conditions would provide this information as well, as could in-service performance reviews of roadside safety hardware.

The FARS data used for this analysis only includes fatal crashes. Compared to other crash modes, roadside barrier crashes are far from the most dangerous. Roadside barrier is, after all, designed to be safer to hit than the hazards it is shielding. Because FARS contains only fatal crashes, this study can provide no analysis of possible changes to the distribution of impact conditions or crash outcomes due to ESC.

It is possible that some of the fatality reduction in barrier crashes attributed to ESC was due to improvements in roadside barriers themselves over time. However, any contribution from barrier improvements were likely to be small in this study due to two factors: First, the range of model years for each vehicle model was very narrow, so for each model ESC-equipped vehicles always appeared within a few years of non-ESC vehicles. Fatal crashes of ESC-equipped vehicles would tend to be concentrated later in time than non-ESC fatalities on average, but not by more than a few years at most. The overall safety of roadside barriers nation-wide would not change drastically in that amount of time. Second, fatalities were sampled across a wide range of FARS case years, so any changes to roadside barriers over time will be well represented in both the ESC and non-ESC samples.

The estimation of ESC fleet presence given in Figure 6.1 incorporates significant assumptions. Fleet size is not constant, but will presumably tend to increase with time, and older vehicles are more likely to be replaced than newer vehicles. By not allowing the fleet size to grow and assuming that every new vehicle sold replaces a vehicle already in the fleet, the calculation removes more old vehicles from the fleet each year than actually leave. Since 2012, every new vehicle sold is equipped with ESC, so the controlling factor on how quickly ESC will saturate the fleet is how quickly the remaining non-ESC vehicles leave. Assuming constant fleet size will therefore tend to saturate the fleet with ESC sooner. However, assuming that all vehicles are as likely to be replaced regardless of age has the opposite effect and tends to retain non-ESC vehicles for longer than they would actually remain in the fleet.

As discussed earlier, at least some of the barrier-associated rollovers in this sample are not barrier-tripped rollovers, but are simply rollovers that happened in the same crash as a barrier impact. ESC may be more or less effective at preventing rollovers that are not tripped by barrier, so there is some additional uncertainty in the results for barrier-associated rollovers.

Lastly, the accuracy of this analysis is of course dependent on the accuracy of the vehicle information contained in the FARS database itself.

## 6.6 CONCLUSIONS

For cars, ESC reduces odds of fatal crashes with roadside barriers by about 50 percent and reduces odds of fatal rollovers occurring in association with roadside barriers by about 45 percent. Both findings are statistically significant. For LTVs, ESC reduces barrier fatality odds by about 40 percent and barrier-associated rollover fatality odds by about 55 percent. The latter finding is statistically significant, and the former is very nearly significant, and there is reason to believe it is in fact a real effect as well. Based on the effectiveness levels observed in this study, it is estimated that ESC could prevent about 410 out of 1180 possible barrier-related fatalities per year by 2028, when 75 percent of the fleet is estimated to be equipped with ESC. All findings are nationally representative, are based on a representative sample of U.S. vehicles, and control for possible confounding factors such as improved vehicle crashworthiness and introduction of rollover curtain airbags. The study findings suggest that ESC significantly reduces road departures into roadside barriers, and/or that ESC changes departure conditions so that barrier crashes have less severe outcomes.

## 7 IMPROVED METHOD FOR ROADSIDE BARRIER LENGTH OF NEED MODELING

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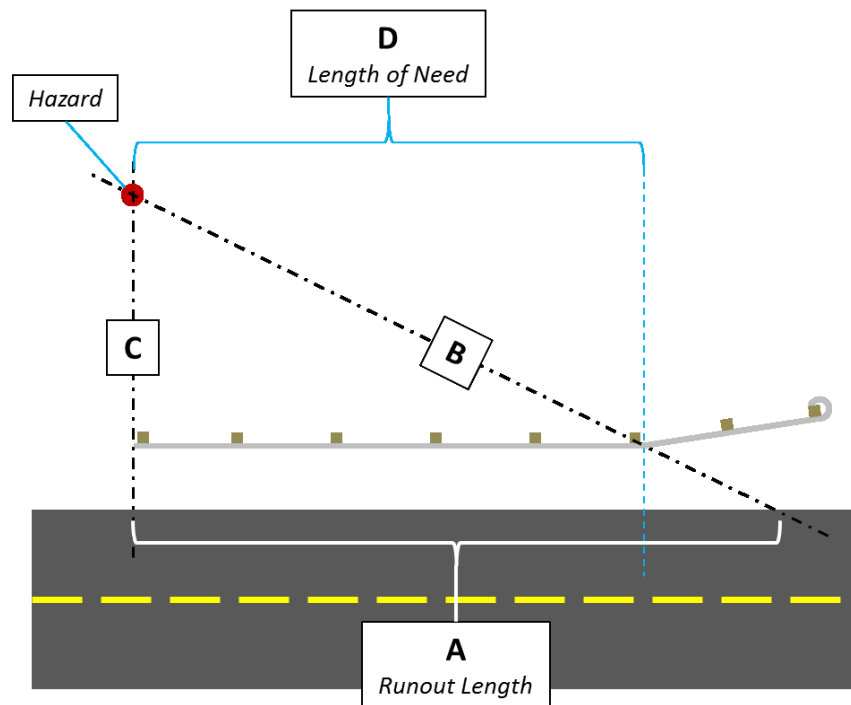
### 7.1 INTRODUCTION

Longitudinal barrier is a key safety feature of modern roadways. When longitudinal barrier is used to shield an off-road hazard, what is the appropriate length to use? On the one hand, collisions between vehicles and many roadside hazards, e.g. trees and poles, are dangerous and longitudinal barrier prevents many such impacts. Zou et al. (2014) compared odds of moderate-to-serious injury between matched roadway segments with and without longitudinal barrier in Indiana between 2008 and 2012. The analysis found that concrete barrier reduced injury odds by 39 %, guardrail face reduced injury odds by 65 % and near-side median cable barrier reduced injury odds by 85 %. Martin, Mintsá-Eya and Goubel (2013) studied the effect of longitudinal barrier on the risk of injury in run-off-road crashes in France between 1996 and 2010. That analysis found that the presence of longitudinal barrier on a roadway segment halved the risk of run-off-road crashes resulting in serious injury. On the other hand, the injury risk presented by the barrier itself must also be considered, as well as the expense of installing and maintaining the barrier, when designing roadside barrier installations. Determining the optimal length of barrier needed to shield a given hazard, or “length of need” (LON), is therefore an important task for roadway engineers.

The AASHTO Roadside Design Guide (RDG) contains one of the most widely used procedures for estimating an appropriate LON (AASHTO 2011). Cost-benefit procedures for computing LON, e.g. Roadside Safety Analysis Program (Mak and Sicking 2003; Ray et al. 2012), are also increasingly being used but they can require much more time and effort than the RDG procedure. Figure 7.1 shows the RDG procedure for computing LON recommendations. First, the designer chooses a longitudinal runout length to shield a hazard from line [A]. Table 5-10 in the 2011 edition of the RDG contains suggested runout lengths for different traffic volumes and design speeds. A line is then drawn from the roadside one runout length upstream of the hazard to the hazard itself (line [B]). According to the RDG, any barrier that spans

the distance between this line and another line between the hazard and the road edge perpendicular to the road (line [C]) provides adequate shielding. LON (line [D]) is the distance between line [B] and the intersection of the barrier with line [C].

The runout length recommendations forming the basis of this procedure were derived from a 1980 study of road departures conducted by Cooper (1980) and a 1966 study of road departures by Hutchinson and Kennedy (1966) (Coon, Sicking and Mak 2006; Wolford and Sicking 1996). Runout length recommendations are a function of traffic volume and design speed. Within each design speed, lower runout lengths are recommended for lower traffic volumes.

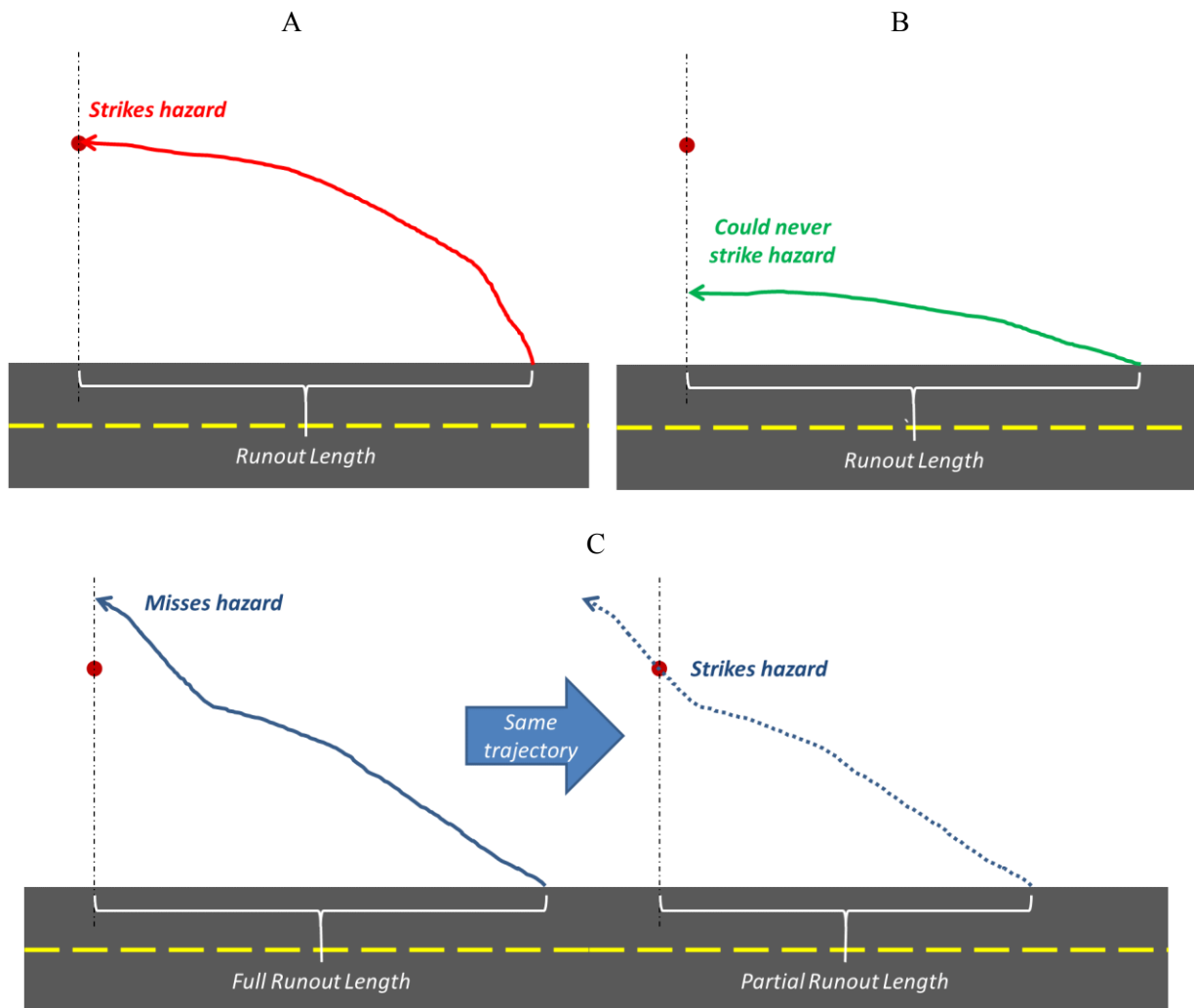


**Figure 7.1. The RDG computes LON recommendations based on the hazard location and a runout length suggestion for the design speed and traffic volume.**

By considering only the runout length of departures, the 2011 RDG procedure assumes every departure that occurs within one runout length of a hazard could potentially strike the hazard. This is a prudently conservative assumption if little other than the runout length is known about road departure trajectories, as was the case when the RDG procedure was devised. However, as Figure 7.2 shows, whether

or not a departing vehicle strikes a hazard is determined not only by its potential runout length, but also by where the departure occurs relative to the hazard and the shape of the trajectory. For example, while trajectory [A] in Figure 7.2 strikes the hazard, trajectory [B] does not despite having the same runout length. Trajectory [C] will only strike the hazard if it departs closer to the hazard than its full runout length. Runout length alone cannot fully determine the shielding needed to prevent crashes with roadside hazards.

The RDG LON procedure seeks to increase the fraction of departures intercepted as traffic volume increases (Coon, Sicking and Mak 2006; Wolford and Sicking 1996; Mak, Sicking and Coon 2010). However, the RDG procedure does not provide a method to design for a specific level of protection. This might be desired by transportation agencies seeking to optimize safety benefits on limited budgets. As discussed above, the actual proportion of *hazardous* crashes intercepted is not obvious when barrier is designed to intercept the recommended fraction of runout length. A useful improvement would be to provide the actual proportion of hazardous crashes intercepted as runout length is modified. The procedure could also be improved by expanding the small selection of “recommended runout lengths provided in the 2011 RDG.



**Figure 7.2. Because the RDG only considers runout length, the RDG LON procedure implicitly assumes that all departures are like [A]. However, departures [B] and [C] are also possibilities.**

## 7.2 OBJECTIVE

The goal of this analysis is to propose and demonstrate an improved technique for estimating LON requirements for barriers.

## 7.3 METHODS

Existing single vehicle collision trajectories will be compared to the 2011 AASHTO RDG LON recommendations using an improved analysis procedure that more completely addresses vehicle trajectories



in run off road crashes. The first step in the new analysis was to generate “road departure corridors”, using vehicle trajectories from real-world road departure crashes. These “road departure corridors” constitute a new, alternative procedure for computing LON recommendations, one that overcome many of the limitations of the RDG procedure.

Road departure trajectories were obtained from data collected under National Cooperative Highway Research Program (NCHRP) Project 17-22 (Mak, Sicking and Coon 2010). This project developed a database of 890 police-reported ran-off-road crashes in the U.S., spanning the years 1997 – 2004. Project 17-22 cases have detailed information on the roadside environment, including full off-road vehicle trajectories for most of the 890 cases.

After generating road departure corridors from real-world data, equivalent corridors were generated using the LON computation procedure from the 2011 AASHTO RDG. The two sets of corridors – real-world-derived and 2011-RDG-derived – were then compared to determine the difference between the two approaches.

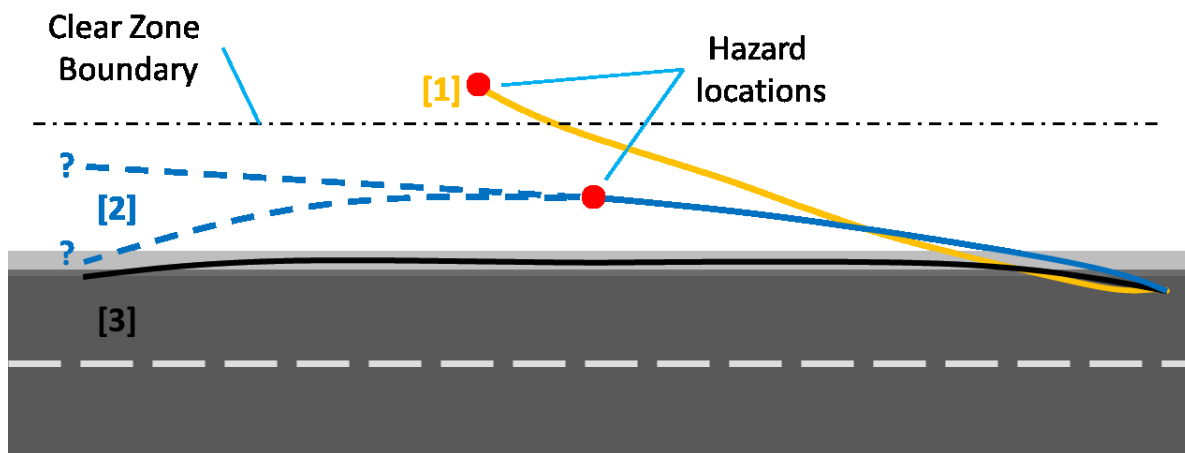
### *7.3.1 REAL – WORLD DEPARTURE CORRIDORS*

#### **7.3.1.1 Selection of Road Departure Data**

The first step in generating real-world departure corridors was to obtain a sample of real-world road departure trajectories. This analysis used the NCHRP Project 17-22 database of road departure crashes (Mak, Sicking and Coon 2010). The 17-22 dataset is a subset of the National Automotive Sampling System – Crashworthiness Data System (NASS-CDS), which is a nationally representative database of police-reported tow-away crashes maintained by the NHTSA. NASS-CDS cases are investigated by trained crash investigators and contain more complete information than that found in police accident reports. NASS-CDS is a clustered and stratified sample that oversamples injury and fatality crashes. The NASS-CDS therefore assigns each case a weighting factor representative of its prevalence in the population of U.S. crashes. Being a subset of NASS-CDS, each crash in 17-22 has a NASS-CDS case weight.

