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In-Service Safety Evaluation of Indiana Impact Attenuators and Barrier End Treatments

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SPR-4541 • Report Number: FHWA/IN/JTRP-2024/24 • DOI: 10.5703/1288284317765

RECOMMENDED CITATION

Pineda-Mendez, R. A., Guo, Q., Romero, M. A., & Tarko, A. P. (2024). *In-service safety evaluation of Indiana impact attenuators and barrier end treatments* (Joint Transportation Research Program Publication No. FHWA/IN/JTRP-2024/24). West Lafayette, IN: Purdue University. https://doi.org/10.5703/1288284317765

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ACKNOWLEDGEMENTS

This project was funded by the Federal Highway Administration (FHWA) and the Indiana Department of Transportation (INDOT) through the Joint Transportation Research Program (JTRP) via Grant No. SPR-4541. The authors would like to acknowledge INDOT and FHWA members who served in the study advisory committee. Their collaboration in acquiring data and providing continuous constructive feedback are greatly appreciated. Thanks to Subhi Bazlamit, Shuo Li, Randall Post, Katherine Smutzer, Mark Muenz, Mike Holowaty, Dave Boruff, Elizabeth Mouser, Rick Drumm, and Taylor Ruble.

Finally, we thank INDOT personnel at the district offices for sharing valuable information on the repair and maintenance of barrier end treatment. Thanks to Sarah Bump, Lisa Zebrun, Andrew Blackburn, Kevin Munro, Frank Sailer, Chris Jilg, Scott Montgomery, Steve Giese, and Tyler Armstrong.

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No. FHWA/IN/JTRP-2024/24	**2. Government Accession No.**	**3. Recipient's Catalog No.**
4. Title and Subtitle In-Service Safety Evaluation of Indiana Impact Attenuators and Barrier End Treatments		**5. Report Date** August 2024 **6. Performing Organization Code**
7. Author(s) Raul A. Pineda-Mendez, Qiming Guo, Mario A. Romero, and Andrew P. Tarko		**8. Performing Organization Report No.** FHWA/IN/JTRP-2024/24
9. Performing Organization Name and Address Joint Transportation Research Program Hall for Discovery and Learning Research (DLR), Suite 204 207 S. Martin Jischke Drive West Lafayette, IN 47907		**10. Work Unit No.** **11. Contract or Grant No.** SPR-4541
12. Sponsoring Agency Name and Address Indiana Department of Transportation (SPR) State Office Building 100 North Senate Avenue Indianapolis, IN 46204		**13. Type of Report and Period Covered** Final Report **14. Sponsoring Agency Code**

15. Supplementary Notes

Conducted in cooperation with the U.S. Department of Transportation, Federal Highway Administration.

16. Abstract

Crashes related to barrier end treatments and impact attenuators generally have higher severity levels than those colliding with barrier faces. To select the most effective end treatments, the in-service safety evaluation of such end treatments under various operational conditions was needed. This study linked 7 years of crash records with the corresponding end treatments using inventory from the Indiana Road Network Dataset. Factors affecting crash severity, including speed, weather, roadway features, and vehicle types, were extracted and integrated with crashes in the modeling sample. Both random parameter and fixed effect ordered logit models were used to estimate the effects of various end treatments on crash severity under studied conditions. The probabilities of severity levels outcomes were estimated for barrier end treatments and impact attenuators. These probability distributions were converted into economic costs with proper adjustments for the estimated underreporting rates. The corresponding crash and cost reduction factors were also estimated. The expected average crash costs under various operational conditions should help select a roadside safety device that performs best for the road and traffic conditions.

17. Key Words barrier end treatment, impact attenuator, in-service evaluation, crash severity, ordered logit model	**18. Distribution Statement** No restrictions. This document is available through the National Technical Information Service, Springfield, VA 22161.

19. Security Classif. (of this report) Unclassified	**20. Security Classif. (of this page)** Unclassified	**21. No. of Pages** 47 including appendices	**22. Price**

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

Introduction

Barrier end treatments and impact attenuators are safety devices installed at barrier ends or before important infrastructures to mitigate crash severity. Indiana historical crash records (2004–2013) revealed that crashes related to such treatments are generally more severe than those related to barrier faces. The Indiana Department of Transportation (INDOT) reported more than 34,000 barrier end treatments and impact attenuators operating across state-administered roads. Safety performance evaluation of these treatments is required to select the most effective design under various operating conditions.

Various types of barrier end treatments and impact attenuators may perform differently under different conditions. To estimate the safety effects of selected treatments, the severity-based in-service evaluation should also account for road and traffic conditions that affect crash severity. This study applied advanced statistical methods for estimating such effects, including average costs of collisions with the studied types of barrier end treatments and impact attenuators.

Findings

This study conducted the severity analysis for crashes related to barrier end treatments and impact attenuators. The end treatment inventory from INDOT's Road Network Dataset was linked to crash records, and the operational conditions, including traffic, weather, speed, vehicle types, and roadway features, were collected from various data sources and included in the analysis. Both random parameter and fixed effect ordered logit models were applied to identify various factors' effects on crash severity.

Among the studied barrier end treatments, the newly introduced barrier end treatment, MASH MSKT, outperformed other studied treatments. The success of the MASH MSKT was followed by the widely used types: SKT 350, ET-Plus, and CAT. The effects of vehicle type, snow, dry surface, intersection, and speed limit were estimated. Among the studied impact attenuators, the BARRELS device was found to be the most effective type, while the safety performance of the other types was comparable. Due to a rather small sample of impact attenuators, the study could not identify additional statistically significant factors other than the attenuator types.

Implementation

The results of the estimated crash severity models and NTSHA-reported injury costs were summarized in tables for all the studied types of barrier and treatments and impact attenuators at interstates, other arterial roads, speed limits, intersection, and road segments. The tables include the probabilities of crashes at three levels of severities and the corresponding average costs of crashes under these different scenarios. This information should help policymakers, designers, and road engineers.

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1. INTRODUCTION

1.1 Motivation

Roadside barriers and impact attenuators are designed to contain and redirect run-off-road vehicles, preventing them from striking vehicles in the opposite travel direction or fixed objects on the roadside or in a median. A previous research project, SPR-3705: *Performance Assessment of Road Barriers in Indiana*, provided a practical tool for estimating the safety benefit of alternate barrier design scenarios to help engineers select the most suitable one (Zou & Tarko, 2016a; 2018). However, that project focused on longitudinal barriers and included neither barrier end treatments nor impact attenuators. A prior study by Zou and Tarko (2016b) on the safety performance of longitudinal barrier runs pointed out that the severity outcome of colliding with a barrier end is higher than that of colliding with its face and is comparable to colliding with a high-risk hazard. In Indiana, the number of recorded crashes involving impact with barrier ends is surprisingly high, a notable finding since their exposure area is much smaller than longitudinal barrier runs. From 2004 to 2013, there were 6,154 vehicle collisions with longitudinal barrier elements and 2,514 crashes with barrier ends. Vehicle occupants, including drivers and passengers, were killed or injured in 13.2% of guardrail end strikes. The previous statistics do not include collisions with impact attenuators.

Barrier end treatments and impact attenuators are a group of safety hardware devices installed on barrier ends or in front of fixed obstructions to mitigate crash severity outcomes. The Indiana Department of Transportation (INDOT) reported more than 34,000 guardrail end treatments and impact attenuators operating across state-administered roads. Safety performance evaluation of these safety devices is required to select the most effective style and design for specific traffic conditions. A proper selection of barrier end treatment for the site-specific traffic characteristics (e.g., speed limit, traffic volume, presence of heavy trucks and motorcycles), adjacent roadway attributes, and barrier end location (e.g., road segment, intersection) is necessary for a continuous improvement of safety conditions and the effective use of limited resources. In addition, reducing the number of barrier end treatment types could help reduce the maintenance cost. These cost savings are linked to having fewer available replacement parts and the fact that new end treatment types, e.g., SCI 100 GM, tend to be more easily repairable.

Additionally, due to the recent changes in barrier end treatment design and standards promoted by adopting the 2016 *Manual for Assessing Safety Hardware (MASH)* (AASTHO, 2016), it is critical to establish up-to-date, state-specific barrier end treatment selection guidelines for Indiana. These guidelines would consider the potential reductions in crash injury severity and the cost differences between barrier end treatment or impact attenuator alternatives.

1.2 Research Objectives

This study evaluates barrier end treatment and impact attenuators under various traffic and road characteristics to help state departments select suitable types for installation or replacement. The proposed guidelines are expected to promote the most effective barrier end treatments while reducing the number of treatment types to facilitate maintenance. The present study has three research objectives.

1. Estimate the effects of barrier end treatments, roadway features, traffic characteristics, and other conditions on the severity of crash outcomes.
2. Compare the in-service safety performance of viable types of barrier end treatments under similar conditions.
3. Provide the required input to select the most promising barrier end treatment for specific road and traffic characteristics.

1.3 Research Scope

Table 1.1 summarizes the research scope of the present study. This study assesses the in-service safety performance of various barrier end treatments and impact attenuators on INDOT-administered roads, including freeway and non-freeway segments and signalized and unsignalized intersections. The study focuses on permanent installations and does not include work zone temporary barriers such as truck-mounted devices. In addition, impact attenuators installed to protect road users from hitting bridge piers and other solid obstacles on the median and roadside are included. The analysis investigates both rural and suburban locations. End treatments of cable barriers were considered but not included due to the lack of types, as only anchored cable end treatment is used in Indiana. Furthermore, Indiana crash records do not distinguish between longitudinal sections and end terminals of cable barriers.

While barrier end treatments and impact attenuators are expected to affect the severity of crash outcomes, they are not expected to affect the frequency of crashes. Therefore, this study focuses on the effect guardrail end treatments and impact attenuators have on crash severity.

2. BACKGROUND

2.1 Indiana Barrier End Treatments

This section overviews barrier end treatments and impact attenuators currently operating on Indiana's state-administered roads. A brief description and an image are provided for each type of safety device.

- *ADIEM:* The Advanced Dynamic Impact Extension Module (ADIEM) is a redirective, energy-absorbing, narrow impact attenuator comprising ten light, crushable concrete modules. The ADIEM crash cushion is tested to NCHRP Report 350 Test Level 3. Figure 2.1 shows a picture of an ADIEM from Valtir's website.

TABLE 1.1
Summary of research scope

Included	Not Included
State-administered roads	Local roads
Barrier end treatments and impact attenuators	Collisions with longitudinal barrier elements
Freeway and non-freeway segments	Temporary barriers located at work zones
Signalized and unsignalized intersections	Cable barriers
Rural and suburban locations	Barrier transitions
Median and roadside barriers	Crash frequency analysis
Crash injury severity analysis	—

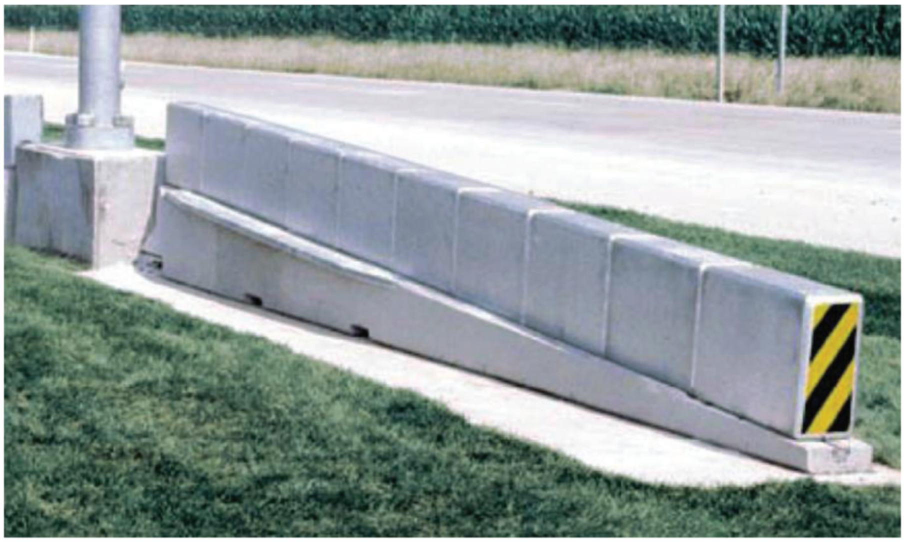


Figure 2.1 Advanced Dynamic Impact Extension Module by Valtir.

Figure 2.2 Energite III sand barrels by Valtir.

- *Barrels:* Sand barrels are a gating, non-redirective impact attenuator consisting of sand-filled modules. Each module in the array consists of a one-piece barrel, a lid, and sometimes a cone insert. Some examples of such crash cushions include Valtir's Energite III (Figure 2.2), TrafFix's Big Sandy (Figure 2.3), and PSS CrashGard (Figure 2.4). Sand barrels can be installed in permanent and work zone applications to shield fixed objects in areas with low historical crash frequency.
- *Breakaway:* The Breakaway Cable Terminal (BCT), aka Breakaway, is a nonproprietary guardrail end treatment that consists of a series of posts that gradually flares away from the road. Typically, they are classified as straight (no offset), flared 6 ft. at the end using a 4.5-degree simple curve over 125 ft., or flared 4 ft. with a parabolic curve over the last 37.5 ft. An example of the Breakaway is shown in Figure 2.5.

Figure 2.3 Big Sandy by TrafFix.

Figure 2.4 CrashGard by PSS.

Figure 2.5 Breakaway cable terminal.

Figure 2.6 Breakmaster by JTI.

(a) Type I (b) Type II

Figure 2.7 Buried guardrail end treatment.

(a) Front view (b) Right side view

Figure 2.8 Crash Cushion Attenuating Terminal by Valtir.

- *Breakmaster:* The Breakmaster, as shown in Figure 2.6, is a guardrail end treatment for wide medians and roadside sites with adequate clear zones. It provides bi-directional protection and does not require a concrete anchor or pad.
- *Buried:* Buried end treatments are nonproprietary guardrail end treatments approved by INDOT's *2013 Indiana Design Manual* (IDM) (INDOT, 2013). As shown in Figure 2.7, there are two types of buried end treatments. Type I is parallel to the road, while Type II is buried in the backslope.
- *Crash Cushion Attenuating Terminal (CAT):* CAT, as shown in Figure 2.8, is an energy-absorbing attenuator or guardrail end treatment with blunt ends of rigid barriers, W-beam, and fixed objects in the median or on the shoulder. It is tested to NCHRP Report 350 Test Level 3.
- *ET-Plus System:* The ET-Plus System, as shown in Figure 2.9, is a cable-anchored, energy-absorbing guardrail end treatment that is used to terminate W-Beam barriers on the shoulder or median of a roadway. It is tested to NCHRP Report 350 Test Levels 2 and 3.
- *FLEAT-MT:* The Flared Energy-Absorbing Terminal Median Terminal (FLEAT-MT), as shown in Figure 2.10, is a guardrail end treatment used in wide medians. Depending on the severity of the impact, the vehicle may be stopped before reaching the second impact head. However, the vehicle will activate the second impact head if the end-on impact is severe enough. This impact head will slide down the rail, sequentially kinking the backside rail.
- *GREAT:* The Guardrail Energy-Absorbing Terminal (GREAT) system, as shown in Figure 2.11, is an impact attenuator that consists of a set of cartridges embedded

Figure 2.9 ET-Plus System by Valtir.

Figure 2.10 Flared Energy-Absorbing Median Terminal by Road Systems.

in a metal diaphragm over a rail that enables it to absorb the energy produced by an impact.

