Texas A&M Transportation Institute

Barrier Striping for the Reduction of Accidents

Technical Report 0-7171-R1

Cooperative Research Program

TEXAS A&M TRANSPORTATION INSTITUTE
COLLEGE STATION, TEXAS

sponsored by the
Federal Highway Administration and the
Texas Department of Transportation
https://tti.tamu.edu/documents/0-7171-R1.pdf

Technical Report Documentation Page

1. Report No. FHWA/TX-26/0-7171-R1	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle BARRIER STRIPING FOR THE REDUCTION OF ACCIDENTS		5. Report Date Published: February 2026 6. Performing Organization Code
7. Author(s) Boniphace Kutela, Srinivas Geedipally, Adam Pike, Nathan Shulz, and Subasish Das		8. Performing Organization Report No. Report 0-7171-R1
9. Performing Organization Name and Address Texas A&M Transportation Institute The Texas A&M University System College Station, Texas 77843-3135		10. Work Unit No. (TRAIS) 11. Contract or Grant No. Project 0-7171
12. Sponsoring Agency Name and Address Texas Department of Transportation Research and Technology Implementation Office 125 E. 11th Street Austin, Texas 78701-2483		13. Type of Report and Period Covered Technical Report: September 2023–September 2025 14. Sponsoring Agency Code

15. Supplementary Notes

Project sponsored by the Texas Department of Transportation and the Federal Highway Administration.
Project Title: Barrier Striping for the Reduction of Accidents
URL: https://tti.tamu.edu/documents/0-7171-R1.pdf

16. Abstract

Barrier striping is a roadway safety countermeasure designed to enhance driver awareness of concrete barriers, particularly under adverse weather and low-visibility conditions. This study evaluated the short- and long-term safety effectiveness of retroreflective barrier striping across multiple sites in Texas. The research involved a comprehensive literature review of barrier delineation practices, a detailed examination of existing installations, and the implementation and evaluation of new treatments at selected high-crash locations. Data collection included crash records, roadway geometry, traffic volume, meteorological conditions, and probe vehicle speed data. Analytical methods encompassed descriptive statistics, crash rate comparisons, logistic and linear regressions, Negative Binomial, and survival analysis to assess the impact of striping on crash frequency, severity, and operating speeds. The findings revealed notable reductions in barrier-related crashes at treated sites, with relatively stronger improvements observed at nighttime, underscoring the benefits of increased retroreflectivity. Speed analysis suggested limited but measurable effects on vehicle operating behavior. Based on these results, the project team refined the Texas Department of Transportation's draft special specification for barrier striping, offering updated guidance on materials, spacing, and installation procedures. Overall, barrier striping demonstrates promising potential as an effective countermeasure to improve roadway safety, though continued evaluation and site-specific considerations are recommended. Future research should further explore surrogate safety measures, maintenance requirements, and the effectiveness of alternative striping materials.

17. Key Words Barrier Striping, Adverse Weather Conditions, Nighttime Crashes		18. Distribution Statement No restrictions. This document is available to the public through NTIS: National Technical Information Service Alexandria, Virginia http://www.ntis.gov	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 106	22. Price

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

BARRIER STRIPING FOR THE REDUCTION OF ACCIDENTS

by

Boniphace Kutela, Ph.D., P.E., PMP
Associate Research Engineer
Texas A&M Transportation Institute

Srinivas Geedipally, Ph.D., P.E.
Research Engineer
Texas A&M Transportation Institute

Adam Pike, P.E.
Associate Research Engineer
Texas A&M Transportation Institute

Nathan Schulz, Ph.D.
Associate Research Scientist
Texas A&M Transportation Institute

and

Subasish Das, Ph.D.
Assistant Professor
Texas State University

Report 0-7171-R1
Project 0-7171
Project Title: Barrier Striping for the Reduction of Accidents

Sponsored by the
Texas Department of Transportation
and the
Federal Highway Administration

Published: February 2026

TEXAS A&M TRANSPORTATION INSTITUTE
College Station, Texas 77843-3135

DISCLAIMER

This research was sponsored by the Texas Department of Transportation (TxDOT) and the Federal Highway Administration (FHWA). The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of FHWA or TxDOT. This report does not constitute a standard, specification, or regulation.

This report is not intended for construction, bidding, or permit purposes. The engineer in charge of the project was Boniphace Kutela, P.E. #147721.

ACKNOWLEDGMENTS

This project was sponsored by TxDOT and FHWA. Katelyn Kasberg of TxDOT served as the project manager. The authors gratefully acknowledge the assistance and direction that the TxDOT Project Monitoring Committee—Jason Duncan, Kelly Rother, Paul Norman, Seth Frank, and Karen Lorenzini—provided over the course of the project. The authors would like to acknowledge the contributions of Texas A&M Transportation Institute staff members, including Stacey Alejandro and Michelle Benoit. The authors also recognize the efforts of the graduate students on this project (Rohit Chakraborty, Syed Aaqib Javed, Swastika Barua).

TABLE OF CONTENTS

LIST OF FIGURES

Page

LIST OF TABLES

CHAPTER 1: INTRODUCTION

BACKGROUND

Barrier striping is one approach used to increase motorists' awareness of a roadway's barriers, particularly in low-visibility conditions (e.g., heavy rain and snow). The Texas Department of Transportation (TxDOT) Traffic Safety Division (TRF) drafted a special specification (SS) for the vertical application of a retroreflective solid stripe on concrete barriers. The draft SS was used to install barrier striping at four locations, but no formal evaluation to assess the safety benefits of the barrier striping at the existing sites had been performed. Therefore, for this project, the Texas A&M Transportation (TTI) research team evaluated the short- and long-term safety effectiveness of these treatments. Furthermore, the project involved the installation and assessment of barrier striping at newly selected high-crash locations. The research team used the findings of this project to inform updates to the SS draft for the vertical application of a retroreflective solid stripe on concrete barriers. Specifically, the research team developed recommended modifications to specific wording, tables, graphs, figures, and diagrams to guide installation of the treatments for effective results. The SS will serve as the guidance for the vertical application of a retroreflective solid stripe on concrete barriers across Texas and beyond.

PROJECT OBJECTIVES AND SCOPE

This research project evaluated the short- and long-term safety effectiveness of concrete barrier stripes. The project included the following specific technical objectives:

- Performed a traditional crash reduction analysis for three years prior to and three years following the installation of barrier striping.
- Implemented test sections of barrier striping for newly identified locations.
- Conducted a robust analysis to determine the safety effectiveness of barrier striping.
- Refined SS guidelines for barrier stripe installation.

REPORT ORGANIZATION

This report consists of seven chapters. In addition to this introductory chapter, the report contains the following material:

- Chapter 2 provides a summary of the literature review.
- Chapter 3 discusses the identification of study sites.
- Chapter 4 presents database development.
- Chapter 5 describes the safety analysis.
- Chapter 6 presents the SS guideline update.
- Chapter 7 summarizes researchers' findings and provides recommendations for future action.

CHAPTER 2: LITERATURE REVIEW

OVERVIEW

To achieve the task objectives, the research team conducted a detailed literature review using computerized searches. The review involved searching several state-based, national, and international databases and other online information to obtain relevant literature for this project. These sources included:

- Transport Research International Documentation (TRID).
- Science Direct.
- Web of Science.
- Google Scholar.
- Other state and city practice guidelines.
- Google Maps and Google Street View.

These sources provided numerous reports and manuscripts relevant to this study, including:

- National Cooperative Highway Research Program reports.
- Transportation Research Board meeting compendiums and research records.
- Federal Highway Administration reports and technical publications.
- State department of transportation reports.
- National reports (e.g., from the National Highway Traffic Safety Administration and National Traffic Safety Board).
- Articles from such journals as the *Journal of Safety Research*, *Accident Analysis & Prevention*, *Transportation Research Record*, and other relevant safety journals.

The research team used keywords such as curve delineation and barrier striping to obtain relevant literature from the databases. The team then scanned the reports and manuscripts to identify the relevant ones to include in this study. The obtained materials were summarized into four main themes and are presented accordingly in this chapter, as follows: (1) barrier delineation practices, (2) measures for safety assessment, (3) methods for safety assessment, and (4) data needs for effective barrier striping evaluation.

BARRIER STRIPING/DELINEATION PRACTICES

Barrier delineation is the application of reflective delineators on barriers (1). In most cases, especially during nighttime or adverse weather conditions, barriers are usually only visible if delineated. The delineated barrier provides drivers with information about the barrier and the road alignment. The barrier stripes can be applied to concrete barriers, steel guardrails, or other road safety barriers. This section presents a summary of barrier striping practices, including details on the materials, types of striping/delineation, existing barrier striping/delineation projects/sites across the United States, guidelines, and installation procedures.

Materials Used for Barrier Striping/Delineation

Various materials can be applied for barrier striping/delineation. These materials can be grouped into two major categories: liquid-based and reflective sheet. The composition, application, and quality of these two categories of materials differ significantly.

Liquid-Based Materials

Liquid-based materials are composed of colored spray and glass beads or microprisms that reflect light back toward its source to increase retroreflectivity. The HD-21 resin waterborne paint system with water as a solvent is preferred. In most cases, the paint should have a volatile organic compound concentration of less than 150 g/L. Further, paint of over 75 percent solids by weight and greater than 60 percent solids by volume is preferred.

Three types of beads are available. Type I is the smallest, while Type III is the largest. Type II, also referred to as “Texas standard,” is commonly applied in Texas. The size of the beads affects their retroreflectivity, whereby larger beads (Type III) have slightly higher retroreflectivity than standard beads (Type II) under dry conditions and significantly higher retroreflectivity under wet conditions. Further, although higher reflective index beads are available, most states use beads with a reflective index of 1.50 since higher reflective index beads are more expensive and slightly less durable (2).

A sprayer, rail system, airless paint gun, bead gun capable of painting concrete, w-beam guard rail, and all hoses and controls should be available to apply the materials.

Reflective Sheeting

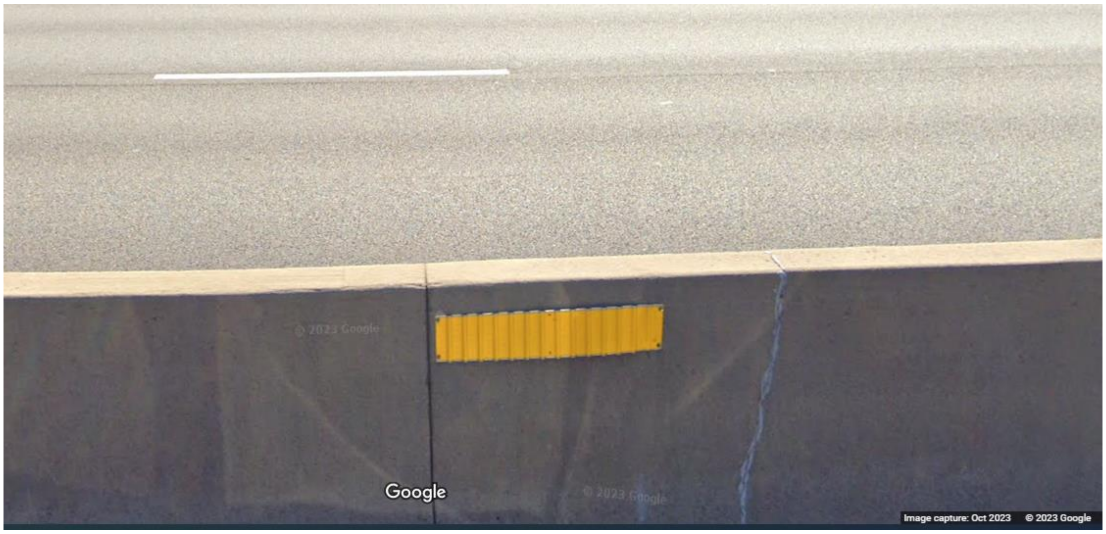
Reflective sheeting, which is a thin layer of sheet with adhesive materials on one side and reflective materials on the other side, is primarily used to increase the nighttime conspicuity of traffic signs, high-visibility clothing, and other items to make them visible in the light of an approaching driver’s headlamps. Reflective sheeting comprises retroreflective glass beads, microprisms, or encapsulated lenses sealed onto a fabric or plastic substrate.

Table 1 presents nine types of retroreflective sheeting, each determined by its adherence to the retro-reflectance, color, and durability specifications outlined in ASTM 4956-19. The specific construction of the sheeting may vary if it meets these criteria (3).

Table 1. Type and Typical Application of Retroreflective Sheeting.

Type	Definition	Typical Application
I	Medium-intensity retroreflective sheeting that is referred to as "engineering grade" and is typically an enclosed-lens glass-bead sheeting.	Highway signing, construction zone devices, and delineators
II	Medium-to-high-intensity retroreflective sheeting that is sometimes referred to as "super engineer grade" and is typically an enclosed-lens glass-bead sheeting.	Highway signing, construction zone devices, and delineators
III	High-intensity retroreflective sheeting that is typically an encapsulated glass-bead retroreflective material.	Highway signing, construction zone devices, and delineators
IV	High-intensity retroreflective sheeting that is typically an unmetallized micro-prismatic retroreflective element material.	Highway signing, construction zone devices, and delineators
V	Super-high-intensity retroreflective sheeting that is typically a metalized micro-prismatic retroreflective element material.	Delineators
VI	Elastomeric high-intensity retroreflective sheeting without adhesive that is typically a vinyl micro-prismatic retroreflective material.	Temporary roll-up signs, warning signs, traffic cone collars, and post bands
VII	Super-high-intensity retroreflective sheeting that has the highest retroreflective characteristics at long and medium road distances. This sheeting is typically an unmetallized micro-prismatic retroreflective element material.	Highway signing, construction zone devices, and delineators
VIII	Super-high-intensity retroreflective sheeting that has the highest retroreflective characteristics at long and medium road distances. This sheeting is typically an unmetallized micro-prismatic retroreflective element material.	Highway signing, construction zone devices, and delineators
IX	Very-high-intensity retroreflective sheeting that has the highest retroreflective characteristics at short road distances. This sheeting is typically an unmetallized micro-prismatic retroreflective element material.	Highway signing, construction zone devices, and delineators

Reflective sheeting can be customized to create various products, such as 3M™ linear delineation systems (LDSs), butterfly reflectors, and directional reflectors. In this case, reflective sheeting is normally overlaid on metal or plastic materials to improve visibility. 3M LDSs are commonly applied to barriers to enhance visibility. They consist of a 3M Diamond Grade™ reflective sheeting laminated onto a thin gauge aluminum substrate. The panels usually are about 34 inches long and 4–6 inches wide (4). They have a "crimped wave" shape that makes them highly visible from different angles. They can be attached to the concrete barrier or guardrail using adhesive materials and anchor bolts through six punched holes. Figure 1 shows a typical 3M LDS panel installed on a concrete barrier.



Source: Google Street View

Figure 1. Typical 3M LDS Installed on a Concrete Barrier.

Types of Barrier Striping/Delineation

Various barrier delineations have been utilized in the United States and globally. Such barrier delineations can be categorized into four major groups: linear delineation systems, directional reflectors, safety roller barrier striping, and saddle-type barrier striping.

Linear Delineation Systems

An LDS involves providing linear markings or reflective materials on the barrier. These systems are vital for road safety by helping drivers differentiate between the driving area and the barrier, enhancing traffic flow and safety. Depending on the need, continuous yellow and white striping with constant and varying gaps/spaces are used.

The 3M LDS barrier is the commonly utilized material for LDSs (4). The product is available in yellow, fluorescent yellow, red, white, and fluorescent orange (4). The LDS panels can be installed either on one side of the travel way or on both sides. For instance, 3M LDS panels are installed on both sides of the travel way along the northbound ramp at Highway 121 and Dallas North Tollway. Further, the 3M LDS was temporarily used in Oregon at three locations: the approaching lane shift onto a temporary structure at the Bob Creek Bridge, approaching lane shift at the Medford Viaduct, and approaching lane shift at the Coast Fork Willamette River Bridge. The 3M LDSs were installed at these locations to direct traffic during bridge construction, and they lasted for 12 months. Figure 2 shows the day and night comparison of the 3M LDSs (4).

Figure 2. Day and Night Comparison of Bob Creek Bridge (4).

Barrier striping/delineation can also be applied on a guardrail. Either 3M LDSs or retroreflective spray can be used in this case. Figure 3 shows the 3M LDS panels on the guardrail at one site in Michigan (5). Figure 4 shows that LDSs can be combined with other treatments to improve visibility and curve guidance, such as at one site in Michigan, where barrier delineation was combined with chevrons (5).

Figure 3. 3M LDS Panels on a Guardrail in Michigan (5).

Figure 4. Combination of Delineated Guardrails and Chevrons in Michigan (5).

The evaluation of the tested sites showed that 3M LDS is a promising alternative to traditional concrete barrier markers. However, the installation was more time-consuming than anticipated, and maintenance challenges, like keeping panels clean for optimal retroreflectivity, were noted in the evaluation (4).

In addition to the 3M LDSs, various places have utilized retroreflective sheeting. Retroreflective sheeting encompasses white or colored sheets with smooth outer surfaces that exhibit retroreflective properties across their entire area.

Directional Reflectors

Barrier striping can be single or bi-directional, meaning the reflectivity can be either on one or on both sides of the reflector. Most bi-directional reflectors have red on the wrong side and yellow/white on the right side of the traffic flow. Two existing sites in Michigan have a Luciol Systems bi-directional reflector installed in a guardrail channel and on the concrete (1).

Metal butterfly reflectors can also be used as mono or bi-delineation treatment on guardrails. They fit securely within the guardrail's center channel, protecting against accidental damage, and can be easily installed using existing guardrail bolts. These reflectors are available with amber or white reflective sheeting, making them suitable for mono-directional and bi-directional traffic delineation. They offer excellent visibility in all weather conditions; have a durable, weather-resistant surface; and are resistant to vandalism. However, some studies have suggested avoiding the metal type of butterfly delineators at sections where the bolt holds the rail to the post. This type might act as a washer, which may decrease the guardrail's performance level in a crash (5). Further, contrary to previously discussed systems, reflectors and signs are not continuous, so they do not provide a constant line of guidance to drivers.

Safety Roller Barrier Striping

The safety roller barrier is a road safety fixture designed to prevent fatal crashes by absorbing and converting shock energy into rotational energy. It effectively absorbs shocks and redirects vehicles to prevent significant accidents. There are different types of safety rollers, including the road central safety roller, which divides roadway lanes to prevent head-on collisions; the road cross safety roller, installed at intersections to prevent cars from entering greenbelts; and the safety roller for highways, which protects drivers and passengers during high-speed driving on the roadway. Striped safety roller barriers (Figure 5) are visible to road users, especially during nighttime (6).

Figure 5. Safety Roller Barrier (6).

The safety roller barrier has been implemented in other countries, such as India and Malaysia, but no study has shown the use of such an approach in the United States. These safety rollers are essential for enhancing road safety and minimizing the risk of crashes. The shock absorbent system of the roller barriers reduces sudden shocks on vehicles. A study on the use of rolling barriers on horizontal curves found that using a rolling barrier system can reduce the damage due to accidentsClick or tap here to enter text.. The roller barrier also effectively prevented sudden stoppage and vehicle overthrowing after a collision (7). These barriers also have a more serviceable life than standard barriers. Additionally, the barriers can be made with recyclable materials, providing good nighttime visibility (6,7).

Another study was conducted on the effectiveness of a rolling barrier system for straight and curved roads. Researchers suggested that rolling barriers can be used as straight roadside moving barriers, curved roadside rolling barriers, steep roadside rolling barriers, and median rolling barriers. Urethane was the preferred material in numerous performance-oriented applications due to its outstanding physical and mechanical properties, which surpass those of other materials. It was found that the rolling barriers minimized crashes by 94 percent on selected highways in Malaysia (6).