### 7.3.1.2 Processing of Road Departure Data

When a vehicle departs the roadway, a number of scenarios are possible as shown in Figure 7.3. The vehicle may depart the road and return without incident; this scenario is shown by trajectory [3]. If the vehicle does strike an object, the vehicle path will be altered from what would have happened had there not been a hazard present. This scenario is shown by trajectory [2]. The vehicle may also depart beyond the edge of the provided clear zone and contact hazards there as in [1]. The NCHRP Project 17-22 database (Mak, Sicking and Coon 2010) contains exclusively crashes (i.e. trajectories [2] and [1]). Every vehicle in 17-22 collided with an off-road object or overturned and each of these crashes was severe enough to result in a towed vehicle and a police report. This means that some vehicle trajectories in 17-22 may be shorter than the trajectory would have been had the vehicle not contacted anything.

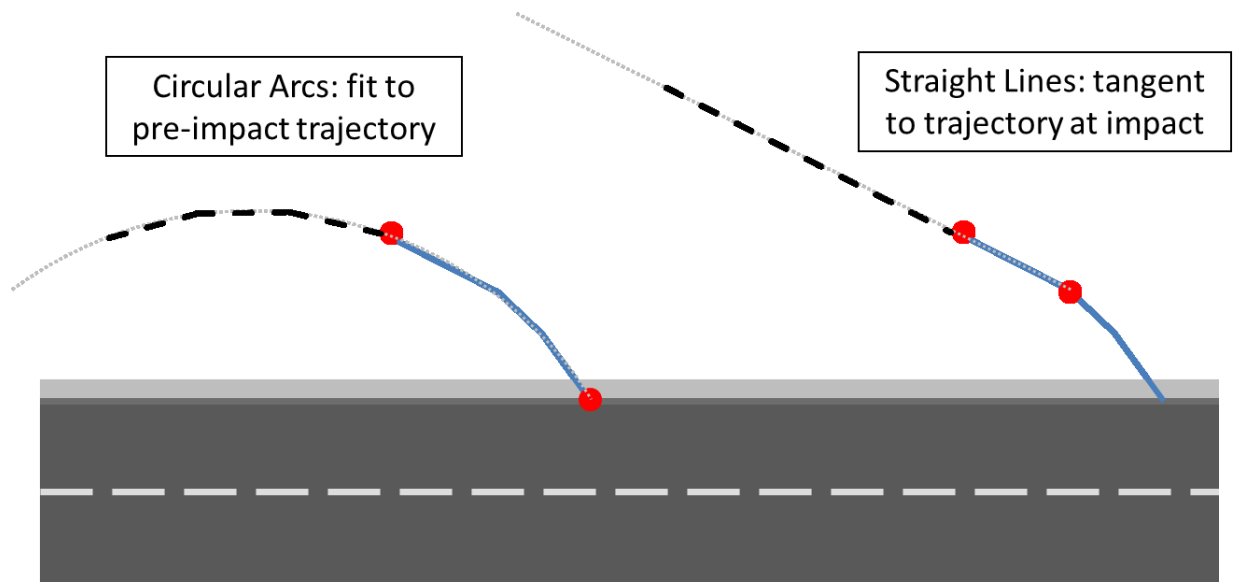


**Figure 7.3. Road departures may [1, 2] or may not [3] result in impacts with off-road objects. When a departure involves impacts, it is not certain what the trajectory would have been had an obstacle not been at that point in the vehicle path. All 17-22 road departures involve impacts, so it was necessary to extrapolate the interrupted vehicle path.**

Uninterrupted trajectories were reconstructed from the interrupted trajectories in 17-22 in two segments. The first segment consisted of the vehicle trajectory as documented in the 17-22 database only up to the first impact event. In the second segment, the vehicle path after the impact was extrapolated by assuming that the vehicle had the same average deceleration after the impact as before it. Trajectories were extrapolated until the vehicle decelerated to a stop. This additional distance was extrapolated in two ways,

both shown in Figure 7.4: as a straight line tangent to the vehicle path at impact, and along a circular arc fit to the vehicle path between departure and impact. These two approaches describe 2 possible outcomes if the impact had not occurred.

Circular arcs were fit by constraining the arc to pass through the departure and impact points, and choosing a third point to define an arc with a least squares curve fit to the actual trajectory. For crashes where the average deceleration could not be computed due to unknown departure or impact speed, or where the average deceleration was zero, the trajectory was extrapolated until the vehicle either re-entered the roadway or went more than 15 m laterally from the road (wider than most recommended clear zones). When extrapolating with straight lines, trajectories parallel to the roadway at impact and trajectories that had already exceeded 15 m from the road edge were not extrapolated. When extrapolating with circular arcs, the extrapolated path was stopped if it reached a point where the vehicle began to travel back toward the departure location in the longitudinal direction (i.e. vehicles were not allowed to turn around).



**Figure 7.4. Trajectory extrapolation methods used in this analysis. All NCHRP 17-22 trajectories involve off-road impacts, which may shorten and redirect vehicle paths compared to the paths had nothing been struck.**

Extrapolating with a straight line implicitly assumes that the roadside and driver do not substantially change the vehicle trajectory and that the vehicle continues more or less in the direction it was

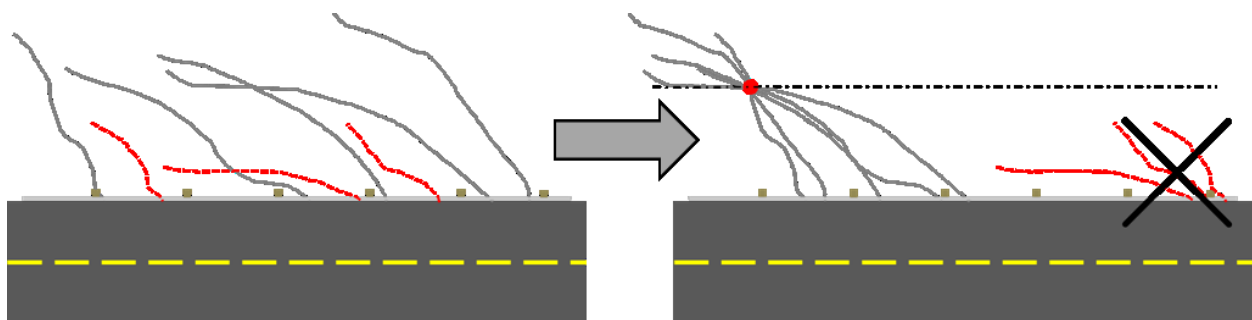
heading had an impact not occurred. Typically, this direction is away from the roadside. This can be a reasonable approximation if the vehicle was out of the driver's control at the time of the initial impact. Extrapolating on a curve implicitly assumes that the vehicle continues to turn at about the same average rate that it turned between departure and the initial impact, and that the driver is already making their desired steering inputs. This can be a reasonable approximation if the driver retains directional control of the vehicle and is attempting to maneuver. While these are both somewhat naïve extrapolation methods, they nevertheless give a first-order estimate of post-impact vehicle behavior without introducing complicated assumptions about driver intent. More realistic extrapolation might be obtained using detailed dynamic simulations and driver modeling for each individual departure. However, extrapolating trajectory in this way would require a great deal of analysis to validate any vehicle modeling parameters or presumed driver inputs. It is also not guaranteed that such detailed extrapolation would result in departure corridors reflecting a more accurate outcome than those created here using simpler extrapolations. There is insufficient reference information to implement and validate any detailed vehicle/driver/terrain simulation model. This may be appropriate to explore in what-if simulations if future databases provide sufficient data.

As a check on the extrapolation methods used here, corridors were also generated using the complete, unaltered trajectories – including all impacts and the path to final rest – as originally coded by Project 17-22. While unaltered crash trajectories are not subject to any uncertainty introduced by extrapolation, they also do not fully represent where vehicles might *potentially* have travelled. Instead, they only represent where vehicles went after striking a particular sequence of objects. Unaltered trajectories thus provide a lower bound on the total distance travelled off-road, but still may not represent the exact path that needs to be considered when analyzing where departing vehicles *could* travel.

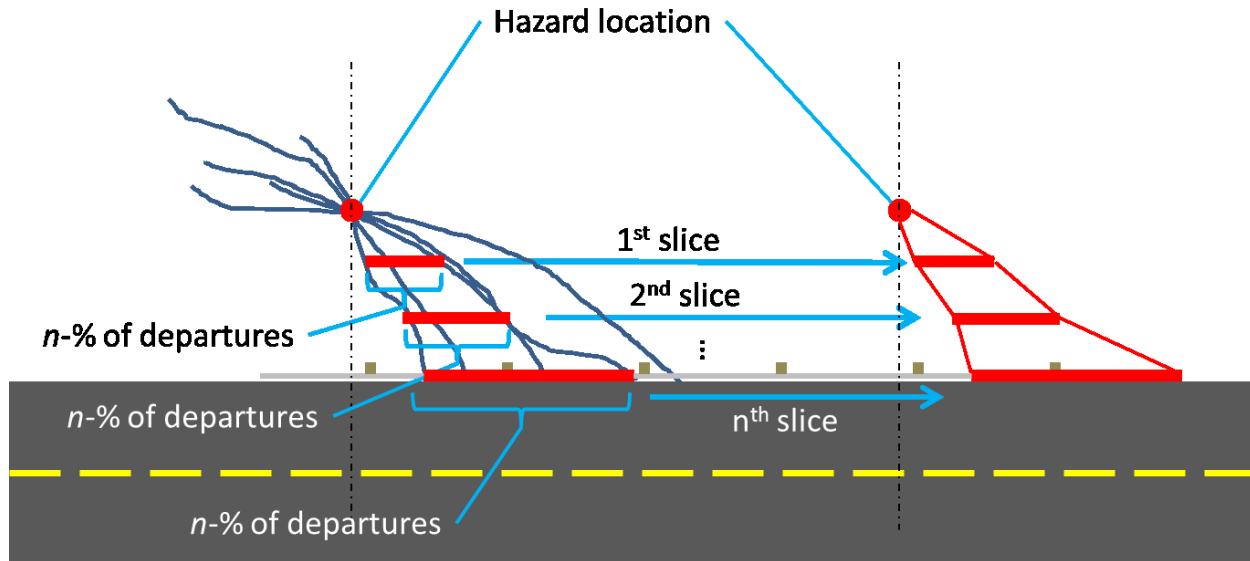
### **7.3.1.3 Creation of Road Departure Corridors**

Cases in NASS-CDS are sampled from all police-reported tow-away crashes in the U.S. and, through the use of sample weights, each case represents some portion of all such crashes occurring annually. Each 17-22 trajectory corresponds to a case in NASS-CDS and is thereby representative of some portion

of all U.S. road departures determined by the sampling weight of the crash in the CDS database. If it is assumed that any of the trajectories could in principle occur at any point along a given roadway, then it is possible to choose a hazard location some lateral distance from the roadway and then arrange the trajectories so that they all intersect at the hazard as shown in Figure 7.5. In cases where it is possible for a trajectory to intersect the hazard at multiple points, the earliest potential contact is used. This gives a family of trajectories and departure points that would result in a collision with a hazard located at the chosen lateral offset distance. Note that trajectories that do not span the lateral distance from the roadside to the hazard could not possibly contact the hazard; they are not included in this family. A corridor is then generated in slices progressing from the hazard location toward the roadway as shown in Figure 7.6. Each slice of the corridor is a contiguous interval, parallel to the road, that contains some specified percentage of the total departures represented by the chosen set of cases. 17-22 cases are from a weighted sample, so the corridor slices are made to intercept x-% of the total case *weight* in the set rather than simply x-% of the *total cases* in the set. Some complex trajectories can be intercepted at multiple points along their length by a given slice. For such trajectories, the intersection point chosen is the one furthest downstream along the vehicle path (going from the road to the hazard).



**Figure 7.5. Representative road departure trajectories are arranged to intersect at a common hazard location. This gives a range of potentially hazardous departure points. Trajectories that cannot possibly reach the hazard are excluded.**



**Figure 7.6. Departure corridors are generated from trajectory data in slices. Each slice spans a specified percentage of the total sample weight.**

The end result of the trajectory processing is a corridor that, at every point, encloses  $x\%$  of road departures that would otherwise contact a hazard located at the specified distance from the roadside if not intercepted by a physical barrier. Any barrier that connects one side of the corridor to the other will intercept the specified percentage of otherwise hazardous departures. LON can then be specified to intercept exactly  $x\%$  of departures that would otherwise reach the hazard. Corridors generated in this manner fully account for the actual shape of road departures and hence, possibilities [B] and [C] in Figure 7.2. However, each corridor is only valid for hazards located the specified distance from the roadside. Changing the hazard location would require re-positioning the trajectories to intersect at a new point, which would change the shape of the corridor. More trajectories will become relevant as the hazard is placed closer to the road since more of them will reach the hazard and, conversely, trajectories will drop out as the hazard is placed further away.

### 7.3.2 COMPARISON OF REAL-WORLD DEPARTURE CORRIDORS AND THE 2011 AASHTO ROADSIDE DESIGN GUIDE

The LON recommendations of the RDG procedure can be readily compared to the departure corridors. As shown in Figure 7.1, the RDG procedure for computing LON is to define two lines connecting

different points on the road edge to the hazard point, representing the boundaries of the area that requires shielding. Any barrier connecting these two boundaries will have an acceptable LON according to the RDG procedure. Thus, the two lines constructed in the RDG procedure effectively constitute a “corridor” that can be compared directly with the real-world corridors proposed here. In this analysis, RDG corridors were constructed using runout length recommendations given by the 2011 RDG.