- *HEX-FOAM:* The Hex-Foam Sandwich System, as shown in Figure 2.12, is a restorable impact attenuator. It is effective in head-on and angle hits at speeds up to 60 mph. It is commonly used at bridge piers and toll booths. The system consists of a series of crushable Hex-Foam cartridges placed between lightweight tubular steel diaphragms and surrounded by telescoping fender panels. When hit head-on, the energy-absorbing cartridges are crushed, stopping the vehicle. Hit at an angle, The Hex-Foam Sandwich System safely redirects the vehicle. Bidirectional fendering is available for two-way traffic situations.
- *QuadGuard:* The QuadGuard, as shown in Figure 2.13 and Figure 2.14, is a redirective, non-gating impact attenuator that consists of crushable, energy-absorbing cartridges surrounded by a framework of steel Quad-Beam panels. The system is tested to NCHRP Report 350 Test Levels 2 and 3. It can be used to shield fixed objects 2′ to 10′-6″ wide within less than 22′ in length.
- *REACT:* The REACT, as shown in Figure 2.15, is a redirective, non-gating impact attenuator that consists of High Molecular Weight/High-Density Polyethylene (HMW/HDPE) cylinders. It is tested to NCHRP Report 350 Test Levels 1, 2, and 3. The REACT crash cushion can shield narrow fixed objects up to 36″ wide. It can be utilized in permanent and work zone applications or where traffic congestion and maintenance management is a concern for work crews.
- *SCI 100 GM:* The Smart Cushion, as shown in Figure 2.16, is a speed-dependent crash attenuator that varies stopping resistance during an impact. The SCI 100 GM crash attenuator allows lighter and slower-moving vehicles to have longer ride-down distances and lower g-forces. In addition, the SCI 100 GM crash attenuator is fully re-directive, non-gating, bidirectional, and reusable.
- *SKT:* The Sequential Kinking Terminal (SKT), as shown in Figure 2.17, is an energy-absorbing guardrail end

Figure 2.11 Guardrail Energy-Absorbing Terminal.

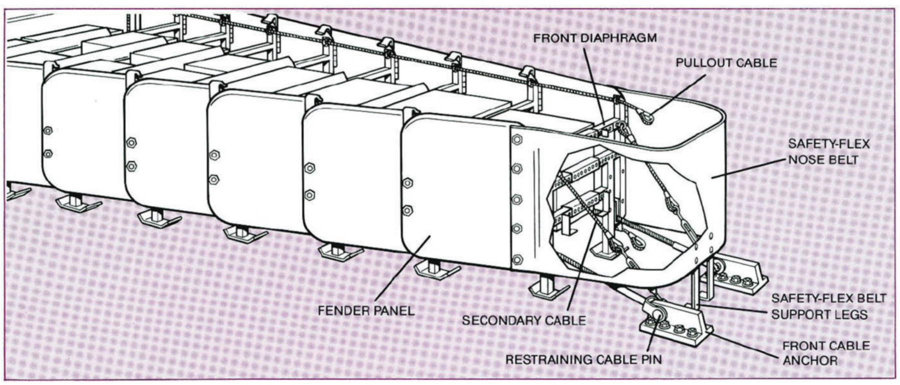


Figure 2.12 HEX-FOAM by Valtir.

treatment available in 25- or 50-ft. extended options and meets NCHRP 350 Test Levels 2 and 3 requirements. During a design impact, the rail is sequentially kinked as it moves through the head and curls away from the roadway. Side impacts result in safe redirection of the errant vehicle when impacted within the length of need. A hinged steel post system is available for the SKT. The MASH-compliant SKT is called MSKT (see Figure 2.18).

- *SENTRE:* Sentre, as shown in Figure 2.19, is a crash-worthy guardrail end treatment that consists of fender panels, support posts with slip bases, and sand-filled boxes, which help dissipate a portion of the collision energy. With a system of telescoping panels plus a redirecting cable that directs the panels sideways, Sentre guides an impacting vehicle away from roadside obstacles. When struck, the fender panels telescope longitudinally to redirect and decelerate the errant vehicle. INDOT has decommissioned most Sentre end treatments.
- *SoftStop:* The SoftStop System, as shown in Figure 2.20, is a tangent, single-sided, energy-absorbing, redirective, and gating guardrail end treatment. The SoftStop System meets MASH 2016 Test Level 3 criteria and may be used in Test Levels 1, 2, and 3 applications.
- *TAU-II:* The redirective, non-gating, universal TAU-II Crash Cushion Family, as shown in Figure 2.21, consists of a full line of impact attenuators ideally suited for virtually all roadway hazards on asphalt or concrete roads. This family of crash cushions is available in lengths and capacities for both low- and high-speed applications from 30–70 mph and widths up to 102".
- *TRACC:* The TRACC, as shown in Figure 2.22, is a redirective, non-gating, energy-absorbing impact attenuator tested to NCHRP Report 350 Test Level 3. It can be used for unidirectional or bidirectional applications.
- *No Terminal*: It should be noted that the no terminal type used in the analysis is the definition borrowed directly from the INDOT inventory. After checking dozens of these types using Google Street Views, the authors concluded that it refers to barrier ends without specific treatments. Usually, a bent fishtail shape at the barrier ends (as shown in Figure 2.23).

According to the latest specifications from INDOT, MSKT, SoftStop, FLEAT-MT, and CAT are the only

Figure 2.13 QuadGuard by Valtir.

Figure 2.14 QuadGuard M10 by Valtir.

guardrail end treatment types approved to be installed after July 1, 2018. Similarly, TAU-II, CrashGard, SCI 100 GM, Big Sandy, CAT-350, Energite III, QuadGuard II, REACT, and TRACC are the only impact attenuators approved to be installed after January 1, 2019. All other barrier end treatment types will be phased out as they get hit or via special update programs organized by INDOT district offices.

2.2 Selection of Barrier End Treatments and Impact Attenuators

Chapter 49 of the *2013 Indiana Design Manual* (IDM) classifies barrier end treatments and impact attenuators based on the roadside obstruction's width, traffic characteristics, and crash history. Additionally, the barrier end treatments that may be installed are indicated via the Qualified Products List (QPL). The manufacturer of a median or roadside safety device to be included in the QPL must submit documentation to INDOT. Then, INDOT deploys a small sample of locations and checks the device's maintenance and operational performance before making a final decision.

A barrier end treatment or an impact attenuator is replaced for two common reasons: (1) in the presence of damage caused by collisions, and (2) scheduled upgrading program at the district level. In addition,

Figure 2.15 REACT-350 by Valtir.

Figure 2.16 SCI 100 GM by Traffic Safety Supply Company.

(a) Right side view

(b) Left side view

Figure 2.17 Sequential Kinking Terminal (SKT-350) by Road Systems, Inc.

after being hit, some end treatments are not entirely replaced but rather recommissioned by exchanging some of their damaged components, e.g., cartridges. The replacement versus repairment decision depends to some extent on the availability of parts. A specific type of barrier end treatment can be installed based on its availability and conformity with the IDM classification. This classification is summarized in Figure 2.24 and Figure 2.25 for barrier end treatments and impact attenuators, respectively.

2.3 Previous Research on Barrier End Treatments

The literature on the safety performance of roadside barrier end treatments was revised, and the main findings are summarized in this section.

Figure 2.18 MSKT end treatment by Road Systems, Inc.

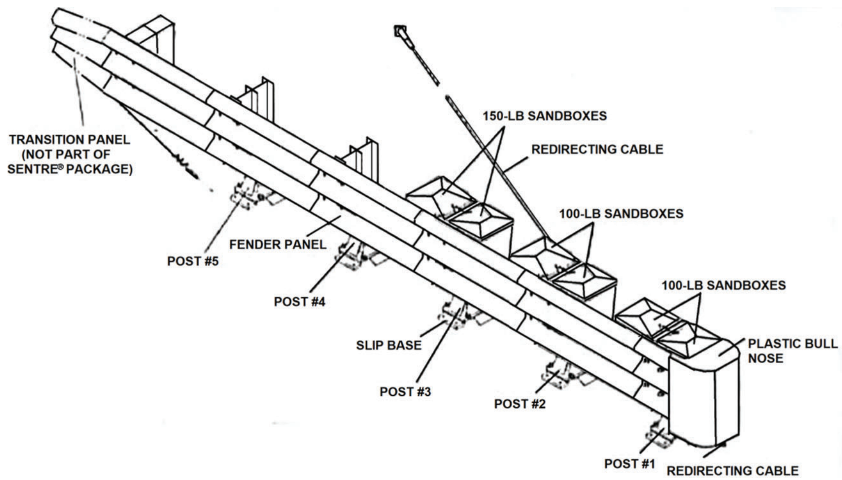


Figure 2.19 SENTRE guardrail end treatment (drawing by Arizona DOT).

Figure 2.20 SoftStop System by Valtir.

Figure 2.21 TAU-II by CSP.

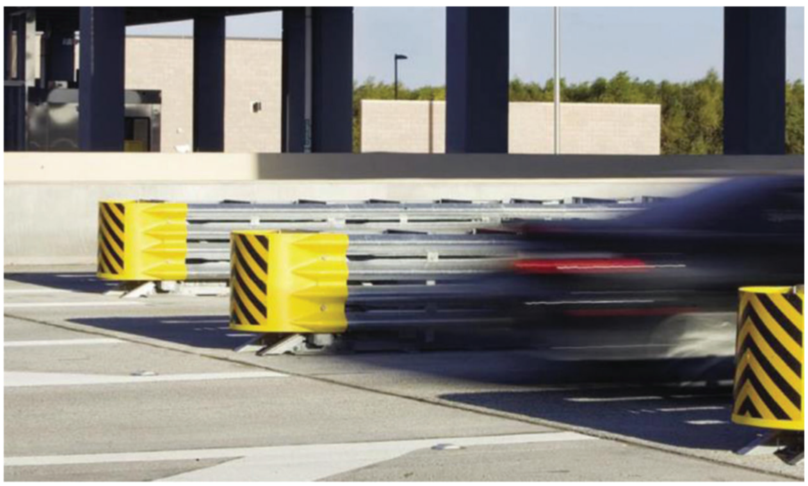


Figure 2.22 TRACC by Valtir.

Past studies of the effect of barrier end treatments on the frequency and severity of crashes yielded conflicting results. In 1984, Griffin found that crash cushions reduce injury severity but may increase crash rates (Griffin, 1984). Specifically, crash cushions were found to reduce severe (-67%), moderate (-8%), and minor (-12%) injuries. Contrary, in 1995, Elvik performed a meta-analysis to determine the safety effect of crash cushions (Elvik, 1995). He found that crash cushions reduce crash frequency and severity. Recently, a detailed study on barrier end treatments' geometric characteristics on crash severity (Molan et al., 2019) concluded that end treatments nearer to the traffic lane had lower crash severity.

Several published studies reported the results of full-scale crash tests with FHWA standards. For example, the Guard Rail Energy Absorbing Terminal (GREAT) was evaluated by Hinch et al. (1988), who, in addition to the typical factors such as angle, speed, impact point, and vehicle type, also considered the fill material and temperature. Pfeifer and Sicking (1996) described the development of a metal-cutting guardrail terminal, while Carney et al. (1999) evaluated a reusable high-molecular-weight, high-density polyethylene crash cushions for wide hazards, eventually accepted by FHWA for use in the National Highway System. Sheikh et al. (2005) reported the development and testing of a hybrid energy-absorbing reusable terminal (HEART). More recently, Abu-Odeh et al. (2018) evaluated a newly proposed guardrail system for short-radius intersections.

Other studies focused on the comparison of multiple barrier end treatment types. Pigman et al. (1985) compared various types of end treatments, including Hi-Dro cell, GREAT, GREAT-T, sand-barrel, and steel-drum, based on a small crash sample (127 collisions) from Kentucky. These crash cushions properly functioned 85% of the time, and the most typical adverse consequences involve rebounding the vehicle into or across the adjacent roadway and overturning the vehicle. In all cases, they found that the crash severity was lower than expected from a BCT. Hunter et al. (1993) compared the performance of various guardrail ends and found that rollover produced the highest rate of driver injury. Barrier-end hits were more likely to result in driver injury than barrier-face hits by being more likely to produce rollovers and by producing more severe injuries when no rollovers occur.

Notably, Johnson and Gabler (2013) compared standard-compliant end treatments to non-compliant devices accounting for the effect of rollover. They found frontal crashes to end terminals compliant with NCHRP Report 350 safety criteria have injury odds between 11 and 19 times lower than non-compliant designs. Rollover and unbelted occupants were associated with 25% of all frontal guardrail crashes yet were present in 61% of severe injury crashes. Rollovers occurred in 9.2% of all frontal guardrail crashes and were linked to the guardrail in roughly 49% of instances.

Schrum et al. (2015) performed a cost-benefit analysis of crash cushion systems classified by their redirecting capabilities and maintenance cost. Crash cushions were categorized into three different classes: redirecting with repair costs (RGM) > $1,000, redirecting with repair costs < $1,000 (RLM), and non-redirecting sacrificial (NRS). Only RGM and RLM are cost-effective on freeways and divided rural arterials. All three were found competitive on undivided rural arterials and local roads.

More recently, Molan and Ksaibati (2021) performed a severity analysis of guardrail end crashes. Model predictors include end treatment type, surface condition, weather, speed limit, longitudinal grade, vehicle type, rollover indicator, sex of driver, alcohol, fatigue, and seat belt use. The end anchorage type A-FLEAT 350 was least likely to result in severe injuries in crashes. On the other hand, the turned-down end terminal and the end anchorage WYBET were involved with higher injury severity in crashes.

Various states have adopted FHWA's call for in-service performance evaluation of their barrier end treatments. For instance, Spainhour et al. (1999) developed a multicriteria decision support system to rank attenuators based on past safety performance in Florida. This application supports the design and selection of attenuators for new locations; it can also be used to analyze current placement recommendations for common scenarios. Other in-service performance evaluations took place in Wyoming (Molan & Ksaibati, 2021) and Washington (Igharo et al., 2004).

Previous research in Indiana focused on collisions with longitudinal barrier faces. Villwock et al. (2011) studied the safety effects of cable barriers. They found that cable barriers eliminate 94% of multi-vehicle opposite-direction crashes. However, a 70% increase in single-vehicle crashes was observed on wide, depressed medians. More recently, Zou and Tarko (2016a, 2016b, 2018) developed crash modification factors and estimated the average crash cost applicable to three types of barriers: cable, guardrail, and concrete. Intuitively, barrier-related crashes are higher on roads with barriers. The average unit cost of a crash is reduced by 50% with barriers installed in the median. Roadside guardrails tend to reduce the unit cost by 20%–30%.

The present study aims to expand the current knowledge of the safety performance of barrier end treatments by performing a large-scale in-service performance evaluation of barrier end treatments and impact attenuators. Results from this evaluation are

Figure 2.23 Typical no terminal treatment.

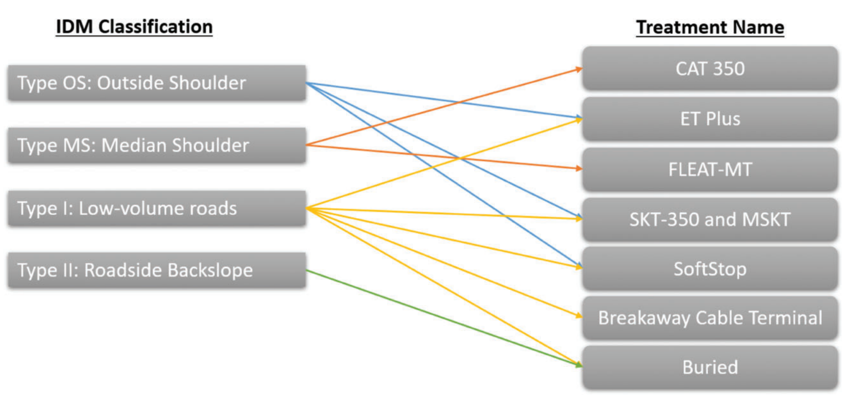


Figure 2.24 Indiana Design Manual's classification of barrier end treatments.