Saddle-Type Barrier Delineator

A saddle-type barrier delineator is a road safety device typically installed on or alongside traffic barriers. It enhances visibility with reflective materials and a distinctive shape resembling a saddle. These are often made of highly reflective materials in white or yellow colors. They provide continuous guidance along the barrier's length and help drivers anticipate and respond to road conditions, improving overall safety on the road. The primary purpose is to make barriers more conspicuous to drivers, aiding navigation through curves or warning of obstacles. These devices are handy during low-light conditions and serve as a vital component of road safety infrastructure. Saddle delineators are often made of highly reflective materials in white or yellow colors (3).

Existing Barrier Striping Projects/Sites across the United States

The existing literature lacks details on the barrier striping practices in other states. Thus, the research team utilized Google Maps and Google Street View to identify such locations and extract the required information. Researchers found that several states have some forms of barrier delineation but do not have barrier striping. Michigan, Colorado, Oregon, Washington, West Virginia, Montana, Pennsylvania, Missouri, Mississippi, and Iowa are among the states that have installed barrier delineation at various locations. A general review of the locations revealed that most sites are along sharp curves, including a few on the connecting ramps. This section presents the details of the existing barrier striping sites in various locations around the United States.

In Kalamazoo County, Portage, Michigan, a median concrete barrier of the main travel lanes was delineated with an LDS. The delineation spans about 15 mi long, including tangents and horizontal curves. The LDS panels were installed close to the top of the barrier and are spaced at equal distances. According to Google Street View, the LDS can be traced back to October 2016. Bi-directional reflectors were also installed on the on-ramp section of the guardrail along the 760-ft curve on Barton Shore Drive in Ann Arbor, Michigan. According to Google Street View, directional reflectors were installed at this location in October 2009. Although the guardrail had reflectors, the Google Street View image indicates that a crash involving the treated guardrail occurred between July 2019 and November 2020. Similar directional reflectors were installed on both sides of the travel way along a 2,200-ft ramp from southbound (SB) Mound Road to eastbound (EB) I-696 in Warren, Michigan, between October 2008 and June 2012. While the LDS panels were installed near the top of the barrier, the directional reflectors were installed near the middle of the barrier. Recent images show missing or broken directional reflector systems at several locations. At the same location, but on the ramp from northbound (NB) Mound Road to westbound (WB) I-696, directional reflectors were installed around September 2011. The yellow reflectors were installed on the left-hand side of the travel way, while white reflectors were installed on the right-hand side. The most recent image shows that almost all reflectors on the right-hand side and a significant number of the reflectors on the left-hand side are no longer attached to the barrier. Although no information is available, it is suspected that the delineators fell from the barrier due to a loss of adhesion because there are no indications that a significant number of vehicles hit the barriers.

LDS panels were also installed along I-84 in Portland, Oregon. The site is along the reverse horizontal curves. Google Street View indicates that these LDSs have been at this location since before 2007. The LDS panel section spans about 0.7 mi between northeast (NE) 28th Ave and Sandy Blvd along I-84. The figure indicates that the panels were installed at a relatively lower level than those along I-94 in Michigan. A review of the images indicates that some panels were damaged between August 2016 and October 2018. Although the reason for the damage is not documented, the markings on the barrier suggest several crashes. Another site with directional reflectors is located along I-5 in Portland, Oregon. According to Google Street View, until July 2015, only a top-mounted delineator was installed. The directional reflectors were installed between July 2015 and March 2016. The section is 1.61 mi long, connecting several horizontal curves.

In Colorado, at least three sites with LDSs were found. One site with LDS panels is along I-70 in Jefferson County, Colorado. The panels were installed on a guardrail between October 2009 and September 2011. In October 2020, damage was observed on the barrier and LDS panel. The 0.76-mi site is located along the curve on I-70. At another site along I-70 in Wheat Ridge, Colorado, butterfly delineators were used along with the LDS panel. Both delineation systems were installed between June and November 2018. A closer look at the guardrail showed that a crash damaged it. The length of the site is about 0.63 mi. Further, LDS panels were installed along I-70 in Denver, Colorado. The delineators were installed between November 2022 and October 2023. The segment is on a curve that is about 2,556.21 ft long. The panels were installed near the top of the barrier, like the installation along I-94 in Michigan. A review of the panel over time showed that some LDS panels were missing or damaged.

In West Virginia, at least two sites along I-64 and I-77 have LDS panels. Both sites used LDS and top-mounted delineators. The alignment of the LDS panels was changed from horizontal to diagonal on I-64 between November 2016 and April 2018. The horizontally installed panels were in a position similar to the ones in Michigan and Colorado. The LDS panels were installed on a curvature that spans about 2,315 ft. The alignment of the LDS panels at the site along I-77 in Eskdale, West Virginia, was changed from horizontal to diagonal between October 2013 and October 2015. The curve where the delineators are in use is about 2,115 ft long. In several portions, the LDS panels were slightly damaged.

In Washington, at least two sites with barrier delineation were observed. First, the LDS panels were used on the median barrier on I-90 in Quincy, Washington. Until September 2012, only top-mounted delineators were used. LDS panels and top-mounted delineators were installed between September 2012 and September 2014. The LDS panels were installed on a roadway section that spans about 1.22 mi and includes the Vantage Bridge roadway. Considering the position, the panels were installed at a relatively lower position from the top compared to those in Michigan, Colorado, and West Virginia but relatively similar to those in Oregon. Other delineators were also installed on the median barrier along I-5 in Tacoma, Washington. The site is on a curved roadway about 3,510 ft long. The striping type is side-mounted directional reflectors on the edge-side road barrier. The striping was installed around July 2021. Before that, side-mounted directional reflectors were installed on the barrier. There was no damage observed in the delineators.

The use of LDS panels was also noted at several locations in Montana. One site is along US-191/I-90 in Livingston, Montana. Initially, top-mounted barrier delineators were installed before July 2018 and then changed into LDSs between July 2018 and October 2021. The roadway segment includes several curves. The panels were closely spaced and closer to the top than the ones in Michigan. Some LDS panels were damaged at some sections of this site, and a few were half detached. Further, top-mounted barrier delineators with LDS panels were installed at several locations along I-15 in Basin and Boulder, Colorado. The LDS panels in these locations are used on median barriers at curves. The site in Basin spans about 2,533 ft, and the panels were installed before July 2012. The site in Boulder is about 2,160 ft long, and the panels were installed between September 2008 and June 2012. The panels in Boulder were installed at a lower position than the barriers at the other two sites within the same state.

Top-mounted barrier delineators and striping were installed along Raymond P. Shafer in Coraopolis, Pennsylvania. The delineators were used at a curved section that spans about 1.10 mi. The barrier on this roadway was constructed around September 2023 and is assumed to be for construction purposes. Similarly, the directional reflectors were installed in another location along I-70 in Charleroi, Pennsylvania, where the roadway segment spans about 1.01 mi. The installation was done between September 2019 and December 2021. The delineation system at this site includes top- and side-mounted delineators.

LDS panels were installed along a 0.6-mi segment on US-40/I-70 in Wentzville, Missouri. Until September 2018, only top-mounted directional reflectors were installed at this site. The additional LDS panels were installed in August 2021. However, between December 2021 and June 2022, the top-mounted barrier delineators were removed at some sections. The panels were positioned relatively lower than the ones in Michigan but at a similar location to those in Washington. Moreover, the median barrier and top-mounted delineators were broken in several areas due to crashes. Two other sites in Missouri used directional reflectors. A site along I-44 in Rolla spans about 2,035 ft and was installed between July 2014 and July 2017. Directional reflectors installed along I-70 in St. Louis span about 3,516 ft. This curved section has been delineated with directional delineators on the median since September 2014.

In Jackson, Mississippi, LDS panels were used at a site along US-44/I-20. The curved roadway segment on which the LDS panels are applied spans around 1,473 ft. These LDS panels have been installed since December 2007. The panels were installed around the middle of the barrier, with the space between them being relatively shorter than the one observed in the sites found in other states, such as Michigan and Oregon. Recent images show existing damage on the panels, such as faded areas and damage from vehicles.

LDS panels were installed on I-35 at Urbandale, Iowa, between October 2008 and July 2011. Before the installation of LDS panels, side-mounted bi-directional delineators were in use. The panels are installed along a curve that is around 3,570 ft long. The space between panels is relatively wider than in other states, such as Michigan, Oregon, and Washington. Other LDS panels were installed on guardrails in West Des Moines, Iowa. The panels were installed between October 2007 and June 2011 along a 2,225-ft-long curve. Some damage, such as the bending of the LDS panels, was noticed in several locations.

Guidelines/Special Specifications for Barrier Striping/Delineation

Colorado, Washington, Kentucky, California, North Carolina, and Tennessee are among the states with some form of guidelines for barrier striping/delineation. All of these states provide guidelines for installing directional reflectors. Colorado provides guidelines for installing both LDSs and reflectors. This section presents a summary of the reviewed guidelines from various states.

Colorado

The Colorado Department of Transportation published guidelines on barrier delineator installation in 2019 (8). The guidelines include the installation requirements of top-mounted delineators and striping, as follows:

- Delineators are mandatory on all roadways on the state highway system.
- Yellow delineators are mandatory on the left side of the expressway roadways. Interchange ramps shall also be delineated with a yellow delineator on the roadway’s left, right, or both sides.
- Red delineators could be installed on the reverse side of any delineators.
- Frontage road delineators should not be installed where they might be misleading to mainline traffic.
- If curb to curb width of a bridge is equal to or greater than the roadway width plus usable shoulder width, only triple yellow delineators should be used.
- If the approach end of a guardrail is not flared, then triple yellow delineators should be installed before the approach end.
- The color of the reflective surface of the barrier reflector shall match with the adjacent line.

- Reflector strips shall be spaced at intervals of 20 feet off-center for tangent and 10 feet off-center for curved sections of barrier.
- For mounting the reflector strip to the guardrail, including the brackets, 3M window-weld super-fast urethane glue or equivalent shall be applied at 60 degrees Fahrenheit in dry weather.

Figure 6 portrays a typical detail diagram of the installation of barrier striping/delineation on concrete barriers and guardrails.

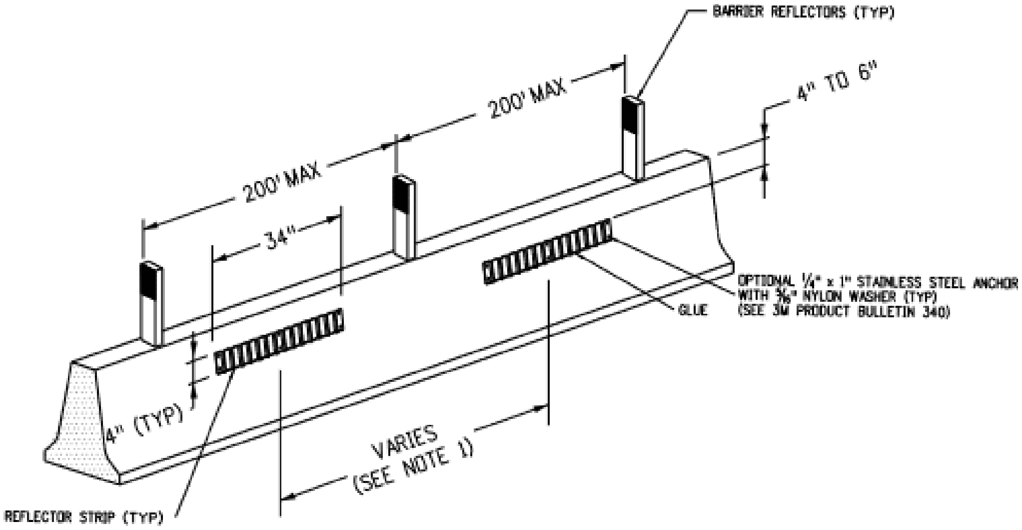


Figure 6. Typical Installation Detail for Continuous Concrete Barrier and Guardrails (8).

Washington

In 2014, the Washington State Department of Transportation provided barrier delineation requirements for guardrails and concrete barriers (9). However, the guidelines do not include information regarding barrier striping or LDSs—just barrier directional reflectors. Guidance presents the spacing, housing, color, and shape of top- and side-mounted (Figure 7) barrier reflectors.

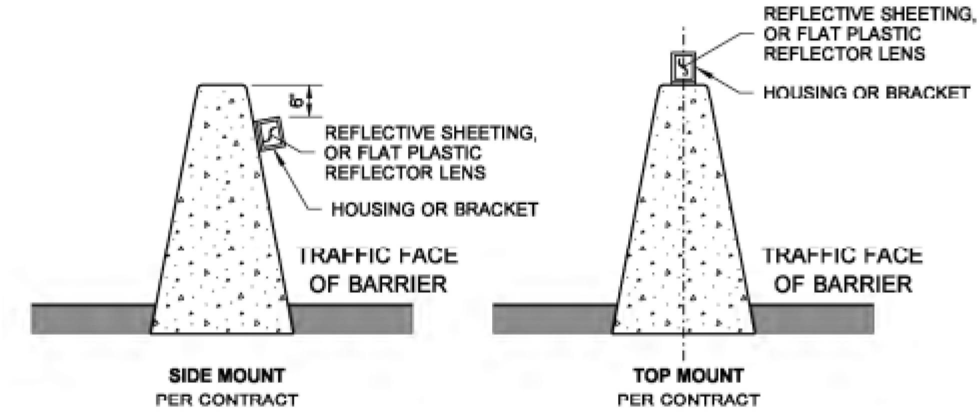


Figure 7. Side- and Top-Mounted Barrier Reflector Specification for Washington (9).

According to the guidelines, the requirements for barrier delineators are as follows:

- The delineators should be one-directional for one-way traffic and bi-directional for both-way traffic.
- The colors are preferred to be white on the right side of the traffic and yellow on the left side of the traffic.
- The reflective surface should be rectangular or trapezoidal.
- Reflective sheeting: 12 square inches minimum surface area; Type III, IV, V, or VI selected from approved materials listed in the Qualified Product List.
- Plastic reflector: 9 square inches minimum surface area; acrylic or polycarbonate conforming to AASHTO M 290.
- The spacing between the barrier delineators is also specified.

Kentucky

The Kentucky Department of Highways has guidance (10) for the installation of barrier delineators. The guidelines specify the color, location, and installation position for barrier directional reflectors. The specified requirements include the following:

- The color of the delineators is to be the same as the color of the edge lines.
- The delineators should also be placed at a vertical height of 4 feet from the pavement for both concrete and steel beam guardrails.
- Delineators should be mounted at a height of approximately 4 feet above the pavement.
- For 50” or less barrier walls, delineators may be installed on top of the barrier wall. However, for median barriers of similar characteristics that separate two-way traffic, bi-directional yellow delineators may be installed on top of the barrier instead of side-mounted mono-directional yellow delineators (Figure 8).
- Delineators shall be installed in accordance with the manufacturer's recommendations.

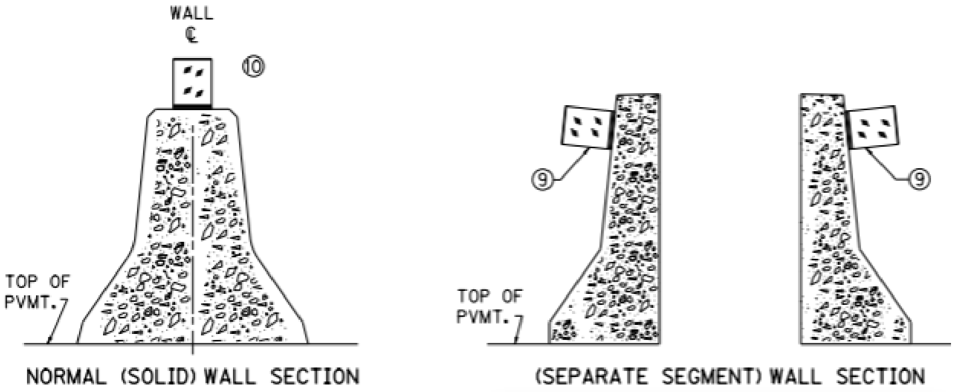


Figure 8. Directional Barrier Reflector Specification for Kentucky (10).

California

The 2014 edition of the *California Manual on Uniform Traffic Control Devices* specifies guidelines on delineators' spacing and position based on lane width, continuity, and color (11). According to the guidelines, the requirements for barrier delineators are the following:

- Retro-reflective units should be used for enhanced delineation on thrie-beam and concrete barrier for narrow medians 36 feet wide or less. Additionally, it is preferred that a barrier should be delineated if the clearance from the barrier to the edge of the traveled way is less than 12 feet.
- Delineators shall consist of retroreflective devices capable of clearly retroreflecting light under normal atmospheric conditions from a distance of 1,000 feet when illuminated by the high beams of standard automobile lights. Retroreflective elements for delineators shall have a minimum dimension of 3 inches.
- Delineators should be mounted on suitable supports at a mounting height, measured vertically from the bottom of the lowest retroreflective device to the elevation of the near edge of the roadway, of approximately 4 feet.
- Delineators should be placed 2 to 6 feet outside the outer edge of the shoulder or, if appropriate, in line with the roadside barrier 8 feet or less outside the outer edge of the shoulder.
- Delineators should be spaced 530 feet apart on mainline tangent sections and should be spaced 200 feet apart on ramp tangent sections.
- If the uniform spacing is interrupted by such features as driveways and intersections, delineators that would ordinarily be located within the features may be relocated in either direction for a distance not exceeding one-quarter of the uniform spacing. Delineators still falling within such features may be eliminated.
- The spacing of delineators should be adjusted on approaches to and throughout horizontal curves so that several delineators are simultaneously visible to the road user.

- When needed for special conditions, delineators of the appropriate color may be mounted closely on the face of or on top of guardrails or other longitudinal barriers to form a continuous or nearly continuous ribbon of delineation.

North Carolina

The North Carolina Department of Transportation has specifications on guardrail and barrier delineation spacing (12). According to the guidelines, the barrier delineator requirements are:

- The position of the reflective sheeting should be perpendicular to the roadway.
- For undivided roadways of two-lane and multilane, the placement of the delineators should begin at 1.5 meters from the barrier approach ends and at 7.5 meters from the guardrail approach ends.

Tennessee

The Tennessee Department of Transportation created specifications for installing top-mounted delineators (13). The specifications include the size, preferred spacing, and application of different types of delineators based on barrier types (see Figure 9).

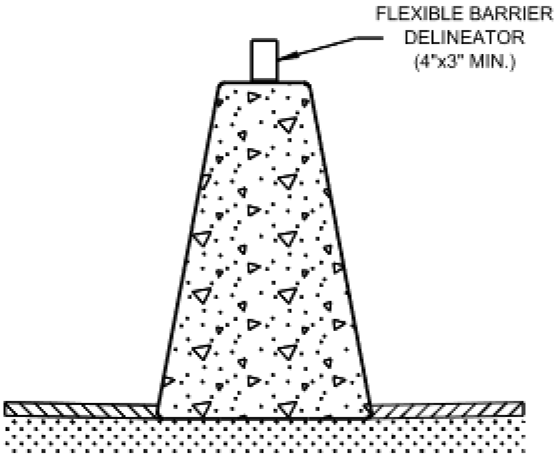


Figure 9. Top-Mounted Delineator on Flexible Barrier (13).