## 7.4 RESULTS

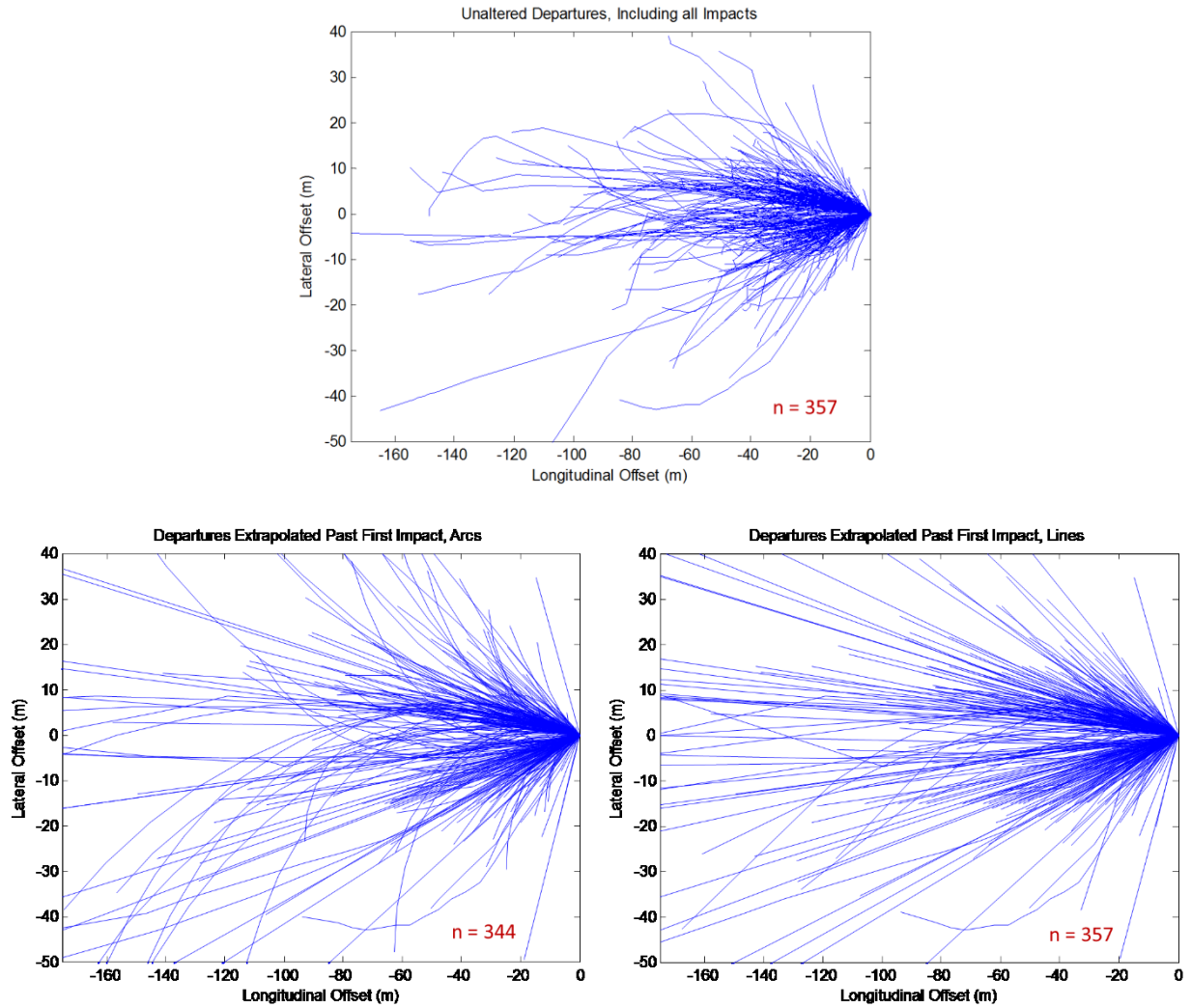
Out of the 890 cases in the 17-22 database, 46 cases were initially excluded from the analysis For the following reasons: 23 cases had no useable trajectory data; 14 cases had CDS case weights so extreme that they represented over 90% of the total weight by themselves; 3 cases struck objects at the road edge but had no impact angle coded (preventing any extrapolation); 2 cases had trajectory data but were missing impact location; in 1 case the vehicle had rolled over prior to departure; 1 case had erroneous trajectory data; 1 case was not part of the standard CDS sample and had a case weight of zero; and in 1 final case it appeared that the vehicle had not departed the roadway.

From the remaining 844 departures with valid data, the 357 departures occurring on 55 mi/h roads were selected for use. A number of different roadway speeds are represented in the 17-22 dataset, but the majority were on 55 mi/h roads. Departure speed and departure angle are known to correlate with speed limit (Mak, Sicking and Coon 2010). Departure speed in particular will have a dramatic effect on distance traveled off-road. The corridors presented here are only applicable to roads with a 55 mi/h speed limit. Although this single roadway speed is sufficient to demonstrate the improved LON procedure, corridors for other roadway speeds should be developed as suitable data becomes available.

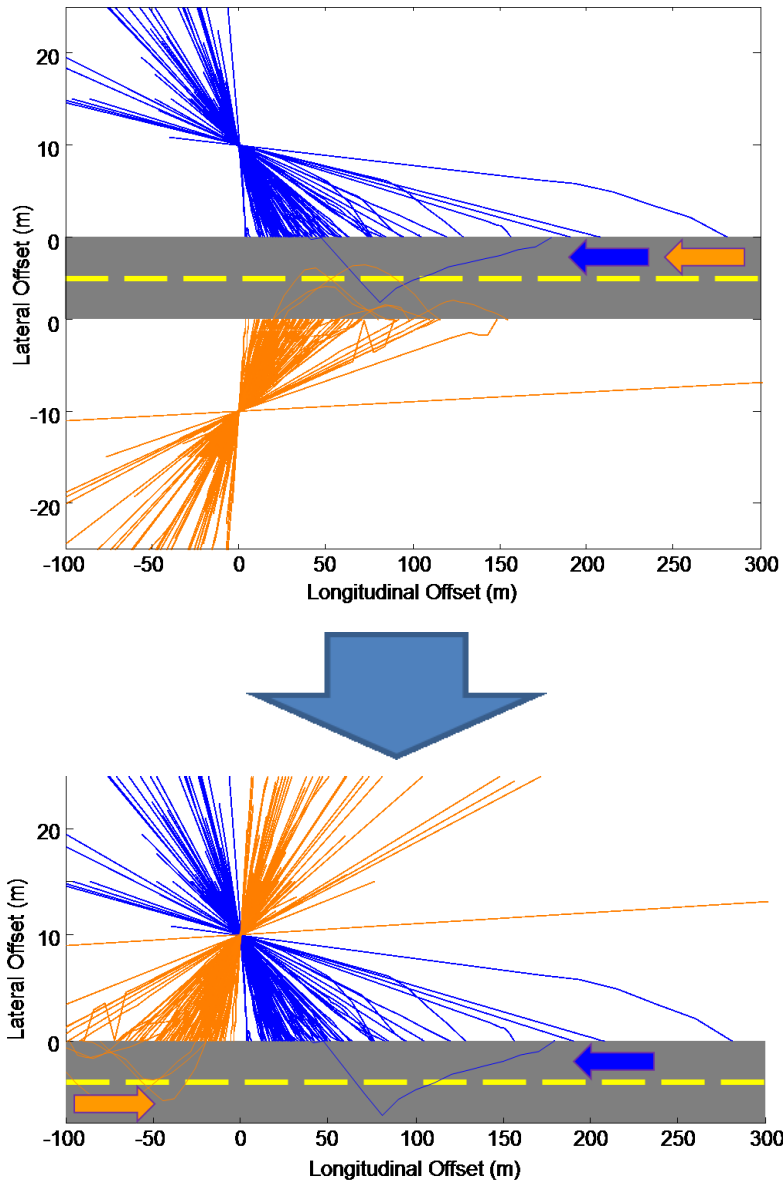
Figure 7.7 shows the set of 55 mi/h departure trajectories used in this analysis. The bottom left panel shows the departures extrapolated past the first impact using fitted arcs. The bottom right panel shows the departures extrapolated using a tangent line. The top panel shows the same departures without any extrapolation, but including observed trajectory to subsequent impacts. A total of 344 out of 357 departures

had trajectory data suitable for extrapolation with circular arcs. Tangent line extrapolation was possible for all 357 departures. Figure 7.8 shows the linearly-extrapolated trajectories in the sample arranged to converge at a common hazard location 10 m from the roadside (departures that do not reach that far are omitted from the plots). In most road departures, vehicles only depart to one side of the roadway. Departures to the right contribute to corridors for near-side departures, while departures to the left contribute to corridors for opposite-direction vehicles. In some departures, vehicles first depart one side of the road, re-enter the roadway, and then depart the opposite side. Such departures can potentially strike objects on either side of the roadway, so some trajectories contribute to both near-side and far-side departure corridors.





**Figure 7.7. 55 mi/h departure trajectories. Top: unaltered trajectories including all impacts. Bottom left: extrapolation past first impact using fitted arcs. Bottom right: extrapolated past first impact using straight lines tangent at the point of impact.**



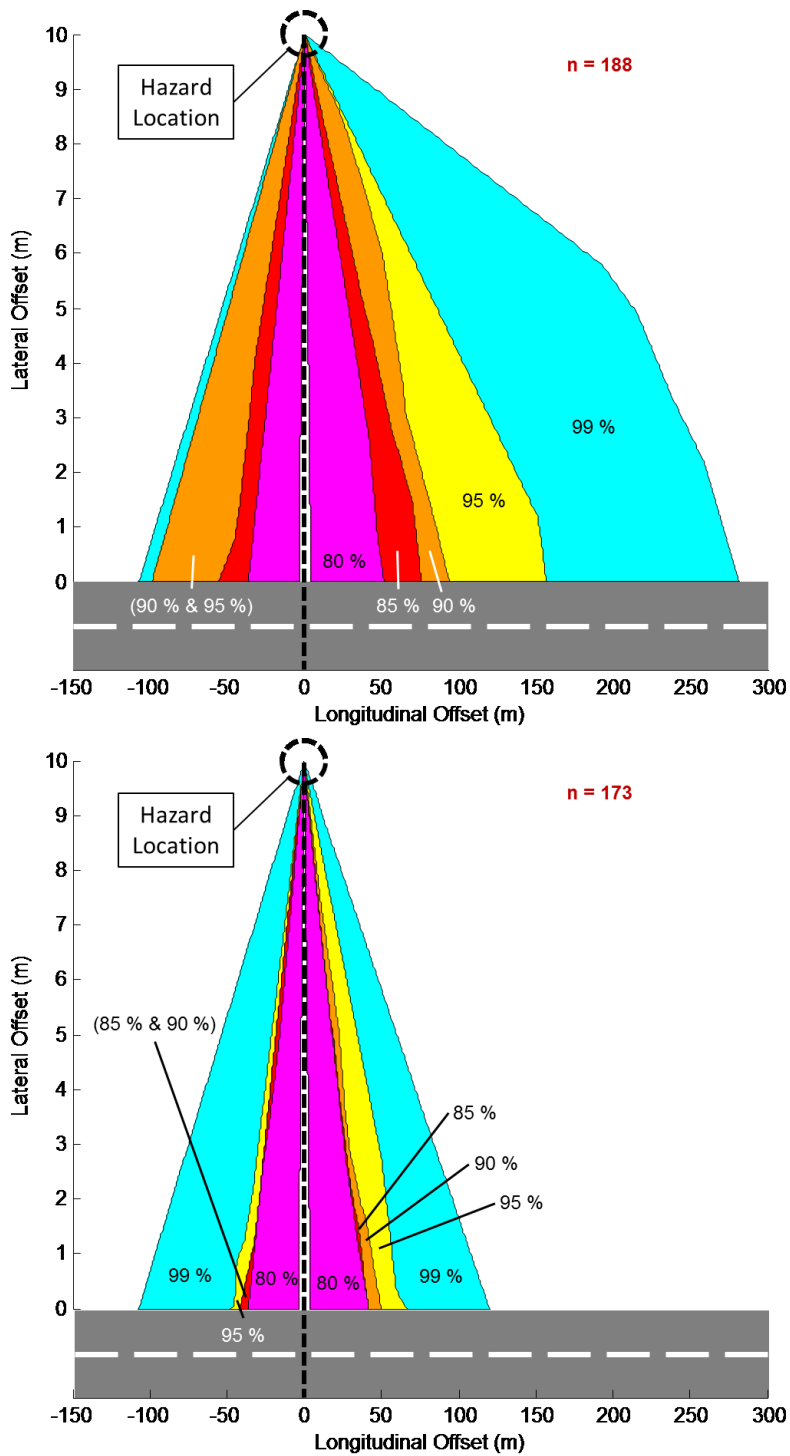
**Figure 7.8. 55 mi/h near-side and far-side departure trajectories arranged to converge at a hazard location 10 m from the roadway. A few trajectories count as both near-side and far-side departures. Figure shows linearly-extrapolated trajectories.**

#### *7.4.1 EFFECT OF PERCENTILE*

Real-world departure corridors for right- and left-side departures from 55 mi/h roads are shown in Figure 7.9. Corridors made using tangent line extrapolation are shown at the top; corridors using fitted arcs are shown at the bottom. Percentile bands are shown to demonstrate the effect of percentile choice on required LON. For right-side departures, going from 80% to 90% or 95% interception approximately

doubles the required LON. For left-side departures, going from 80% to 99% interception more than doubles the required LON. As would be expected, most trajectories will be concentrated in the middle of the distribution. Percentile bands towards the middle of the corridor will tend to be narrower, and percentile bands towards the extremes will tend to be wider. Note there appears to be no 95% band in the tangent line left-side departure corridor (top), and no 90% band in the fitted arc left-side departure corridor (bottom). This is because of the use of weighted trajectories. The same trajectory forms the boundary for both the 90% and 95% left-side departure corridor (or 85% and 90% corridor at bottom). In both cases, one corridor completely covers the other.

In Figure 7.9, tangent line extrapolation appears to be much more conservative than extrapolation with fitted arcs. Using the tangent line extrapolation method would result in longer LON recommendations than the fitted arc extrapolation method.



**Figure 7.9. The percentile of departures intercepted has a dramatic effect on the required LON. Top: tangent line extrapolation. Bottom: fitted arc extrapolation.**

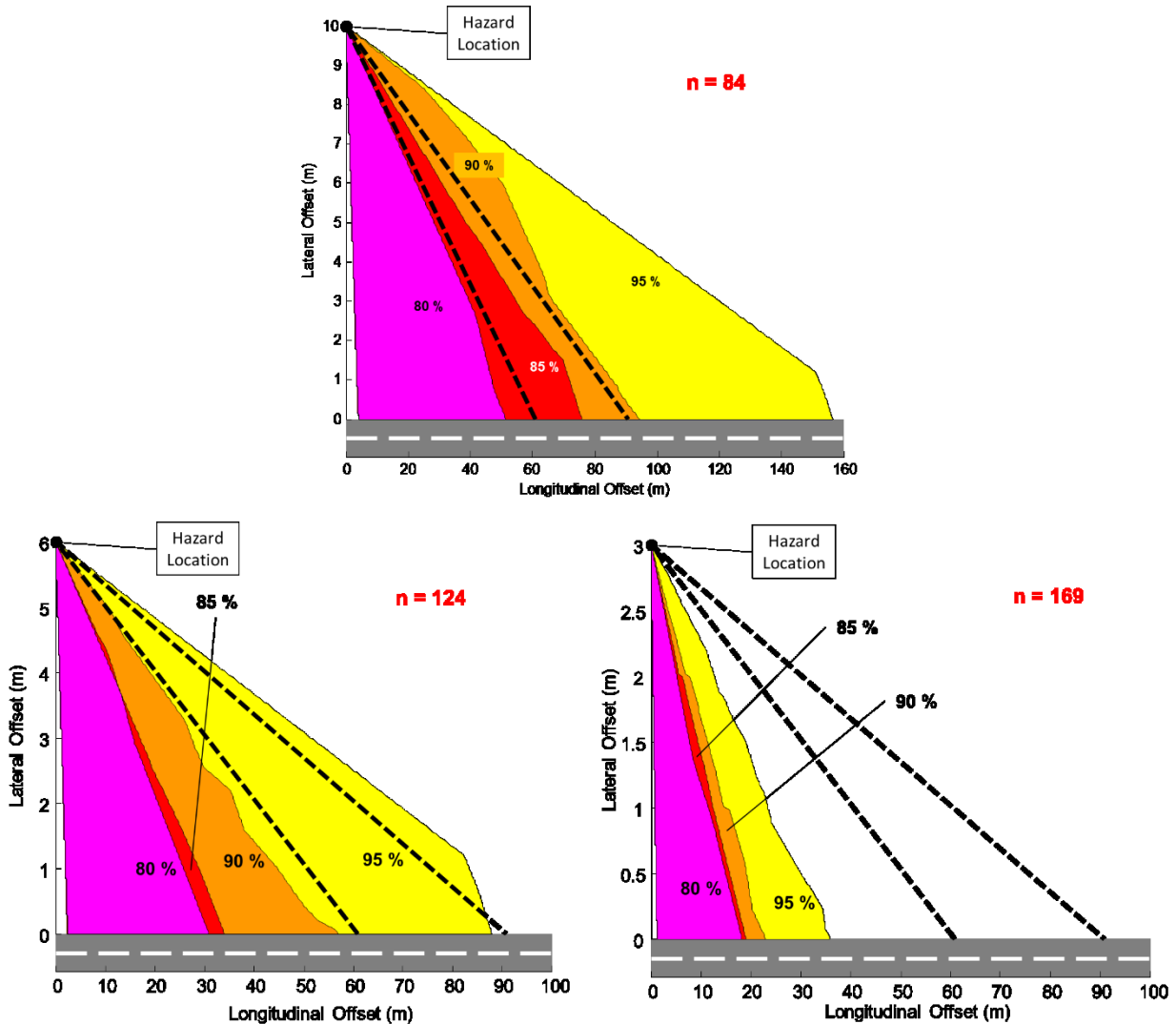
Selecting an appropriate level of protection for a roadside hazard and justifying that selection to decision-makers and the public is a difficult – but important – task that roadway designers and policy

makers must grapple with. The acceptable level of protection is a crucial issue in public policy and is likely to vary among transportation agencies. However, once policy makers provide an acceptable level of protection, roadside designers can use departure corridors to determine the optimal LON with which to achieve that level of protection. In contrast, the 2011 RDG does not provide levels of protection as a function of LON. Specifying an optimal LON to provide a desired level of protection is therefore much more difficult when using the RDG procedure.