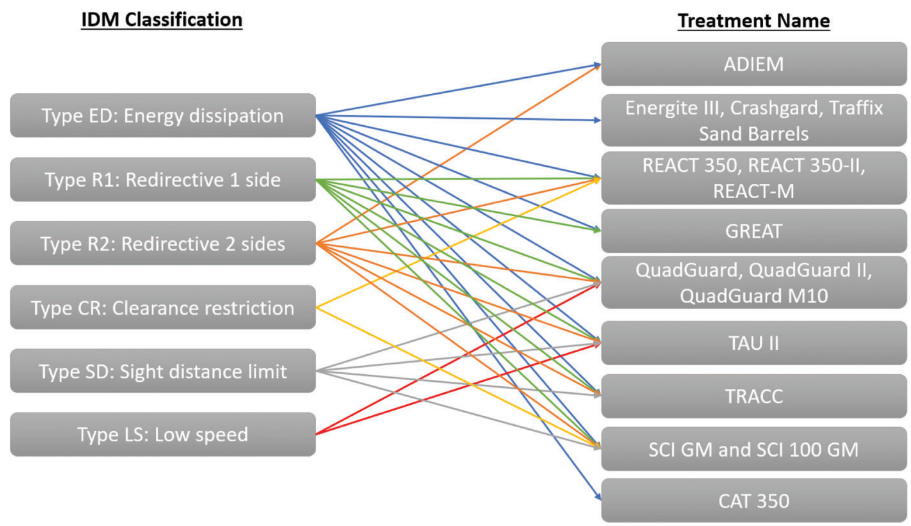


Figure 2.25 Indiana Design Manual's classification of impact attenuators.

summarized for specific traffic and road conditions to select the most effective barrier end treatment. In addition, the average unit crash costs by end treatment types are also estimated to provide one of the inputs needed in benefit-cost analysis.

3. METHODOLOGY

This chapter introduces the overall methodology and procedure applied in this project (Section 3.1), the statistical modeling considerations (Section 3.2), the adjustment for crash underreporting (Section 3.3), and the estimation of the average cost (Section 3.4).

3.1 Overview

The main objective of this project is to evaluate the in-service performance of barrier end treatments and impact attenuators on crash severity reported by police after the safety device was hit by a vehicle. To accomplish this objective, five key factors were considered.

1. Barrier end treatments and impact attenuators perform differently. They are considered by designers for different conditions, and therefore they should be evaluated separately.
2. Police crash reports do not include the type of safety device being hit. Therefore, the location of reported crashes must be linked with the location of the safety device to identify the specific type of barrier end treatment or impact attenuator.
3. In addition to the type of safety device hit by a vehicle, other factors also affect the crash severity outcome: vehicle types, weather conditions, and operating speed, among other variables. Statistical modeling must separate these effects from one another to properly evaluate the effect of the safety device itself.
4. Single-vehicle collision underreporting is a well-known issue. After hitting a roadside or median element, some drivers leave the crash scene without reporting the event to the police. Ignoring these under-reported crashes skews the distribution of severity towards more severe ones. To mitigate this issue, guardrail end treatment and attenuator repair data must be used to correct the results, at least to some extent.
5. The National Highway Traffic Safety Administration (NHTSA) provides average costs of personal injuries for different severity levels. These unit costs may be used to calculate the average costs of collisions with end treatment and attenuators at various levels of crash severity (the highest personal severity) and for different road classes (interstate or U.S./state routes).

The above considerations are summarized in the diagram in Figure 3.1, which presents the framework of this project. More detailed information is provided in the following sections. Section 4.2 introduces the crash assigning process that links end treatment inventory to crashes; Section 3.2 introduces the statistical considerations to model barrier end treatment effects; Section 3.3 and Section 3.4 introduce the methods used to adjust under-reporting and estimate average cost.

3.2 Statistical Framework

The primary objective of this study is to estimate the barrier end treatments' effect on crash injury severity. A proper definition of crash severity levels is needed. The KABCO scale is widely used for this purpose, where K = fatality, A = incapacitating injury, B = non-incapacitating injury, C = possible injury, and O = property damage only, aka PDO. In a crash, several persons may be injured at different levels of severity. Crash severity is defined by the most severe injury among the involved persons, regardless of the number of injured. In the reported study, crash severity was measured at three levels after grouping some of the original levels: KA, BC, and O. This report denotes the severity levels using numbers growing with the growing severity level: 1 = PDO, 2 = BC, and 3 = KA. These three numerical levels are used in the statistical analysis.

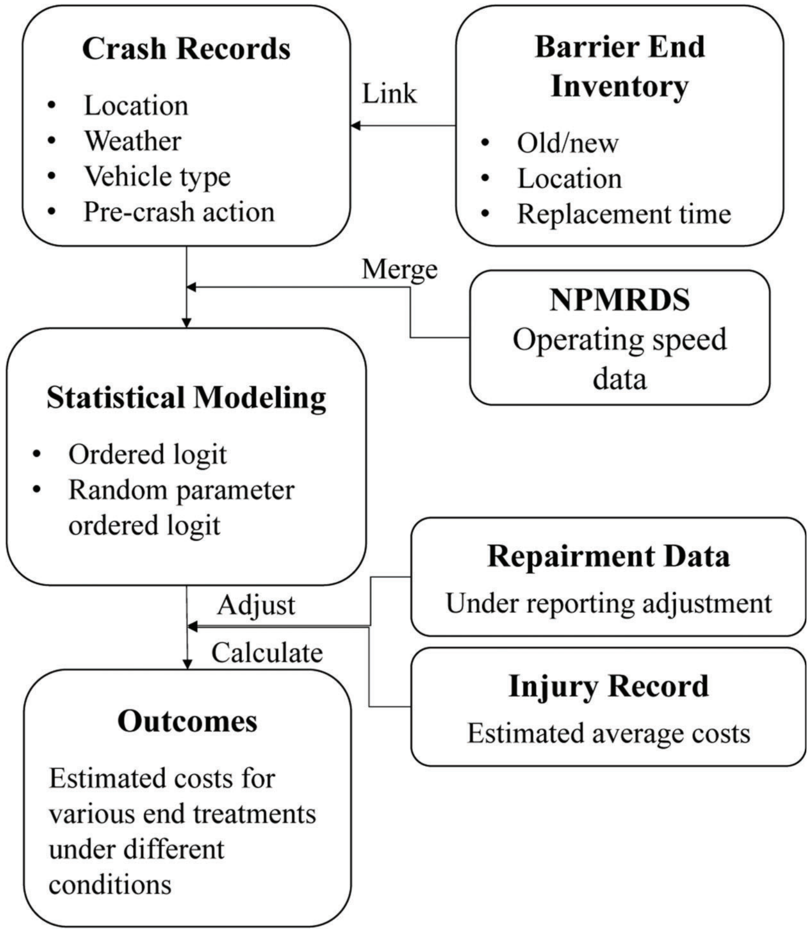


Figure 3.1 Analysis framework.

3.2.1 Ordered Logit Model

Multiple statistical methods can model the probability of falling into defined crash severity levels. Such models use a link function, e.g., logit or normal, to estimate a categorical variable, aka response or Y, based on a defined set of conditions, aka predictors or X. Considering the intrinsic ordering property of crash severity, i.e., PDO crashes are less severe than BC crashes, and BC crashes are less severe than KA crashes, the ordered logit model is selected for our analysis. The ordered logit model assumes proportional odds. The proportional odds assumption indicates that the effects of X variables are the same between PDO and BC and between BC and KA. This assumption needs to be validated using a test such as the Brant-Wald statistic.

The ordered logit model introduces an unobservable latent variable z, which is used as a basis for modeling the ordinal ranking of data. The discrete severity levels were assumed to be associated with this latent variable. This variable is mainly specified as a linear function for each observation (Equation 3.1) where $\boldsymbol{X_i}$ is a vector of variables (barrier end treatment dummy variables and all other factors that might influence the crash severity), $\boldsymbol{\beta}$ is a vector of estimated parameters, and ε_i is a random error term.

$$Z_i = \boldsymbol{X_i \beta} + \varepsilon_i \qquad \text{(Eq. 3.1)}$$

When the values of this latent variable z_i fall into a specific range, observation *i* corresponds to one of the three crash severity levels, $\boldsymbol{y_i}$=1, 2, or 3 (Equation 3.2), where μ_0 and μ_1 estimated thresholds:

$$\begin{cases} y_i = 1, \; if \; z_i \le \mu_0 \\ y_i = 2, \; if \; \mu_0 < z_i \le \mu_1 \\ y_i = 3, \; if \; z_i > \mu_1 \end{cases} \qquad \text{(Eq. 3.2)}$$

To estimate the model's parameters, an assumption is made that random error ε follows either the logistic distribution or the random distribution. An ordered logit model results from a error term logistically distributed while an ordered probit model results from a normally distributed error term. After obtaining the model estimates, the probability that y_i belongs to one of the three severity categories: 1, 2, or 3 is estimated with Equation 3.3, where function *F*() is either the logistic distribution function (cumulative value) or the standardized normal density function.

$$P(\mu_{j-1} < y_i < \mu_j) = F(\mu_j - \boldsymbol{x_i \beta}) - F(\mu_{j-1} - \boldsymbol{x_i \beta}) \qquad \text{(Eq. 3.3)}$$

3.2.2 Random Parameters Ordered Logit Model

A methodological concern related to the ordered logit model is that unobserved heterogeneity across observations could exist in the data. Unobserved heterogeneity refers to the variability in Y due to factors not included in the model. Unobserved factors include vehicle type, drivers' risk perception, vehicle safety technology, and vehicle occupants' characteristics. Therefore, it is necessary to apply a methodological approach that allows for parameter estimates of variables to vary across observations of the crash data. A random-parameters (RP) ordered logit model is proposed to account for possible unobserved heterogeneity across the samples. The main difference between RP ordered logit model and the standard ordered logit is the variation of the estimated model parameter (Equation 3.4), where δ_i represents a randomly distributed error term for each sample. This term could be specified as normal, log-normal, truncated normal, triangular, or any other reasonable distribution to mimic the randomness among sample parameters. In this study, it is assumed that unobserved random parameters are randomly distributed. The log-likelihood function of the random parameter is shown in Equation 3.5 where $g(\beta_i)$ is the probability function of β_i. The numerical integration of the model with random parameters is obtained with a simulation-based maximum likelihood analysis using Halton draws.

$$\beta_i = \beta + \delta_i \quad \text{(Eq. 3.4)}$$

$$LL = \sum_i \ln \int g(\beta_i) P(x_i \beta_i) d\beta_i \quad \text{(Eq. 3.5)}$$

3.3 Crash Underreporting

In most safety studies, researchers investigate the effects of various factors on the frequency and severity of crashes by relying on police records. Police crash records are widely available and have proven helpful in identifying risk factors. However, this data source is not exempt from crash underreporting. Not accounting for crash underreporting may lead to biased estimates. (Wood et al., 2016). Some authors have linked police records to other data sources, such as hospital databases and road maintenance records, to estimate underreporting rate (Janstrup et al., 2016; Watson et al., 2015). They found that high underreporting rates decrease with the injury severity level but also increase with the involvement of vulnerable road users, young male drivers, and when a crash occurs on weekends (Janstrup et al., 2016). Additionally, advanced statistical modeling approaches such as the multinomial logit, the ordered probit, and the random parameters logit (aka mixed logit) are not immune to bias due to crash underreporting (Ye & Lord, 2011). Therefore, estimating the crash underreporting rate is recommended before performing any crash severity analysis.

In the case of barrier-related crashes, maintenance data continues to be the best way to account for crash underreporting. In this sense, repair and maintenance records from INDOT's district offices were acquired and processed. This data includes the Work Management System (WMS), DamageWise, item detail reports (aka dailies), damage to state property worksheets, and pay items. All underreported collisions were assumed to be PDO crashes. The underreporting rate was calculated for individual barrier end treatment types. Unfortunately, due to the lack of information, crash underreporting for different impact attenuator types could not be estimated.

Figure 3.2 illustrates the procedure used to detect an underreported crash. All the maintenance records included repair IDs (DW#), many of which also included crash IDs (Master Record Number) obtained from the police crash records. The repair records without crash IDs and the crash records from the police database were matched by the location of the damaged safety device (barrier end or impact attenuator) and with an additional inspection of the crash description in the police data. This process allows the identification of additional crashes that were reported to the police but were not included in the repair records. Such crashes were included in the in-service analysis. All the remaining unmatched repair records indicated collisions that were not reported to the police. Since most underreported collisions are of low severity, they were assumed to be PDO crashes in the statistical analysis.

3.4 Average Cost Estimation

Costs of collisions of different levels of severity and by safety device type are needed to estimate the average crash costs by safety device type. These costs are used to measure the in-service performance of the devices. In this study, the latest average economic costs of personal injuries from the National Safety Council site (NSC, 2022) were used to estimate the cost of individual crashes. These costs of individual crashes reflected the number of injured persons and their injury severity. Equation 3.6 considers the number of damaged vehicles and the number of injured persons at different severity levels. The average crash costs by type of roads (interstates, interchanges and ramps, U.S. routes and state routes), barrier end treatment type, and crash severity levels were calculated based on Indiana's crash data from 2015 to 2021.

$$C = \$4{,}600 \cdot DV + CO \cdot \$12{,}500 + \$155{,}000 \cdot CP + \$336{,}000 \cdot BP + \$1{,}219{,}000 \cdot AP + \$11{,}148{,}000 \cdot KP \quad \text{(Eq. 3.6)}$$

where C is the crash cost ($), KP is the number of fatalities (persons), AP is the number of incapacitating injuries (persons), BP is the number of non-incapacitating injuries (persons), CP is the number of possible injuries (person), CO is the number of no injuries or PDO units (person), and DV is the number of damaged vehicles.

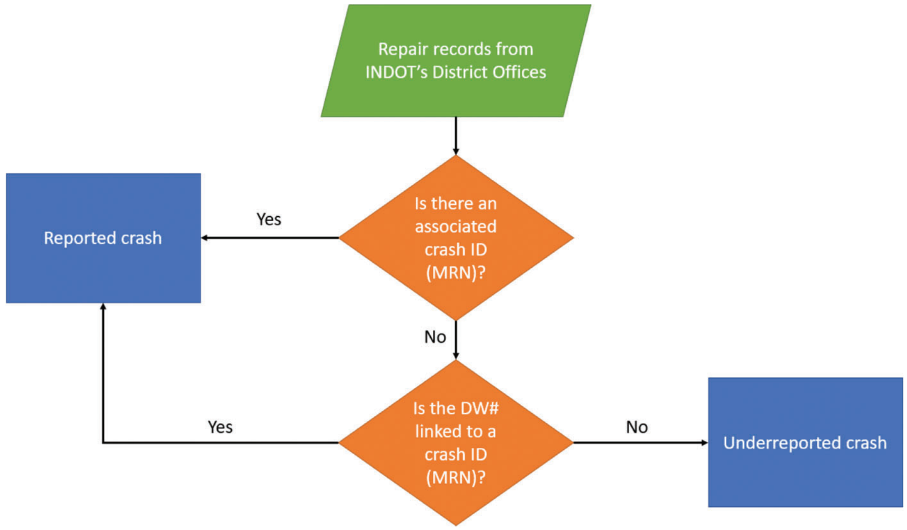


Figure 3.2 Detecting non-reported collisions with barriers and attenuators.