According to the guidelines, the specifications for the installation of delineators are:

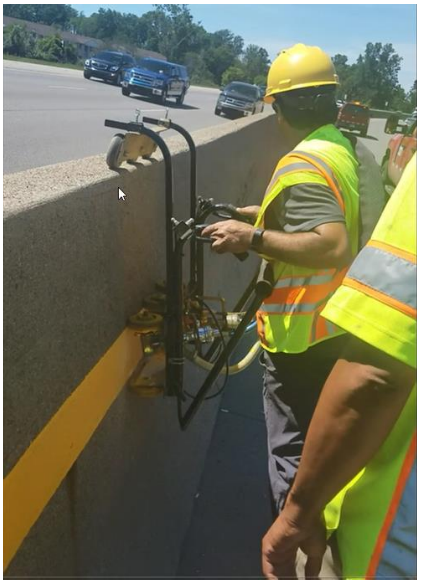
- Different sizes or manufactured delineators should not be used in the same lane. The spacing was preferred to be 50 feet or less for guardrail and cable barriers. Two connections should connect the delineators. The holes in steel guardrails that are used for attaching the delineators shall be ¼ inch in diameter.
- Double yellow reflective sheeting should be used for concrete median barriers instead of single reflective sheeting where the traffic on both sides is going in the same direction.

Installation Procedures

LDS panels are usually installed near the top of a barrier to avoid dirt. Four steps are followed for the installation procedure: marking the area, laying out the panels, drilling the holes to attach the panels to the barrier, and installing the panels. In a project at Bob Creek Bridge in Medford Crater Lake, Oregon, the panels were installed using ¼-inch × 1-inch (6.3-mm × 25.4-mm) stainless steel anchors and a 5⁄16-inch (7.9-mm) nylon washer. Each panel contained six pre-punched holes for attaching the panels to the barriers (4). Figure 10 shows a typical LDS panel installation at a site in Oregon.

Figure 10. Typical LDS Panel Installation in Oregon (4).

Unlike with the LDS panels, liquid-based materials can be applied to a concrete barrier/guardrail using a sprayer, rail system, airless paint gun, and bead gun. Figure 11 shows a typical barrier striping using liquid-based materials.



Source: TxDOT

Figure 11. Typical Application of Liquid-Based Materials on the Concrete Barrier.

MEASURES FOR THE EFFECTIVENESS ASSESSMENT

Measures for the effectiveness assessment of any treatment are the criteria used to determine whether the treatment has been effective based on the project objectives. The measures of effectiveness can be based on either crash reduction, event (e.g., near-crash or hard-braking) reduction, speed reduction, or vehicle travel trajectory changes. The following subsections present a discussion of the measures of effectiveness used in curve delineation projects.

Crash/Accident Measures

To utilize crash reduction as a measure of effectiveness, several years of crash data must be collected before and after installing the treatment. In most studies, three years before and after the treatment have been considered (14); however, due to the scarcity of data, a shorter period can be considered. A study by Albin et al. used a three-year before-after analysis of locations with a combination of treatments installed between 2000 and 2008 (5). A study by Montella used crash data from between two to four years before installation and one to three years after installation of various curve waning treatments (15). Treatments considered in this study included the warning sign, flashing beacon, chevrons, and sequential flashing beacon.

Surrogate Safety Measures

Because it is known that crashes are rare and probabilistic in nature, various studies have utilized other surrogate safety measures instead of crashes (16). Various researchers have been interested in the use of surrogate safety measures to promote a safe transportation system with a proactive approach to traffic safety. This section discusses six surrogate measures: near-crash, heavy braking, time to collision, post-encroachment time, speed reduction, and vehicle trajectory. Note that no curve delineation study has used surrogate measures to evaluate the effectiveness of the treatments.

Near-crash events are one of the surrogate measures extensively studied due to their close relationship to crashes (17,18). Guo et al.'s research was among the early studies that focused on the use of near-crash events as a surrogate measure for crashes (16). Two metrics, the precision and bias of the risk estimation, were used to assess the suitability of near-crash events as a surrogate measure. The study concluded that in cases where naturalistic studies are not large enough to represent crash scenarios, near-crash events can be used as surrogate measures for crash risk assessments.

In addition to near-crash events, heavy-braking events, time to collision, and post-encroachment time have been used to assess the safety effectiveness of treatments (17,19–22). A study by Johnsson et al. compared various surrogate safety measures, including time to collision and post-encroachment time, to select the best measure (17). The researchers reported that the minimum time-to-collision indicator outperformed the post-encroachment time.

Speed reduction and changes in vehicle trajectory have also been used to assess treatment safety effectiveness (23–25). A Moreno and García study used speed reduction as a surrogate safety measure for evaluating traffic calming devices in Valencia, Spain (23). They used GPS trackers to collect naturalistic speed data to develop two surrogate measures: the absolute accumulated speed variations relative to the average speed and the accumulated speed variations above the speed limit. The two measures were then used to determine the safety performance of the treatments. A study by Ambros et al. collected speed data using the floating car technique to collect the speed-related indicators (speed, acceleration, jerk) (24). Their study concluded that speed measures can be used as surrogate safety measures. Furthermore, Astarita and Giofrè explored vehicle trajectory as a safety surrogate measure(25).

METHODS FOR THE EFFECTIVENESS ASSESSMENT

Various approaches have been utilized to determine whether a treatment has been effective. These approaches can be grouped into descriptive analysis, crash or event rates, and statistical models/regressions. The following subsections present detailed information about the methods used to assess the effectiveness of treatments.

Descriptive Analysis

Descriptive analysis is among the most straightforward approaches used to assess the effectiveness of a treatment. This approach uses various measures, such as frequency, average, maximum, minimum, standard deviation, and median. Multiple researchers have traditionally utilized descriptive analysis to determine the effectiveness of treatments (15). Crash frequency and average crashes before and after treatment installation have been commonly used. However, such measures need to consider other exposure variables; thus, they are deemed very simplistic and cannot be applied to complex situations.

Crash/Event Rate Analysis

Crash rates are also among the most utilized approaches to determine the effectiveness of treatments. Contrary to crash frequency, crash rate considers other exposure variables, such as annual average daily traffic (AADT), section length, and time (26). Crash rate is usually expressed as Equation (1):

$$Crash\ rate = \frac{Crash\ frequency}{AADT * 365 * Number\ of\ years * Length} \tag{1}$$

Several previous studies utilized crash rates to evaluate treatment effectiveness, while others compared crash rates across similar locations with and without treatments (26–28). In the absence of crashes, heavy-braking events may be utilized to determine event rates using a similar approach. Desai et al. reported a significant correlation between heavy braking and crashes (29). Other studies have utilized heavy/hard braking to indicate safety concerns (30–32). Crash rates are appropriate for site-to-site comparison and multiple-site comparisons; however, this approach is biased toward low-volume sites.

Statistical Models

Statistical models, which generally involve complex computation, are typically considered for a thorough effectiveness assessment. The objective of applying statistical models is to consider various factors that may affect the crash's occurrence, including the treatment, land use, geometric features, weather conditions, etc. Most of the studies have utilized count models in the application of empirical Bayesian and full Bayesian methods (33–37). A few studies have utilized duration-based models, such as survival analysis and changepoint analysis (38–40).

Empirical Bayes

Empirical Bayes (EB) is one of the most dominant before-and-after study approaches. This approach is preferred because it considers the treated sites and the comparison sites. The EB method usually consists of five significant steps: developing the safety performance function (SPF); determining the overdispersion parameter, φ; computing the relative weights, α; estimating the expected crashes, π; and determining the index of effectiveness, θ (41). The SPF can take any form, but the generalized linear count response variable model is common as shown in Equation (2).

$$SPF_i = \beta_0 + \beta_1 X_{i1} + \beta_1 X_{i1} \dots\dots.. + \beta_n X_{in} + \mathcal{E}_i \tag{2}$$

Where,
SPF_i = the dependent variable (i.e., number of crashes for a given roadway segment).
X_{i1} through X_{in} = the explanatory variables (e.g., AADT, number of lanes, etc.).
β_0 through β_n = the coefficients.
ε_i = the error term.

Although studies focused on barrier striping/delineation are relatively scarce, various studies have utilized the EB approach for the safety evaluation of curve delineation (15,34,36). A study by Montella applied the EB approach to estimate the safety effectiveness of curve delineation improvements for 15 curves on the motorway A16 Naples–Canosa in Italy (15). In this study, the before period varied between two and four years, while the after period varied between one and three years. Lyon et al.'s study applied the EB approach to develop the crash modification factors and functions for high-friction surface treatments on curves and ramps (36). Their study consisted of 146 treated sites and 1,239 control curved sites across West Virginia, Pennsylvania, and Kentucky. Further, Wood and Donnell applied the EB method to evaluate the safety effectiveness of horizontal curve warning pavement markings on two-lane rural highways in Pennsylvania (34). Their analysis used 263 treated curved sections; the reference group had 21,902 curved sections.

Full Bayes

In contrast to the EB, full Bayes (FB) requires less data but additional prior information. With the increased need to explore the uncertainty in developed models, the availability of modern tools, and the increased computational power of computers, the FB approach has gained more attention in recent years (33,35,42). A study by Park et al. provided a step-by-step procedure to implement FB methods for a before-after evaluation with a comparison group (42). The same study applied the FB approach to evaluate the safety benefits of decreasing speed limits on expressways in Korea. The analysis used 33 treated sites and 44 comparison sites with similar before and after conditions. Compared to naïve Bayes and EB, the FB approach performed relatively better in estimating crash reduction in response to speed limit reduction (42). A study by Persaud et al. reached a similar conclusion when comparing FB and EB for estimating the safety improvement of a road segment that was converted from a four-lane to a three-lane cross-section with two-way left-turn lanes (35). Another study by Park et al. applied both EB and FB to assess the safety effects of roadside barriers with different crash conditions (33). FB was applied in the study because most of the studies that developed crash modification factors did not consider information from prior studies.

Difference in Differences

For observational data analysis, the difference-in-differences (DID) method has been widely used in many branches of science (43–45). In traditional before-after (BA) observational studies, analysts examine identical locations during pre- and post-intervention periods to assess the safety impact of a treatment or countermeasure. However, if the implementation of a countermeasure is prolonged or the observable effects take time to manifest, various other factors may change during that duration. Consequently, the difference in the response variable Y cannot be attributed solely to the treatment's effect. In the DID method, a treatment qualification variable appears such that the treatment group is treated at some point, but the control group is never treated. Whereas the other BA methods use the difference of the treatment group before and after periods, DID uses the difference of the two periods across the treatment and control groups. As for changes in the confounder ε are same as the changes in the confounder in control groups, the BA difference in the treatment group due to ε may be removed. This explains how the confounder effect gets removed in DID. Even if X is not controlled, its effect can be removed in DID if the effect is common between the two groups. The DID equation can be written as Equation (3) (46).

$$Y_{it} = X_{it}'\beta_x + C_{it}1[t_0 \leq t]\beta_c + 1[t_0 \leq t]\beta_0 \tag{3}$$

Where,
Y_{it} = response variable.
X_{it}' = explanatory variables.
β_c = effect for the treatment sites.
β_0 = effect for both treatment and control sites.
C_{it} = time varying qualification dummy.

The effect of the interaction between C_{it} and the time dummy $1[t_0 \leq t]$ for the post-treatment can be written as Equation (4):

$$E(Y_{it}|C_{it} = 1, X_{it}) - E(Y_{it}|C_{it} = 0, X_{it}) = \beta_c \tag{4}$$

Survival Analysis

The widely used EB and FB methods for BA safety assessment are sometimes limited by the extensive data needs and more extended periods required to obtain reliable results. Survival analysis was recently introduced to address the issue of crash aggregation over a long period (39,40). Survival analysis focuses on the time between two consecutive crashes (47). The change in the time between crashes for before and after periods signifies the effectiveness of the treatment. Survival analysis can also be used to determine the impact of the treatment over different periods, such as after one month, six months, and five years (40). Figure 12 presents the schematic of the before and after crash data collection.

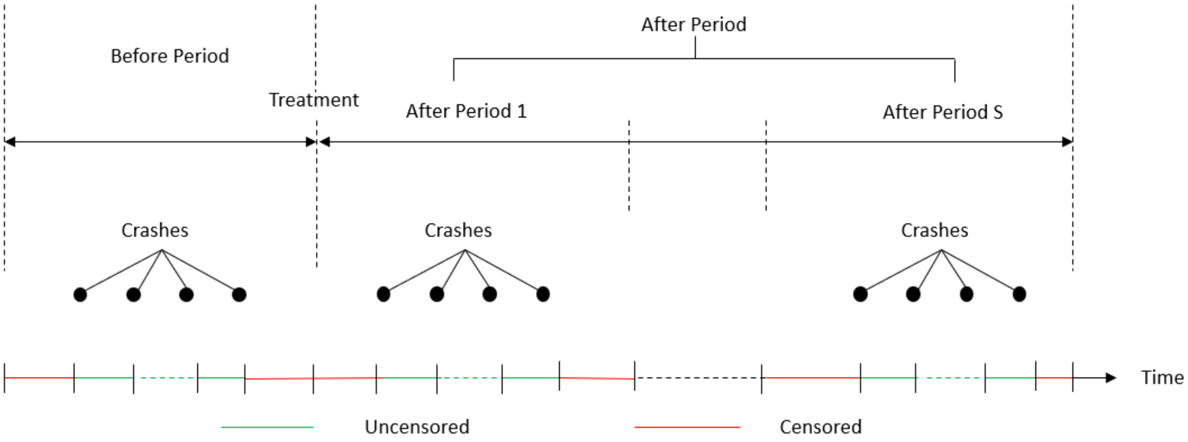


Figure 12. Before-After Settings (40).

In addition to the disaggregated benefits, survival analysis can utilize only the treated sites, so its results will not be affected by insufficient reference sites (39).

Changepoint Analysis

Although survival analysis resolves the data aggregation issue, it is relatively complex to pinpoint the time when changes occurred. Thus, changepoint analysis was introduced to solve this issue (48–50). The advantage of changepoint analysis compared to the widely used EB and FB methods is the ability to utilize the treated sites only. A study by Tay applied a continuous time Poisson changepoint analysis to evaluate the effectiveness of various intervention programs to lower crashes in New Zealand (48). The study intended to understand the point in time and the type of intervention that was effective. Figure 13 shows a pattern change in crashes for before and after treatment and the actual changepoint.

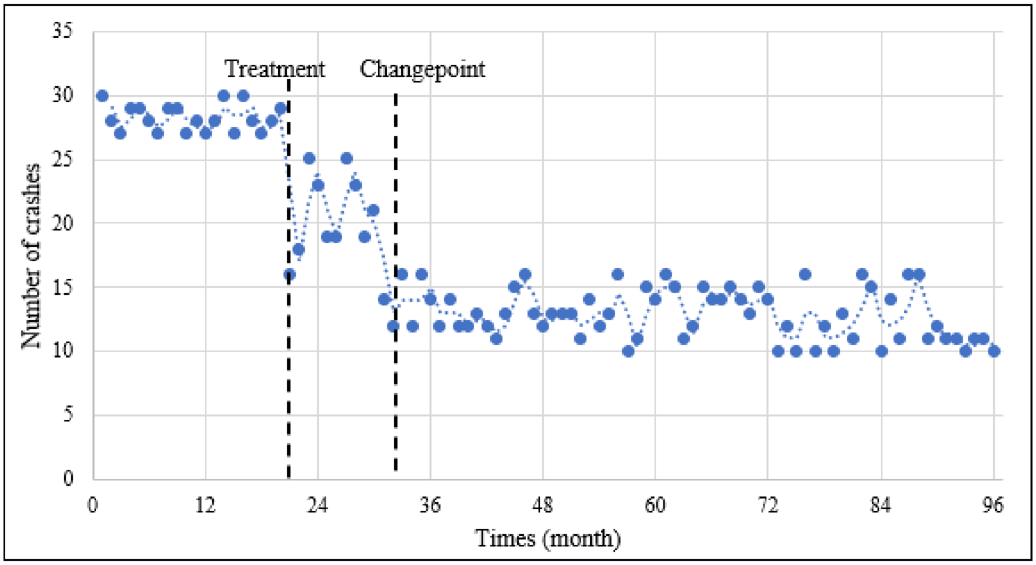


Figure 13. Typical Changepoint after Treatment.

DATA NEEDS FOR BARRIER STRIPING SAFETY EFFECTIVENESS ASSESSMENT

Safety effectiveness assessment of any treatment requires various types of data depending on the nature and the extent of the analysis. This section provides an overview of these data sources and corresponding data characteristics and elements. The data covered in this section are crash and event data along with exposure data such as AADT, roadway geometry, social demographic, meteorological, and visibility data.

Crash and Event Data

Crash data have predominantly been used to effectively assess any countermeasure including barrier striping. Researchers have utilized state and nationwide databases such as the Fatality Analysis Reporting System (FARS) (51). In Texas, the crash data stored in the Crash Records Information System (CRIS) database have been utilized by researchers to evaluate the safety effectiveness of various countermeasures (52).

CRIS data elements are divided into three major categories: (1) crash event characteristics, (2) primary person characteristics, and (3) vehicle (unit) characteristics. CRIS has over 150 fields that contain data about spatial and temporal characteristics (e.g., time, date, and geodesic coordinates), roadway characteristics, contributing factors (e.g., weather, lighting, and pavement conditions), manner of collision (e.g., head-on, rear-end, and sideswipe), crash severity, vehicle type, driver characteristics, and passenger characteristics, among others.

The available elements can help quantify the crashes before and after the installation of the countermeasure. Such elements include the crash coordinates for location identification, the crash date and time for before and after period identification, the object hit to identify barrier-related crashes, and the crash severity. A preliminary review of the crash data revealed that concrete-barrier-related crashes are widespread all over the state, although they are mainly concentrated on the east side (Figure 14).