#### *7.4.2 COMPARISON WITH THE 2011 ROADSIDE DESIGN GUIDE*

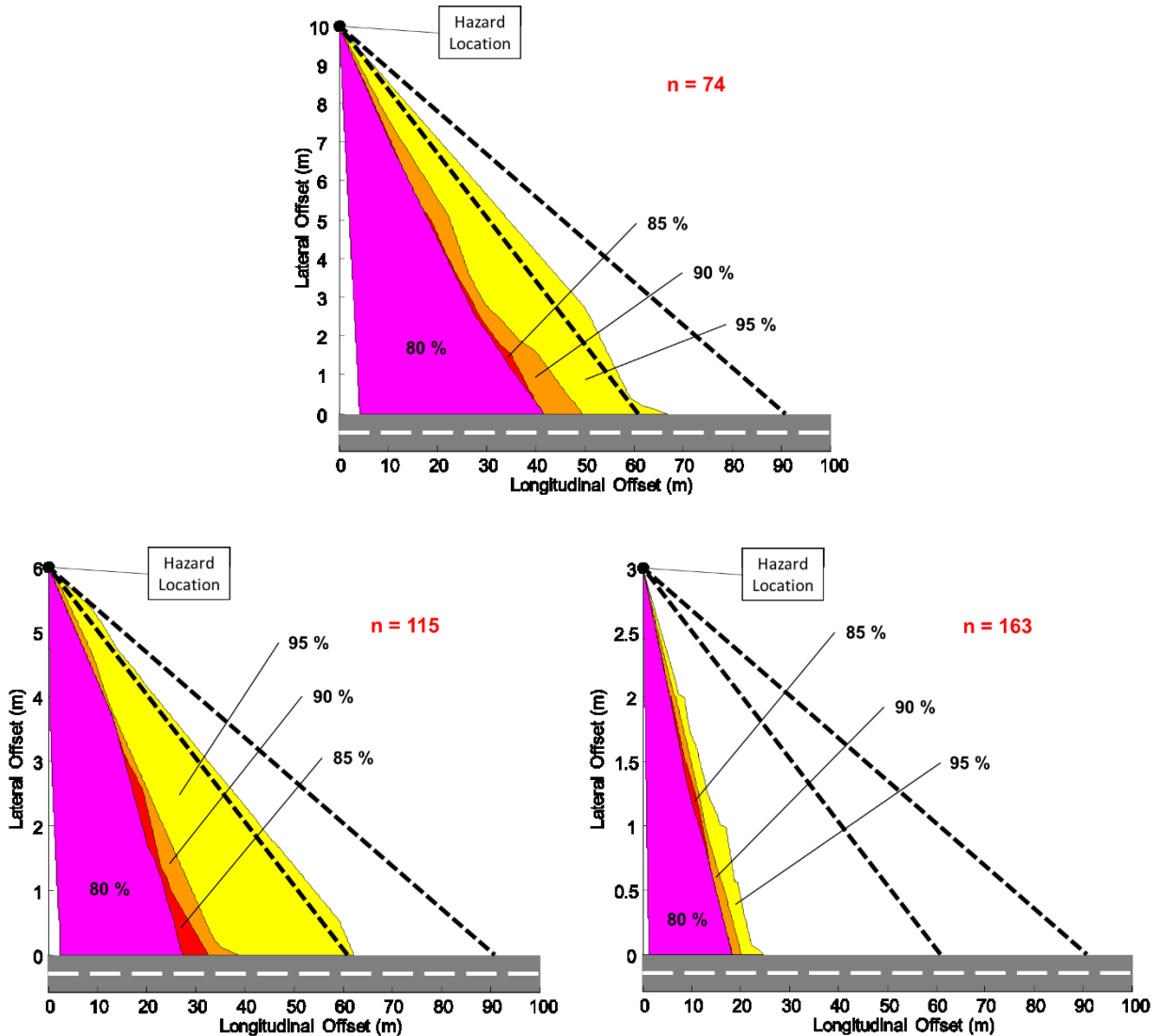
To simplify the following analysis, only right-side departures will be considered. As discussed earlier, the 2011 RDG gives recommended runout lengths for computing LON by roadway design speed and service level (vehicles/day). Roadway design speeds are generally higher than posted speed limits to provide a factor of safety. The 55 mi/h departure corridors presented in Figure 7.9 were based on speed limit, not design speed. Also, the 2011 RDG gives runout length recommendations for 50 mi/h and 60 mi/h roads but not 55 mi/h roads. Therefore, this comparison used RDG corridors corresponding to a design speed of 60 mi/h. Two RDG corridors were used to represent the lower and upper boundaries of the AADT range.

Figure 7.10 shows departure corridors for 55 mi/h roadways (shaded areas labeled with percentages) overlaid with the minimum and maximum LON recommendations computed using the 2011 RDG procedure (black dashed lines). Corridors are shown for hazards 10 m, 6 m and 3 m from the road edge, and were made using linearly extrapolated trajectories. LON recommended by the 2011 RDG appears to intercept between 80% and 90% of real-world departures on 55 mi/h roads that would otherwise strike a hazard 10 m from the roadway. For hazards located closer to the roadway than 10 m, the RDG procedure recommends LON greater than that suggested by the corridor approach. The difference becomes more pronounced as the lateral hazard offset decreases. This occurs because the RDG procedure for computing LON completely decouples runout length and lateral excursion distance.



**Figure 7.10. RDG procedure (dashed lines) versus departure corridors using tangent line extrapolation (shaded areas). Hazards at 10 m (top), 6 m (left) and 3 m (right) from the roadside. Two lines are shown for the 2011 RDG procedure representing the lowest and highest LON recommended for a 60 mi/h design speed.**

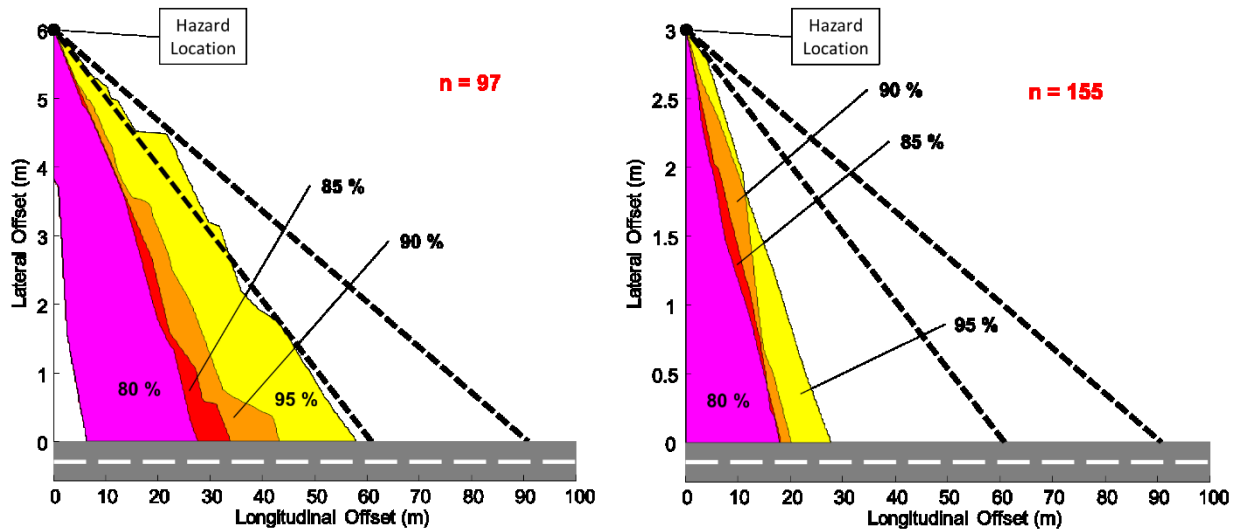
Figure 7.11 shows the same corridors as Figure 7.10, but using fitted arc extrapolation rather than tangent line extrapolation. As expected, these corridors recommend shorter LON than tangent line corridors. This makes the 2011 RDG recommendations appear more conservative by comparison. For hazard offsets of 10 m and 6 m, the RDG procedure recommends LON sufficient to intercept 95% or more of otherwise hazardous departures. For hazards at 3 m, the RDG recommendations intercept substantially more departures than this.



**Figure 7.11. RDG procedure (dashed lines) versus departure corridors using fitted arcs for extrapolation (shaded areas). Hazards located 10 m (top), 6 m (left) and 3 m (right) from the roadside. Two lines are shown for the 2011 RDG procedure representing the lowest and highest LON recommended for a 60 mi/h design speed.**

The method used in this analysis for extrapolating trajectories past the first impact is limited to the data available up to the point of initial impact as discussed in Methods. As a check on the effects of extrapolation, corridors were also made using the complete, unaltered trajectories, including all off-road impacts. Figure 7.12 shows non-extrapolated corridors for hazards at 3 m and 6 m. There were insufficient trajectories with the lateral excursion needed to generate meaningful 10 m corridors, so no 10 m corridor is shown. With off-road impacts included, the lower-percentile bands (80<sup>th</sup>, 85<sup>th</sup>) are much the same as they

are using tangent line extrapolation in Figure 7.10, but the higher percentile bands (90<sup>th</sup>, 95<sup>th</sup>) are noticeably narrower. Corridors made using un-extrapolated trajectories are very similar to the corridors in Figure 7.11 that use fitted arc extrapolation.



**Figure 7.12. Departure corridors for 6 m (left) and 3 m (right) hazards, made using un-extrapolated trajectories including all roadside impacts. RDG corridors are identical to Figure 7.10.**

## 7.5 DISCUSSION

The real-world departure corridors developed in this analysis show that, for the trajectories in our analysis, increasing LON from intercepting 85 % of right-side departures to 95 % entails roughly doubling the length of installed barrier, regardless of the hazard offset. Even in the 3 m and 6 m corridors made using non-extrapolated trajectories (Figure 7.12), the additional recommended barrier length needed from 85 % to 95 % interception is close to the length required to intercept the first 85 %. The corridors made using extrapolated trajectories are even wider. Multiple studies (Mak, Sicking and Coon 2010; Mak, Sicking and Ross 1986; Kusano and Gabler 2013) have found that road-departure angle distributions are skewed heavily towards low values – i.e. shallow departures. Therefore, the highest percentile bands are wider than the lower percentile bands in corridors based on real-world departures.

The 2011 RDG procedure may specify excessive barrier lengths for hazards very near the roadway. As shown in Figure 7.10, for a hazard offset of 10 m, the RDG procedure recommends LON that would



intercept between 80% and 90% of vehicle departures when using corridors made with tangent line extrapolation. For hazards closer to the roadside, i.e. 6 m and 3 m, the RDG recommendations intercept even larger percentages of hazardous departures. Regardless of the method used to generate corridors, it is apparent that the RDG LON recommendations become more conservative the closer the hazard is to the roadside. As shown earlier, the RDG procedure appears to be inherently conservative because of the way it simplifies the two-dimensional shape of departures.

Departures with lateral movement of less than 4 m may be under-reported in the 17-22 data used to make departure corridors for this analysis (Mak, Sicking and Coon 2010; Sicking, Lechtenberg and Peterson 2009); this may contribute to the observed narrowing of corridors for smaller hazard offsets. While this effect is unlikely to be as significant as the effect demonstrated by trajectory [C] in Figure 7.2, it still bears mention. Many high-volume highways have very wide paved shoulders, which are clear of hazards. Vehicles that experience uncontrolled departures on such roads but do not exceed the shoulder width are unlikely to experience a reported crash or to leave any evidence of a departure. As a result, departures with smaller lateral movement may be under-represented in the departure sample used here. Such departures would not be of concern for hazards with larger lateral offsets, so their absence would not affect the 6 m and 10 m corridors in this analysis.

#### **7.5.1.1 Advantages of Departure Corridors Compared to the RDG Procedure**

The departure corridors developed in this analysis have several advantages over the existing RDG procedure for computing LON recommendations. Perhaps the most important advantage is that LON recommendations are given for a specified level of protection. Once a sample of road departure trajectories representative of the roadway of interest is assembled, corridors can be generated for many hazard offsets and percentages of departures. Since this is automated, it is relatively simple to generate corridors with contours for different percentiles or different hazard offsets. By contrast, the 2011 RDG procedure limits designers to four levels of protection for any given design speed, and does not inform designers what fraction of crashes would be prevented at those levels of protection (AASHTO 2011).

The degree of protection provided by the departure corridor technique is more precisely defined than in the RDG procedure. As discussed in the Introduction, because the RDG technique is based on only vehicle runout length, it is not known exactly which crashes will be intercepted or which ones would have been hazardous for a given LON design. Departure corridors, by contrast, consider the entire vehicle path to determine where vehicles would have to depart in order to contact a hazard. Departure corridors include only those departure trajectories that could contact a hazard and excludes any trajectories that could not. LON recommendations from this technique may therefore also be easier to communicate to decision makers and the general public; e.g. “the proposed barrier will intercept x-% of errant vehicles that would otherwise strike the shielded hazard”.

Departure corridors also have the advantage of allowing designers to specify protection using variables other than the percentage of impacts prevented. Departure corridors enclose a specified percentage of the trajectories likely to result in a crash with a hazard. Trajectories need not be weighted on only their likelihood of resulting in a crash. A second option would be to develop corridors that protect against a given percent of injury-causing crashes. Using injury cost and fatality figures, a third option would be to design corridors that prevent a given fraction of the societal cost of collisions. This flexibility makes the departure corridor technique adaptable to an individual transportation agency’s policies and safety concerns. For the analysis presented herein, corridors were made based on percentage of impacts intercepted.

Finally, for a given sample of trajectories there are many different corridors that can be constructed to intercept a given percentage of encroachments, some of which are substantially narrower or wider than others. Some examples are: the x-% closest to the hazard can be intercepted; the x-% furthest from the hazard can be intercepted; and corridor boundaries can even be optimized to intercept x-% of trajectories/weight using the narrowest interval possible. In the presented analysis, which is the initial demonstration of this technique, corridors were constructed to intercept the x-% nearest the hazard.

Many of the RDG procedure's simplifications were necessary because of the limited detail of road departure data at the time the procedure was designed. The NCHRP 17-22 Project has provided a more detailed (and more recent) set of road departure trajectories, thereby enabling the development of the departure corridor technique presented here. However, for roadway speeds other than 55 mi/h the 17-22 dataset provides rather scarce data with which to build corridors. Departure speed has a strong influence on road departure trajectory and trajectory data used to construct departure corridors must be representative of the departures that will occur on a roadway for the corridors to be valid. It is therefore difficult at present to construct departure corridors for roadways with speed limits other than 55 mi/h. NCHRP Project 17-43 is expected to provide data similar to 17-22 for approximately 1,000 additional road departure crashes. These crashes will also involve newer vehicles than the Cooper (1980) and Hutchinson and Kennedy data (1966) upon which the RDG procedure has been based. Features present on newer vehicles, such as electronic stability control, may change departure trajectories (Johnson and Gabler 2015; Zobel et al. 2005). That data is still being collected as of this analysis, but when this data becomes available it will enable departure corridors to be made for additional road categories.

The real-world departure corridor technique described here directly computes the length of barrier required to intercept any precisely defined percentage of departures that would otherwise strike a hazard. Assuming a representative sample of departure trajectories is used, LON recommendations given by departure corridors account for the 2-dimensional nature of departures and only consider departures that could actually contact a hazard. Since the procedure allows for weights or costs to be assigned to each sample trajectory, it is a straightforward to generate corridors that intercept a percentage of almost any parameter, e.g. probability of severe injury or total potential crash cost. This flexibility makes the procedure adaptable to changing safety priorities. The ability to design for a precisely specified level of protection allows designers to more easily communicate design benefits to the public and decision makers, and gives them a greater ability to protect road users while at the same time using cost-effective barrier lengths.