4. DATA

4.1 Data Sources

High-quality data on barrier end collisions and related factors is paramount for performing the proposed crash severity analysis. Therefore, a complete list of data sources and a description of their characteristics are presented in this section. The data includes crash records, weather conditions, operating speeds, roadway characteristics, and maintenance operations.

4.1.1 Crash Records

The Automated Reporting Information Exchange System (ARIES) is the State of Indiana's crash repository. First responders generate the crash reports and diagrams to be later stored in ARIES. Data are available from 2007 to the present. These data include crash details such as vehicle information, road conditions, crash severity, weather conditions, location, date, and time.

This study used ARIES crash records to assess individual vehicles' crash severity and link it to various risk factors. Based on the study's focus, single-vehicle and multi-vehicle crashes where vehicles initially collide with barrier ends are selected for further analysis. In addition, the crash location, i.e., geographical coordinates, were revised using the Crash Location Improving Program (CLIP) software tool.

4.1.2 Weather Conditions

Information on short-term weather conditions was acquired from the Local Climatological Dataset (LCD). LCD is a database maintained by the National Oceanic and Atmospheric Administration (NOAA)'s National Center for Environmental Information (NCEI). It consists of detailed weather conditions gathered from a network of sophisticated weather stations located primarily at urban centers near airports. There are 32 weather stations in Indiana. These stations provide information on precipitation, temperature, wind speed, wind direction, and visibility every 15 minutes.

4.1.3 Travel Speeds

Operating travel speeds at the segment level were acquired from the National Performance Monitoring Research Data Base (NPMRDS). NPMRDS is a vast historical archive of travel times aggregated in 5-minute increments covering the entire National Highway System (NHS). While this dataset started in 2012, the NPMRDS v2, which started in 2017, is currently the only one readily available. The variables included in the NPMRDS are segment ID (TMC code), state, county, date, time, travel time for all vehicles/passenger vehicles/freight vehicles, segment length, and the geographical coordinates of the segment end.

Operating speeds offer a dramatic advantage when performing crash severity analysis over the posted speed limit. Ideally, one should access the operating speed of a vehicle in the immediate moment before a crash occurs. However, operating travel speeds correlate with individual speeds, especially in low-volume conditions.

4.1.4 Roadway Characteristics

Roadway characteristics, including access control, Average Annual Daily Traffic (AADT), barriers, functional classification, number of lanes, median width, median treatment, shoulder width, and speed limits, are well-known factors affecting the frequency and severity of crashes. Particularly, the inventory of barriers and barrier ends is at the center of this study. Such data was gathered from INDOT's Road Network Dataset (RND). RND is an inventory of various roadway characteristics collected from May 2014 to February 2020 on state-administered roads.

INDOT is currently collecting a new inventory to update the RND. The research team acquired both previous and new inventories. While incomplete, the new inventory offers the latest information on barrier end treatment types and will be preferred over the old inventory where available.

There are three significant limitations of the RND. First, the lack of an installation date for individual barrier end treatments. It is recommended that barrier end treatments be given a unique identification number linked to crash and repair records. Not having this information impacted the present study significantly by intensifying the data preparation task and reducing the certainty of the end treatment type in the event of a crash. The second limitation refers to the labels of "other," "unknown," and "no terminal" for end treatments. An additional manual data collection was made for more than 600 barrier-related crashes linked to these end treatments. Most of these crashes were linked to a known barrier end treatment type using crash narratives and Google's Street View imagery. The last limitation applies to the new inventory. The new inventory has separated barrier end treatments' shapefiles (dots) and the barriers' shapefiles (lines) without unique ID linkage between them. The old inventory recorded the end treatment types and the barrier's shapefile in one spatial feature (line), so the bearing of the barriers could help to identify whether the vehicle hit the "head" or "trail" of the barrier. A similar procedure is not possible with the graphical representation of the new inventory.

4.1.5 Maintenance and Repairs

Maintenance and repair records provide information on the specific barrier end treatment type between consecutive road inventories. In addition, maintenance data can be used to estimate the crash underreporting rate. Several datasets were acquired for these purposes, including the Work Maintenance System (WMS), daily work reports (aka dailies), DamageWise, pay items, and repair information from INDOT's district offices.

WMS provides information on maintenance operations performed by INDOT. However, most barrier end treatment replacements are now outsourced to contractors, and only a tiny portion of these operations (114 records since 1998) are recorded in WMS. Nevertheless, it is recommended to start inputting all records into the WMS format to facilitate future analysis related to barriers or other roadside safety hardware.

Daily reports offer maintenance operations performed by INDOT contractors. However, there is no unique format, and each contractor has their way of filling out this form. In addition, the end treatment type is unavailable in most sites, and the location description is insufficient to identify which barrier end is being maintained.

DamageWise contains billing information for barrier elements and is attached to crash records. While the specific type of barrier end treatment is unavailable, the link to the crash records permits an exact location of the repair. It facilitates the link to a nearby end treatment type. In this study, this dataset is primarily used to estimate the crash underreporting rate.

The pay items are a summary of maintenance operations with the annual number of items and costs. It helps to calculate the average cost of replacing groups of end treatments. However, it does not provide enough information to estimate the cost of replacing/repairing specific barrier end treatment types.

Finally, maintenance and repair information at the district level was acquired. Table 4.1 summarizes the available data for each INDOT district. Crawfordsville and Vincennes districts did not reply to the call for data. Most districts do not store data older than 1 or 2 years. It is recommended to use a system maintained by INDOT's central office, such as WMS, to store these items. Greenfield District data is by far the one with the highest quality having the date and time of the repair linked to crash records. Therefore, Greenfield data was used to estimate the crash underreporting rate. It is assumed that this rate is transferable to all districts across Indiana. While Greenfield District's repair and maintenance data were used to estimate the underreporting rate of guardrail end treatment hits, it is assumed that these estimated rates are applicable in other districts. Future research may confirm this assumption once data becomes available. The comparative results from the in-service safety performance evaluation regarding the most effective barrier end treatments are based on crash records and inventory data from all districts across Indiana.

4.2 Data Preparation

As shown in Figure 4.1, the data preparation process consists of two major phases: assigning correct barrier end treatments to crashes and linking other factor data.

4.2.1 Crash Assigning

The crash assigning phase consists of four steps. These steps enable a semi-automatic linkage between barrier end treatments and crashes.

1. *Identification of Barrier End-Related Crashes*
   Two filters, including barrier end keywords in the narratives or reported to collide with "guardrail end," "impact attenuator/crash cushion," "crossing center line/median," or "ran off the roadway," were firstly used to collect crash samples. The collision sequence of all vehicles involved in these crashes was then examined to ensure that barrier ends were the first object the vehicles hit. In this study, only crash samples

TABLE 4.1
Available maintenance and repair data from INDOT's district offices

District	From	To	Number of Records	Format	Pictures	Crash ID	Cost
Fort Wayne	6/2019	12/2020	43	PDF	Yes	Alternative	Yes
Greenfield	8/2016	6/2021	724	XLSX	Yes	Yes	Yes
LaPorte	3/2019	3/2021	59	PDF	No	No	No
Seymour	1/2020	12/2020	121	XLSX	No	Alternative	Yes

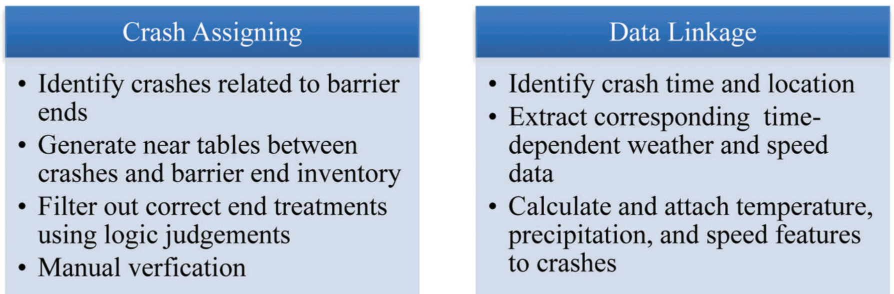


Figure 4.1 Data preparation process.

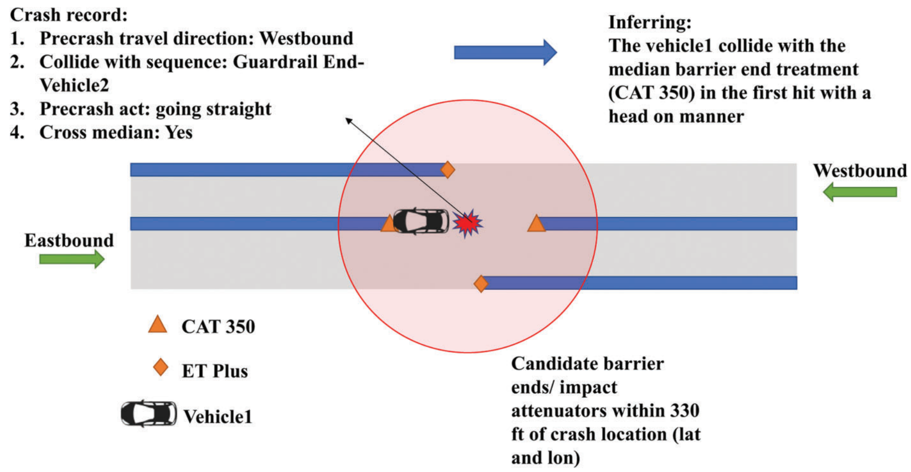
that "first hit end treatment" are considered. When vehicles hit other objects first, the "real" effects of barrier end treatments might be masked due to biased conditions. The reason to include "crossing center line/ median" and "ran off roadway" is that the crash records will sometimes describe the collision sequence as running off the road first and then hitting the barrier ends. Still, these cases are comparable to hitting barrier ends first, so these samples are also included in the analysis.

2. *Generating Near Tables*
Using GIS, the geographical coordinates of barrier end treatments and crashes are compared by spatial proximity. All barrier end treatments within 50 meters of crash locations are filtered out as candidates. It should be noted that in the first step, over 7,000 barrier end-related crashes were identified. Still, since the provided barrier inventory only covers interstates and state roads (missing local roads), only 30% of these crashes were assigned with barrier ends.
3. *Logic Judgments*
After obtaining all candidates, logic rules were used to determine the correct barrier end treatments for each crash. Figure 4.2 shows an example of several candidate barrier end treatments for one crashed vehicle. In Scenarios A and B, there are four candidates within 50 meters of Vehicle 1, but the reported pre-crash maneuvers and collision information from the crash records differed. In Scenario A, Vehicle 1 was going straight to the west before the crash and was reported to cross the median, so it was inferred that this vehicle had collided with the median barrier end treatment CAT 350. While in Scenario B, Vehicle 1 was going straight to the east and was not reported to cross the median, so it was inferred that this vehicle had collided with the shoulder barrier end ET-Plus.
4. *Manual Verification*
Using the above automatic assigning process, over 95% of crashes could be successfully assigned to reasonable barrier ends. However, some crashes still had different candidates for barrier end treatments due to missing information or complicated scenarios. For these samples, manual verifications were performed using historical satellite images and street view records from Google.

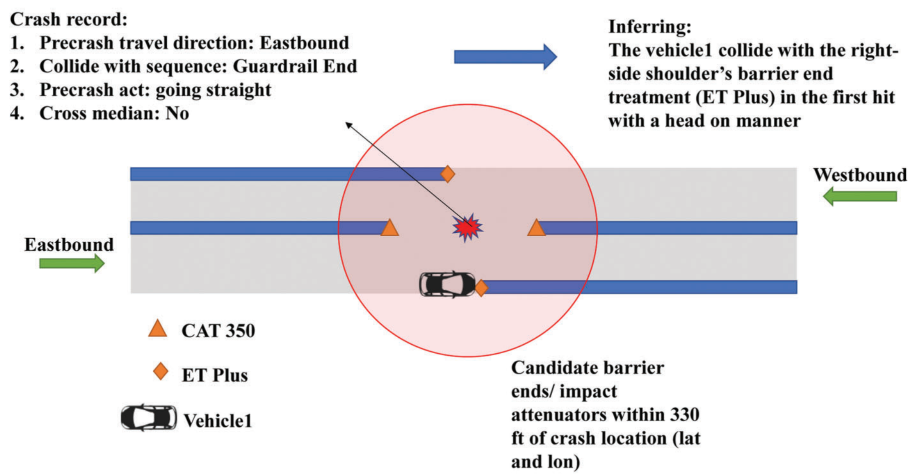
4.2.2 Data Linkage

After assigning the barrier end treatment types, other factors, including weather and operating speed features, were linked to the modeling data set in the second phase. The assigning of such factors involved three major steps described below.

1. *Crash Time and Location Identification*
The crash times were recorded with a precision of up to 1 minute. The segment with a crash was determined based on its spatial proximity to the crash location and its bearing.
2. *Speed and Weather Data Extraction*
The operating speeds were reported in 5-minute intervals. Depending on the segment (speed) or region (weather) ID, the speed and weather conditions of the crash were extracted from various databases. The shapefiles—spatial backbones of speed data—were updated every half a year.
3. *Attaching Speed and Weather Features*
The average speed data in 5-minute intervals do not provide precise speeds at which vehicles hit barrier ends or impact attenuators. Instead, they reflect the overall operating condition. To check which speed aspect is the best predictor of crash severity, multiple options were tried in the analysis—the average speed during the crash hour, the hour before the crash, and the average speed during the week when the crash occurred. In addition, the weather conditions at the time of the crash were also included in the data set to be used in the analysis.



Scenario A: The vehicle collides with CAT 350



Scenario B: The vehicle collides with ET-Plus

Figure 4.2 Barrier end treatment and crash linkage example.

4.3 Data Summary

4.3.1 Barrier End Treatments and Impact Attenuator Inventory

According to the old inventory, the INDOT Road Network Dataset included 28,584 records with barrier end treatments and impact attenuators. Figure 4.3 shows the distribution of barrier end records by end treatment type. The most common barrier end treatment was Buried I, followed by ET-Plus, and CAT 350. In terms of impact attenuators, the most frequent were barrels, followed by QuadGuard. The database contained more than 20 barrier end treatment or impact attenuator types.

As already discussed, only portions of the new inventory were provided to the research team. Figure 4.4 compares the complete old inventory data and the new inventory data collected up to the time of the study.

4.3.2 Estimated Crash Underreporting Rate

Table 4.2 presents the total number of maintenance records, the number of records successfully linked to crashes, and the resulting underreporting crash rate by barrier end treatment type. Although the underreporting rate shows a significant difference among different end treatments, it is probably due to the randomness of counts in small samples. For end treatment types with relatively large samples, e.g., CAT 350, ET-Plus, and SKT 350, the underreporting rates are similar (25%–30%). In this study, the adjustments of underreporting were performed for CAT 350, ET-Plus, MSKT, and SKT 350, according to this table. For other end treatments, the average underreporting rate of 27.3% was used.