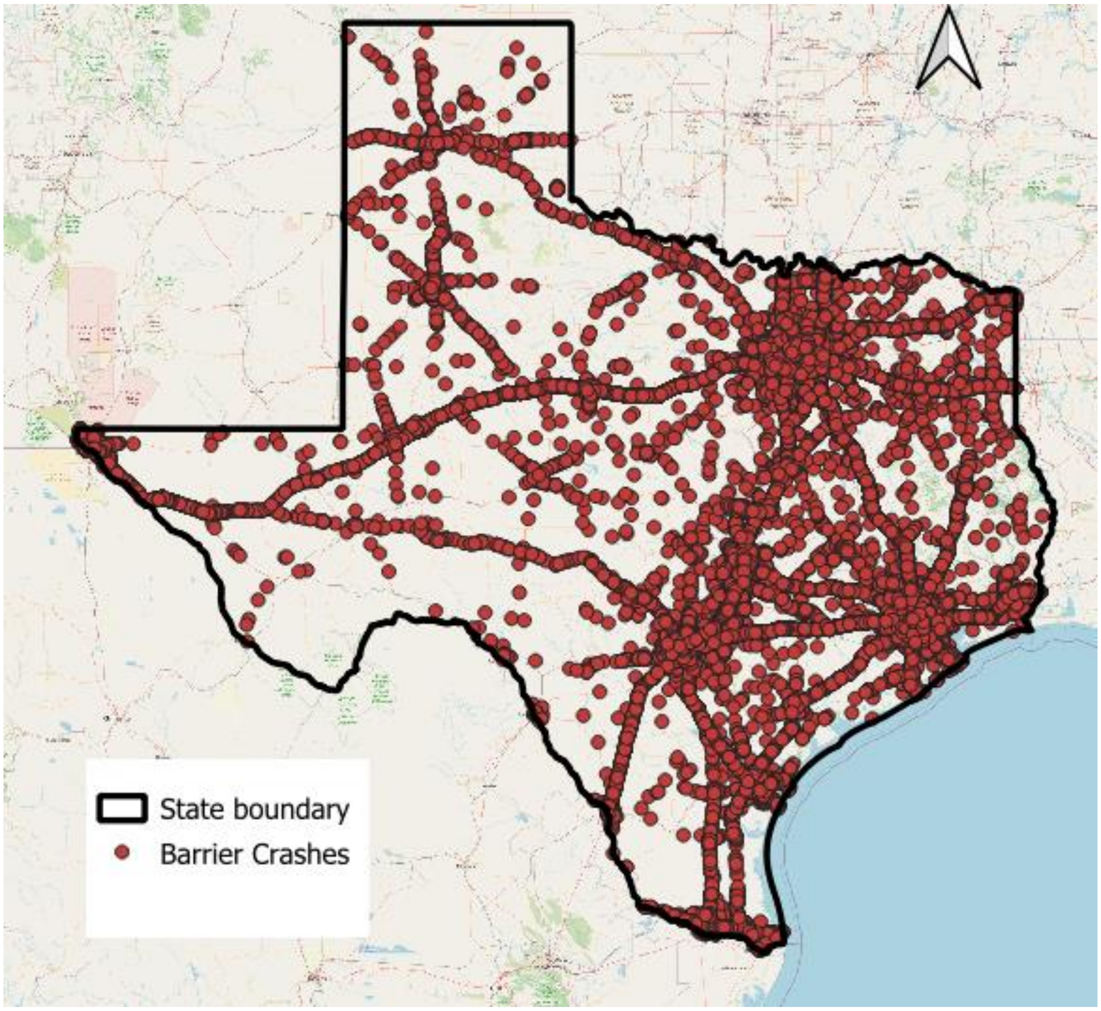
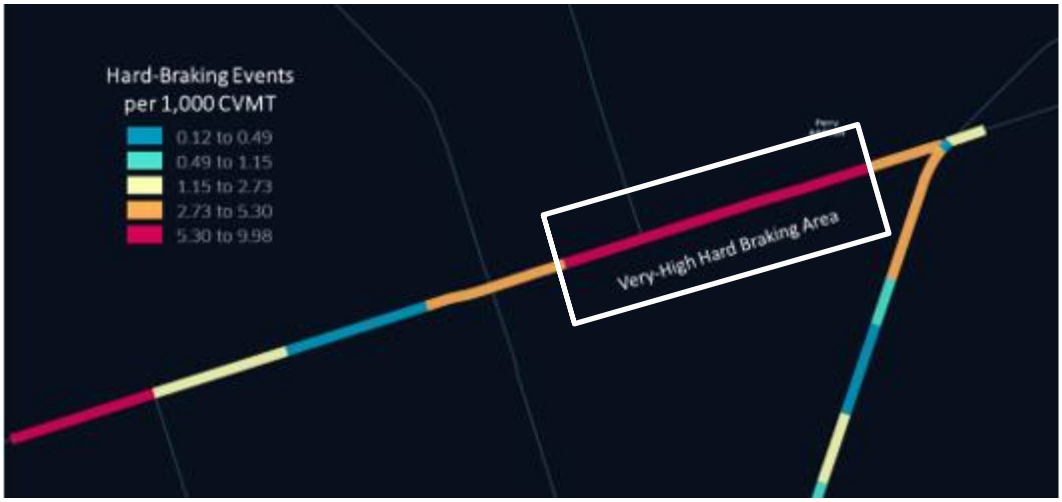


Figure 14. Distribution of Barrier Crashes along Texas Roadways (52).

Since crashes are rare and random, not all studies have utilized crash data, especially if the analysis period is relatively short. Various event data, such as near-miss, heavy braking, speed, and vehicle trajectory, have been utilized (29–32).

Various databases, such as Wejo and INRIX XD, provide segment-level and trajectory-level information on operating speed measures and events (53,54). Wejo is a data aggregator that identifies and combines connected vehicle data (CVD) across original equipment manufacturers (53). Wejo data include location points and information to identify the operating speed of each vehicle at the waypoint level. With Wejo data, the speeds and speeding-related driving events can be identified. Figure 15 illustrates how acceleration and hard-braking events can be visualized at the point level using Wejo data.



Source: Wejo database (53)

Figure 15. Hard-Braking Events Extracted from CVD.

INRIX provides real-time speed data coverage across the roadway network in the United States (54). The highly granular floating vehicle data of INRIX are prepared with traditional real-time traffic flow information and hundreds of market-specific criteria that affect traffic. INRIX compiles and aggregates crowdsourced, passively collected data from various sources and data resellers, including smartphones, connected cars, fleet telematics, and fixed-sensor networks. The multi-source data fusion uses proprietary algorithms to produce several different traffic data products. The most popular data product of INRIX is segment-based traffic speeds. Historically, the INRIX dataset has been robust for interstates and freeways; however, the addition of the INRIX XD™ Traffic service has added a rich dataset for non-freeways and low-volume roadways in many locations across the country, incorporating more than a million roadway segments. Table 2 lists the descriptions of the field names used in the INRIX XD files.

Table 2. INRIX XD™ Data File Format (54).

Field Name	Type	Example	Description
xdsegid	Integer	167115703	Identification number of the roadway segment in the XD database
dayname	Text	FR	Two-letter abbreviation for the day of the week in which the speed data were collected
ffspd	Integer	23	Free-flow mean speed representing the 66th percentile of the 168 hourly speed bins at a given location for the week
spdXX	Integer	21	Average speed for a given hour of the day corresponding to XX, where XX is a number from 00 to 23
road	Text	E Villa Maria Rd	Name of the roadway on which the segment is located
direction	Text	W	Direction of travel (N, S, E, or W) for which the data were recorded
roadorder	Text	B4-E1	Code showing the order in which the segments are arranged in the data file
startlat	Float	30.63972	Latitude for the start of the roadway segment
endlat	Float	30.64354	Latitude for the end of the roadway segment
startlon	Float	−96.35821	Longitude for the start of the roadway segment
endlon	Float	−96.35343	Longitude for the end of the roadway segment
state	Text	Texas	State in which the roadway segment is located
county	Text	Brazos	County in which the roadway segment is located
zipcode	Integer	77802	Zip code in which the roadway segment is located
seglength	Float	0.398	Length of the roadway segment (mi)

Exposure Data

Traffic Volume

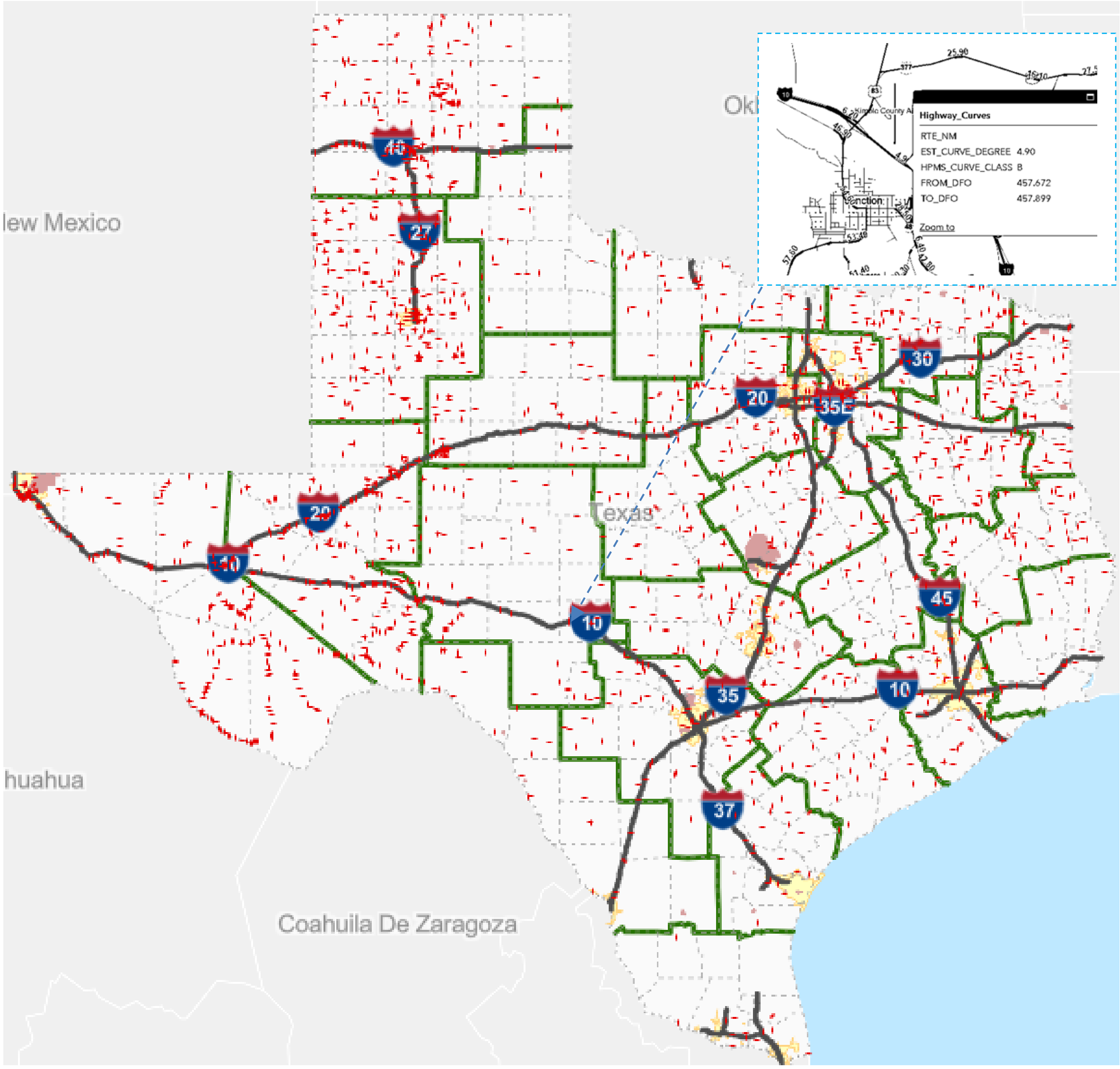
Traffic volume measures the exposure to crashes for a given segment of the roadway. Because any traffic crash should involve a vehicle, the number of vehicles in the given segment is usually associated with the likelihood of a traffic crash.

AADT is the volume measure used predominantly in safety analysis. It involves estimating the average number of vehicles per day for the entire year for a given road section. Various state-based and nationwide databases store AADT data. The AADT for Texas can be found in the TxDOT Roadway Inventory database (55). The AADT data from the TxDOT Roadway Inventory database is assigned to a segment of the road.

Roadway Geometry

Like traffic volume data, the roadway geometry data for Texas are stored in the TxDOT Roadway Inventory database (55). The roadway geometry data include the number of lanes, lane width, and shoulder width, among others. The roadway geometry data may be used to determine the comparison sites.

Additionally, the Texas Highway Curves Geographic Information System (GIS) layer (Figure 16) provided by TxDOT has all the highway horizontal curves in Texas. The available horizontal curve-related data are the roadway name (RTE_NM), estimated curve degree (EST_CURVE_DEGREE), curve class (HPMS_CURVE_CLASS), beginning distance from origin (FROM_DFO), and ending distance from origin (TO_DFO).



RTE_NM
EST_CURVE_DEGREE 4.90
HPMS_CURVE_CLASS B
FROM_DFO 457.672
TO_DFO 457.899

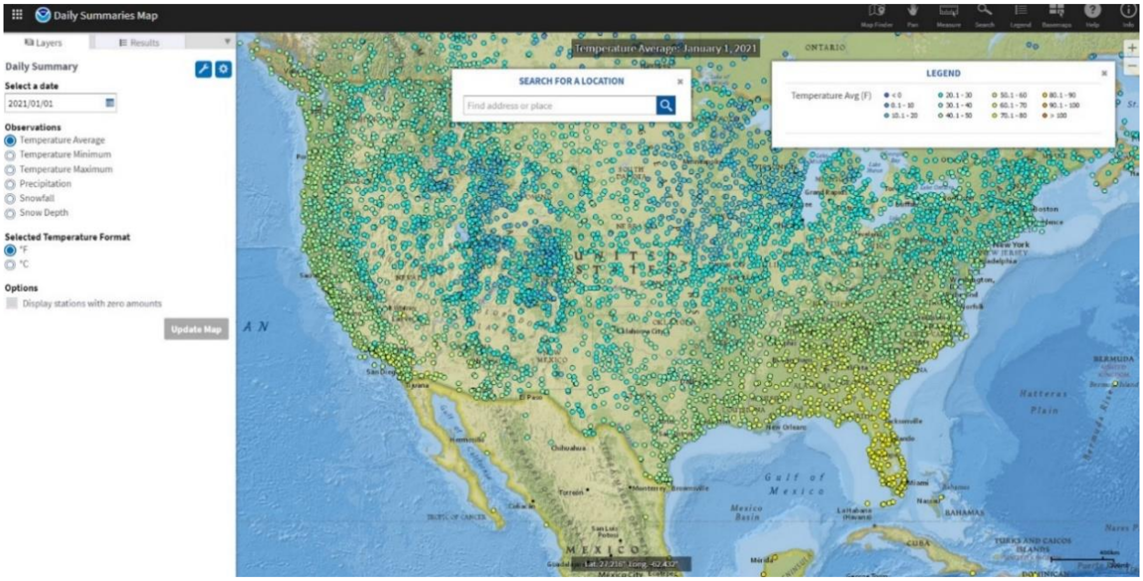
Figure 16. Distribution of Horizontal Curves across Texas (56).

Reflectivity Data

Reflectivity data are a measure of the material retroreflectivity level. Retroreflectivity is a measure of how efficient the material is at returning light back toward the light source. Material with higher retroreflectivity will appear brighter at night. Minimum performance levels can be established to determine initial and maintained performance for the retroreflective devices. A retroreflectometer is used to measure the retroreflectivity of the materials.

Meteorological Data

Meteorological data, which provide details about the temperature, precipitation, snowfall, and other weather-related events, are of interest for safety analysis. The National Oceanic and Atmospheric Administration (NOAA) maintains the meteorological database, and it can be used by researchers and the public. It covers the entire United States (Figure 17), and the information can be retrieved by station name, zip code, city, county, state, or country. The stored data are aggregated on hourly, daily, and monthly granulation.



Daily Summary

Select a date

2021/01/01

Observations

● Temperature Average
○ Temperature Minimum
○ Temperature Maximum
○ Precipitation
○ Snowfall
○ Snow Depth

Selected Temperature Format

● °F
○ °C

Options

☐ Display stations with zero amounts

Figure 17. Daily Weather Summaries Map (57).

CHAPTER 3: STUDY SITE EXPLORATION

OVERVIEW

This project utilized data from two categories of sites: (a) existing sites where barrier striping had already been installed, and (b) new sites where the research team installed barrier striping. The two categories required different assessment approaches; thus, the data needed to differ significantly. The target was to assess the safety performance of existing sites based on crash data and new sites based on speed data. This chapter presents the details on the existing sites and the new sites selected for treatment.

EXISTING TREATED SITES

TxDOT previously installed barrier striping at five sites in four locations/interchanges across the state. These sites were used for long-term before-and-after evaluation. The research team identified the existing sites with barrier stripes through the project manager (PM). The PM provided the research team with a Google Earth file showing the location of the treated sites. Table 3 lists the existing sites with treatments. Most of these sites are ramp connectors striped white and yellow on the right and left sides, respectively. The installation dates spanned from March 2013 to August 2016, with the majority of treatments installed between July 2015 and August 2016. The following subsections present the detailed characteristics of the existing treated sites.

Table 3. Existing Sites with Treatment.

Site	Location	Coordinates	Installation Date	Segment Type	Length (ft)	Striping Type
1	Ben White Interchange (I-35 SB to TX 71)	30.216835, −97.750353	July 2015–June 2016	Ramp connector	1,300	White and yellow
2	Turnaround Bridge (I-20 at McCart Ave)	32.668167, −97.356141	July 2015–August 2016	U-turn	350	White
3	Fort Worth (I-20 EB to I-35W NB)	32.664940, −97.322533	July 2015–August 2016	Ramp connector	1,900	White and yellow
4	Fort Worth (I-20 EB to I-35W SB)	32.666535, −97.320271	July 2015–August 2016	Ramp connector	3,100	White and yellow
5	Paris (SE Loop 286, US-271)	33.646139, −95.501681	March 2013–August 2016	Ramp connector and main lanes	5,500	White and yellow

Ramp Connecting I-35 SB and SH 71 EB in Austin, Texas

This study site is an interchange connecting I-35 and SH 71 in Austin. It is an approximately 0.25-mi ramp that connects traffic from I-35 SB to SH 71 EB (Figure 18[a]). The site was striped with white and yellow markings for the right and left barriers, respectively (Figure 18[b]). According to the image obtained using Google Street View, the striping was performed between July 2015 and June 2016. Prior to the installation, the site had pavement markings and butterfly reflectors on the barriers.

(a) Aerial view of the treated ramp from I-35 SB to SH 71 EB

(b) Street view of the treated ramp from I-35 SB to SH 71 EB

Figure 18. Treated Ramp from I-35 SB to SH 71 EB.

Turnaround Bridge at I-20 and McCarter Ave in Fort Worth, Texas

This site is at the turnaround bridge at McCarter Ave along I-20 in Fort Worth (Figure 19[a]). It has white directional marking stripes that indicate the direction of traffic flow (Figure 19[b]). The entire ramp spans about 250 ft, with the marked section spanning about 160 ft. The markings were installed between July 2015 and August 2016. The ramp had lane pavement markings before the installation of the barrier stripes.

(a) Aerial view of the turnaround bridge at I-20 and McCarter Ave

(b) Street view of the turnaround bridge at I-20 and McCarter Ave

Figure 19. Treated Site on Turnaround Bridge at I-20 and McCarter Ave.

Treated Ramps on I-20 and I-35 Interchange in Fort Worth, Texas

The interchange that connects I-20 and I-35W in Fort Worth has two treated ramps, I-20 EB to I-35W SB and I-20 EB to I-35W NB ramps. The I-20 EB to I-35W SB ramp is relatively short, about 0.25 mi, while the I-20 EB to I-35W NB ramp spans about 0.5 mi (Figure 20[a]). Both ramps were striped between July 2015 and August 2016, with the right and left sides striped with yellow and white markings, respectively (Figure 20[b]). In addition to the barrier stripes, the sites have lane marking delineation that indicates the ends of the lanes.

(a) Treated ramps from I-20 EB to I-35W SB and I-20 EB to I-35W NB

(b) Street view of the treated ramp from I-20 EB to I-35W SB

Figure 20. Treated Ramps at the I-20 and I-35W Interchange.

Site along SH 286 and US 271 in Paris, Texas

This is the only site with treated guardrails. The treatment was performed between March 2013 and August 2016. The eastbound direction has treatments installed for a major portion, while only a small part of the westbound section is treated (Figure 21).

(a) Plan view of the treated sections along SH 286 and US 271 in Paris

(b) Street view of the treated sections along SH 286 and US 271 in Paris

Figure 21. Treated Sections along SH 286 and US 271 in Paris.

NEW SITES SELECTED FOR TREATMENT

In addition to the existing sites with barrier stripes, the research team identified new locations to install stripes. These locations were critical for the short-term before-and-after analysis.

Criteria for Selecting New Sites

The identification of the potential sites by the research team was based on five criteria: crash frequency, roadway geometry, spatial representation, lighting and weather conditions, and TxDOT preference. The following subsections present the details for each criterion.

Crash Frequency

The target crashes in this project were barrier-related crashes. Thus, locations with a high frequency of crashes involving concrete barriers or guardrails were of interest. However, a high crash frequency does not always mean a high crash rate. Thus, crash rates were also determined to aid in the final selection of the sites for the selected high-crash-frequency locations.

Roadway Geometry

Roadway geometry is an essential feature in barrier-related crashes. In this case, curved sections were preferred because drivers must be more attentive at these locations to avoid running off the road and hitting the barrier.