The RDG procedure makes LON recommendations that intercept an approximate percentile of all departures, hazardous or otherwise, ranked on runout length. The exact protection level actually afforded by this technique is not precisely specified and, as this analysis has shown, inherently becomes more conservative for hazards located closer to the roadside.

## 7.6 CONCLUSIONS

The 2011 RDG procedure for calculating recommended LON makes LON recommendations based only on runout length distributions without taking into account the ability of vehicles to travel towards and away the roadside while off-road. This analysis has compared the LON recommended by the 2011 RDG procedure with “departure corridors” based on real-world road departure trajectories, which do not simplify the geometry of off-road vehicle trajectories. For hazards offset 10 m from the roadside on 55 mph roads, the 2011 RDG procedure appears to give LON sufficient to intercept at a minimum between 80% and 90% of right-side departures that would otherwise strike a hazard, possibly more. Due to its simplified treatment of road departure geometry, the 2011 RDG procedure gives LON that intercepts significantly higher percentages of otherwise-hazardous departures for hazards located closer to the roadside. By contrast, LON given by the departure corridor technique developed here provides a known, precisely defined level of protection that remains the same for different hazard offsets. Departure corridors can be made for any desired level of protection, and the technique provides flexibility in how protection may be defined. Most importantly, the departure corridor technique is fundamentally more realistic than the RDG treatment of road departure trajectories and gives LON recommendations that provide protection levels that can be easily communicated to policy makers and other stakeholders.

## 8 SUMMARY OF RESEARCH PROGRAM AND CONTRIBUTION TO THE FIELD

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### 8.1 RESEARCH SUMMARY

Guardrails are a key safety feature of modern roadways. Collisions with many roadside hazards, e.g. trees, poles and culverts, can be dangerous and guardrail prevents many crashes with such hazards. Even so, in an average U.S. year (2006-2009) there were still about 940,000 police-reported passenger-vehicle crashes with fixed objects, resulting in about 8,700 fatalities and 66,000 incapacitating injuries. The cost of these crashes in terms of lost productivity, medical costs and property damages totaled about \$110 billion in 2000 dollars (Council et al. 2005). These fixed object crashes accounted for about 43 % of all fatalities, 32 % of all incapacitating injuries and 21 % of the total economic cost due to U.S. passenger vehicle crashes annually. Guardrail can be effective in helping to reduce this toll, but it can be challenging to use effectively. How much guardrail is needed to protect a given hazard? How much is prudent? These are critical questions for any road safety engineer, particularly as funds for installing and maintaining roadside safety hardware become ever more scarce, even as the roads are used more and more.

Although guardrail can be an effective means of preventing crashes with roadside hazards, the risks associated with guardrail crashes must be understood and accounted for in order to provide a safety benefit. Figure 1.1 shows an example of a road departure crash with guardrail that resulted in fatality. The 1999 Volkswagen Passat in the photograph lost control after exiting a turn, entered a lateral skid, and struck the guardrail end treatment shown lodged in the vehicle. The 18 year old driver was fatally injured, sustaining multiple head trauma and a transected aorta. The 20 year old right front passenger survived, but was admitted to a trauma center for open lower right leg fractures. How much guardrail can be installed before the guardrail becomes a greater hazard than the danger being shielded? In an average U.S. year (2006-2009), passenger vehicle crashes where guardrail was the most harmful event account for approximately 99,000 towed vehicles, 13,000 incapacitating injuries and 1,600 fatalities. The average yearly economic

cost associated with these crashes is approximately \$7.2 billion, or about 7 % of the total for fixed-object crashes.

### *8.1.1 INJURY RISK IN FRONTAL CRASHES WITH GUARDRAIL*

This analysis examined the effect of a number of factors on injury risk in frontal guardrail crashes. High-risk cofactors including rollover, ejection and non-use of seatbelts were associated with 22 % of all frontal guardrail crashes, yet were associated with 71 % of the resulting serious injuries. Odds of an injury crash were significantly elevated when one or more high-risk cofactors are present. When high-risk cofactors were controlled for, vehicle body style was not observed to have a statistically significant influence on injury risk in this crash mode, although the differences that were observed were consistent with prior studies using recent data (Gabler and Gabauer 2007). When controlling for other variables, car crashes with end terminals were not observed to carry statistically significantly greater odds of injury than crashes with the guardrail face. For LTVs however, end terminal crashes showed injury odds 3.9 times greater than guardrail face crashes. This finding came very close to statistical significance and it is likely that contact with the end terminal itself increases the risk of injury in LTV crashes at least somewhat, compared to contact with the guardrail face.

In end terminal crashes, terminals compliant with NCHRP 350 carried injury odds between 3.9 and 5.0 times lower than non-compliant end terminals when other factors were controlled for. Bryden and Fortuniewicz (1986) studied crashes with guardrail in New York State during 1982-1983. They observed that fatalities and A-injuries (on the KABCO scale) occurred in 15.4 % of crashes with guardrail considered “obsolete [*sic*]”, but in only 10.5 % of crashes with guardrail considered “current [*sic*]”. This equates to an odds ratio of about 1.5 for serious injury, comparing then-obsolete hardware to then-current hardware. This difference is much smaller than the 4.3 to 5.2 odds ratio observed here. This may suggest that advances in end terminal design have made greater strides in the recent past.

Airbags were present in about 86 % of vehicles in frontal guardrail crashes, and deployed in about 38 % of equipped vehicles. Airbag deployment in frontal guardrail crashes appears to be a strong function of the number of total impact events. Airbag deployments are correlated with high crash severity and consequently increased injury risk. The data gives no significant evidence that end terminal crashes are more likely to result in airbag deployment than guardrail face crashes. Neither does end terminal compliance with NCHRP 350 appear to have any significant effect on airbag deployment.

Rollover occurred in 10.0% of all frontal guardrail crashes. Forty-six point three percent (46.3 %) of those rollovers were initiated by the high-severity guardrail impact itself; the remainder was initiated prior to guardrail impact or by objects subsequent to the high-severity guardrail. Overall, LTVs were observed to have odds of guardrail-initiated rollover 7.7 times higher than cars in frontal guardrail crashes. This difference was significantly higher than what Gabler and Gabauer (2007) found, but their comparison was not restricted to only frontal-mode guardrail crashes. End terminals were observed to carry 6.9-times greater odds of initiating rollover than guardrail face when the striking vehicle was an LTV. When the striking vehicle was a car, there was no statistically significant evidence that end terminals were more likely than guardrail face to initiate rollover. In end terminal crashes, NCHRP 350 compliance was not observed to have any significant effect on the likelihood of rollover initiation.

Even if striking an end terminal in an LTV is not, in reality, any more dangerous than striking the guardrail face, the risk of injury in an LTV-end-terminal crash is still elevated due to the increased likelihood that the end terminal will initiate a rollover. Viner, Council and Stewart (1994) observed that pickup trucks (which are a large proportion of LTVs) were over-represented in fatal crashes with roadside safety appurtenances. They attributed this to pickup trucks being more likely to roll over, and to their drivers being less likely to use seatbelts and therefore more likely to be ejected. In this analysis, LTVs were observed to be more likely than cars to roll over, but no statistically significant difference was observed in belt use between car and LTV drivers. Additionally, rollover, unbelted drivers and ejection were all controlled for in this analysis. End terminal contact itself may be inherently somewhat more dangerous for

LTVs than guardrail face contact, but even if it is not, the increased likelihood of end-terminal-initiated rollover for LTVs still increases the risk of injury that end terminals pose for LTVs.

Out of 639 frontal guardrail crashes studied in this analysis, spearing was only observed in 3 crashes. Nationally, these 3 cases represent 0.087 % of all frontal guardrail crashes and 0.63 % of all frontal crashes with end terminals. In the 2 spearing cases where the end terminal could be identified, both end terminal designs were not compliant with NCHRP-350.

### *8.1.2 INJURY RISK IN SIDE CRASHES WITH GUARDRAIL*

This study has investigated the issue of non-tracking side impact using a dataset of 142 guardrail side crashes extracted from the NASS/CDS. Any impact with an end terminal, tracking or not, is highly over-represented in terms of driver injury. Although terminal crashes represented only about 25% of guardrail side crashes, they accounted for more than 70% of the injuries sustained in such crashes. When terminal side crashes were considered separately from LON crashes, cars were observed to be roughly 2.5 times as likely to sustain driver injury. This result was consistent with other studies, but it was not statistically significant. Terminals compliant with NCHRP-350 may be about five times as safe as non-compliant designs, but the difference appears to be overshadowed by the high degree of risk involved in striking any narrow fixed object with the side of the vehicle. A somewhat larger sample appears necessary to make this finding significant at the 95% confidence level.

Intrusion appears to be a major risk factor in guardrail side crashes, particularly terminal crashes. Crashes directly involving the occupant compartment (SHL of “P”) were the most dangerous, accounting for only 3% of all non-tracking side guardrail crashes yet almost 40% of the total injuries. For terminal side crashes, driver-side impacts significantly greater injury risk compared to passenger-side impacts.

Only about 20% of rollovers in non-tracking guardrail side crashes are initiated by contact with the rail; 80% are initiated by some subsequent contact (none of the sampled cases were rolling prior to contact).



Those rollovers which are rail-initiated appear to be about twice as likely to be initiated by a terminal as by LON.

Most observed injuries occurred in crashes involving some combination of rollover, unbelted drivers and ejection. When these high-risk cofactors were removed from the sample, the risk presented by terminal contact was accentuated, as was the disparity in injury risk between cars and LTVs for terminal side crashes. The difference between NCHRP-350-compliant terminals and non-compliant terminals remained relatively unchanged.

### *8.1.3 INJURY IN CRASHES WITH GUARDRAIL END TERMINALS*

K+A injury occurred in 3.8 % of end terminal crashes, K+A+B injury occurred in 11.8 %, and 72.3 % of end terminal crashes involved property damage only. Cars are at greater risk of injury in end terminal crashes than LTVs. Cars showed odds of K+A+B injury 3.6 times greater than LTVs in end terminal crashes. The area of the vehicle damaged in an end terminal crash was also significantly associated with injury outcome, with damage to the driver-side showing higher injury odds than frontal damage. End terminal designs compliant with NCHRP 350 were not observed to carry significantly different odds of K+A+B injury than non-compliant end terminals. The findings control for driver seat belt use, rollover occurrence, terminal orientation (leading/trailing), control-loss and the number of impact events. Rollover and non-use of seatbelts were observed to carry much larger increases in risk than end terminal type. Rollover occurrence was not significantly associated with end terminal type.

### *8.1.4 REDUCTION IN FATAL LONGITUDINAL BARRIER CRASHES DUE TO ELECTRONIC STABILITY CONTROL*

For cars, ESC reduces odds of fatal crashes with roadside barriers by about 50 percent and reduces odds of fatal rollovers occurring in association with roadside barriers by about 45 percent. Both findings are statistically significant. For LTVs, ESC reduces barrier fatality odds by about 40 percent and barrier-associated rollover fatality odds by about 55 percent. The latter finding is statistically significant, and the

former is very nearly significant, and there is reason to believe it is in fact a real effect as well. Based on the effectiveness levels observed in this study, it is estimated that ESC could prevent about 410 out of 1180 possible barrier-related fatalities per year by 2028, when 75 percent of the fleet is estimated to be equipped with ESC. All findings are nationally representative, are based on a representative sample of U.S. vehicles, and control for possible confounding factors such as improved vehicle crashworthiness and introduction of rollover curtain airbags. The study findings suggest that ESC significantly reduces road departures into roadside barriers, and/or that ESC changes departure conditions so that barrier crashes have less severe outcomes.

#### *8.1.5 IMPROVED METHOD FOR ROADSIDE BARRIER LENGTH OF NEED MODELING*

The 2011 RDG procedure for calculating recommended LON makes LON recommendations based only on runout length distributions without taking into account the ability of vehicles to travel towards and away the roadside while off-road. This analysis has compared the LON recommended by the 2011 RDG procedure with “departure corridors” based on real-world road departure trajectories, which do not simplify the geometry of off-road vehicle trajectories. For hazards offset 10 m from the roadside on 55 mph roads, the 2011 RDG procedure appears to give LON sufficient to intercept at a minimum between 80% and 90% of right-side departures that would otherwise strike a hazard, possibly more. Due to its simplified treatment of road departure geometry, the 2011 RDG procedure gives LON that intercepts significantly higher percentages of otherwise-hazardous departures for hazards located closer to the roadside. By contrast, LON given by the departure corridor technique developed here provides a known, precisely defined level of protection that remains the same for different hazard offsets. Departure corridors can be made for any desired level of protection, and the technique provides flexibility in how protection may be defined. Most importantly, the departure corridor technique is fundamentally more realistic than the RDG treatment of road departure trajectories and gives LON recommendations that provide protection levels that can be easily communicated to policy makers and other stakeholders.

### 8.1.6 FINAL THOUGHTS

All of the research in this dissertation has examined only passenger vehicle crashes with guardrail. However, motorcyclists comprise a substantial fraction of guardrail-related fatalities and injuries. Despite being only about 2 % of the U.S. vehicle fleet, motorcycles are second only to passenger cars (about 56 % of the U.S. fleet) for number of guardrail fatalities (Gabler 2007a; Gabler 2007b). About 1 in 10 motorcyclists involved in roadside barrier crashes are fatally injured, which is over 100 times the rate for passenger cars (Gabler 2007a; Gabler 2007b). Even though all motorcycle crashes are, in general, particularly dangerous compared to passenger vehicle crashes, motorcycle crashes with guardrails are still 7 times more likely to be fatal than motorcycle crashes involving only the ground (Daniello and Gabler 2011b). About 40 % of motorcyclists in roadside barrier crashes are fatally or severely injured (Daniello and Gabler 2011a) and motorcyclists involved in guardrail crashes have greater odds of thorax injuries (i.e. broken ribs, pneumothorax, etc.) than motorcyclists involved in crashes where only the ground is contacted (Daniello and Gabler 2012). Motorcycle-guardrail crashes are challenging to mitigate, as guardrails are designed solely for enclosed vehicles such as cars and LTVs (Ross et al. 1993; AASHTO 2009), whereas every motorcycle crash is an ejection crash where the rider makes contact with their surroundings. Clearly, motorcycle crashes to guardrail are an important problem in need of further study.

Based on the findings in Chapter 6, it might be tempting to ask “At what point will guardrail no longer be necessary because of active safety systems?” While ESC and other active safety technologies will reduce the number of injuries due to road departure crashes, they will not completely eliminate road departures. The analysis in Chapter 6 found that ESC would prevent about 1/3 of possible barrier fatalities, and the prior research cited in Chapter 6 generally found that ESC reduced injury and fatality crashes of other modes by about 40-50 %. Two-thirds of possible barrier fatalities, and about 50-60 % of injuries in other crash modes, remain. Furthermore, ESC is effective at reducing crashes related to loss-of-control; many road departure crashes are not related to loss-of-control. Kusano and Gabler (2014) found that other active safety systems which are meant to mitigate crashes that do not involve loss-of-control could

potentially mitigate about 1 in 5 serious injury crashes and 1 in 4 fatal crashes. While this is a very significant portion of the total crash population, this still leaves 4 out of 5 serious injury crashes and 3 out of every 4 fatalities unaffected. Since road departure crashes will still occur in a vehicle fleet equipped with active safety technologies, there will still be a need to install roadside barriers from both an ethical and litigious/liability standpoint. As the risk of road departure is reduced, because transportation agencies have finite budgets, the places where guardrail is installed may become fewer, but it is unlikely that it will fall completely out of use. For example, it is doubtful that traffic barriers will be removed from large suspension bridges or urban flyovers in the foreseeable future.

The research presented in Chapters 3, 4 and 5 has focused on identifying and quantifying the injury risks posed by roadside barriers, and the study in Chapter 7 has presented an improved method for quantifying the protection level of a given length of need. The intended use of this information is to design better, safer roadside barriers. But exactly how should road designers quantify better and safer? That is an important question, and although it is a question that is outside the scope of this research, it is nonetheless useful to reflect on the issues surrounding it.