4.3.3 Linked Crashes Distribution

The distribution of linked crashes among barrier end treatments is shown in Table 4.3. Indiana crash data from 2014 to 2021 was used for this purpose. There are

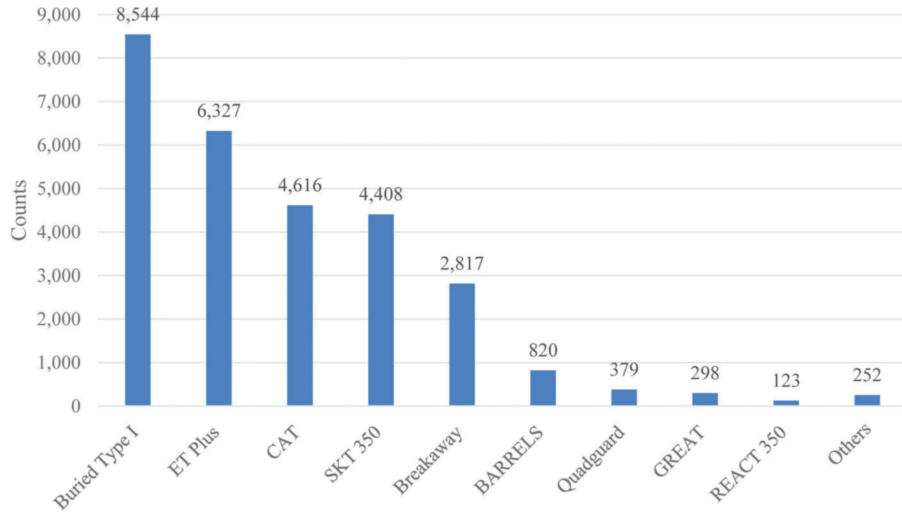


Figure 4.3 Distribution of barrier end treatment and impact attenuator types.

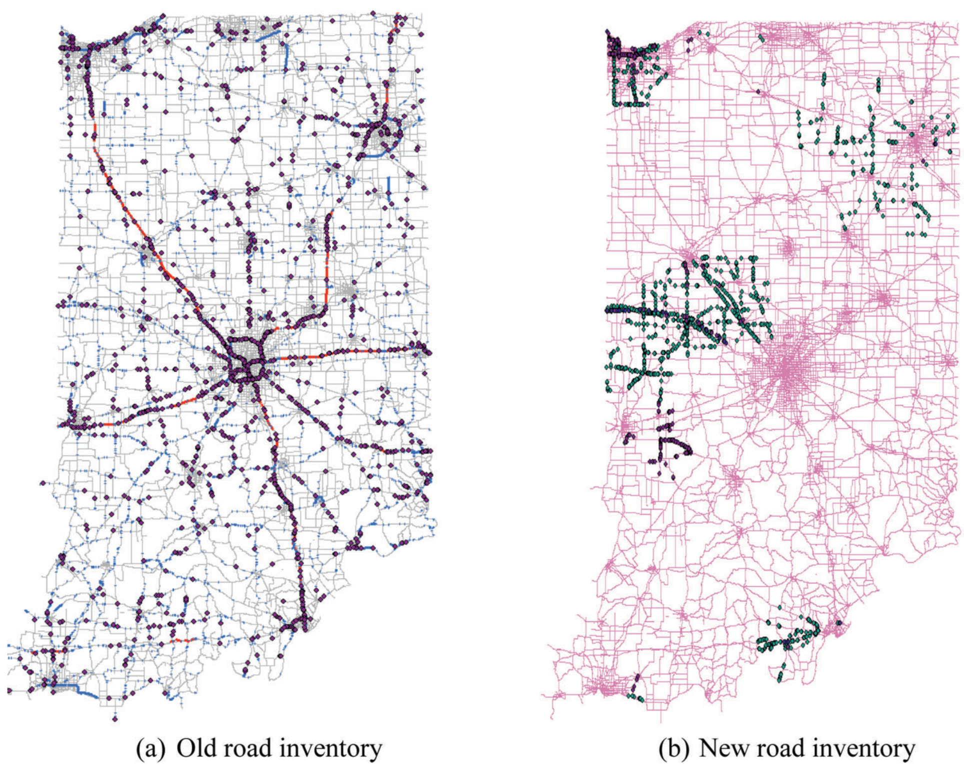


Figure 4.4 Comparison of old and new inventories.

crash data for ten barrier end types and six impact attenuator types. However, some of the newly implemented types, e.g., SOFT STOP, and some rarely used types, e.g., HEX-FOAM, do not offer a sufficient sample. Therefore, barrier end treatments with less than five crashes are excluded from the analysis.

It should be noted that not all crashes that are reported to be related to barrier end treatments or impact attenuators are linked to end treatment devices. The spatial distributions of such crashes and end treatment inventory are shown in Figure 4.5, which shows the discrepancies between available end treatment inventory and such crashes. Most of these unlinked crashes are in urban areas where end treatments inventory data is not complete. Improving the coverage of barrier end treatments inventory would bring back more samples for future analysis.

4.3.4 Descriptive Summary

In the analyzed period of 2014–2021, there were 2,250 reported collisions with barrier ends, and 398

TABLE 4.2
Estimated crash underreporting rates by barrier end treatment type

End Treatment Type	Total Number of Records	Records Linked to Crashes	Underreporting Rate (%)
Breakaway Cable Terminal	15	9	40.0
Buried	13	12	7.7
CAT 350	108	79	26.9
ET-Plus	204	144	29.4
MSKT	76	56	26.3
SKT 350	122	89	27.0
SOFTSTOP	1	0	100.0
TRACC	2	2	0.0

TABLE 4.3
Barrier end treatment and impact attenuator distribution among linked crashes

Barrier End Treatments	Frequency	Percentage (%)
ETPlus	504	22.4
CAT	438	19.5
No Terminal	381	16.9
SKT_350	360	16.0
Buried	248	11.0
Others	132	5.9
MASH_MSKT	72	3.2
Breakaway	61	2.7
Fleat-MT	40	1.8
Breakmaster	14	0.6
Total	*2,250*	*100*
Impact Attenuators	**Frequency**	**Percentage (%)**
QuadGuard	172	50.0
REACT_350	58	16.9
GREAT	40	11.6
SCI_100_GM	37	10.8
TRACC	21	6.1
QuadGuard_M10	16	4.7
Total	*344*	*100*

reported collisions with impact attenuators. Approximately, 70%–75% of these crashes were PDO crashes while the numbers of BC and KA crashes were comparable one to another. The summary of crash data can be found in the dependent variable table (Table 4.4).

The summary of independent variables for the investigated barrier end treatments is presented in Table 4.5 and for the impact attenuators in Table 4.6. In these two tables, the variables related to measured speeds are continuous while the other factors: weather, vehicle type, location, speed limit, and barrier end treatments are categorical. It should be noted that the threshold 150 ft. in the variable "Intersection" from Table 4.5 was determined during the modeling process. Different ranges (from 100 ft. to 600 ft.) as well as upstream or downstream of intersections were tested and this 150-ft. threshold was finally selected by model fitness.

4.3.5 Estimated Average Crash Costs

Using the average cost estimation method described in Section 3.4, the estimated average crash costs were calculated and are shown in Table 4.7. The estimated costs are based on 2,393 crashes in Indiana from 2015 to 2021. All the costs have been rounded to $1,000 in 2018 USD.

The mean crash costs between different locations are generally close when there are enough samples. For non-interstates, the costs for impact attenuator-related crashes are higher than those for guardrail end treatments. It is probably due to different application scenarios. Impact attenuators are near solid roadside obstacles like bridge piers, overhead signs, and concrete barriers.

Although in the final application models, the road functional class were found to be insignificant, their

Figure 4.5 Spatial distribution of barrier-end-related crashes (red) and end treatments inventory (black).

TABLE 4.4
Descriptive summary of dependent variable (severity levels)

	Barrier Ends		Impact Attenuators	
Severity Levels	**Counts**	**Percentage**	**Counts**	**Percentage**
PDO	1,709	76.0	277	69.6
BC	233	10.4	61	15.3
KA	308	13.7	60	15.1
Total	*2,250*	*100.0*	*398*	*100.0*

Note: For severity levels, K = fatality, A = incapacitating injury, B = non-incapacitating injury, C = possible injury, and PDO = property damage only.

summarized costs vary according to Table 4.7. This discrepancy is probably due to the definition of severity level, which only consider the level of the most injured person. In this average crash costs estimates, we also consider numbers of injured persons for practical use of the results.

TABLE 4.5
Descriptive summary of modeling data (barrier ends)

Continuous Variable	Mean	Standard Deviation	Description
Speed	51.65	13.07	Speed of the crash hour
Speed0	56.752	10.026	Speed of the hour before the crash
Opersp	57.074	8.672	Average speed of the same crash hour of one week before the crash date
Stdsp	6.869	5.607	Standard deviation of speed
Stdsp0	4.304	3.902	Standard deviation of speed0
Newspeed	52.104	13.354	Merged speed limit and speed (when there is missing data for speed, replace with the posted speed limit)
Newspeed0	56.521	14.035	Merged speed limit and speed0 (when there is missing data for speed0, replace with the posted speed limit)
Categorical Variable	**Percentage (%)**		
Daylight	49.93		Equals 1 if the crash happened during daytime
Rain	15.91		Equals 1 if it was raining when the crash happened
Snow	7.98		Equals 1 if it was snowing when the crash happened
Drysurf	63.40		Equals 1 if the pavement was dry when the crash happened
Wetsurf	20.20		Equals 1 if the pavement was wet when the crash happened
Icesurf	16.26		Equals 1 if the pavement was icy when the crash happened
Interstate	53.26		Equals 1 if the crash happened on interstate
Usroute	17.24		Equals 1 if the crash happened on a U.S. route
Stateroad	23.79		Equals 1 if the crash happened on a state road
Countyroad	1.06		Equals 1 if the crash happened on a county road
Localroad	3.85		Equals 1 if the crash happened on a local road
Truck	12.20		Reference = passenger car; vehicle type dummy variables
Otherveh	1.30		
Pickup	13.80		
VanSUV	12.90		
PassengerCar	59.80		
Intersection	15.46		Equals 1 if the crash happened within 150 ft. from the center of intersections
InterchangeRamp	10.80		Equals 1 if the crash happened on interchanges or ramps
Speed limit ≥ 40	93.75		Equals 1 if the speed limit is greater than or equal to 40 mph
Speed limit (mph)	<40	6.3%	Distribution of speed limits (The distributions of barrier end treatments on different speed limits in the modeling sample set are attached in appendix for the reference)
	40	3.1%	
	45	11.9%	
	50	4.9%	
	55	45.8%	
	60	5.9%	
	65	7.3%	
	70	15.0%	
Precipitation	23.88		Equals 1 if sum (snow, rain) > 0
Breakmaster	1.20		Barrier end treatment dummy variables
Breakaway	1.00		
BuriedT1	4.90		
CAT	25.20		
Fleat-MT	3.20		
MASH_MSKT	4.00		
SKT_350	14.30		
Other_End	5.40		
ET plus	20.70		
NoTerm	20.10		

TABLE 4.6
Descriptive summary of modeling data (impact attenuators)

Continuous Variable	Mean	Standard Deviation	Description
Speed	50.36	13.42	Speed of the crash hour
Speed0	55.34	8.51	Speed of the hour before the crash
Opersp	56.95	7.95	Average speed of the same crash hour of one week before the crash date
Stdsp	6.852	4.02	Standard deviation of speed
Stdsp0	4.02	3.902	Standard deviation of speed0
Newspeed	52.01	13.32	Merged speed limit and speed (when there is missing data for speed, replace with the posted speed limit)
Newspeed0	56.397	13.6	Merged speed limit and speed0 (when there is missing data for speed0, replace with the posted speed limit)

Categorical Variable		Percentage	Description
Daylight		43.01	Equals 1 if the crash happened during daytime
Rain		12.37	Equals 1 if it was raining when the crash happened
Snow		6.18	Equals 1 if it was snowing when the crash happened
Drysurf		73.39	Equals 1 if the pavement was dry when the crash happened
Wetsurf		14.78	Equals 1 if the pavement was wet when the crash happened
Icesurf		11.83	Equals 1 if the pavement was icy when the crash happened
Interstate		76.61	Equals 1 if the crash happened on interstate
Usroute		8.06	Equals 1 if the crash happened on a U.S. route
Stateroad		6.72	Equals 1 if the crash happened on a state road
Countyroad		1.08	Equals 1 if the crash happened on a county road
Localroad		4.57	Equals 1 if the crash happened on a local road
Truck		9.95	Reference = passenger car; vehicle type dummy variables
Otherveh		0.27	
Pickup		10.48	
VanSUV		21.24	
PassengerCar		58.06	
InterchangeRamp		23.12	Equals 1 if the crash happened on interchanges or ramps
Speed limit ≥ 55		66.39	Equals 1 if the speed limit is greater than or equal to 55 mph
Speed limit (mph)	<40	7.3%	Distribution of speed limits (The distributions of impact attenuators on different speed limits in the modeling sample set are attached in appendix for the reference.)
	40	2.2%	
	45	16.7%	
	50	7.5%	
	55	55.1%	
	60	1.3%	
	65	3.5%	
	70	6.5%	
Precipitation		18.55	Equals 1 if sum (snow, rain) > 0
BARRELS		13.57	Impact attenuator dummy variables
GREAT		10.05	
QuadGuard		43.22	
QuadGuard_M10		4.02	
REACT_350		14.57	
SCI_100_GM		9.30	
TRACC		5.28	

TABLE 4.7
Estimated average crash costs by type, location, and severity

Cost by Type, Location, and Severity (2018 USD)		Interstate		Interchanges and Ramps		U.S. Route		State Route	
		Crash Counts	Mean Cost	Crash Counts	Mean Cost	Crash Counts	Mean Cost	Crash Counts	Mean Cost
Impact Attenuator	PDO	196	$32k	30	$21k	94	$33k	172	$38k
	BC	27	$321k	6	$368k	7	$369k	27	$385k
	KA	38	$1,936k	9	$2,525k	10	$1,860k	11	$3,323k
Guardrail End Treatments	PDO	531	$22k	154	$22k	292	$20k	367	$20k
	BC	69	$303k	18	$340k	31	$267k	46	$303k
	KA	107	$2,287k	28	$1,694k	53	$1,544k	70	$2,294k

5. RESULTS AND DISCUSSION

To identify the effects of various barrier end treatments, it is essential to account for factors that might influence the severity of crashes and cause potential heterogeneity among observations. Therefore, random parameter ordered logit models were developed to better account for the heterogeneity. On the other end, not all the factors are controllable by road engineers (e.g., the type of vehicle that hit the treatment), and randomness are assumed for new end treatments. Therefore, another set of models that include only fixed effects and controllable factors was developed to implement the obtained results accurately. These two sets of models are discussed in Section 5.1, while Section 5.2 provides an example of applying the results obtained with simpler and more practical models.

5.1 Model Interpretation

5.1.1 Random Parameter Ordered Logit Model

The estimation results of the random parameter barrier end treatment model are shown in Table 5.1. There are 15 significant variables at a 90% confidence level, including two thresholds to differ from three severity levels and two standard deviations of random parameters. All the variables listed in Table 4.5 have been tested for their significance when estimating models, so those variables that did not show up in the final model imply no significant influence over crash severity. Since the severity levels are defined as PDO-1, BC-2, and KA-3, a positive value implies the severity increases when the factor is induced, and a negative value implies the opposite influence. For all the factors, their effects are compared with the corresponding reference, and the greater the absolute value of the coefficients, the larger effects it will have on crash severity.

Although not all significant variables discussed in the following section will be used in practical models, these discussions will help increase the general knowledge and users' understanding of the safety performance of the studied safety devices under conditions included in the models.

5.1.1.1 Barrier end treatment-related variables. Four barrier end treatments, MASH_MSKT, SKT 350, ET-Plus, and CAT, were identified to be significantly better than the reference (no terminal). Among them, *CAT* has the most considerable absolute coefficient value of -1.72. Still, this factor was also identified as a random parameter with a significant 1.81 standard deviation, as shown in Figure 5.1, which implies that in 82.9% of cases, the CAT performs better than the no terminal. This significant randomness among CAT samples implies that its performance is not as stable as the other three treatments. According to their coefficients, the performance ranking for the other three treatments is MASH_MSKT > SKT 350 > ET-Plus.