Spatial Representation

Spatial representation was a significant factor since the traffic pattern varies across the state. Obtaining sites from various parts of the state, such as rural and urban areas, enabled the effective application of the countermeasure across the entire state. In addition, spatial representation plays an important role in installation since TxDOT might have in-house strategies for barrier stripping installation that could necessitate the inclusion or exclusion of a certain location/region.

Lighting and Weather Conditions

Lighting conditions were important because they play a great role in the reflectivity of barrier stripes. For instance, barriers may be more appropriate at locations with a higher nighttime crash frequency/rate. Further, barrier stripping may also be appropriate at locations with adverse weather conditions such as rain, fog, snow, etc., thus making weather conditions an important factor.

TxDOT Preference

In addition to the criteria mentioned above, the research team considered the fact that TxDOT might have a preference regarding where barrier stripes needed to be installed based on the experiences and needs of the district representatives.

Selected Sites for Treatment

The research team used ArcGIS to determine the curved locations with a high crash frequency. First, the Road-Highway Inventory Network (RHiNO) shapefile, which contains all major roadways across the state, was plotted in the GIS application. Then, the Texas Curves shapefile was overlaid to map locations with curves. A buffer of 250 ft was applied on the Texas Curves shapefile. The crash data were then overlaid on the buffered curved sections. The research team used the crashes that occurred between 2021 and 2023. Via the join function, all crashes within the buffered area were joined to their respective curves. An additional check was performed to remove crashes that occurred along cross streets, especially in urban areas.

Since the project focused on nighttime barrier crashes, the research team applied additional filtering to obtain crashes needed for further analysis. This step involved using the OBJ_STRUCK_ID variable to select barrier-related variables. Crashes hitting the guardrail, median barrier, end of bridge (abutment or rail end), side of bridge (bridge rail), attenuation device, concrete traffic barrier, and retaining wall were considered. Further, to filter the nighttime crashes, the LIGHT_COND_ID variable was used. The categories of interest were dark not lighted, dark lighted, dusk, dawn, and unknown lighting.

Based on the evaluation of the overall barrier-related crashes and nighttime barrier crashes, the researchers provided a list of 12 sites to TxDOT. Upon review, TxDOT selected seven sites for treatment. Table 4 presents the list of the selected sites, all of which were within the Dallas and San Antonio Districts. Additionally, these sites had the highest number of overall barrier crashes and dark-time barrier crashes. The following subsections present the details of each site.

Table 4. Selected Sites for Treatment.

Site Number	Location	Barrier Type	District	Length (mi)	Barrier Crashes	Nighttime Barrier Crashes
Site 1	I-35E near W Twelfth St	Concrete barrier	Dallas	0.52	92	58
Site 2	I-30 over 1st Ave	Concrete barrier	Dallas	0.61	81	56
Site 6	I-35 E near Mockingbird Ln	Concrete barrier	Dallas	0.90	124	84
Site 9	I-35E near S Ewing Ave	Concrete barrier	Dallas	1.31	148	91
Site 3	I-10 near I-410	Concrete barrier	San Antonio	1.42	98	61
Site 7	US 281 and Hildebrand Ave	Concrete barrier	San Antonio	0.63	133	67
Site 8	US 281 and Josephine St	Concrete barrier	San Antonio	0.68	110	56

I-35E near W Twelfth St in Dallas

This site is located along I-35E near the W Twelfth St overpass. It is a 0.23-mi curve on the five main lanes with concrete barriers. It has a relatively sharp curve with an estimated 52.7-degree central angle (see Figure 22). The AADT is 196,525, and about 58 nighttime barrier-related crashes occurred in this area between 2021 and 2023.

Figure 22. Site along I-35E near W Twelfth St.

I-30/US 67 over 1st Ave in Dallas

This site is located along I-30 near 1st Ave in Dallas. It is on the four main lanes with concrete barriers. Its central angle is estimated to be 66 degrees (see Figure 23), stretching for about 0.4 mi. The AADT is 167,256, and about 56 nighttime barrier-related crashes occurred in this area between 2021 and 2023.

Figure 23. I-30 over 1st Ave in Dallas.

I-10 near I-410 in San Antonio

This site is located along I-10 near I-410 in San Antonio. It is on the five main lanes with concrete barriers. Its central angle is estimated to be relatively sharp (87 degrees; see Figure 24), stretching for about 0.4 mi. The AADT is 187,705, and about 61 nighttime barrier-related crashes occurred in this area between 2021 and 2023.

Figure 24. I-10 near I-410 in San Antonio.

I-35E near Mockingbird Ln in Dallas

This site is located along I-35E near Mockingbird Ln in Dallas. It is on the five main lanes with concrete barriers. Its central angle is estimated to be 73 degrees (see Figure 25), stretching for about 0.7 mi. The AADT is 213,695, and about 84 nighttime barrier-related crashes occurred in this area between 2021 and 2023.

Figure 25. I-35E near Mockingbird Ln in Dallas.

US 281 and Hildebrand Ave in San Antonio

This site is located along US 281 and Hildebrand Ave in San Antonio. It is on the four main lanes with concrete barriers. Its central angle is estimated to be 37 degrees (see Figure 26), stretching for about 0.4 mi. The AADT is 160,892, and about 67 nighttime barrier-related crashes occurred in this area between 2021 and 2023.

Figure 26. US 281 and Hildebrand Ave in San Antonio.

US 281 and Josephine St in San Antonio

This site is located along US 281 and Josephine St in San Antonio. It is on the four main lanes with concrete barriers. Its central angle is estimated to be 75 degrees (see Figure 27), stretching for about 0.2 mi. The AADT is 160,892, and about 56 nighttime barrier-related crashes occurred in this area between 2021 and 2023.

Figure 27. US 281 and Josephine St in San Antonio.

I-35E near S Ewing Ave in Dallas

This site is located along I-35E near S Ewing Ave in Dallas. It is on the five main lanes with concrete barriers. Its central angle is estimated to be 39 degrees (see Figure 28), stretching for about 0.4 mi. The AADT is 160,892, and about 91 nighttime barrier-related crashes occurred in this area between 2021 and 2023.

Figure 28. I-35E near S Ewing Ave in Dallas.

Barrier Striping Installation

The installation of the barrier striping at selected locations was performed by TxDOT technicians. The research team purchased the sprayer machine, yellow and white paints, and beads. Research team members were on site to work with the technicians and understand any issues that might arise during installation.

Test Installation and Lessons Learned

Prior to installation, the research team hosted a training on October 15, 2024, to familiarize TxDOT technicians and the research team members with the striping machine. A representative/trainer from Epic Solutions delivered a training on how to use the sprayer (see

Figure 29). The training started around 8:30 a.m. and finished around noon. For training purposes, white paint, beads, and concrete barriers 32 inches high were used.

Figure 29. Trainer Illustrating the Use of Barrier Striping Sprayer.

The trainer utilized details from th*e* TxDOT's Special Specification 6508, Safety Barrier Line Markings (58), to train TxDOT technicians. The TxDOT technicians had several questions that needed further discussion between the research team, the trainer, and the PM. For example:

- The manual shows that the width of the stripe can be 6, 8, or 10 inches (see Figure 30). The technicians asked which width they should use when installing barriers at the sites.

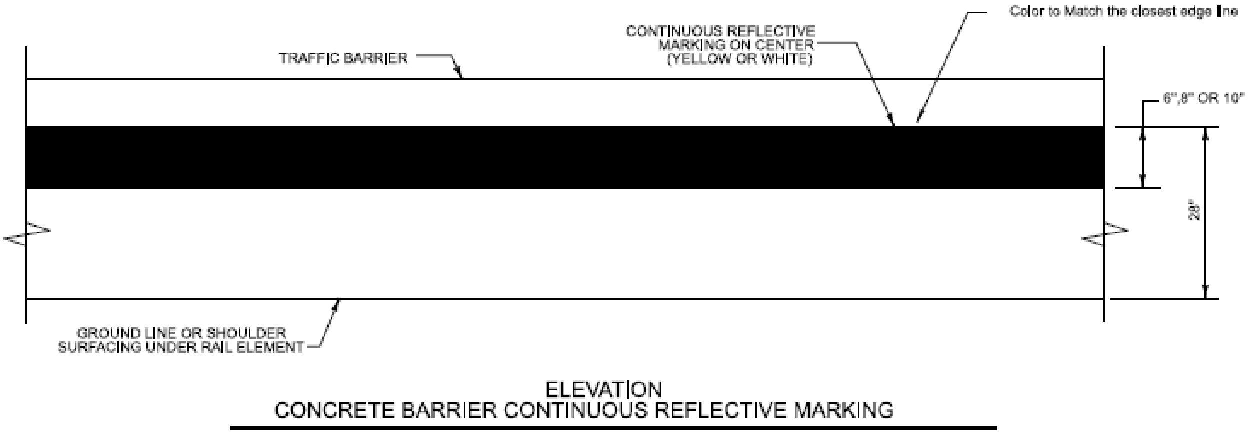


Figure 30. Barrier Striping Specifications from Special Specification (58).

- The manual specifies that the distance from the bottom/surface to the top of the stripe should be 28 inches. The technicians noted that the barriers used for training were 32 inches high, which means only 4 inches remained to the top of the barrier (see Figure 31).

- The trainer mentioned that based on his experience, other states keep a 10-inch distance from the top surface to the top of the barrier stripe.
- The TxDOT technicians noted that most available barriers on the sites were 42 inches high, which would be appropriate for this setup. However, there also could be barriers with a 50-inch height. Thus, guidelines should consider where the stripe should be located for different barrier heights.

Figure 31. Striped Barrier after Training.

Site Installation

The TxDOT team implemented the barrier striping in multiple phases across various locations, with the initial installation taking place along I-10 near I-410 in San Antonio on April 8, 2025. This location marked the first implementation site and served to demonstrate installation logistics and refining of field procedures. Before installation, TxDOT coordinated a dedicated installation crew and a traffic management team to ensure the operation proceeded safely and efficiently.

Installation activities began at approximately 8:00 p.m. and continued overnight to minimize disruption to traffic flow. To create a secure work zone, the traffic management team closed one exit ramp, one travel lane, and the adjacent shoulder. This closure configuration provided technicians with the space needed to apply the striping without interference from live traffic. Reflective barrier striping was applied to the southbound concrete barriers, while the northbound side remained untreated to allow for comparative evaluation of visibility and safety performance. Figure 32 shows TxDOT technicians performing barrier installation at a site along I-10 near I-410 in San Antonio.

Technicians followed the guidelines outlined in TxDOT’s Special Specification 6508, Safety Barrier Line Markings, in terms of the distance from the top of the pavement. The team applied a 10-inch-wide reflective stripe using a controlled walking speed of approximately 3.5 to 4 ft per second to ensure uniform application.

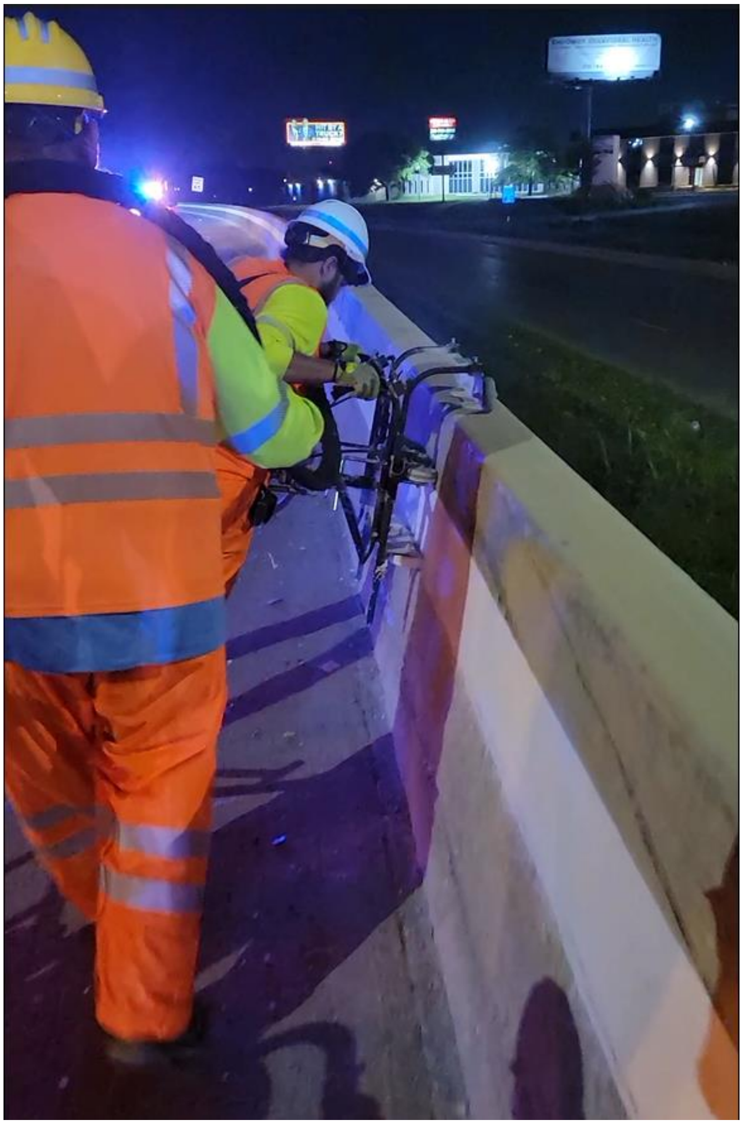


Figure 32. TxDOT Technicians Installing Barrier Stripe at Site along I-10 near I-410 in San Antonio.

CHAPTER 4: DATABASE DEVELOPMENT

OVERVIEW

The research team utilized various approaches to collect and assemble site characteristics and related safety/operational data. To provide a better understanding of the data collection process, the researchers divided this chapter into two subsections: data for the existing sites and data for the new sites selected for treatment. This subdivision is based on the differences in the countermeasure installation time. Further, the data collected for the two categories of sites differ significantly. While the existing sites' safety effectiveness was based on crash data, the new sites' effectiveness was based on event/speed data from big data.

DATA COLLECTION FOR EXISTING SITES

For the existing study sites where the countermeasures had already been installed, the installation time and crash data before and after the installation were important to determine the effectiveness of the countermeasures. Thus, as a first step, the research team collected the countermeasure installation time and crash data for the safety analysis.

Countermeasure Installation Date

The installation date was crucial for determining the before and after periods. Since the installation date was not provided, the research team utilized Google Street View to obtain the estimated installation date. To do so, the team zoomed to the site of interest using the coordinates and browsed street view images using the human-like icon in Google Maps. While in the Google Street View, the research team members clicked to view the "see more dates" option. The earliest date/year when the striping was observed was considered as the installation date/year. For instance, treatments along the ramp that connects I-35 SB and SH 71 EB were estimated to be installed in 2016 since they were not visible in the July 2015 Google Street View image.

Crash Data Collection

Crash data are a key component of any safety analysis. Crash data provide information on the trend of crashes over a given time for a given location. A comparison of the crash trend before and after a period at the treated sites indicates whether the treatment installed is effective. Even for cross-sectional studies, comparing the crash trend between the treated and comparison sites provides a similar indication. To perform an analysis, crash data should be collected and matched to the sites of interest.

The research team collected crash data from in-house sources. The available period of crash data ranged from 2009 to 2023. Three files of crash data were obtained: the crash file, the unit file, and the person file. The crash file consists of various details related to the location of the crashes. This information includes the geometric characteristics, temporal variables, and collision type, among others. One of the important details from the crash file is the crash geocoordinates—the estimated latitudes and longitudes of the crash location. This information is used to estimate the position of the crash. Further, since the barrier striping is more visible during nighttime, the variable related to lighting conditions at the time of the crash from this file is also important.

The unit crash data provide details of the vehicles involved in a crash and the drivers' contributing factors. This dataset includes information about vehicle type, model year, license state, damage details, and more. One important piece of information is the vehicle's travel direction at the time of the crash. The variable Veh_Trvl_Dir_ID provides information on the cardinal direction that the vehicle was traveling prior to the first harmful event or loss of control. This variable was important for this project because some sites had treatment in only one direction of travel. Thus, the vehicles' travel direction before a crash had to be identified to understand the crashes in the given direction.

The personal data file includes information about the people involved in the crash, including personal information such as gender, age, ethnicity, driver's residence location (zip code), injury severity levels for each vehicle occupant, ejection status, etc. However, the information from this file was not very useful in this project.

Crash Data Merging and Reduction

To perform a safety analysis, the location of crashes must be identified. The crash location can then be matched with the site location to identify the frequency, type, and severity of crashes before and after treatment. Crash data have various elements to help identify the crash location. Among the elements are coordinates, route ID, route name, route part name and description, vehicle travel direction, etc.

The research team utilized a GIS application to plot crashes using the coordinates. Similarly, the treated sites were mapped using a GIS application. A 350-ft buffer was then created for each site location. Using spatial join in the GIS application environment, all crashes within the buffer were assigned to the study site. Figure 33 shows an example of buffered crashes.

Figure 33. Example of Buffered Crashes.

Since the buffer is likely to include crashes not at the location of interest, the research team performed a manual review to obtain only appropriate crashes for the analysis. The research team performed the following steps to obtain relevant crashes.

- **Step 1. Match road names:** The research team matched the road name from Google Maps to that from the crash database. The team used two variables from the crash database—Street_Name and Rpt_Street_Name—to match the road names.
- **Step 2. Match road part:** The research team identified the treated road parts, which could be ramps, connectors, or main lanes, depending on the study site. The team then matched the identified part using the Road_Part_ID, Street_Desc, and Sec_Street_Desc variables from the crash database.
- **Step 3. Match the direction of the vehicle:** The research team identified the direction of the traffic flow based on the direction of the treated site. For instance, for a ramp that connects I-20 EB and I-35W NB, the possible directions are east, north, and northeast. By utilizing the unit data, the research team matched the direction of traffic flow and that of vehicles involved in a crash using Veh_Trvl_Dir_ID. This variable has the direction of each vehicle prior to involvement in a crash. Each crash appears multiple times in the unit database, depending on the number of vehicles involved. Thus, after matching the data, the research team used the variable Crash_ID to filter the details of crashes by removing duplicate crash IDs in Excel.
- **Step 4. Select barrier-related crashes:** The research team utilized the Obj_Struck_ID variable to select barrier-related variables. The variable and associated categories in Table 5 were retained for further analysis.

Table 5. Variable Categories Used to Identify Barrier-Related Crashes.

Obj_Struck_ID	Obj_Struck_Desc
23	Hit guardrail
39	Hit median barrier
40	Hit end of bridge (abutment or rail end)
41	Hit side of bridge (bridge rail)
45	Hit attenuation device
56	Hit concrete traffic barrier
58	Hit retaining wall

In addition to the barrier-related crashes, the research team retained non-barrier-related crashes obtained after Step 3 for comparison purposes. The team retained such crashes with the assumption that they might be secondary crashes whose primary crashes were barrier-related.

After completing the data extraction, merging, and cleaning, the researchers determined that 437 crashes occurred at the sites with the existing barrier stripes between 2010 and 2023. This included 74 barrier-related crashes and 363 non-barrier-related crashes.

Traffic and Roadway Data Collection and Merging

In addition to crash data, the research team collected traffic and roadway geometry data. The crash data have several variables indicating the traffic volume level at the crash location. For this case, the research team used the variable Adt_Adj_Curnt_Amt, which indicates the adjusted current AADT at the crash location for the respective crash year. To facilitate further analysis of crash rates, the research team used Google Maps to measure the length of the segments for each site. The final database has the crashes, associated characteristics, and treated segment lengths.