Just a few decades ago, roadside safety design was a matter of engineering judgment. The field of road safety was completely new, and there was simply no data or prior experience with which to work. Limited data describing road departure crashes has slowly become available over the years (Hutchinson and Kennedy 1966; Cooper 1980; Hunter, Stewart and Council 1993; Mak, Sicking and Coon 2010), but most guidance on barrier placement is surprisingly vague (see Chapter 7) and still places the onus of deciding what is “optimal” on individual agencies and designers (AASHTO 2009; AASHTO 2011). As of the writing of this manuscript, a great deal of recent and currently ongoing research (e.g. Ray et al. 2012; NCHRP project 22-31) is focused on determining what an “optimal” level of roadside protection really means.

A significant portion of this research makes use of cost-benefit techniques, where monetary costs associated with crash outcomes are compared to the monetary costs of installing and maintaining a barrier in order to determine which of several alternatives gives the greatest net (monetary) benefit (Mak and Sicking 2003; Council et al. 2005). While these techniques are certainly powerful, they have important limitations. Crash costs, construction costs, maintenance costs and litigation costs all vary from place to place, often markedly. These variations are driven in large part by factors other than human suffering. With cost-benefit approaches it is thus possible to design barrier systems for two hazards with identical potential for injury, and to end up with two different barriers that are both optimal from a cost-benefit standpoint yet prevent different fractions of the total possible injuries. Costs also change with time, and predicting longer-term economic trends with any specificity is notoriously difficult, even for economists and financial analysis, let alone engineers. So, a barrier system with optimal cost-benefit when designed can easily become sub-optimal during its intended lifetime. With cost-benefit techniques, there is also the significant research problem of assembling reliable cost data for injury outcomes, litigation and lost economic productivity, as well as the challenge and ethical dilemmas of assigning monetary costs to human pain and suffering. How many more dollars is a fatality worth than a permanent disability? If a motorist loses a vehicle due to a road departure crash, does the anxiety and stress of their family due to economic hardship have a dollar value? To use cost-benefit, a designer must answer questions like these.

Cost-benefit is not the only way to design optimal roadside barriers. Costs must certainly be weighed against benefits somehow, as no safety hardware can be installed or maintained without an expenditure of money. But, if a designer wishes simply to prevent the most injury possible with the budget available, there are still decisions that must be made. Not all injuries are created equal. Is a barrier that prevents all possible fatalities and all serious injuries at the expense of a large amount of minor-injuries and property damage better than a barrier that results in significantly fewer minor injuries at the expense of the possibility of one or two more serious injuries? How should injury be counted? MAIS3+, MAIS2+, K+A+B? Should the designer be concerned with protecting unbelted occupants or speeding drivers? Many

of these issues are ultimately the same value judgements that must be made when using cost-benefit techniques, but without the added wrinkle of assigning a dollar value to different levels of harm.

I have purposely avoided making such value judgments in this research, and have instead focused on providing quantitative information about the harm in crashes with guardrail. It is my hope that the information I have presented in Chapters 3, 4, 5 and 6, and the technique developed in Chapter 7, will help the roadside design community to make informed decisions and to prevent as much harm as possible with the available resources.

## 8.2 PUBLICATION SUMMARY

The research presented in this dissertation has examined the injury risks associated with guardrail crashes, and has developed improved methods for choosing guardrail length. Table 8.1 lists the publications corresponding to each chapter of this dissertation.

**Table 8.1. Publication Summary**

<b>Chapter</b>	<b>Title</b>	<b>Venue</b>	<b>Date</b>
3	Injury Risk in Frontal Crashes with Guardrail and Guardrail End Terminals	Proceedings of the 93rd Annual Meeting of the Transportation Research Board, paper no. 14-3143	2014
4	Injury Risk due to Side Impact of Non-Tracking Vehicles into Guardrail	Transportation Research Record 2377, pp. 21-28	2013
5	Incidence and Injury Outcome in Crashes with Guardrail End Terminals	Traffic Injury Prevention (in review)	2015
6	Reduction in Fatal Longitudinal Barrier Crash Rate due to Electronic Stability Control	Transportation Research Record (accepted)	2015
7	Improved Method for Roadside Barrier Length of Need Modeling Using Real-World Trajectories	Accident Analysis and Prevention 80, pp. 162-171	2015

## 9 REFERENCES

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- AAAM (2008), Abbreviated Injury Scale (AIS) 2005 – Update 2008, Association for the Advancement of Automotive Medicine.
- AASHTO (2006), Roadside Design Guide, 3<sup>th</sup> edition, American Association of State Highway and Transportation Officials, Washington, D.C.
- AASHTO (2009), Manual for Assessing Safety Hardware, American Association of State Highway and Transportation Safety Officials, Subcommittee on Bridges and Structures, Washington, D.C.
- AASHTO (2011), Roadside Design Guide, 4<sup>th</sup> edition, American Association of State Highway and Transportation Officials, Washington, D.C.
- Albuquerque FDB, Stolle CS, Sicking DL, Faller RK, Lechtenberg KA and Emmerson E (2015), “Optimization of Guardrail Length-of-Need for Interstate Highways”, *Transportation Research Board 94<sup>th</sup> Annual Meeting Compendium of Papers*, paper 15-3366, Transportation Research Board.
- Alliance of Automobile Manufacturers (2014). *2013 Sales Data*, <http://www.autoalliance.org/auto-marketplace/sales-data>, accessed 2014-11-4.
- Bligh RP and Mak KK (1999), “Crashworthiness of Roadside Features Across Vehicle Platforms”, *Transportation Research Record* 1690, pp. 68-77.
- Bullard LD, Bligh RP, Menges WL and Haug RR (2010), “Evaluation of Existing Roadside Safety hardware Using Updated Criteria – Technical Report,” National Cooperative Highway Research Program, Web-Only Document 157.
- Bryden JE and Fortuniewicz JS (1986), “Performance of Highway Traffic Barriers”, *Effectiveness of Highway Safety Improvements* 1986, pp. 242-252.
- Coon BA, Sicking DL and Mak KK (2006), “Guardrail Run-Out Length Design Procedures Revisited”, *Transportation Research Record* 1984, pp. 14-20.
- Cooper P (1980), “Analysis of Roadside Encroachments – Single Vehicle Run-off Accident Data Analysis for Five Provinces”, British Columbia Research Council, Vancouver, British Columbia, Canada.
- Council F, Zaloshnja E, Miller T and Persaud B (2005), “Crash Cost Estimates by Maximum Police-Reported Injury Severity Within Selected Crash Geometries”, Federal Highway Administration, report FHWA-HRT-05-051, Washington, D.C.
- Daniello A, Cristino D, and Gabler HC (2014), “Relationship Between Rider Trajectory and Injury Outcome in Motorcycle-Barrier Crashes”, *Transportation Research Record: Journal of the Transportation Research Board*, Transportation Research Board of the National Academies, Issue 2388, pp 47–53.
- Daniello A and Gabler HC (2012), “The Characteristics of Injuries in Motorcycle to Barrier Collisions in Maryland”, *Transportation Research Record: Journal of the Transportation Research Board*, Transportation Research Board of the National Academies, Issue 2281, pp. 92-98, doi 10.3141/2281-12.

- Daniello A and Gabler HC (2011a), “The Effect of Barrier Type on Injury Severity in Motorcycle to Barrier Collisions in North Carolina, Texas, and New Jersey”, *Transportation Research Record: Journal of the Transportation Research Board*, No. 2262, Transportation Research Board of the National Academies, pp. 144–151.
- Daniello AL and Gabler HC (2011b), “Fatality Risk in Motorcycle Collisions with Roadside Objects in the United States”, *Accident Analysis and Prevention*, v.43, pp. 1167–1170.
- Daniello A, Swanseen K, Mehta Y, and Gabler HC (2010), “Rating Roads for Motorcyclist Safety: Development of a Motorcycle Road Assessment Program”, *Transportation Research Record: Journal of the Transportation Research Board*, No. 2194, Transportation Research Board of the National Academies, pp. 67-74.
- Davis GA and Morris PM (2006), “Reanalysis of Hutchinson and Kennedy’s Encroachment Frequency Data”, *Transportation Research Record 1953*, pp. 65-70.
- Derrig RA, Segui-Gomez M and Abtahi A (2000), “The Effect of Seat Belt Usage Rates on the Number of Motor Vehicle-Related Fatalities”, *Proceedings of the 2000 Risk Theory Society Seminar*, Minneapolis, Minnesota.
- Farmer CM (2003), “Reliability of Police-Reported Information for Determining Crash and Injury Severity”, *Traffic Injury Prevention*, 4:1, pp. 38-44.
- Farmer CM (2006). “Effects of Electronic Stability Control”, *Traffic Injury Prevention*, 7:4, pp. 319-324.
- Ferguson SA (2007). “The Effectiveness of Electronic Stability Control in Reducing Real-World Crashes: A Literature Review”, *Traffic Injury Prevention*, 8:4, pp. 329-338.
- FHWA (2015), “Peer Review of Report: Relative Comparison of NCHRP 350 Accepted Guardrail End Terminals,” available at: < <http://www.fhwa.dot.gov/guardrailsafety/peerreview.pdf> >, retrieved 2015-3-15.
- Gabauer DJ and Gabler HC (2009a), “Differential Rollover Risk in Vehicle-to-Traffic Barrier Collisions”, *Annals of Advances in Automotive Medicine*, v.53, pp. 131-140.
- Gabauer DJ and Gabler HC (2009b), “Evaluation of Current Repair Criteria for Longitudinal Barrier with Crash Damage”, *Journal of Transportation Engineering*, vol. 135, no. 4, pp. 255-234.
- Gabauer DJ and Gabler HC (2010), “The Effects of Airbags and Seatbelts on Occupant Injury in Longitudinal Barrier Crashes”, *Journal of Safety Research*, vol. 41, pp. 9-15.
- Gabler HC (2007a), “The Emerging Risk of Fatal Motorcycle Crashes with Guardrails”, *Proceedings of the 86<sup>th</sup> Annual Meeting of the Transportation Research Record*, Washington, DC.
- Gabler HC (2007b), “The Risk of Fatality in Motorcycle Crashes with Roadside Barriers”, *Proceedings of the Twentieth International Conference on Enhanced Safety of Vehicles*, Paper No. 07-0474, Lyons, France.
- Gabler HC and Gabauer DJ (2007), “Opportunities for Reduction of Fatalities in Vehicle-Guardrail Collisions”, *51st Annual Proceedings of the Association for the Advancement of Automotive Medicine*, Melbourne, Australia.



- Gabler HC, Gabauer DJ and Hampton CE (2010), "Criteria for Restoration of Longitudinal Barriers", National Cooperative Highway Research Program Report 656, Transportation Research Board, National Academy Press, Washington, D.C.
- Gabler HC, Gabauer DJ, Newell H and O'Neill M (2004), "Use of Event Data Recorder (EDR) Technology for Highway Crash Data Analysis, Final Report", Report to the Transportation Research Board, National Academies of Science, NCHRP Project 17-24.
- Gabler HC, Hampton CE and Hinch J (2004), "Crash Severity: A Comparison of Event Data Recorder Measurements with Accident Reconstruction Estimates", SAE Paper No. 2004-01-1194.
- Gabler HC, Hampton C and Roston T (2003), "Estimating Crash Severity: Can Event Data Recorders Replace Crash Reconstruction?" *Proceedings of the Eighteenth International Conference on Enhanced Safety of Vehicles*, Paper No. 490, Nagoya, Japan.
- Gabler HC, Weaver AA and Stitzel JD (2015), "Automotive Field Data in Injury Biomechanics", in *Accidental Injury*, 3<sup>rd</sup> edition, editors Yoganandan N et al., Springer Science+Business Media, New York City, New York, U.S., chapter 2, pp. 33-49. DOI 10.1007/978-1-4939-1732-7
- Gattis JL, Varghese JP and Toothaker LE (1993), "Analysis of Guardrail-end Accidents in Oklahoma," *Transportation Research Record* 1419, pp. 52-56.
- Gorman TI, Kusano KD, and Gabler HC (2013), "Mathematical Model of Road Departure Events and Estimates of Lane Departure Warning Benefits", *Proceedings of the Second International Symposium on Future Active Safety Technology toward Zero-Traffic-Accidents*, Nagoya, Japan.
- Hampton CE and Gabler HC (2009a), "Influence of the Missing Vehicle and CDC only Delta-V Reconstruction Algorithms for Prediction of Occupant Injury Risk", *Biomedical Sciences Instrumentation* 45: pp. 238-43.
- Hampton CE and Gabler HC (2009b), "NASS/CDS Delta-V Estimates: The Influence of Enhancements to the WinSmash Crash Reconstruction Code", *Annals of Advances in Automotive Medicine*, v.53, pp. 91-102.
- Hampton CE and Gabler HC (2010), "Evaluation of the Accuracy of NASS/CDS Delta-V Estimates from the Enhanced WinSmash Algorithm", *Annals of Advances in Automotive Medicine*, v.54, pp. 241-252.
- Hampton CE and Gabler HC (2013), "Development of a Missing Post Guideline for Longitudinal Barrier Crash Safety", *Journal of Transportation Engineering*, vol. 139, no. 6, pp. 549-555.
- Hampton CE, Gabauer DJ, and Gabler HC (2010), "Limits of Acceptable Rail and Post Deflection in Crash-Damaged Strong-Post W-Beam Guardrail", *Transportation Research Record* 2195, pp. 95-105.
- Hampton CE and Gabler HC (2012), "Crash Performance of Strong-Post W-Beam Guardrail with Missing Blockouts", *International Journal of Crashworthiness*, vol. 17, no.1, pp. 93-103.
- Høyve A (2011). "The effects of Electronic Stability Control (ESC) on crashes – An update", *Accident Analysis and Prevention*, 43, pp. 1148-1159.
- Hunter WW, Stewart R and Council F (1993), "Comparative Performance of Barrier and End Treatment Types Using the Longitudinal Barrier Special Study File", *Transportation Research Record* 1419, pp. 63-77.

- Hutchinson JW and Kennedy TW (1966), “Medians of Divided Highways – Frequency and Nature of Vehicle Encroachments”, *Engineering Experiment Station Bulletin 487*, University of Illinois.
- HRB (1962), “Full Scale Testing Procedures for Guardrails and Guide Posts”, *Highway Research Board Circular*, no. 482, Highway Research Board Committee on Guardrails and Guide Posts.
- Johnson NS and Gabler HC (2011), “Accuracy of a Damage-Based Reconstruction Method in NHTSA Side Crash Tests”, *Traffic Injury Prevention*, 13:1, pp. 72-80.
- Johnson NS and Gabler HC (2013), “Injury Risk due to Side Impact of Non-Tracking Vehicles into Guardrail”, *Transportation Research Board 92<sup>nd</sup> Annual Meeting Compendium of Papers*, paper 13-4694, Washington, DC.
- Johnson NS and Gabler HC (2015), “Reduction in Fatal Longitudinal Barrier Crash Rate due to Electronic Stability Control,” *Transportation Research Board 94<sup>th</sup> Annual Meeting Compendium of Papers*, paper 15-0829, Transportation Research Board.
- Johnson NS and Gabler HC (2014), “Evaluation of NASS-CDS Side Crash Delta-V Estimates using Event Data Recorders”, *Traffic Injury Prevention*, v. 15, no. 8, pp. 827-834, DOI:10.1080/15389588.2014.88199516.
- Kahane CJ (2014). “Updated Estimates of Fatality Reduction by Electronic Stability Control”, report no. DOT HS 812 020, National Highway Traffic Safety Administration, Washington, D.C.
- Kusano KD and Gabler HC (2012), “Safety Benefits of Forward Collision Warning, Brake Assist, and Autonomous Braking Systems in Rear-end Collisions”, *IEEE Transactions – Intelligent Transportation Systems*, 13(4), pp. 1546 – 1555, doi 10.1109/TITS.2012.2191542.
- Kusano KD and Gabler HC (2013), “Driver Response to Road Departures in the 100-Car Naturalistic Study”, *Proceedings of the 2013 Road Safety and Simulation International Conference*, Rome, Italy (October 2013).
- Kusano KD and Gabler HC (2014). “Comprehensive Target Populations for Current Active Safety Systems Using National Crash Databases”, *Traffic Injury Prevention*, 15:7, pp. 753-761.
- Kusano KD, Gabler HC, and Gorman T (2014), "Fleetwide Safety Benefits of Production Forward Collision and Lane Departure Warning Systems", *SAE International Journal Passenger Cars - Mechanical Systems*, 7(2), doi: 10.4271/2014-01-0166.
- Mak KK and Sicking DL (2003), “Roadside Safety Analysis Program (RSAP)—Engineer’s Manual”, National Cooperative Highway Research Program Report 492, Transportation Research Board, National Academy Press, Washington, D.C.
- Mak KK, Sicking DL and Coon BA (2010), “Identification of Vehicular Impact Conditions Associated with Serious Ran-off-Road Crashes,” National Cooperative Highway Research Program Report 665, Transportation Research Board, National Academy Press, Washington, D.C.
- Mak KK, Sicking DL and Ross HE (1986), “Real-World Impact Conditions for Ran-Off-the-Road Accidents”, *Transportation Research Record* 1065, pp. 45-55.
- Martin J, Mintsa-Eya C and Goubel C (2013), “Long-term analysis of the impact of longitudinal barriers on motorway safety”, *Accident Analysis and Prevention*, 59, pp. 443-451.