5.1.1.2 Vehicle type-related variables. The vehicle-related variables: *Truck*, *VanSUV*, and *sd.Truck* indicate that vehicles experience significantly different crash severity after hitting a barrier end treatment compared to the reference vehicle type–passenger car. The positive value of the *VanSUV* coefficient implies a higher probability of severe outcomes than passenger cars. The negative *Truck* coefficient implies a lower probability of severe outcomes than for passenger cars. The result for *Truck* is expected since trucks are generally more robust than other vehicle types and much heavier. When trucks hit barrier ends, the impact tends to damage the barrier considerably, while it seldom causes severe injuries to truck drivers. It relates to a large displacement or a barrier end yield that weakens the rate of energy acting on truck occupants. On the other hand, the significant randomness of the effect on *Truck* (Mean = -1.29, SD = 1.63) implies that truck effects vary greatly across collisions.

On the other hand, the much more severe result of the collision experienced by van or SUV occupants may

TABLE 5.1
Random parameter ordered logit model estimation results (barrier end treatment)

Parameter	Estimate	Standard Error	Z-value	P-value
Limit1	2.0948	0.3372	-6.212	<0.001
Limit2	2.8676	0.0535	14.437	<0.001
Drysurf	0.3861	0.1301	2.968	0.003
VanSUV	0.3544	0.1450	2.444	0.015
Truck	-1.2863	0.6585	-1.953	0.051
Intersection	-0.6729	0.2657	-2.533	0.011
Snow	-0.4571	0.2573	-1.777	0.076
MASH_MSKT	-0.6763	0.3329	-2.031	0.042
SKT 350	-0.3738	0.1520	-2.459	0.014
ETPlus	-0.2776	0.1336	-2.078	0.038
CAT	-1.7177	0.6236	-2.754	0.006
Newspeed0	0.0174	0.0057	3.062	0.002
Drysurf:CAT	1.2743	0.4694	2.714	0.007
sd.Truck	1.6342	0.8202	1.992	0.046
sd.CAT	1.8080	0.6160	2.935	0.003

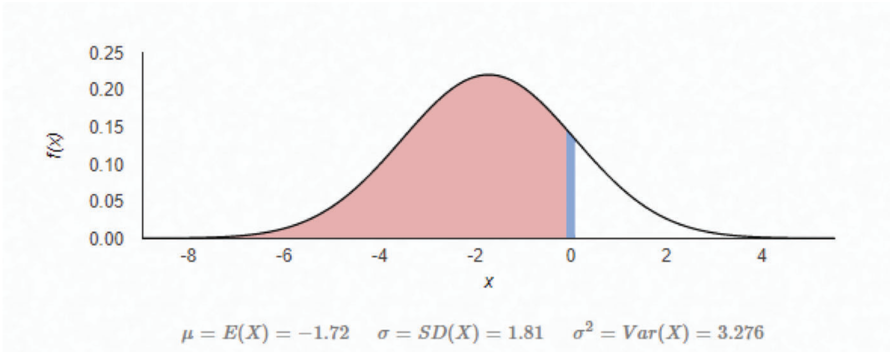


Figure 5.1 Normal distribution (mean = -1.72, SD = 1.81).

be surprising. One possible explanation is that vans and SUVs have higher chassis than passenger cars, so they are more likely to roll over after the collision with a barrier ends. This hypothesis should be checked by analyzing crash reports.

5.1.1.3 Weather, pavement condition, and intersection or not. Snowfall, dry pavement, and the presence of an intersection were found to affect crash severity. Snowfall during a collision and the presence of an intersection reduce the crash severity, while collisions on road segments tend to be more severe. These three effects may be explained via the most intuitive factor of crash severity–vehicle speed at impact. Drivers tend to drive faster on dry pavement. Their speed may be reduced by the presence of an intersection and by making turns. Drivers obviously tend to drive slower during snowfall, particularly if snow accumulates on the pavement. An additional way snow may reduce crash severity is by the cushioning effect of snow accumulated by itself or by plowing. This last explanation is less convincing than the previous two scenarios.

The positive interaction between the two variables, *drysur* and *CAT,* indicates that the effect of the CAT device is much weaker on dry surfaces than in other pavement conditions. Nevertheless, CAT still reduces crash severity.

5.1.1.4 Speed. The speed at impact is expected to be the most critical factor of crash severity. Unfortunately, this information was not available in this study. The speed at impact could be somehow reflected with operating speeds obtained from NPMRDS speed data or approximated with posted speed limits. In this study, three speed statistics were tried: the average operating speed during the hour with the reported crash (*speed*), the average speed one hour before the crash hour (*speed0*), and the average speed of the same hour of the day for the previous week (*opersp*). The second and third options were used to avoid the effect of the crash itself on the speed. When the NPMRDS speed data were missing, the posted speed limit on the segment was used instead. The modeling results indicate that only the average speed one hour before the crash hour (*newspeed0*) is significantly and positively related to crash severity. The estimated effect of the average speed (coefficient of *newspeed0*) was quite strong compared to the other factors. It was equal to 1.14 = coefficient × average speed = 0.02×57.

No randomness among parameters of the model for impact attenuators was detected, most likely, due to the limited sample size. Therefore, the fixed-parameter impact attenuator model is discussed in Section 5.1.3.

5.1.2 Fixed Effect Model for Barrier End Treatments

The fixed effect model includes all the studied end treatments, even if not statistically significant, to enable their comparison. After all, even statistically insignificant coefficients reflect the overall relative performance and carry information even if limited. The no terminal case is used as the reference (its effect is assumed to be 0).

The counts of barrier end treatments are provided in the last column (Table 5.2) to let the user know the basis of the estimated effects and why some of the parameters are not significant. It also helps evaluate the trustworthiness of the results. According to the overall distribution of crash severity levels, non-PDO crashes comprise approximately 20% of all crashes. When there are only 10–20 observations, they may include only one or two BC or KA crashes. Small but highly skewed samples may produce results that may be misleading even if they are significant by chance.

The estimated fix effects in Table 5.2 are generally slightly greater than the effects with all factors included in the random parameters models (Table 5.1). This is because some of the variability of the independent variable (severity distribution difference) from other excluded variables were assigned to the retained variables. Nevertheless, the ranking of barrier end treatments remains the same.

In the fixed effect model for barrier end treatments, two factors other than end treatment were included: the presence of an intersection within 150 ft. (*Intersection*) and a speed limit higher or equal to 40 mph (*Speed Limit* $\geq$ *40*). These two conditions are known during the treatment selection stage, so they can be used to guide selection of end treatments when applying the model. The effect of speed limit applies to all the

TABLE 5.2
Fixed effect ordered logit model estimation results (barrier ends)

Parameter	Estimate	Standard Error	t Value	P Value	Counts
No Terminal	0	–	–	–	381
MASH_MSKT	-0.6497	0.33493	-1.94	0.0524	72
SKT_350	-0.241	0.17732	-1.36	0.1742	360
ETPlus	-0.2665	0.15913	-1.67	0.094	504
Breakaway	-0.379	0.33057	-1.15	0.2515	61
CAT	-0.2665	0.15995	-1.67	0.0956	438
Fleat-MT	-0.2204	0.37804	-0.58	0.5599	40
Buried	0.1108	0.19903	0.56	0.5777	248
Breakmaster	0.1616	0.60749	0.27	0.7902	14
Others	0.0975	0.21772	0.45	0.6542	132
Intersection*Buried	-0.3854	0.31918	-1.21	0.2272	77
Intersection*SKT_350	-0.8041	0.40053	-2.01	0.0447	68
Intersection*ETPlus	-0.4797	0.3464	-1.38	0.1661	69
Speed Limit ≥ 40	0.8459	0.26541	3.19	0.0014	2,109
Limit1	1.7460	0.27643	6.32	<.0001	–
Limit2	2.4469	0.27927	8.76	<.0001	–

Note: The Counts for Intersection*Buried = 77 means that there are 77 crashes linked to Buried end treatments near intersections.

treatments, while the intersection effects have some interactions with the treatments.

The speed limit indicator replaced the *newspeed0* variable in the previous random-parameter model. The speed limit was included in the model as a categorical variable (8 levels: ≤35 mph, 40 mph, 45 mph, and so on) at the beginning. But only one significant discrepancy of model coefficients below and above 40 mph speed limit was found. Therefore, the indicator variable *SpLimit40* was used. The model including speed limits as categorical variables as well as the discussion of speed limits' effects were attached in the appendix.

The negative signs of intersection effects indicated the improved safety when crashes happened near intersections. The large (-0.8041) and significant estimates of *Intersection*SKT_350* implies that such effect is greatest when the type of end treatment is SKT 350.

According to this model, when the barrier end treatments are installed far away from intersections, MASH_MSKT (-0.6497) performs the best, followed by CAT (-0.2665), ET_Plus (-0.2665), and SKT 350 (-0.241). Breakaway (-0.379) and Fleat-MT (-0.2204) although have the second smallest and sixth smallest estimates, they have quite small samples and are not significant. The sample size for Buried and Others are relatively large, but no significant differences between them and the reference case of no treatment (no terminal) could be detected, implying that they perform as poorly as the no-treatment case.

When the barrier ends are installed near intersection, the effects from the interaction terms should be added to treatments' main effect. The new ranking become: SKT_350 (-0.241-0.8041 = -1.0451) > ETPlus (-0.2665-0.4797 = -0.7462) > MASH_MSKT (-0.6497) > Breakaway (-0.379) > Buried (0.1108-0.3854 = -0.2746) > CAT (-0.2665) > Fleat-MT (-0.2204) > No Terminal (0) > Others (0.0975) > Breakmaster (0.1616). Again, it should be noted that the effects for Breakaway and Fleat-MT might be questionable due to their insignificance in their main effects.

For model end users, road functional class (interstates, interchanges and ramps, U.S. routes, and state routes) is important when selecting end treatment. But this factor is not significant according to the model estimates. The model transferability tests between these four road functional classes were conducted to further confirm this conclusion. The assumptions and results for one of those tests are attached in the appendix for reference.

5.1.3 Fixed Effect Model for Impact Attenuators

The model for impact attenuators has fewer significant variables than the model for barrier ends due to a much smaller sample size. As shown in Table 5.3, there are two significant thresholds, *Limit1* and *Limit2*, one significant speed limit indicator, *Speed Limit ≥ 55*, and two significant end treatment types, *BARRELS* and *GREAT*.

For the impact attenuator variables, their significance is compared with the reference (the most prevailing impact attenuator type, QuadGuard). Unlike the no terminal reference in barrier end models, QuadGuard represents a median level of performance in reducing crash severity. Among all impact attenuator types, only BARRELS and REACT 350 perform better than QuadGuard.

Insufficient samples were observed for the two newly implemented impact attenuator types, SCI 100 GM and QuadGuard M10. However, even after 17 samples of SCI 100 GM-related crashes from Ohio were brought to this analysis, its estimated coefficient is still 0.04 (close to 0), indicating a similar performance compared

TABLE 5.3
Fixed effect ordered logit model estimation results (impact attenuators)

Parameter	Estimate	Standard Error	t Value	P Value	Counts
QuadGuard	0	–	–	–	172
BARRELS	-0.8200	0.4044	-2.03	0.0426	54
REACT_350	-0.5040	0.3564	-1.41	0.1573	58
SCI_100_GM	0.0375	0.3830	0.1	0.9221	37
TRACC	0.3057	0.4769	0.64	0.5215	21
GREAT	0.6645	0.3680	1.81	0.0709	40
QuadGuard_M10	0.6687	0.5002	1.34	0.1813	16
Speed Limit ≥ 55	0.6518	0.2618	2.49	0.0128	264
Limit1	1.2852	0.2430	-5	<.0001	–
Limit2	2.2832	0.1209	7.88	<.0001	–

TABLE 5.4
Practical scenario guidance table

Type	Road Functional Class	Location	Table
Barrier Ends	Interstates	Speed limit ≥ 40 mph, Segment	Table 5.5
	Interchanges and ramps	Speed limit ≥ 40 mph, Segment	Table 5.6
		Speed limit < 40 mph, Segment	Table 5.7
		Speed limit < 40 mph, Intersection area	Table 5.8
	U.S. routes	Speed limit ≥ 40 mph, Segment	Table 5.9
		Speed limit < 40 mph, Segment	Table 5.10
		Speed limit < 40 mph, Intersection area	Table 5.11
	State routes	Speed limit ≥ 40 mph, Segment	Table 5.12
		Speed limit < 40 mph, Segment	Table 5.13
		Speed limit <40 mph, Intersection area	Table 5.14
Impact Attenuator	Interstates	Speed limit ≥ 55 mph	Table 5.15
		Speed limit < 55 mph	Table 5.16
	Interchanges and ramps	Speed limit ≥ 55 mph	Table 5.17
		Speed limit < 55 mph	Table 5.18
	U.S. routes	Speed limit ≥ 55 mph	Table 5.19
		Speed limit < 55 mph	Table 5.20
	State routes	Speed limit ≥ 55 mph	Table 5.21
		Speed limit < 55 mph	Table 5.22

TABLE 5.5
Crash severity and cost: barrier ends, interstates, speed limit ≥ 40 mph, and segment

	Severity Distribution (%)			Crash Modification Factor			Average Cost of Crash ($)	Cost Modification Factor
Barrier Ends	PDO	BC	KA	PDO	BC	KA		
No Terminal	79.0	8.8	12.2	1.00	1.00	1.00	323,000	1.00
Breakmaster	76.5	9.6	13.9	0.97	1.09	1.14	364,000	1.13
Breakaway	86.9	5.8	7.3	1.10	0.66	0.60	203,000	0.63
BuriedT1	71.2	11.9	17.0	0.90	1.35	1.39	440,000	1.36
CAT	82.6	7.6	9.8	1.05	0.86	0.80	265,000	0.82
Fleat-MT	82.1	7.8	10.1	1.04	0.88	0.83	273,000	0.85
MASH_MSKT	87.1	5.9	7.0	1.10	0.67	0.58	197,000	0.61
SKT_350	82.3	7.7	10.0	1.04	0.87	0.82	270,000	0.84
ETPlus	83.2	7.3	9.4	1.05	0.83	0.77	256,000	0.79
Others	75.4	10.1	14.4	0.95	1.15	1.18	377,000	1.17

to QuadGuard. Although the model indicates that QuadGuard M10 has the lowest performance among all the evaluated types, this inference might be questioned since the sample size was only 16.

5.2 Model Application

As discussed in the previous chapter, crash severity varies depending on the speed limit and road class.