DATA COLLECTION FOR NEW SITES

Similar to the existing sites, the before-and-after data aided in the assessment of the countermeasure's effectiveness at the new installation locations. However, since the after period was relatively short (about three to six months), it was difficult to observe many crashes. For this reason, the research team utilized speed data for short-term evaluation and collected the before-crash data, with the understanding that after a substantial amount of time, preferably three years, TxDOT would work with TTI to perform a safety analysis.

Operating Speed Data

Operating speed represents the speed at which vehicles travel along the given road segment. The presence of the barrier stripes may affect the operating speed of the vehicles. Various sources are available to collect operating speed data, including tube data, radar speed data, and probe data. In this case, the research team used the INRIX XD database to extract operational speed data for the selected sites for seven years (2017–2023).

INRIX XD provides operational speed data for a given segment every 10 seconds. INRIX XD data were acquired from INRIX's analytical platform (https://analytics.iq.inrix.com/roadway-analytics). To identify the nearest INRIX segments of the selected sites, the researchers conducted data conflation of the RHiNO and INRIX road inventory. The primary challenge in acquiring the speed measures of RHiNO segments was handling different segmentation and misalignment between the two networks (RHiNO and XD). The core objective of conflation was to create an appropriate integration by establishing one-to-one or one-to-many relationships between INRIX XD segments and urban RHiNO roadways. This conflation process aimed to harmonize and align data from the INRIX XD network with urban roadways, overcoming the challenges of segmentation and misalignment to provide a cohesive and accurate dataset for analysis. The main steps were as follows:

- **Step 1: Process RHiNO.** In this initial step, a new field called unique_id was introduced as a unique identifier for road segments within the existing layer. Additionally, the length of each segment was calculated and added to the rhino_len field.
- **Step 2: Create buffers around RHiNO.** This step involved the development of a buffer layer around urban roadways. The buffer distance was set to "25 m or 82 ft." The side type of the buffer was "FULL," and the end type of the buffer was "FLAT." The buffer was generated to provide spatial context and facilitate subsequent conflation.
- **Step 3: Establish the relationship between RHiNO and XD.** During this process, the Intersect_Length was calculated, representing the length of intersections between the polygon and XD segments. Furthermore, the percentage was computed as follows: Percentage = (Intersect_Length / Line_Length (XD)) * 100.
- **Step 4: Clean the data.** The output generated in the previous step required further refinement, which began with the calculation of the sum of urban segments based on the XD line percentage. If the sum exceeded 100, corrective action was taken. Specifically, the percentages were sorted, and the one with the lowest percentage was eliminated until the sum was reduced to less than 100. Subsequently, the remaining percentages were adjusted proportionally to ensure that the cumulative percentage of each urban segment totaled exactly 100.
- **Step 5: Create the XD-level speed summary.** The result of Step 4 was a CSV file detailing the correlation between XD and RHiNO segments. This relationship was quantified by the overlap percentage of each RHiNO segment with corresponding XDs. The unique identifier for XD segments was labeled "xd_id," while for RHiNO segments, it was "unique_id." Utilizing the xd_id obtained from this step, the researchers downloaded raw XD speed data.
- **Step 6: Create the RHiNO-level speed summary.** The XD-level speed summary was aggregated to the RHiNO-level speed summary based on the CSV file acquired in Step 4.

The research team developed 14 different speed measures to examine the impact of different temporal patterns. Table 6 lists the speed measures with their definitions.

Table 6. Speed Measure Variables and Definitions.

Attribute Name	Definition
SpdAve	Average speed determined for year using all data
SpdStd	Standard deviation of speed determined for year using all data
Spd85	85th percentile speed determined for year using all data
SpdAveDay	Average speed determined for year (hour > 5 and hour < 18) using all data
SpdStdDay	Standard deviation of speed determined for year (hour > 5 and hour < 18) using all data
SpdAveNight	Average speed determined for year (hour > 17 and hour < 24 and hour > −1 and hour < 6) using all data
SpdStdNight	Standard deviation of speed determined for year (hour > 17 and hour < 24 and hour > −1 and hour < 6) using all data
SpdAveMTWT	Average speed determined for year (Mon, Tues, Wed, Thurs) using all data
SpdStdMTWT	Standard deviation of speed determined for year (Mon, Tues, Wed, Thurs) using all data
SpdAveFSS	Average speed determined for year (Fri, Sat, Sun) using all data
SpdStdFSS	Standard deviation of speed determined for year (Fri, Sat, Sun) using all data
SpdFFAve	Average speed determined for year using speed data where 5-min speed is > posted speed limit (PSL) (or PSL+5 or +10)
SpdFF85	85th percentile speed determined for year using speed data where 5-min speed is > PSL (or PSL+5 or +10)
PSLSur	Posted speed limit (not real posted speed, a measure derived for INRIX average speed values)

Before-Installation Crash Data Collection

The research team collected crash data for the newly treated sites in preparation for a future safety evaluation. The before-installation crash data spanned from 2021 to 2023 and were obtained using the same procedures applied to previously evaluated locations. A total of 2,743 crashes were identified across the seven sites, providing a baseline for future comparison with post-installation data. Figure 34 illustrates the distribution of crashes by site, highlighting variations in crash frequency across the selected locations. This baseline dataset will be essential for the future before-and-after analysis to assess the impact of the barrier striping on roadway safety. Once a sufficient amount of post-installation crash data have been collected, the team will perform a statistical evaluation to determine any significant changes in crash frequency or severity. This approach aligns with standard safety assessment practices and will contribute to understanding the effectiveness of the treatment in improving driver behavior and reducing crashes.

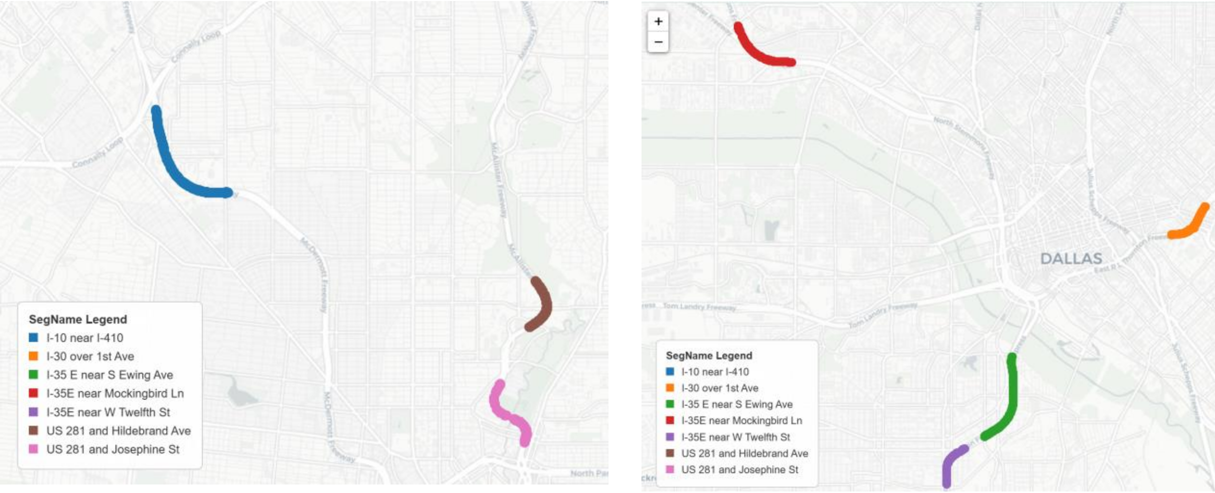


Figure 34. Crash Locations by Site.

CHAPTER 5: SAFETY AND SPEED ANALYSIS

OVERVIEW

The research team performed a safety analysis to explore the impact of barrier striping on barrier-related crashes. The analysis was divided into two main parts: the existing sites and the new sites. This division of the analysis was based on the fact that the two types of sites needed different approaches. A descriptive analysis and statistical models were performed for the existing sites for the before and the after crash data. In contrast, only a descriptive analysis of the before-installation crash data was performed for the new sites. This chapter presents the detailed safety analysis of the existing and new sites.

DESCRIPTIVE CRASH ANALYSIS FOR EXISTING SITES

The research team collected, extracted, and cleaned the data for safety analysis. The initial attempt revealed that 437 crashes occurred within the study area. However, 33 crashes occurred between August 2015 and May 2016, when the barrier striping might have occurred. Since the team had no other images between that time, those 33 crashes were excluded from the analysis.

The research team performed an exploratory analysis of the remaining 404 crashes to understand the distribution of the key variables. These variables included temporal factors such as years and time of day, severity levels, weather and lighting conditions, etc. The exploratory analysis covered barrier-related crashes that involved median barriers, guardrails, or concrete traffic barriers, as well as non-barrier-related crashes. Further, daytime and nighttime crashes were explored.

Overall Summary Statistics of Crash Data

Table 6 presents the summary statistics of the crash data. The descriptive statistics show notable variations in crash patterns across sites before and after barrier striping. Overall, crashes increased sharply at the Paris (SE Loop 286/US-271) site, with the mean rising from 10.33 to 20.25, while the Fort Worth NB and SB sites also experienced post-installation increases. In contrast, the Ben White Interchange saw a decline in mean overall crashes from 3.33 to 2.50. For barrier-related crashes, the Ben White site showed reductions, while the other sites recorded modest increases, particularly at Fort Worth NB. Nighttime barrier-related crashes followed a similar trend, with decreases at Ben White but slight increases at Fort Worth and Paris. These patterns suggest mixed effects of barrier striping, with improvements at some locations but increased crash counts at others, likely influenced by segment length, traffic exposure, and site-specific conditions.

Table 7. Summary Statistics of Crash Data.

Crash type	Location	Before				After			
		Min	Max	Mean	Standard deviation	Min	Max	Mean	Standard deviation
All crashes	Ben White Interchange (I-35 SB to TX 71)	1	6	3.33	1.75	0	5	2.50	2.00
	Fort Worth (I-20 EB to I-35 W NB)	1	3	1.83	0.98	5	11	7.38	2.45
	Fort Worth (I-20 EB to I-35 W SB)	2	6	3.33	1.75	2	11	5.13	3.04
	Paris (SE Loop 286, US-271)	8	15	10.33	2.50	9	28	20.25	5.73
Barrier-related crashes	Ben White Interchange (I-35 SB to TX 71)	0	4	1.50	1.52	0	2	0.88	0.99
	Fort Worth (I-20 EB to I-35 W NB)	0	1	0.50	0.55	0	5	2.00	1.69
	Fort Worth (I-20 EB to I-35 W SB)	1	2	1.50	0.55	0	3	1.38	1.06
	Paris (SE Loop 286, US-271)	0	2	0.67	0.82	0	3	1.38	1.06
Nighttime barrier-related crashes	Ben White Interchange (I-35 SB to TX 71)	0	3	1.33	1.21	0	1	0.50	0.53
	Fort Worth (I-20 EB to I-35 W NB)	0	1	0.17	0.41	0	3	1.00	1.31
	Fort Worth (I-20 EB to I-35 W SB)	1	2	1.17	0.41	0	2	1.00	0.93
	Paris (SE Loop 286, US-271)	0	1	0.17	0.41	0	1	0.25	0.46

Temporal Crash Distribution

The research team assessed the yearly distribution of crash data by focusing on the overall and barrier-related crash distributions. The overall crash distribution covered all crashes, while the barrier-related crash distribution covered only crashes that hit the barrier.

Yearly Distribution of All Crashes

Figure 35 presents the number of crashes per year for all study sites with existing barrier stripes. The distribution suggests that crash frequency within study sites peaked in 2016. While the non-barrier-related crashes indicated a declining trend between 2016 and 2023, the figure indicates that a decline in barrier-related crashes started in 2019.

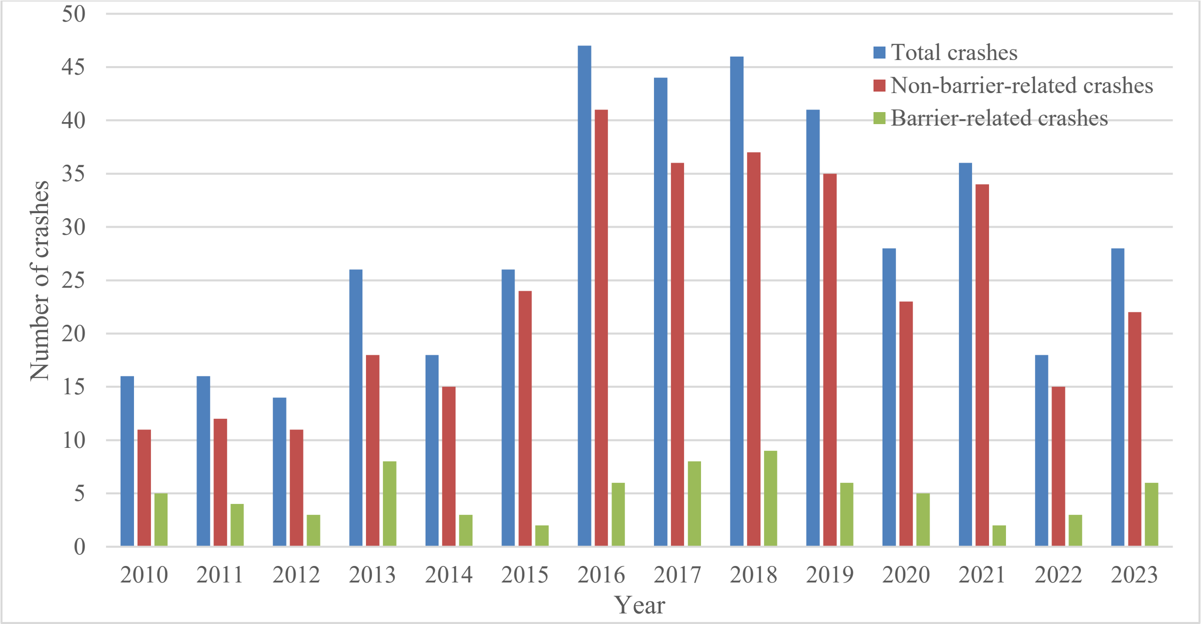


Figure 35. Crash Distribution by Year.

Yearly Distribution of Barrier-Related Crashes

Since the project focused on barrier-related crashes, the research team subdivided crash data into barrier-related crashes and non-barrier-related crashes, and then examined lighting conditions. All the crashes that occurred during daytime formed one category, while crashes that occurred in the dark lighted, dark not lighted, dawn, and dusk conditions formed a second category. Figure 36 presents the yearly distribution of barrier-related crashes by lighting conditions.

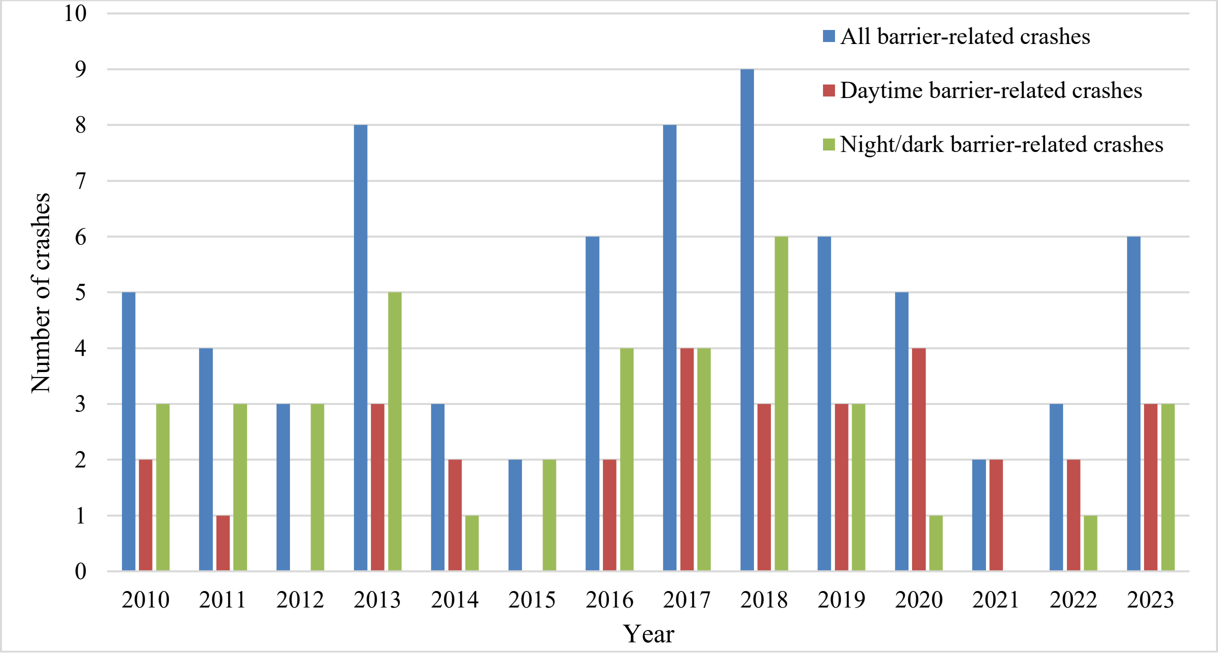


Figure 36. Barrier-Related Crash Distribution by Lighting Conditions.

Time-of-Day Distribution of All Crashes

Figure 37 and Figure 38 present crash distribution and barrier-related crash distribution by time of day. Barrier-related crashes were predominantly higher in the nighttime, peaking at 11 p.m. (23 hours). On the other hand, non-barrier crashes were predominantly in the daytime, with the peak at around 4 p.m. (16 hours).

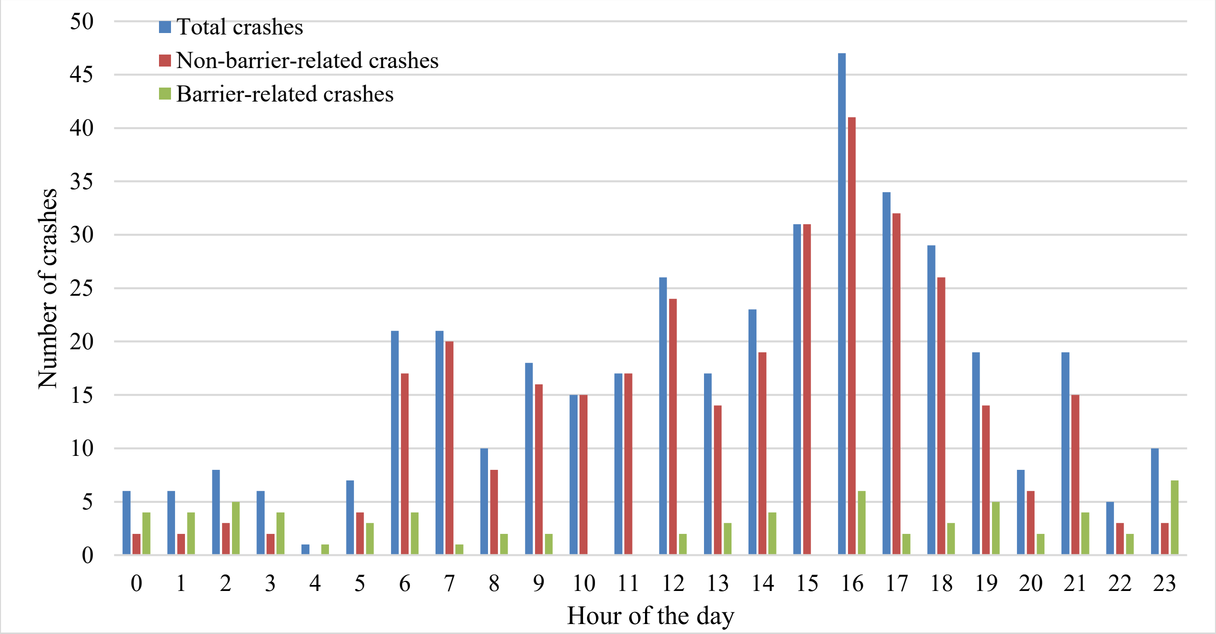


Figure 37. Crash Distribution by Time of Day.