- McGinnis RG (1999), "Reexamination of Roadside Encroachment Data", *Transportation Research Record* 1690, pp. 42 – 58.
- Miaou S, Bligh R and Lord D (2005), "Developing Guidelines for Median Barrier Installation: Benefit-Cost Analysis with Texas Data", *Transportation Research Record* 1904, pp. 3-19.
- Michigan Dept. of State Police (2014), State of Michigan UD-10 Traffic Crash Report Manual, Michigan Department of State Police, Criminal Justice Information Center, available at: <[http://michigan.gov/documents/msp/UD10\\_Manual\\_Plus\\_Electronic\\_2014\\_Revision\\_441848\\_7.pdf](http://michigan.gov/documents/msp/UD10_Manual_Plus_Electronic_2014_Revision_441848_7.pdf)>. Retrieved 2015-4-26.
- Mitchie JD (1981), "Recommended Procedures for the Safety Performance Evaluation of Highway Safety Appurtenances," National Cooperative Highway Research Program Report 230, National Academy Press, Washington, D.C.
- Mitchie JD and Bronstad ME (1974), "Recommended Procedures for Vehicle Crash Testing of Highway Appurtenances", National Cooperative Highway Research Program Report 153, Transportation Research Board, National Academy Press, Washington, D.C.
- Mitchie JD and Bronstad ME (1994), "Highway Guardrails: Safety Feature or Roadside Hazard?", *Transportation Research Record* 1468, pp. 1-9.
- Nadeau, GG (2014), ET-Plus Guardrail End Terminal: Request for Information, *FHWA Docket No. 2014-0039*, document no. 2014-30081, pp. 77595-77596, available at: < <https://federalregister.gov/a/2014-30081> >
- NHTSA (2007). "Federal motor Vehicle Safety Standards; Electronic Stability Control System", docket no. NHTSA-2007-27662, National Highway Traffic Safety Administration, Washington, D.C.
- NHTSA (2009), National Automotive Sampling System (NASS) Crashworthiness Data System Analytical User's Manual, National Highway Traffic Safety Administration, Washington, D.C., available at < <http://www-nrd.nhtsa.dot.gov/Pubs/NASS08.pdf>>.
- NHTSA (2011). "Estimating Lives Saved Annually by Electronic Stability Control", report no. DOT HS 811 545, National Highway Traffic Safety Administration, Washington, D.C.
- NHTSA (2012a), National Automotive Sampling System (NASS) General Estimates System (GES) Analytical Users Manual 1988-2011, National Highway Traffic Safety Administration, Washington, D.C., available at < <http://www-nrd.nhtsa.dot.gov/Pubs/811704.pdf>>.
- NHTSA (2012b), Fatality Analysis Reporting System (FARS) Analytical Users Manual 1975-2011, National Highway Traffic Safety Administration, Washington, D.C., available at < <http://www-nrd.nhtsa.dot.gov/Pubs/811693.pdf>>.
- NHTSA (2013), NHTSA Test Reference Guide, Version 5, Volume I: Vehicle Tests, National Highway Traffic Safety Administration, Washington, D.C., available at <<http://www-nrd.nhtsa.dot.gov/software/NHTSA%20Test%20Reference%20Guides/Version%205/Volume%20I%20-%20Vehicle%20-%20Version%205%20%28Revision%29.pdf>>.
- NHTSA (2014a). "Crashworthiness Data System Overview." National Highway Traffic Safety Administration Official Site, National Highway Traffic Safety Administration, URL <[http://www.nhtsa.gov/Data/National+Automotive+Sampling+System+\(NASS\)/NASS+Crashwo+rthiness+Data+System](http://www.nhtsa.gov/Data/National+Automotive+Sampling+System+(NASS)/NASS+Crashwo+rthiness+Data+System)>, retrieved 26 July, 2014.

- NHTSA (2014b). "U.S. DOT/NHTSA Docket Memo, Availability of Programs and Databases at NHTSA's ftp Site", docket no. NHTSA-2014-0019, ID: NHTSA-2014-0019-0002, National Highway Traffic Safety Administration, Washington, D.C. Available at <http://www.regulations.gov/#!documentDetail;D=NHTSA-2014-0019-0002>, retrieved 2014-6-27.
- NHTSA (2014c). *Traffic Safety Facts 2012*. Report no. DOT HS 812 032, National Highway Traffic Safety Administration, Washington, D.C. Pickrell TM and Ye TJ (2008), "Safety Belt Use in 2008 – Overall Results", National Highway Traffic Safety Administration, report no. DOT-HS-811-036.
- NHTSA and FHWA (1998), "Report to Congress: The Effect of Increased Speed Limit in the Post-NMSL Era", National Highway Traffic Safety Administration and Federal Highway Administration, report no. DOT-HS-808-637, Washington, D.C.
- Ray MH (1999), "Impact Conditions in Side-Impact Collisions with Fixed Roadside Objects", *Accident Analysis and Prevention*, vol. 31, issue 1-2, pp. 21-30.
- Ray MH, Carrigan CE, Plaxico CA, Miaou S and Johnson TO (2012), "Roadside Safety Analysis Program (RSAP) Update", National Cooperative Highway Research Program Project 22-27 final report, Transportation Research Board, National Academy Press, Washington, D.C.
- Ray MH and Carney JF III, "Test and Evaluation Criteria for Side-Impact Roadside Appurtenance Collisions", *Journal of Transportation Engineering*, v. 120, no. 4, pp. 633-651 (1994).
- Ray MH, Weir J and Hopp J (2003), "In-Service Performance of Traffic Barriers", National Cooperative Highway Research Council Report 490, Transportation Research Board, National Academy Press, Washington, D.C.
- Ross HE Jr., Sicking DL, Zimmer RA and Mitchie JD (1993), "Recommended Procedures for the Safety Performance Evaluation of Highway Features," National Cooperative Highway Research Program Report 350, Transportation Research Board, National Academy Press, Washington, D.C.
- Sicking DL, Lechtenberg KA and Peterson S (2009), "Guidelines for Guardrail Implementation", National Cooperative Highway Research Program Report 638, Transportation Research Board, National Academy Press, Washington, D.C.
- Sharma D, Stern S, Brophy J and Choi E (2007), "An overview of NHTSA's crash reconstruction software WinSMASH", *Proceedings of the 20<sup>th</sup> International Technical Conference on Enhanced Safety of Vehicles*, paper 07-0211, Lyon, France.
- Sivinski R (2007). "Crash Prevention Effectiveness of Light-Vehicle Electronic Stability Control: An Update of the 2007 NHTSA Evaluation", report no. DOT HS 811 486, National Highway Traffic Safety Administration, Washington, D.C.
- Stolle CS, JC Bohlken, KA Lechtenberg and DL Sicking (2011), "Recommendations for Impact Conditions Used in Side-Impact and Nontracking Testing", *Transportation Research Board 90<sup>th</sup> Annual Meeting Compendium of Papers*, paper 11-3806, Washington, D.C.
- TRB (1978), "Recommended Procedures for Vehicle Crash Testing of Highway Appurtenances", *Transportation Research Circular*, no. 191, Transportation Research Board, Washington, D.C.

- Tsoi A, Hinch J, Ruth R and Gabler HC (2013), "Validation of Event Data Recorders in High Severity Full-Frontal Crash Tests", *SAE International Journal of Transportation Safety* 1(1), doi: 10.4271/2013-01-1265.
- Tsoi A, Johnson N and Gabler H (2014), "Validation of Event Data Recorders in Side-Impact Crash Tests", *SAE International Journal of Transportation Safety*, 2(1):130-164, doi: 10.4271/2014-01-0503.
- Viano DC and Parenteau CS (2009), "Belt Use: Comparison of NASS-CDS and Police Crash Reports", *Traffic Injury Prevention* vol. 10 issue 5, pp. 427-435.
- Viner JG (1993), "Harmful Events in Crashes", *Accident Analysis and Prevention*, vol. 25, no. 2, pp. 139-145.
- Viner JG, Council FM and Stewart JR (1994), "Frequency and Severity of Crashes Involving Roadside Safety Hardware by Vehicle Type", *Transportation Research Record 1468*, pp. 10-18.
- Wolford D and Sicking DL (1996), "Guardrail Runout Lengths Revisited," *Transportation Research Record 1528*, pp. 78 – 86.
- Zobel R, Stanzel M, Becker H, Scheef J and Rieger G (2005), "Active Safety Systems Change Accident Environment of Vehicles Significantly – A Challenge for Vehicle Design," *Proceedings of the 19<sup>th</sup> International Technical Conference on the Enhanced Safety of Vehicles*, paper 05-0053.
- Zou Y, Tarko P, Chen E and Romero MA (2014), "Effectiveness of cable barriers, guardrails, and concrete barrier walls in reducing the risk of injury", *Accident Analysis and Prevention*, 72, pp. 55-56.

## APPENDIX A. END TERMINAL IDENTIFICATION GUIDE

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### 9.1 END TERMINAL CONCEPTS

Guardrail end terminals are intended to protect vehicles that crash with the end of a guardrail. The first guardrails simply had flattened caps on the ends of the guardrail that would frequently penetrate vehicle occupant compartments, severely injuring or killing any occupants unfortunate enough to be in the path of the rail. Newer end terminals are designed to prevent this from happening and to either contain and redirect striking vehicles, allow them to pass safely behind the barrier, or bring them to a controlled stop with minimal risk of injury (AASHTO 2011).



**Figure A.1. The first guardrail end terminals were prone to penetrating vehicles that struck end-on. Newer end terminal designs aim to prevent this and bring striking vehicles to a stop without injuring vehicle occupants. NASS-CDS case 2005-45-104.**

Guardrail end terminals may be classified as either **energy-absorbing** or **non-energy absorbing** (Figure A.2). Energy-absorbing terminals are designed to dissipate significant amounts of vehicle energy when struck end-on, slowing the vehicle or even stopping it completely. When struck in the side, they may either redirect the vehicle back into the roadway or allow the vehicle to pass through the system. The latter behavior is referred to as **gating**; most end terminal designs are gating up to the third post. Non-energy-absorbing designs are meant to prevent the guardrail from penetrating the vehicle when struck end-on without decelerating the vehicle significantly. This presents less risk of injury to vehicle occupants, but also

means the vehicle will generally travel further after striking the terminal. Non-energy-absorbing designs are also frequently gating up to the third post (AASHTO 2011).



**Figure A.2. Examples of non-energy-absorbing (left) and energy-absorbing (right) terminals.**

Guardrail end terminals may also be classified as either **flared** or **tangent**. In flared terminals, the end of the guardrail is offset some distance back from the face of the guardrail; the left of Figure A.2 shows an example of a flared end terminal. Terminals can flare either in a straight line, or in a parabolic profile (as shown in Figure A.2). Flared end terminals are typically offset by around 3 to 4 feet. Tangent systems are, by contrast, those where the end of the guardrail is at or very near the barrier face. The right of Figure A.2 shows an example of a tangent end terminal. Many end terminals that are considered tangent systems may, however, be installed with a very slight flare – about 1 to 2 feet depending on the total length of the system (AASHTO 2011).

There are a number of guardrail end terminal features that can be useful for distinguishing different systems in the field. These include: impact heads; anchor cables; ground struts; post type and number; and blockouts.

### *IMPACT HEADS*

Energy-absorbing end terminals typically have a large, conspicuous impact head covering the end of the rail, while non-energy-absorbing designs generally have a very simple end cap. The impact head keeps the guardrail from penetrating the vehicle and also dissipates vehicle energy by deforming the guardrail in some controlled fashion. Impact heads are a very conspicuous portion of end terminals that

have them and they typically survive crashes, so they are very useful for identifying different systems.

Figure A.3 shows examples of impact heads.



**Figure A.3. Examples of impact heads.**

### *ANCHOR CABLES*

An anchor cable is a cable connecting the base of the first post to the top of the second post (Figure A.4). The purpose of the anchor cable is to provide tension in the guardrail system, which is necessary for guardrail to function properly. Both leading and trailing ends of guardrail typically have anchor cables on high-speed roads; guardrail installed on very low-speed facilities may lack anchor cables. The bracket that attaches the anchor cable to the guardrail can also be a useful identifying feature; different end terminal systems can attach the anchor cable bracket to the guardrail in visibly different ways.





**Figure A.4. Most, but not all, end terminal systems use anchor cables connecting the bottom of the first post to the top of the second post to help maintain tension in the guardrail.**

### *GROUND STRUTS*

The ground strut is a beam connecting the first and second posts at ground level (Figure A.5). Its purpose is, like the anchor cable, to help develop tension in the guardrail. Most end terminal systems contain an anchor cable, but there are designs (e.g. the BCT and certain variations of the SRT-350) that lack a ground strut.

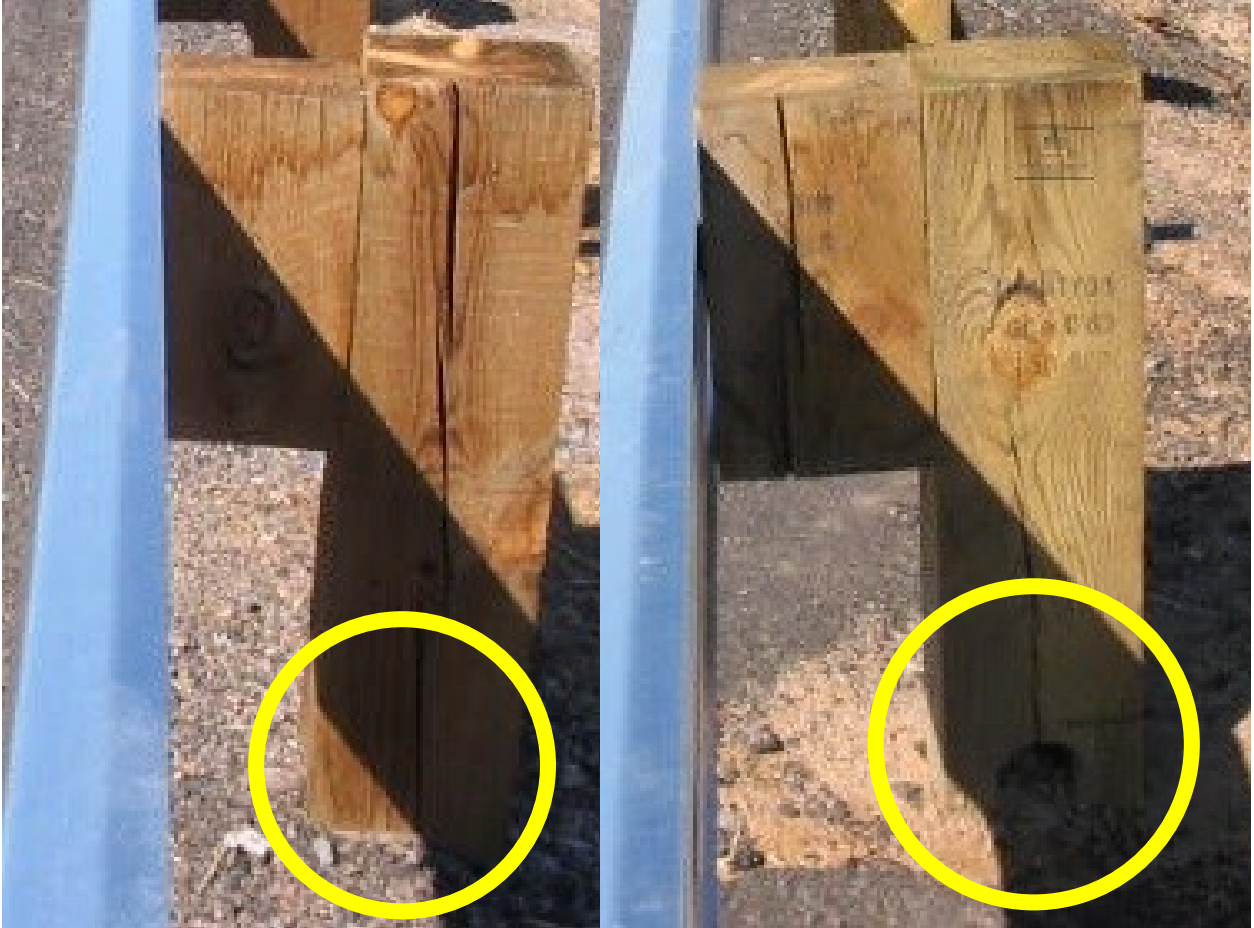


**Figure A.5. Many end terminal system incorporate a ground strut, which is a beam connecting the first two posts in the system at ground level.**

## *POST TYPE AND NUMBER*

Each end terminal system uses a specific number and type of posts in a particular arrangement. Some systems, e.g. the SRT-350, have several permissible configurations, but each configuration has a specific arrangement of posts. Posts can be categorized as either standard posts or **breakaway posts**. Standard posts are designed not to break during a crash, while breakaway posts are. Wooden breakaway posts have large holes drilled completely through the post at approximately ground level as shown in Figure A.6, while non-breakaway wooden posts lack the large holes.