TABLE 5.6
Crash severity and cost: barrier ends, interchanges and ramps, speed limit ≥ 40 mph, and segment

Barrier Ends	Severity Distribution (%)			Crash Modification Factor			Average Cost of Crash ($)	Cost Modification Factor
	PDO	BC	KA	PDO	BC	KA		
No Terminal	79.0	8.8	12.2	1.00	1.00	1.00	254,000	1.00
Breakmaster	76.5	9.6	13.9	0.97	1.09	1.14	285,000	1.12
Breakaway	86.9	5.8	7.3	1.10	0.66	0.60	162,000	0.64
BuriedT1	71.2	11.9	17.0	0.90	1.35	1.39	343,000	1.35
CAT	82.6	7.6	9.8	1.05	0.86	0.80	209,000	0.82
Fleat-MT	82.1	7.8	10.1	1.04	0.88	0.83	216,000	0.85
MASH_MSKT	87.1	5.9	7.0	1.10	0.67	0.58	158,000	0.62
SKT_350	82.3	7.7	10.0	1.04	0.87	0.82	213,000	0.84
ETPlus	83.2	7.3	9.4	1.05	0.83	0.77	203,000	0.80
Others	75.4	10.1	14.4	0.95	1.15	1.18	295,000	1.16

TABLE 5.7
Crash severity and cost: barrier ends, interchanges and ramps, speed limit < 40 mph, and segment

Barrier Ends	Severity Distribution (%)			Crash Modification Factor			Average Cost of Crash ($)	Cost Modification Factor
	PDO	BC	KA	PDO	BC	KA		
No Terminal	89.2	5.0	5.8	1.00	1.00	1.00	134,000	1.00
Breakmaster	87.6	5.7	6.7	0.98	1.13	1.16	152,000	1.13
Breakaway	93.6	3.0	3.4	1.05	0.61	0.58	87,000	0.65
BuriedT1	84.9	6.9	8.1	0.95	1.38	1.41	180,000	1.34
CAT	91.4	4.1	4.5	1.02	0.81	0.78	111,000	0.83
Fleat-MT	91.1	4.2	4.7	1.02	0.84	0.82	114,000	0.85
MASH_MSKT	93.8	3.0	3.2	1.05	0.59	0.55	84,000	0.63
SKT_350	91.2	4.2	4.6	1.02	0.83	0.80	113,000	0.84
ETPlus	91.7	3.9	4.4	1.03	0.79	0.76	107,000	0.80
Others	87.2	5.9	6.9	0.98	1.18	1.19	156,000	1.16

TABLE 5.8
Crash severity and cost: barrier ends, interchanges and ramps, speed limit < 40 mph, and intersection area

Barrier Ends	Severity Distribution (%)			Crash Modification Factor			Average Cost of Crash ($)	Cost Modification Factor
	PDO	BC	KA	PDO	BC	KA		
No Terminal	89.2	5.0	5.8	1.00	1.00	1.00	134,000	1.00
Breakmaster	87.6	5.7	6.7	0.98	1.13	1.16	152,000	1.13
Breakaway	93.6	3.0	3.4	1.05	0.61	0.58	87,000	0.65
BuriedT1	89.2	5.1	5.7	1.00	1.02	0.98	133,000	0.99
CAT	91.4	4.1	4.5	1.02	0.81	0.78	111,000	0.83
Fleat-MT	91.1	4.2	4.7	1.02	0.84	0.82	114,000	0.85
MASH_MSKT	93.8	3.0	3.2	1.05	0.59	0.55	84,000	0.63
SKT_350	95.8	2.1	2.2	1.07	0.41	0.37	64,000	0.48
ETPlus	94.6	2.6	2.8	1.06	0.52	0.48	76,000	0.57
Others	87.2	5.9	6.9	0.98	1.18	1.19	156,000	1.16

To reflect this fact, a set of in-service performance tables were generated based on the results obtained with the fixed effect models for barrier end treatments and impact attenuators to help select a proper safety device for the conditions and standards.

Table 5.4 shows all the possible application scenarios according to both factors included in the model and real distributions of end treatments. The links in this table would guide the end users to the corresponding performance tables. In the performance table, severity distribution (calculated according to model estimates), crash modification factors, average crash costs and cost modification factors are provided.

TABLE 5.9
Crash severity and cost: barrier ends, U.S. routes, speed limit ≥ 40 mph, and segment

	Severity Distribution (%)			Crash Modification Factor			Average Cost of Crash ($)	Cost Modification Factor
Barrier Ends	**PDO**	**BC**	**KA**	**PDO**	**BC**	**KA**		
No Terminal	79.0	8.8	12.2	1.00	1.00	1.00	228,000	1.00
Breakmaster	76.5	9.6	13.9	0.97	1.09	1.14	256,000	1.12
Breakaway	86.9	5.8	7.3	1.10	0.66	0.60	145,000	0.64
BuriedT1	71.2	11.9	17.0	0.90	1.35	1.39	308,000	1.35
CAT	82.6	7.6	9.8	1.05	0.86	0.80	188,000	0.82
Fleat-MT	82.1	7.8	10.1	1.04	0.88	0.83	193,000	0.85
MASH_MSKT	87.1	5.9	7.0	1.10	0.67	0.58	142,000	0.62
SKT_350	82.3	7.7	10.0	1.04	0.87	0.82	191,000	0.84
ETPlus	83.2	7.3	9.4	1.05	0.83	0.77	182,000	0.80
Others	75.4	10.1	14.4	0.95	1.15	1.18	265,000	1.16

TABLE 5.10
Crash severity and cost: barrier ends, U.S. routes, speed limit < 40 mph, and segment

	Severity Distribution (%)			Crash Modification Factor			Average Cost of Crash ($)	Cost Modification Factor
Barrier Ends	**PDO**	**BC**	**KA**	**PDO**	**BC**	**KA**		
No Terminal	89.2	5.0	5.8	1.00	1.00	1.00	121,000	1.00
Breakmaster	87.6	5.7	6.7	0.98	1.13	1.16	136,000	1.12
Breakaway	93.6	3.0	3.4	1.05	0.61	0.58	79,000	0.65
BuriedT1	84.9	6.9	8.1	0.95	1.38	1.41	161,000	1.33
CAT	91.4	4.1	4.5	1.02	0.81	0.78	99,000	0.82
Fleat-MT	91.1	4.2	4.7	1.02	0.84	0.82	102,000	0.84
MASH_MSKT	93.8	3.0	3.2	1.05	0.59	0.55	76,000	0.63
SKT_350	91.2	4.2	4.6	1.02	0.83	0.80	101,000	0.83
ETPlus	91.7	3.9	4.4	1.03	0.79	0.76	97,000	0.80
Others	87.2	5.9	6.9	0.98	1.18	1.19	140,000	1.16

TABLE 5.11
Crash severity and cost: barrier ends, U.S. routes, speed limit < 40 mph, and intersection area

	Severity Distribution (%)			Crash Modification Factor			Average Cost of Crash ($)	Cost Modification Factor
Barrier Ends	**PDO**	**BC**	**KA**	**PDO**	**BC**	**KA**		
No Terminal	89.2	5.0	5.8	1.00	1.00	1.00	121,000	1.00
Breakmaster	87.6	5.7	6.7	0.98	1.13	1.16	136,000	1.12
Breakaway	93.6	3.0	3.4	1.05	0.61	0.58	79,000	0.65
BuriedT1	89.2	5.1	5.7	1.00	1.02	0.98	119,000	0.98
CAT	91.4	4.1	4.5	1.02	0.81	0.78	99,000	0.82
Fleat-MT	91.1	4.2	4.7	1.02	0.84	0.82	102,000	0.84
MASH_MSKT	93.8	3.0	3.2	1.05	0.59	0.55	76,000	0.63
SKT_350	95.8	2.1	2.2	1.07	0.41	0.37	58,000	0.48
ETPlus	94.6	2.6	2.8	1.06	0.52	0.48	69,000	0.57
Others	87.2	5.9	6.9	0.98	1.18	1.19	140,000	1.16

TABLE 5.12
Crash severity and cost: barrier ends, state routes, speed limit ≥ 40 mph, and segment

Barrier Ends	Severity Distribution (%)			Crash Modification Factor			Average Cost of Crash ($)	Cost Modification Factor
	PDO	BC	KA	PDO	BC	KA		
No Terminal	79.0	8.8	12.2	1.00	1.00	1.00	322,000	1.00
Breakmaster	76.5	9.6	13.9	0.97	1.09	1.14	364,000	1.13
Breakaway	86.9	5.8	7.3	1.10	0.66	0.60	202,000	0.63
BuriedT1	71.2	11.9	17.0	0.90	1.35	1.39	439,000	1.36
CAT	82.6	7.6	9.8	1.05	0.86	0.80	264,000	0.82
Fleat-MT	82.1	7.8	10.1	1.04	0.88	0.83	272,000	0.84
MASH_MSKT	87.1	5.9	7.0	1.10	0.67	0.58	196,000	0.61
SKT_350	82.3	7.7	10.0	1.04	0.87	0.82	269,000	0.84
ETPlus	83.2	7.3	9.4	1.05	0.83	0.77	255,000	0.79
Others	75.4	10.1	14.4	0.95	1.15	1.18	377,000	1.17

TABLE 5.13
Crash severity and cost: barrier ends, state routes, speed limit < 40 mph, and segment

Barrier Ends	Severity Distribution (%)			Crash Modification Factor			Average Cost of Crash ($)	Cost Modification Factor
	PDO	BC	KA	PDO	BC	KA		
No Terminal	89.2	5.0	5.8	1.00	1.00	1.00	166,000	1.00
Breakmaster	87.6	5.7	6.7	0.98	1.13	1.16	189,000	1.14
Breakaway	93.6	3.0	3.4	1.05	0.61	0.58	105,000	0.63
BuriedT1	84.9	6.9	8.1	0.95	1.38	1.41	225,000	1.36
CAT	91.4	4.1	4.5	1.02	0.81	0.78	135,000	0.81
Fleat-MT	91.1	4.2	4.7	1.02	0.84	0.82	139,000	0.84
MASH_MSKT	93.8	3.0	3.2	1.05	0.59	0.55	101,000	0.61
SKT_350	91.2	4.2	4.6	1.02	0.83	0.80	137,000	0.83
ETPlus	91.7	3.9	4.4	1.03	0.79	0.76	131,000	0.79
Others	87.2	5.9	6.9	0.98	1.18	1.19	194,000	1.17

TABLE 5.14
Crash severity and cost: barrier ends, state routes, speed limit < 40 mph, and intersection area

Barrier Ends	Severity Distribution (%)			Crash Modification Factor			Average Cost of Crash ($)	Cost Modification Factor
	PDO	BC	KA	PDO	BC	KA		
No Terminal	89.2	5.0	5.8	1.00	1.00	1.00	166,000	1.00
Breakmaster	87.6	5.7	6.7	0.98	1.13	1.16	189,000	1.14
Breakaway	93.6	3.0	3.4	1.05	0.61	0.58	105,000	0.63
BuriedT1	89.2	5.1	5.7	1.00	1.02	0.98	164,000	0.99
CAT	91.4	4.1	4.5	1.02	0.81	0.78	135,000	0.81
Fleat-MT	91.1	4.2	4.7	1.02	0.84	0.82	139,000	0.84
MASH_MSKT	93.8	3.0	3.2	1.05	0.59	0.55	101,000	0.61
SKT_350	95.8	2.1	2.2	1.07	0.41	0.37	75,000	0.45
ETPlus	94.6	2.6	2.8	1.06	0.52	0.48	91,000	0.55
Others	87.2	5.9	6.9	0.98	1.18	1.19	194,000	1.17

TABLE 5.15
Crash severity and cost: impact attenuator, interstates, and speed limit ≥ 55 mph

Impact Attenuators	Severity Distribution (%)			Crash Modification Factor			Average Cost of Crash ($)	Cost Modification Factor
	PDO	BC	KA	PDO	BC	KA		
GREAT	49.2	23.2	27.6	1.00	1.00	1.00	624,000	1.00
BARRELS	81.1	11.0	7.9	1.65	0.47	0.29	215,000	0.34
QuadGuard	65.3	18.3	16.4	1.33	0.79	0.59	397,000	0.64
QuadGuard_M10	49.1	23.2	27.6	1.00	1.00	1.00	625,000	1.00
REACT_350	75.7	13.7	10.6	1.54	0.59	0.38	273,000	0.44
SCI_100_GM	64.5	18.6	16.9	1.31	0.80	0.61	407,000	0.65
TRACC	58.1	20.9	21.0	1.18	0.90	0.76	492,000	0.79

TABLE 5.16
Crash severity and cost: impact attenuator, interstates, and speed limit < 55 mph

Impact Attenuators	Severity Distribution (%)			Crash Modification Factor			Average Cost of Crash ($)	Cost Modification Factor
	PDO	BC	KA	PDO	BC	KA		
GREAT	65.0	18.4	16.5	1.00	1.00	1.00	400,000	1.00
BARRELS	89.1	6.6	4.3	1.37	0.36	0.26	133,000	0.33
QuadGuard	78.3	12.4	9.3	1.20	0.67	0.56	244,000	0.61
QuadGuard_M10	64.9	18.5	16.6	1.00	1.00	1.00	401,000	1.00
REACT_350	85.7	8.5	5.8	1.32	0.46	0.35	167,000	0.42
SCI_100_GM	77.7	12.7	9.6	1.19	0.69	0.58	251,000	0.63
TRACC	72.7	15.1	12.2	1.12	0.82	0.74	307,000	0.77

TABLE 5.17
Crash severity and cost: impact attenuator, interchanges and ramps, and speed limit ≥ 55 mph

Impact Attenuators	Severity Distribution (%)			Crash Modification Factor			Average Cost of Crash ($)	Cost Modification Factor
	PDO	BC	KA	PDO	BC	KA		
GREAT	49.2	23.2	27.6	1.00	1.00	1.00	791,000	1.00
BARRELS	81.1	11.0	7.9	1.65	0.47	0.29	258,000	0.33
QuadGuard	65.3	18.3	16.4	1.33	0.79	0.59	494,000	0.62
QuadGuard_M10	49.1	23.2	27.6	1.00	1.00	1.00	794,000	1.00
REACT_350	75.7	13.7	10.6	1.54	0.59	0.38	333,000	0.42
SCI_100_GM	64.5	18.6	16.9	1.31	0.80	0.61	509,000	0.64
TRACC	58.1	20.9	21.0	1.18	0.90	0.76	619,000	0.78

TABLE 5.18
Crash severity and cost: impact attenuator, interchanges and ramps, and speed limit < 55 mph

Impact Attenuators	Severity Distribution (%)			Crash Modification Factor			Average Cost of Crash ($)	Cost Modification Factor
	PDO	BC	KA	PDO	BC	KA		
GREAT	65.0	18.4	16.5	1.00	1.00	1.00	499,000	1.00
BARRELS	89.1	6.6	4.3	1.37	0.36	0.26	152,000	0.30
QuadGuard	78.3	12.4	9.3	1.20	0.67	0.56	296,000	0.59
QuadGuard_M10	64.9	18.5	16.6	1.00	1.00	1.00	501,000	1.00
REACT_350	85.7	8.5	5.8	1.32	0.46	0.35	196,000	0.39
SCI_100_GM	77.7	12.7	9.6	1.19	0.69	0.58	305,000	0.61
TRACC	72.7	15.1	12.2	1.12	0.82	0.74	378,000	0.76

TABLE 5.19
Crash severity and cost: impact attenuator, U.S. routes, and speed limit ≥ 55 mph

Impact Attenuators	Severity Distribution (%)			Crash Modification Factor			Average Cost of Crash ($)	Cost Modification Factor
	PDO	BC	KA	PDO	BC	KA		
GREAT	49.2	23.2	27.6	1.00	1.00	1.00	614,000	1.00
BARRELS	81.1	11.0	7.9	1.65	0.47	0.29	215,000	0.35
QuadGuard	65.3	18.3	16.4	1.33	0.79	0.59	394,000	0.64
QuadGuard_M10	49.1	23.2	27.6	1.00	1.00	1.00	616,000	1.00
REACT_350	75.7	13.7	10.6	1.54	0.59	0.38	272,000	0.44
SCI_100_GM	64.5	18.6	16.9	1.31	0.80	0.61	404,000	0.66
TRACC	58.1	20.9	21.0	1.18	0.90	0.76	487,000	0.79

TABLE 5.20
Crash severity and cost: impact attenuator, U.S. routes, and speed limit < 55 mph