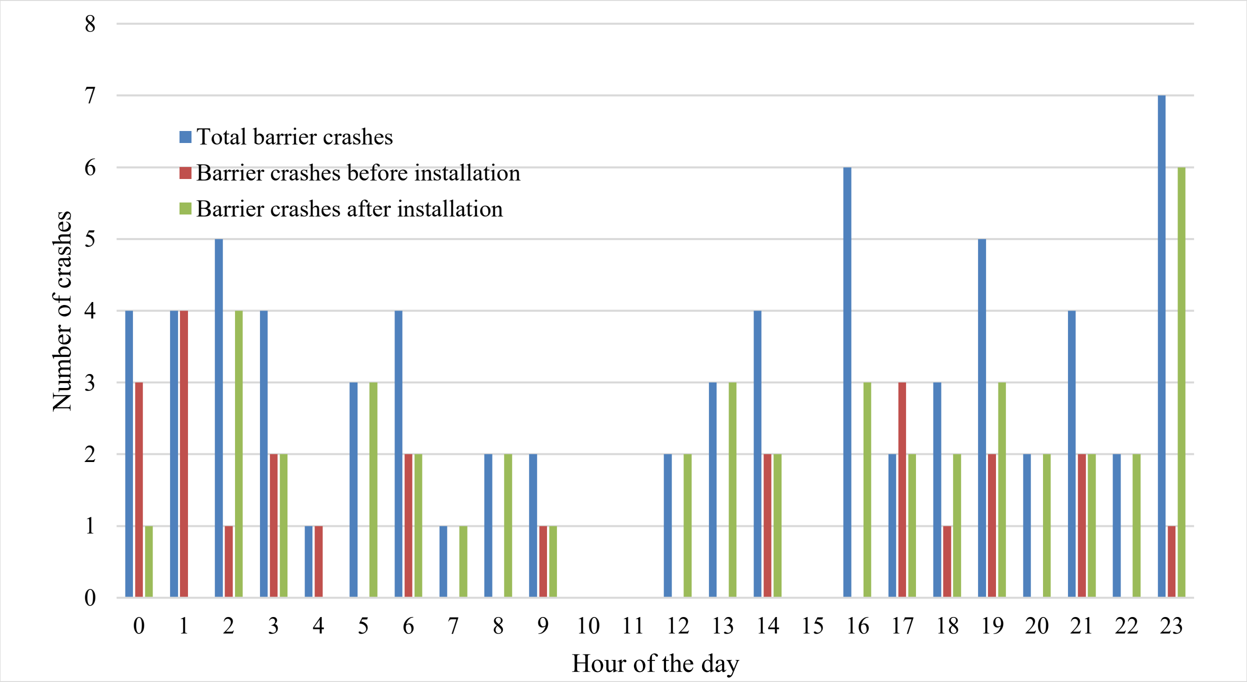


Figure 38. Barrier-Related Crash Distribution by Time of Day.

Weather and Lighting Conditions

Because striped barriers are more visible at night and in adverse weather conditions, the research team was interested in exploring the correlation of weather conditions and lighting conditions to determine the impact of striping on barrier-related crashes. Figure 39 and Figure 40 present crash distribution by lighting conditions and weather conditions, respectively. Figure 39 shows that most of the barrier-related crashes occurred in dark lighting conditions, which included dark lighted, dark not lighted, dawn, and dusk conditions. Figure 40 shows that there were many barrier-related crashes during cloudy and rainy weather conditions, although most occurred when it was clear.

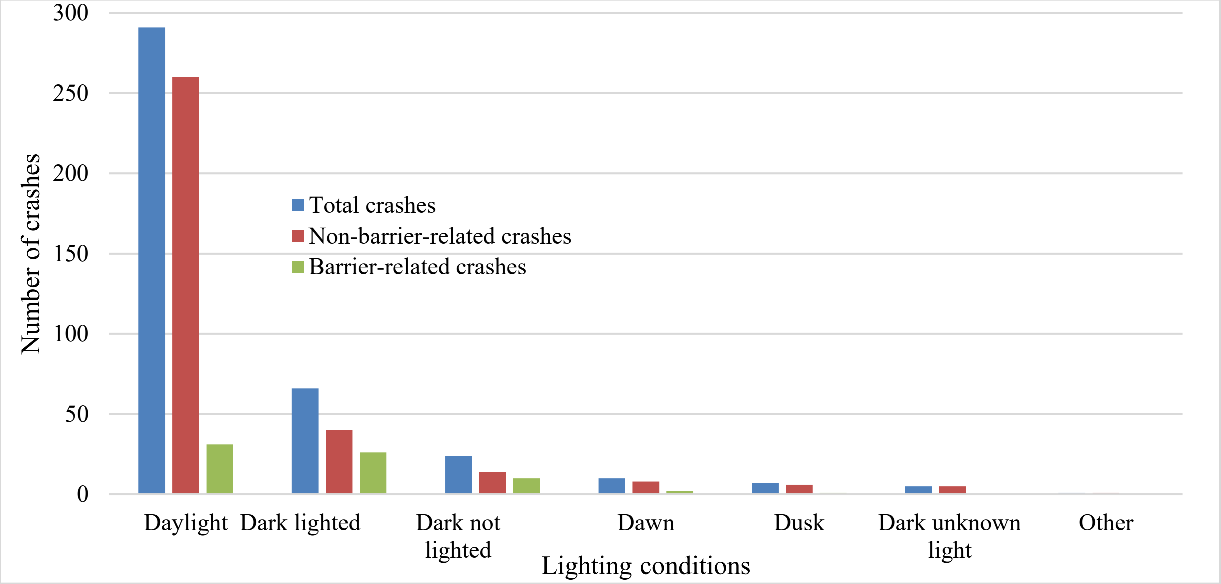


Figure 39. Crash Distribution by Lighting Conditions.

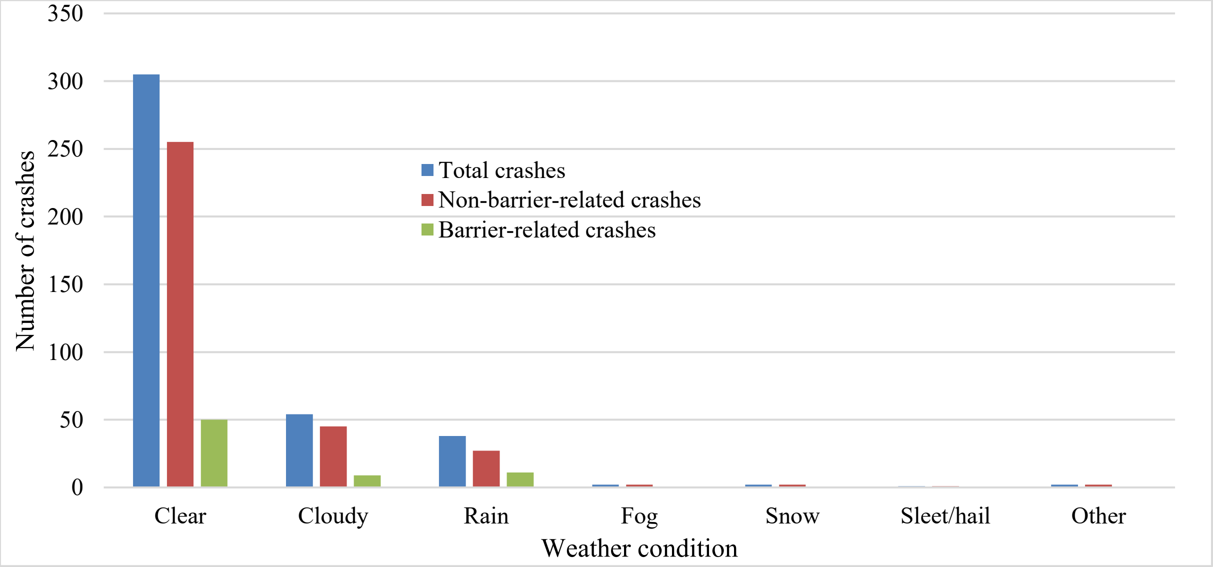


Figure 40. Crash Distribution by Weather Conditions.

Crash Severity

Since this study focused on barrier-related crashes, the research team utilized a crash dictionary to obtain only the crashes of interest. Non-barrier crashes were also retained for further analysis if needed. It was hypothesized that the barrier striping might impact the non-barrier crashes. A typical example is a secondary crash involving a non-barrier crash whose primary crash was a barrier crash. Figure 41 presents crash distribution by severity. Most crashes resulted in property damage only, with only one barrier-related crash being fatal. Further, injury crashes (incapacitating, non-incapacitating, and possible injury) represented a substantial portion of barrier-related crashes.

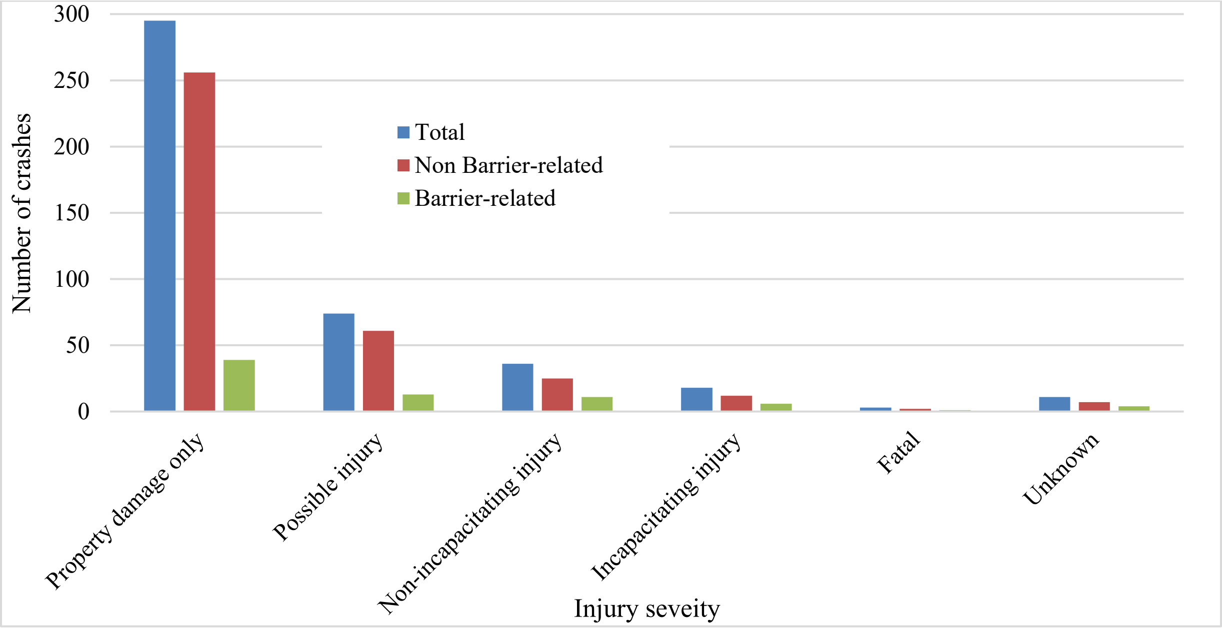


Figure 41. Crash Distribution by Injury Severity.

Crash Distribution per Site

The research team also explored the crash distribution at each site to understand the variation of crash types. In this case, the exploration was divided into two major categories: (a) all crashes, and (b) barrier-related crashes. The barrier-related crashes were further divided for the before- and after-installation explorations.

Overall Crash Distribution per Site

Figure 42 presents crash distribution by study site. As shown, the SE Loop 286/US 271 site had a relatively higher number of overall crashes. This can be explained by the length of the segment. The total length considered for this location was about 1.1 mi, while other locations ranged from 0.04 to 0.52 mi. Barrier-related crashes, on the other hand, were relatively similar across all sites. The maximum number of barrier-related crashes was 20 at the I-20 to I-35 Interchange, while the Ben White Interchange had 18 crashes, and the SE Loop 286/US 271 site had 16 crashes. There was no recorded barrier-related crash in the database for the turnaround bridge at McCart and I-20.

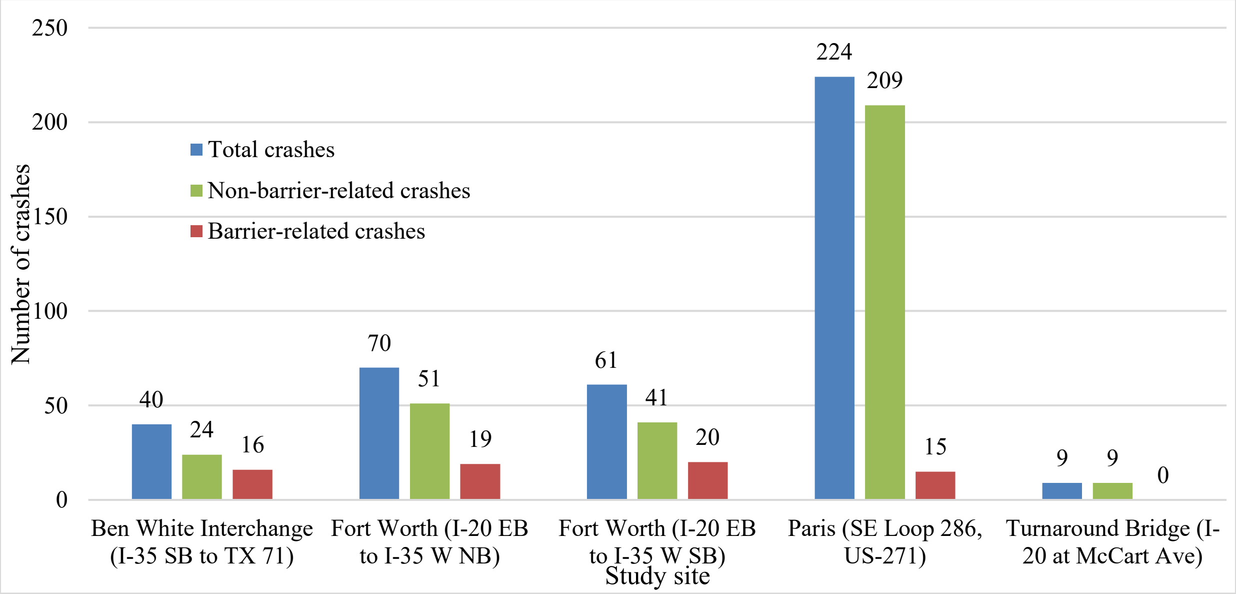


Figure 42. Crash Distribution by Study Site.

Barrier-Related Crash Distribution per Site before and after Installation

Figure 43 presents the distribution of barrier-related crashes before and after installation. As shown, except for the Ben White Interchange site, all other sites experienced more crashes after installation. However, this observation can partly be explained by the number of years after installation considered in this study. The before-installation period spanned from January 2010 to May 2015, while the after-installation period covered from June 2016 to December 2023.

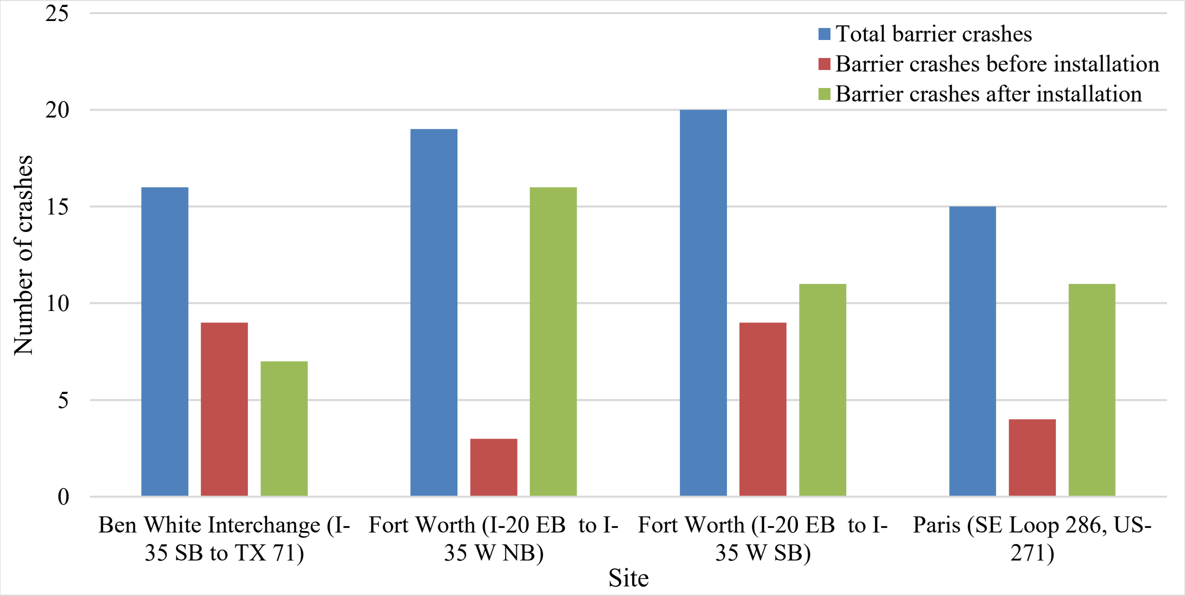


Figure 43. Barrier Crash Distribution by Study Site before and after Barrier Striping.

The research team was also interested in understanding the crash distribution by lighting conditions. The barrier-related crashes were divided into those that occurred in the daylight versus those that occurred in the dark/dusk conditions. For the before-installation period, Figure 44 shows that two sites, Ben White Interchange and Fort Worth (I-20 EB to I-35W SB), experienced more barrier-related crashes during dark/dawn/dusk. In contrast, the remaining two sites had more daylight crashes.

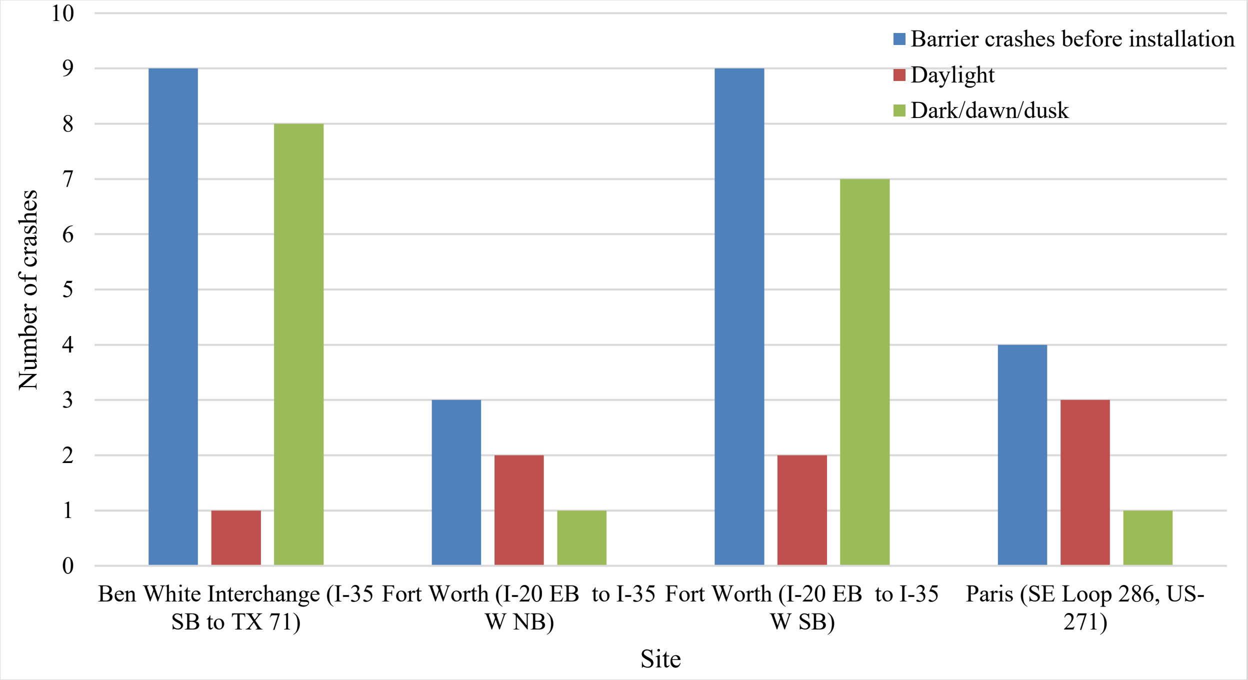


Figure 44. Barrier Crash Distribution by Study Site and Lighting Condition before Barrier Striping.