There are a number of designs for steel breakaway posts, some of which are proprietary to specific manufacturers. In general, a single standard post is either weakened in some way at about ground level so as to bend easily when struck, or is fabricated from two pieces of steel beam that are bolted together in such a way that one bolt breaks and the other acts as a hinge when struck. Most steel breakaway posts are noticeably different from non-breakaway steel posts, but the Trinity Highway Products LLC “Steel Yielding Terminal Post” (SYTP) is an exception. The only difference between this system and a non-breakaway post is four ½” holes drilled in the beam flanges at roughly ground level. In the field, these holes may be several inches below ground, so it is important to look for them closely to distinguish the SYTP from standard steel posts. Figure A.7 shows some examples of steel breakaway posts. The rightmost image shows an SYTP with the ground-level holes circled.



**Figure A.6. Wooden breakaway posts are easily distinguished from non-breakaway wooden posts by the large hole passing completely through the post at approximately ground level (top). Anchor cables are normally attached to the first end terminal post through this hole.**



**Figure A.7. Left: standard, non-breakaway steel post. Center: an example of a steel breakaway post with a typically conspicuous base design (in this example, a shearing-bolt design). Right: a Steel Yielding Terminal Post, or SYTP, is a breakaway steel post whose only distinguishing feature is four 1/2" holes drilled in the flanges at roughly ground level.**



**Figure A.8.** It is a simple matter to distinguish the SYTP from standard non-breakaway steel posts, but in the field, it frequently requires careful, close observation. The distinguishing holes of the SYTP may be obscured by vegetation, or may be slightly below ground level.

### *BLOCKOUTS*

Blockouts are spacers, typically wood or plastic blocks or sections of steel beam, placed between the rail and the posts (Figure A.9). Blockouts help keep striking vehicles from snagging the posts, which can cause the vehicle to breach the guardrail or even roll over. Different systems have blockouts on different posts, hence the placement of blockouts can help to identify end terminal systems.



**Figure A.9.** Wood blockouts (left), steel blockouts (center) and composite blockouts (right).

## ENERGY-ABSORBING W-BEAM GUARDRAIL END TERMINALS

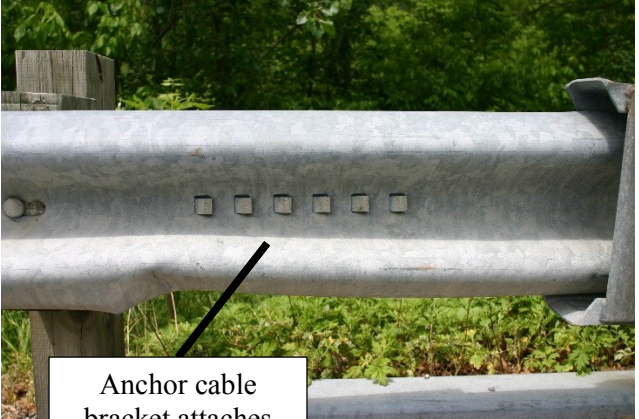
Extruder Terminal 2000 (ET-2000) .....	158
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## NON-ENERGY-ABSORBING W-BEAM GUARDRAIL END TERMINALS

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# ENERGY-ABSORBING W-BEAM GUARDRAIL END TERMINALS

EXTRUDER TERMINAL 2000 (ET-2000)





## *HOW IT WORKS*

End-on impacts force the crash head down the guardrail. The crash head first flattens and then curls the guardrail to dissipate vehicle energy. Guardrail is extruded on the side away from the road in a smooth curl. This system is an earlier version of the ET-Plus and uses the same mechanism to dissipate energy.

## *DISTINGUISHING CHARACTERISTICS*

- Energy-absorbing terminal
- Square, fully enclosed (except for rail outlet) impact head with no visible reinforcing plate
- Guardrail extruded in a smoothly curled, flattened ribbon
- Anchor cable bracket attaches to rail with 6 bent tabs

## *SIMILAR END TERMINALS*

- Sequential Kinking Terminal (SKT-350)
  - o SKT-350 kinks guardrail, ET-2000 extrudes a smooth ribbon
  - o SKT-350 anchor cable bracket is attached with bolts, not bent tabs
  - o Small slots in first rail section of SKT-350; no such slots in ET-2000
- Beam Eating Steel Terminal (BEST)
  - o Impact head is much closer to the first post
  - o No visible center reinforcing plate
  - o BEST shreds guardrail into 4 strips, ET-2000 does not

# EXTRUDER TERMINAL PLUS (ET-PLUS)



## *HOW IT WORKS*

This system is a revised version of the ET-2000 and uses the same mechanism to dissipate energy.

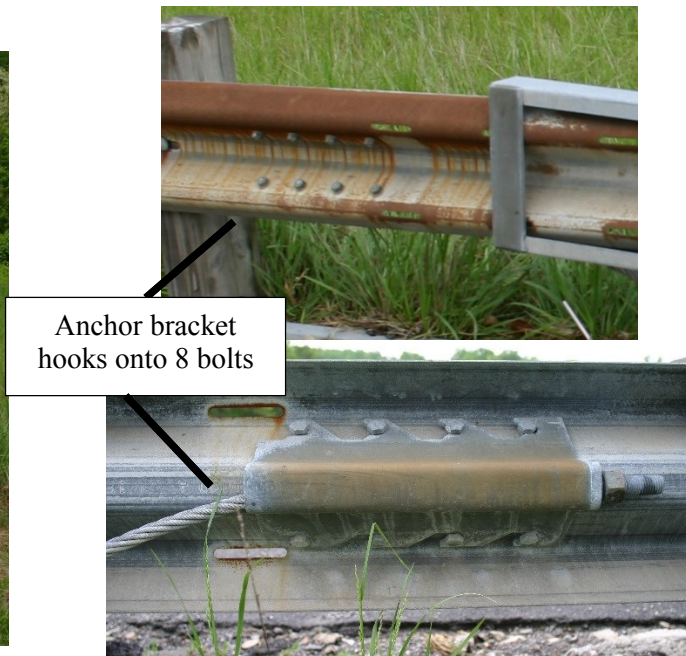
## *DISTINGUISHING CHARACTERISTICS*

- Energy-absorbing system
- Distinctive, rectangular impact head (15" x 28")
- Guardrail extruded in a smoothly curled, flattened ribbon
- Anchor cable bracket attaches to rail with 6 bent tabs
- Tangent system, straight flare up to 25:1 is permissible
- 4, 7 or 8 breakaway posts, may be steel or wood, no blockouts on posts 1 and 2

## *SIMILAR END TERMINALS*

- Flared Energy Absorbing Terminal (FLEAT)
  - o FLEAT impact head is only superficially similar to ET-Plus
  - o FLEAT is a flared system while ET-Plus is not
  - o FLEAT end terminal uses SKT-350 damage mechanism which visibly differs from ET-2000/ET-Plus damage

# FLARED ENERGY ABSORBING TERMINAL (FLEAT)



## *HOW IT WORKS*

End-on vehicle impacts push the impact head down the guardrail. As the guardrail passes through the impact head, it is curled into a kinked ribbon that exits away from the roadway. This is a distinct mechanical process from the flattening and curling that happens with the ET-2000/ET-Plus, and the guardrail damage is visibly different.

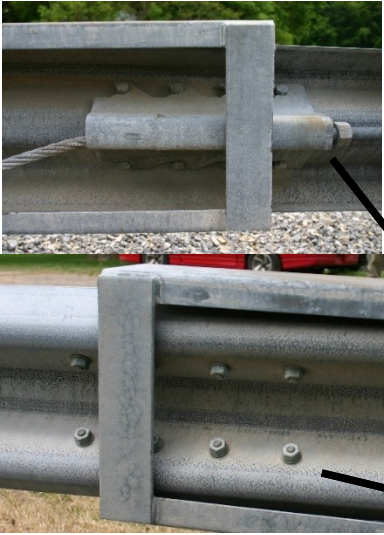
## *DISTINGUISHING CHARACTERISTICS*

- Energy-absorbing system
- Distinctive, rectangular, offset impact head with steel tube welded to top edge
- Damaged guardrail is extruded in a sequentially kinked ribbon
- Anchor cable is bolted to backside of guardrail
- Flared system, head is offset between 2.5' and 4' behind the guardrail face
- 2 or 7 breakaway posts, may be either wood or steel
- Version intended for median installation always consists of two FLEAT terminals installed back-to-back, with the impact heads staggered

## *SIMILAR END TERMINALS*

- Extruder Terminal 2000 Plus (ET-Plus)
  - o FLEAT impact head is only superficially similar to ET-Plus
  - o FLEAT is a flared system while ET-Plus is not
  - o FLEAT end terminal uses SKT-350 damage mechanism which visibly differs from ET-2000/ET-Plus damage

SEQUENTIAL KINKING TERMINAL 350 (SKT-350)



Anchor bracket hooks onto 8 bolts



Square crash head with open sides



## *HOW IT WORKS*

The SKT uses the same energy-dissipation mechanism as the FLEAT. Guardrail extruded through an SKT has the same kinked-ribbon appearance as guardrail extruded through a FLEAT, and vice-versa.

## *DISTINGUISHING CHARACTERISTICS*

- Energy-absorbing system
- Square impact head with visible center reinforcing plate
- Anchor bracket is bolted to backside of guardrail
- Damaged guardrail is extruded in a sequentially kinked ribbon
- Tangent system: maximum permissible flare of 25:1 (2' offset @ 50' length)
- 8 or 2 breakaway posts, may be steel or wood

## *SIMILAR END TERMINALS*

- Extruder Terminal 2000 (ET-2000)
  - o ET-2000 extrudes guardrail in a very smooth curled ribbon, SKT-350 produces a kinked ribbon
  - o ET-2000 impact head is fully enclosed, SKT-350 impact head is open with a visible center reinforcing plate
- Beam Eating Steel Terminal (BEST)
  - o BEST shreds guardrail into 4 strips, SKT-350 curls it into a kinked ribbon
  - o BEST anchor cable bracket attaches with 10 metal tabs, SKT-350 attaches with 8 bolts
  - o Impact head face is closer to 1<sup>st</sup> post in SKT-350

# NON-ENERGY-ABSORBING W-BEAM GUARDRAIL END TERMINALS



BREAKAWAY CABLE TERMINAL (BCT)



Parabolic flare  
(variable in practice)

No Ground Strut, No  
Blockout On Post 2



## *HOW IT WORKS*

The BCT was one of the initial attempts to design an end terminal that would not penetrate vehicles. It attempts to do this by using breakaway posts, a parabolic flare (to increase the obliqueness of end impacts) and a blunted end cap. Despite this, the BCT still has problems with vehicle penetration.

## *DISTINGUISHING CHARACTERISTICS*

- Two wooden breakaway posts
- No blockout on post 2
- Light parabolic flare
- No ground strut
- Blunt end cap

## *SIMILAR END TERMINALS*

- Modified Eccentric Loader Terminal (MELT)
  - o MELT has a blockout on 2<sup>nd</sup> post, BCT does not
  - o MELT has a ground strut, BCT does not
  - o MELT has a much steeper parabolic flare than BCT
- Slotted Rail Terminal 350 (SRT-350)
  - o SRT-350 has only one configuration with a parabolic flare, BCT always has a parabolic flare
  - o SRT-350 has a ground strut, BCT does not
  - o SRT-350 has distinctive slots in the guardrail that the BCT lacks

MODIFIED ECCENTRIC LOADER TERMINAL (MELT)

Parabolic flare



Ground Strut,  
Blockout On Post 2



No slots in rail



## *HOW IT WORKS*

The MELT is a further improvement on the BCT by way of the ELT. The MELT incorporates a strong parabolic flare and a blockout on the 2<sup>nd</sup> post to help prevent vehicle penetration. The guardrail is also only bolted to posts 1 and 9. Downstream impact performance is improved by incorporating a ground strut. Although the MELT does offer improved performance over the BCT, it is still normally found on lower-speed facilities.

## *DISTINGUISHING CHARACTERISTICS*

- Parabolic flare offsets end cap 4' back from barrier face
- Blunt end cap with ground strut, anchor cable and blockout on 2<sup>nd</sup> post
- 8 wooden breakaway posts in the system

## *SIMILAR END TERMINALS*

- Breakaway Cable Terminal (BCT)
  - o BCT always lacks a ground strut, MELT always has one
  - o BCT has only two breakaway posts, MELT has 8
- Slotted Rail Terminal 350 (SRT-350)
  - o Only one SRT-350 configuration has a parabolic flare, all MELTs have a parabolic flare
  - o SRT-350 has distinctive slots in the guardrail, MELT does not
  - o SRT-350 does not have a blockout on post 2, MELT does

SLOTTED RAIL TERMINAL 350 (SRT-350)



## *HOW IT WORKS*

The SRT-350 is a non-energy-absorbing end terminal which is designed to crumple when struck end-on while redirecting vehicles that strike past the third post. The guardrail is made weaker in bending while still maintaining its tensile strength by cutting slots along the length of the rail.

## *DISTINGUISHING CHARACTERISTICS*

- Longitudinal slots cut into the first three sections of guardrail; slots are cut into the crease of the guardrail as well as the two crests
- Ground strut
- No blackout on post 2
- May be installed with either a straight flare or a parabolic flare
- 6 or 8 breakaway posts, may be wooden or steel
  - o 6 post system: either 2<sup>nd</sup> post, or posts 2-5 are not bolted to the guardrail, 4 wood and 2 steel posts or all steel posts, straight flare
  - o 8 post system: wood posts only, parabolic flare, posts 7 and 8 unbolted

## *SIMILAR END TERMINALS*

- Breakaway Cable Terminal (BCT)
  - o BCT has no ground strut
  - o BCT rail is not slotted
  - o BCT is always parabolic flare
  - o SRT-350 always has more breakaway posts than BCT
- Modified Eccentric Loader Terminal (MELT)
  - o MELT has blackout on post 2, SRT-350 does not
  - o MELT guardrail is not slotted, SRT-350 guardrail is

TURNDOWNS



### *HOW IT WORKS*

The turndown prevents penetration of the vehicle by turning the end of the guardrail down into the ground. However, a side effect of this is a high propensity for causing rollovers. Turndowns are not usually found on high-speed facilities.

### *DISTINGUISHING CHARACTERISTICS*

End of guardrail is turned down into the ground - unique