Impact Attenuators	Severity Distribution (%)			Crash Modification Factor			Average Cost of Crash ($)	Cost Modification Factor
	PDO	BC	KA	PDO	BC	KA		
GREAT	65.0	18.4	16.5	1.00	1.00	1.00	397,000	1.00
BARRELS	89.1	6.6	4.3	1.37	0.36	0.26	134,000	0.34
QuadGuard	78.3	12.4	9.3	1.20	0.67	0.56	244,000	0.61
QuadGuard_M10	64.9	18.5	16.6	1.00	1.00	1.00	398,000	1.00
REACT_350	85.7	8.5	5.8	1.32	0.46	0.35	168,000	0.42
SCI_100_GM	77.7	12.7	9.6	1.19	0.69	0.58	251,000	0.63
TRACC	72.7	15.1	12.2	1.12	0.82	0.74	306,000	0.77

TABLE 5.21
Crash severity and cost: impact attenuator, state routes, and speed limit ≥ 55 mph

Impact Attenuators	Severity Distribution (%)			Crash Modification Factor			Average Cost of Crash ($)	Cost Modification Factor
	PDO	BC	KA	PDO	BC	KA		
GREAT	49.2	23.2	27.6	1.00	1.00	1.00	1,024,000	1.00
BARRELS	81.1	11.0	7.9	1.65	0.47	0.29	337,000	0.33
QuadGuard	65.3	18.3	16.4	1.33	0.79	0.59	639,000	0.62
QuadGuard_M10	49.1	23.2	27.6	1.00	1.00	1.00	1,026,000	1.00
REACT_350	75.7	13.7	10.6	1.54	0.59	0.38	433,000	0.42
SCI_100_GM	64.5	18.6	16.9	1.31	0.80	0.61	657,000	0.64
TRACC	58.1	20.9	21.0	1.18	0.90	0.76	800,000	0.78

TABLE 5.22
Crash severity and cost: impact attenuator, state routes, and speed limit < 55 mph

Impact Attenuators	Severity Distribution (%)			Crash Modification Factor			Average Cost of Crash ($)	Cost Modification Factor
	PDO	BC	KA	PDO	BC	KA		
GREAT	65.0	18.4	16.5	1.00	1.00	1.00	645,000	1.00
BARRELS	89.1	6.6	4.3	1.37	0.36	0.26	202,000	0.31
QuadGuard	78.3	12.4	9.3	1.20	0.67	0.56	385,000	0.60
QuadGuard_M10	64.9	18.5	16.6	1.00	1.00	1.00	647,000	1.00
REACT_350	85.7	8.5	5.8	1.32	0.46	0.35	258,000	0.40
SCI_100_GM	77.7	12.7	9.6	1.19	0.69	0.58	397,000	0.62
TRACC	72.7	15.1	12.2	1.12	0.82	0.74	490,000	0.76

For scenarios of barrier ends, an intersection is the roadway area within 150 ft. from the intersection center and a segment is the part of the roadway between intersection areas.

For barrier ends, the crash modification factors, and cost modification factors are compared with the reference no terminal for impact attenuator, the worst performed type "GREAT" is used as the reference.

For the performance tables of barrier ends, it should be noted that the sample sizes for Breakaway, Fleat-MT, and Breakmaster were too small to generate significant results and their corresponding underreporting rates might be questionable, the end users should be careful when using the expected costs for these barrier ends.

For the safety performance tables of impact attenuators, it should be noted that the sample sizes for TRACC and Quardguard_M10 were too small to have enough samples for KA and BC crashes (just 1 or 2 samples). Due to the randomness of crash occurrence, the estimated probability for different severity levels might be questionable, end users should be careful when using the expected costs for these impact attenuators.

6. CLOSURE

The study results presented in this report are meant to provide information needed when deciding which types of barrier end treatments and impact attenuators should be installed at considered locations based on safety performance of these devices in the traffic and road conditions. This element of the decision-making requires research presented here. Other factors possibly considered include the types of devices in current use, the past record of their maintenance, the capital and maintenance costs, and other. These elements do not require research, and they had not been included in the proposed scope of the presented study.

The in-service performance of barrier end treatments and impact attenuators measured with the reduced crash injury severity was estimated with extensive data and using fixed and random effects ordered logit models. Other confounding risk factors, such as roadway attributes, traffic characteristics, and environmental conditions, were included in the models to help estimate the net safety effect of the studied safety devices. In addition, a special effort was undertaken to account for the underreported crashes.

The developed in-service performance tables provide a convenient basis for selecting barrier end treatments and impact attenuators under conditions known to the end user at the time of decision making. These conditions include the road functional class, presence of an intersection, and a speed limit. In addition, these tables provide the average crash cost for specific conditions to facilitate benefit-cost analyses and the distribution of crash severities to allow updating these costs in the future. Additional information in the tables includes the crash modification factors (CMF) and crash cost modification factors (CCMF). These factors are not necessary if the average crash cost is provided by the device type. They have been included since the research proposal anticipated them among the results.

The provided research outcomes may be useful in design, rehabilitation, reconstruction, and new construction projects. INDOT personnel and contractors may use information in the delivered safety performance tables to compare alternative guardrail end treatments and impact attenuators for a specific location based on their performance or via a more comprehensive life service analysis. This decision process includes identification of the recommended group of guardrail end treatments or impact attenuators in Section 49-8.0 of the *2013 Indiana Design Manual*. The up-to-date list of acceptable guardrail end treatments and impact attenuators is provided in the INDOT Qualified Products List.

The reported results indicate the good performance of guardrail end treatments and impact attenuators included in the latest QPL. Nevertheless, the performance of the recently added barrier end treatment types: FLEAT-MT, SoftStop, SCIGM, and TAU-II should be re-evaluated once sufficient in-service data become available. In addition, analysis of specific impact attenuators models of sand barrels and QuadGuard approved in the QPL should be evaluated. The current inventory makes no distinction between these models.

Potential modifications of the current practice of selecting barrier end treatments and impact attenuators may be decided during the implementation discussion. Other decision factors beyond the scope of this research include costs of purchase, repair, and maintenance, and the availability of specific models. The life cycle analysis may be an option although the open question to be decided if a supporting analysis should be done case by case, for each district, or for the entire state.

The information in the provided safety performance tables includes the crash modification factors (CMF). Such factors could be implemented in other routine practices of the agency, including the Safety Needs Identification Program (SNIP) and Road Hazard Analysis Tool (HAT). The crash cost modification factors (CCMFs) are another result that allows faster calculation of the safety benefits for alternatives based on the benefit already estimated for a reference case.

Our experience with acquiring and preparing data for analysis allowed making a number of recommendations regarding the data management. First, it would be helpful if consistent unique IDs for roadside elements be introduces for all databases owned by INDOT (property inventories and repairment datasets). This practice would greatly help link facilities with crashes. Second, the inventory data could be further improved by adding installation and removal/replacement dates for individual guardrail end treatments and impact attenuators. Lastly, all maintenance and repair records performed by contractors, available at the district offices, could be put into the WMS format to help facilitate future analysis of barriers and other roadside safety devices.

This study focused on permanent installations. An in-service safety evaluation of temporary barrier end treatments, such as truck-mounted devices, may benefit Indiana's work zones' safety. Second, it would be potentially beneficial to establish a link between the in-service performance as the one presented in this report and the in-lab safety performance from tests as described in the *Manual for Assessing Safety Hardware (MASH)* (AASHTO, 2016) and the NCHRP Report 350. Third, the effectiveness of barrier end treatment repairs could be checked by evaluating the safety performance of repaired and not repaired road safety devices. Such a study could develop guidelines on replacement vs. repairment for specific barrier end treatment types. Finally, barrier end treatments at local roads could not be considered since the current inventory only records state-administered safety hardware. These roads are essential for a system-wide effect since ~60% of crashes involving end treatments occur there. A technical and technological transfer of the findings of this report should be carried out to procure a uniform implementation of the guidelines and operational aspects of the guardrail end treatment and impact attenuator selection.

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APPENDICES

Appendix A. Estimated Crash Severity Model

APPENDIX A. ESTIMATED CRASH SEVERITY MODEL

A.1 Speed Limit Effects

Table A.1 shows the estimated model including speed limit as categorical variable and Figure A.1 shows the corresponding changes of speed limit effects. Comparing to the reference level speed limit smaller than 40 mph, all other speed limits (from 40 mph to 70 mph) show significant increased risk on severe crashes, while the difference among them is not significant. The fluctuations of speed limit effects as shown in Figure A.1 do not have a clear increase or decrease trend, indicating no need to separate their effects.

Table A.1 Speed limit effects on crash severity (barrier ends)

Parameter		Estimate	Standard Error	t-value	P-value
intersection		-0.6682	0.25776	-2.59	0.0095
Breakmaster		0.07114	0.60632	0.12	0.9066
Breakaway		-0.3248	0.3292	-0.99	0.3239
BuriedT1		0.00386	0.17392	0.02	0.9823
CAT		-0.2758	0.1502	-1.84	0.0663
Fleat-MT		-0.2391	0.37563	-0.64	0.5245
MASH_MSKT		-0.6924	0.33097	-2.09	0.0364
SKT_350		-0.3823	0.16047	-2.38	0.0172
ETPlus		-0.3591	0.14406	-2.49	0.0127
Other		0.0864	0.1954	0.56	0.7536
Speed Limit	<40	0	–	–	–
	40	0.93336	0.37202	2.51	0.0121
	45	0.77274	0.29702	2.6	0.0093
	50	0.96193	0.33774	2.85	0.0044
	55	0.90029	0.26924	3.34	0.0008
	60	0.697	0.3365	2.07	0.0383
	65	0.92648	0.31571	2.93	0.0033
	70	0.73826	0.29187	2.53	0.0114
_Limit1		1.70229	0.27089	6.28	<.0001
_Limit2		2.40376	0.27371	8.78	<.0001

Figure A.1 Changes of speed limit effects on crash severity (barrier ends).

A.2 Model Transferability

The model transferability test compares model with all data (Model T) and the models with partial data (Model A and Model B). If the difference of the model performance is statistically small, it would be safe to claim the transferability between Model A and Model B.

Here we show one example to compare whether samples from interchanges and ramps are model transferable to samples from non-interstate roadways (U.S. routes and state routes). Three models were estimated with the same variables: all data model (Model T), the model of interchange and ramp samples only (Model A) and model of other non-interstate samples only (Model B).

The difference between their log likelihoods follows Chi-square distribution. The degree of freedom of the constructed Chi-square parameter is the number of contains in all data model. The equation below shows the process and results of the test. Because the significant threshold for the corresponding degree of freedom (23) is 35.172 larger than the obtained values (34), so we could conclude that the model of interchanges and ramps and the model of other non-interstates are transferable.

$$\chi^2 = -2[LL(\beta_t) - LL(\beta_a) - LL(\beta_b)] = -2 * (-1{,}597 + 164 + 1{,}416) = 34$$

Table A.2 Model transferability test

	Model T	Model A	Model B
Number of Observations	2250	255	1995
Log Likelihood	-1597	-163.88369	-1416
Maximum Absolute Gradient	0.00230	0.0000170	0.0001842
Number of Iterations	67	55	75
Optimization Method	Quasi-Newton	Quasi-Newton	Quasi-Newton
AIC	3239	365.76738	2878
Schwarz Criterion	3371	433.05138	3007

A.3 Distribution of Barrier End Treatments

Table A.3 Distribution of barrier end treatments on speed limits (interstate)

Speed Limit	Breakmaster	Buried Type I	CAT	ET Plus	Fleat-MT	MASH MSKT	No Terminal	Other End	SKT 350	Total
25	0	0	0	0	0	0	0	0	0	0
30	0	0	0	0	0	0	0	0	0	0
35	0	0	0	0	0	0	0	0	0	0
40	0	0	1	2	0	1	0	0	0	4
45	0	3	6	9	1	0	11	6	3	39
50	1	2	6	16	0	0	6	3	2	36
55	8	5	89	97	11	24	102	33	52	421
60	0	0	4	6	0	1	7	1	8	27
65	2	2	31	21	9	1	30	5	33	134
70	2	4	111	56	6	10	51	10	51	301
Total	13	16	248	207	27	37	207	58	149	962

Table A.4 Distribution of barrier end treatments on speed limits (non-interstate)

Speed Limit	Breakmaster	Breakaway	Buried Type I	CAT	ET Plus	Fleat-MT	MASH MSKT	No Terminal	Other End	SKT 350	Total
15	0	0	0	0	0	0	0	1	1	3	5
20	0	0	1	0	1	0	1	0	0	1	4
25	0	0	1	2	1	0	0	3	2	2	11
30	0	3	1	7	4	0	3	15	4	5	42
35	0	0	17	4	16	0	5	13	11	12	78
40	1	3	17	10	15	0	0	10	2	8	66
45	0	15	43	41	50	9	5	16	15	35	229
50	0	5	14	13	15	0	1	4	6	16	74
55	0	29	128	68	160	3	19	64	33	105	609
60	0	7	8	26	23	1	1	23	1	15	105
65	0	0	2	5	7	0	0	9	3	3	29
70	0	0	0	11	6	0	0	6	3	4	30
Total	1	62	232	187	298	13	35	164	81	209	1282

Table A.5 Distribution of impact attenuators on speed limits (interstate)

Speed Limit	BARRELS	GREAT	QuadGuard	QuadGuard M10	REACT 350	SCI 100 GM	TRACC	Total
25	1	1	1	1	0	0	0	4
35	2	0	3	0	0	0	1	6
40	0	1	0	0	0	0	0	1
45	3	4	25	1	5	4	1	43
50	0	3	7	0	4	10	0	24
55	18	4	88	11	42	10	13	186
60	2	1	0	0	0	0	0	3
65	5	1	4	0	0	0	1	11
70	15	3	4	0	0	0	1	23
Total	46	18	132	13	51	24	17	301

Table A.6 Distribution of impact attenuators on speed limits (non-interstate)

Speed Limit	BARRELS	GREAT	QuadGuard	QuadGuard M10	REACT 350	SCI 100 GM	TRACC	Total
25	0	2	1	0	0	0	0	3
30	0	0	3	0	0	0	0	3
35	0	4	5	0	1	0	0	10
40	0	5	2	0	0	0	0	7
45	3	6	11	0	1	0	1	22
50	1	2	8	0	1	3	0	15
55	2	3	8	3	5	10	3	34
60	1	0	1	0	0	0	0	2
65	1	0	0	0	0	0	0	1
Total	8	22	39	3	8	13	4	97

About the Joint Transportation Research Program (JTRP)

On March 11, 1937, the Indiana Legislature passed an act which authorized the Indiana State Highway Commission to cooperate with and assist Purdue University in developing the best methods of improving and maintaining the highways of the state and the respective counties thereof. That collaborative effort was called the Joint Highway Research Project (JHRP). In 1997 the collaborative venture was renamed as the Joint Transportation Research Program (JTRP) to reflect the state and national efforts to integrate the management and operation of various transportation modes.

The first studies of JHRP were concerned with Test Road No. 1—evaluation of the weathering characteristics of stabilized materials. After World War II, the JHRP program grew substantially and was regularly producing technical reports. Over 1,600 technical reports are now available, published as part of the JHRP and subsequently JTRP collaborative venture between Purdue University and what is now the Indiana Department of Transportation.

Free online access to all reports is provided through a unique collaboration between JTRP and Purdue Libraries. These are available at http://docs.lib.purdue.edu/jtrp.

Further information about JTRP and its current research program is available at http://www.purdue.edu/jtrp.

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An open access version of this publication is available online. See the URL in the citation below.

Pineda-Mendez, R. A., Guo, Q., Romero, M. A., & Tarko, A. P. (2024). *In-service safety evaluation of Indiana impact attenuators and barrier end treatments* (Joint Transportation Research Program Publication No. FHWA/IN/JTRP-2024/24). West Lafayette, IN: Purdue University. https://doi.org/10.5703/1288284317765