Likewise, for the after-installation period, the same two locations, Ben White Interchange and Fort Worth (I-20 EB to I-35W SB), had a higher frequency of dark/dawn/dusk-related crashes (Figure 45).

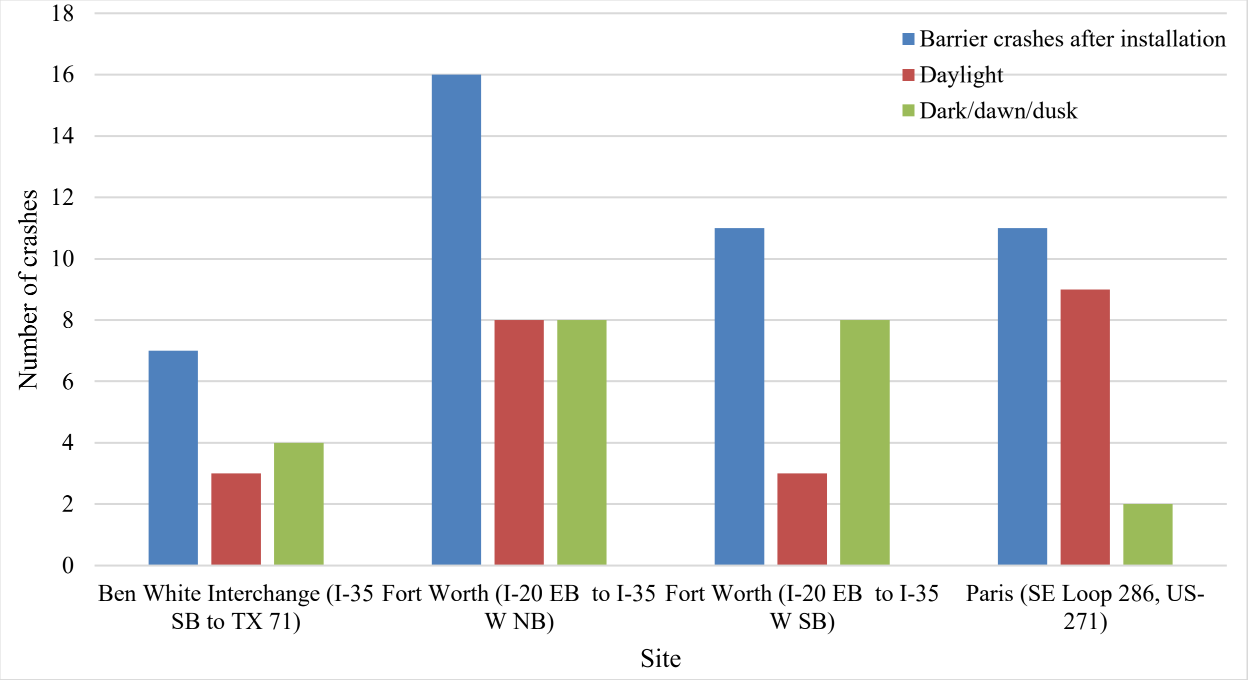


Figure 45. Barrier Crash Distribution by Study Site and Lighting Condition after Barrier Striping.

Crash Rates

Crash frequency is one of the indicators when assessing safety improvement. However, crash frequency does not take into account several exposure variables, such as traffic volume, or the number of years before and after treatment installation. To incorporate other exposure variables, the research team computed crash rates for each year and accounted for traffic volume and segment length.

Overall Crash Rates

Figure 46 presents the trend of crash rates for all crashes, barrier crashes, and nighttime barrier crashes. As shown, crash rates for the study sites peaked in 2016 and started declining slowly in the following years, followed by a sharp decline in 2019. Further, the barrier crashes revealed two peaks, one in 2013 and another in 2018, which is different from the overall trend of the crash rates. There was a declining trend in crash rates from 2019 onward; however, the rate of decline was not as steep as that for all crashes. Furthermore, the nighttime barrier crashes portrayed a similar trend as the barrier crashes.

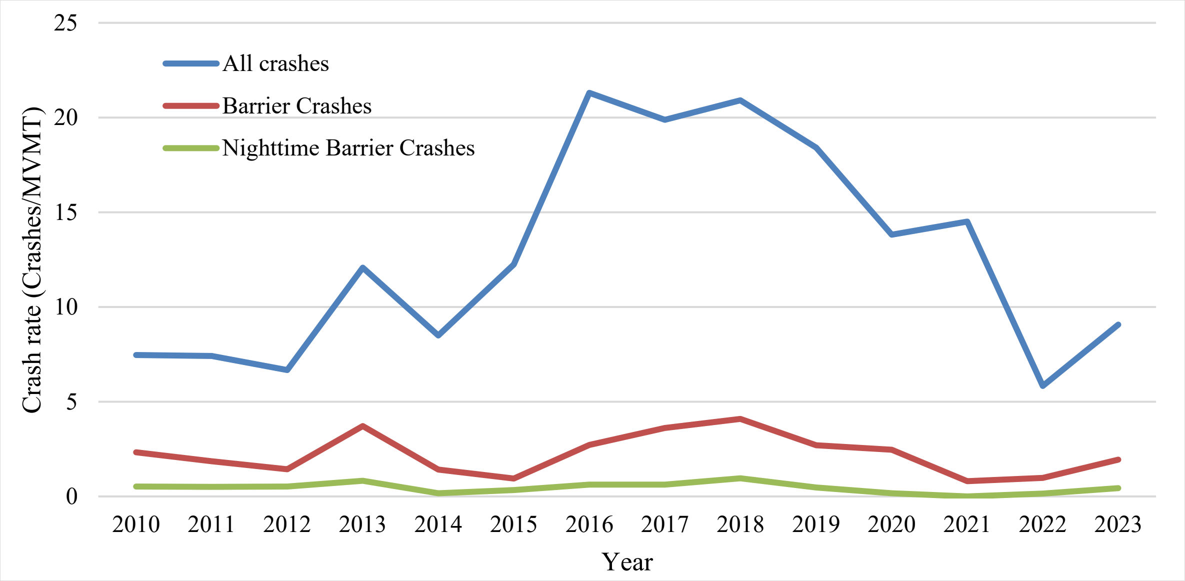


Figure 46. Trend of Crash Rates for All Crashes.

Crash Rates per Site

According to the trends shown in Figure 47, Figure 48, and Figure 49, crash rates varied by site. The Ben White Interchange and Fort Worth (I-20 EB to I-35W SB) sites depicted relatively higher crash rates compared to the other two sites. This can be explained by the large number of crashes for the two sites, despite similar traffic volume.

A similar trend can be observed for barrier-related crashes, whereby the two aforementioned sites had relatively large crash rates. In contrast, the nighttime barrier crashes revealed a slightly different trend. Although the two sites still had relatively high crash rates, the magnitude of their differences to the other two sites was relatively small.

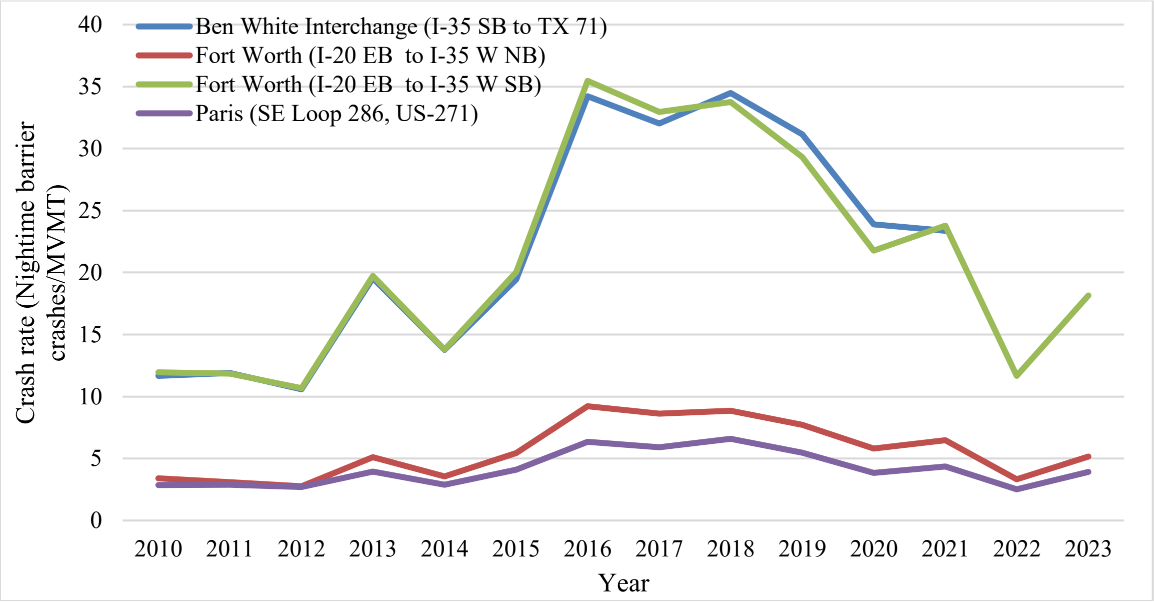


Figure 47. Trend of Crash Rates for All Crashes by Site.

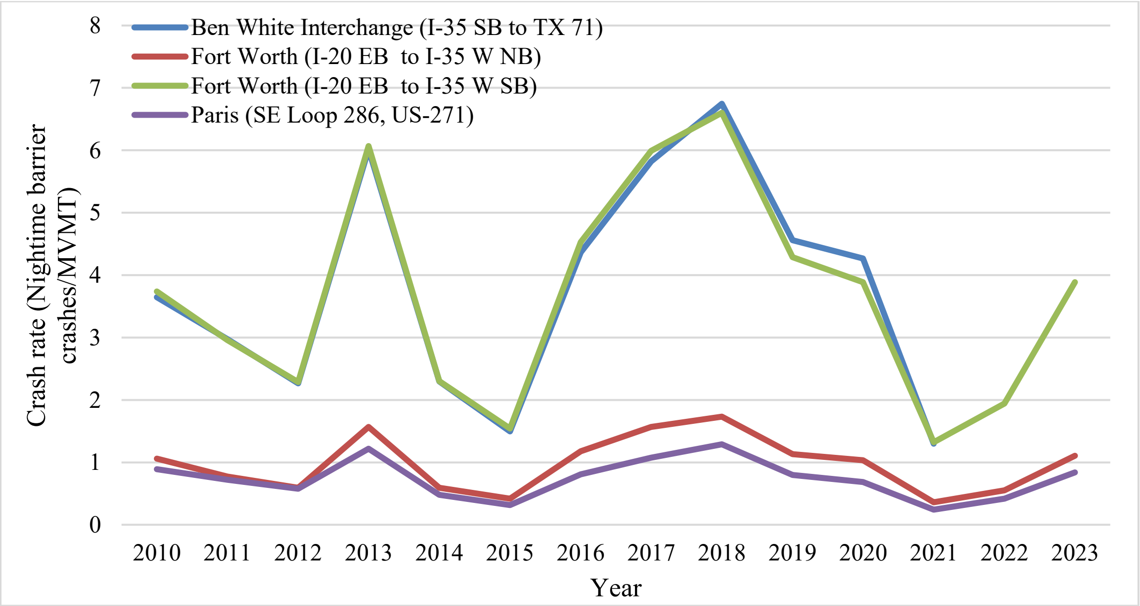


Figure 48. Trend of Crash Rates for Barrier Crashes by Site.

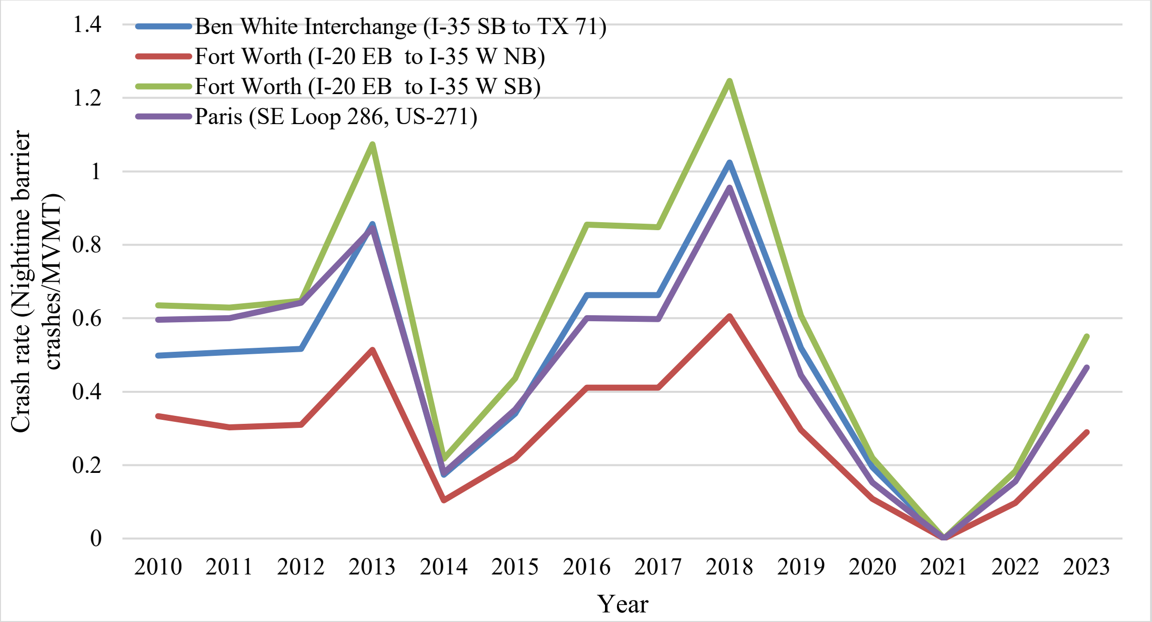


Figure 49. Trend of Crash Rates for Nighttime Barrier Crashes by Site.

The descriptive analysis provided statistical information about the observed data but did not provide inference information. Inference information could facilitate the determination of whether the treatment produced statistically significant results. Thus, the research team developed several statistical models to determine whether the treatment produced statistically significant outcomes. The next section presents the model results.

STATISTICAL MODEL RESULTS FOR EXISTING SITES

The research team developed several statistical models to evaluate all barrier crashes, daytime barrier crashes, and nighttime barrier crashes. Four sets of regression models—logistic regression, linear regression, Negative Binomial, and survival analysis models—are presented in this section. The logistic regression model was intended to evaluate the probability of observing barrier-related crashes against other crashes in the after period. The negative binomial, linear regression, and time-to-event models evaluated the crash rates for the period after. Only one independent (before-after period) variable was considered. In this case, the before period was a base category, while the after period was evaluated.

Logistic Regression Results

Table 8, Table 9, and Table 10 present the logistic regression results for all barrier crashes, daytime barrier crashes, and nighttime barrier crashes, respectively. Overall, the results indicate a decline in crashes within the study site in the after period, as indicated by the negative coefficients of the estimates. First, the analysis of all barrier crashes shows that the odds of all barrier crashes declined after barrier installation. The overall odds ratio (OR = 0.59) implies that barrier crashes declined by about 41 percent in the after period. Furthermore, to understand the odds of the barrier crashes during the day and night, the sample data were split into two samples, and an analysis was performed. The results indicate that the odds of barrier crashes for both daytime and nighttime decreased. However, the magnitude of the decline was higher in the nighttime than daytime crashes, and the daytime results were not statistically significant at a 95 percent confidence level. More specifically, the odds for daytime crashes (OR = 0.78) imply that the daytime barrier crashes decreased by about 22 percent after installation, while the odds of nighttime crashes (OR = 0.38) show that the presence of the barrier treatment was associated with an approximately 62 percent decline in barrier-related crashes.

AADT was also considered. As expected, as AADT increased, the odds of observing barrier-related crashes also increased. However, the variable was statistically significant for daytime only.

Table 8. Logistic Regression Results of All Barrier-Related Crashes.

Variable	Estimate	OR	Std. Error	z-value	p-value
Intercept	−7.279	0.00	4.158	−1.751	0.080
After period	−0.530	0.59	0.294	−1.800	0.072
Log (AADT)	0.623	1.87	0.431	1.447	0.148

Note: Model performance summary: observations = 404, Akaike information criterion (AIC) = 373, Bayesian information criterion (BIC) =385.

Table 9. Logistic Regression Results of Daytime Barrier-Related Crashes.

Variable	Estimate	OR	Std. Error	z-value	p-value
Intercept	−18.902	0.00	8.393	−2.252	0.024
After period	−0.243	0.78	0.470	−0.518	0.605
Log (AADT)	1.729	5.64	0.865	2.000	0.046

Note: Model performance summary: observations = 292, AIC = 199, BIC = 210.

Table 10. Logistic Regression Results of Nighttime Barrier-Related Crashes.

Variable	Estimate	OR	Std. Error	z-value	p-value
Intercept	−2.452	0.09	3.532	−0.694	0.488
After period	−0.955	0.38	0.428	−2.229	0.026
Log (AADT)	0.254	1.29	0.364	0.698	0.486

Note: Model performance summary: observations = 112, AIC = 145, BIC = 154.

In summary, logistic regression results show a decline in the likelihood of barrier crashes in the after period. However, the findings are based on a comparative analysis of the other crashes, not solely nighttime barrier crashes. In other words, nighttime barrier crashes declined in the after period compared to other crashes, such as daytime barrier crashes and non-barrier crashes. This approach, however, did not consider other exposure variables, such as segment length. Therefore, another approach that considered other exposure variables was deemed necessary. The next section presents the analysis of the crash rates.

Linear Regression for Crash Rate Results

The research team developed several linear regressions for crash rates to explore the impact of barrier striping on barrier crashes. The developed models for crash rates considered AADT and segment length to evaluate crash rates at the study sites in the after period.

Table 11 presents the linear regression results for crash rates for all crashes. As shown, the crash rates for the after period increase irrespective of the time of day. However, the increase is statistically significant for the daytime only. Further, Table 12 presents the linear regression results for the barrier-related crashes only. The results show an increase in all barrier crashes and daytime barrier crashes but a decrease in nighttime barrier crashes. However, the results for nighttime crashes are not statistically significant at a 95 percent confidence level.

Table 11. Linear Regression Results for Crash Rates (All Crashes).

Crash type	Variable	Estimate	Std. Error	t-value	p-value	Model summary
All crashes	Intercept	9.067	2.085	4.348	<0.001	Observation = 56, Adj R-squared: 0.06
	After period	6.933	2.759	2.151	0.036	
Nighttime	Intercept	11.654	2.759	4.224	<0.001	Observation = 22, Adj R-squared: 0.007
	After period	4.390	4.092	1.073	0.296	
Daytime	Intercept	6.480	3.075	2.107	0.043	Observation = 34, Adj R-squared: 0.09
	After period	9.499	3.823	2.105	0.043	

Table 12. Linear Regression Results for Crash Rates (Barrier Crashes).

	Variable	Estimate	Std. Error	t-value	p-value	Model summary
All barrier crashes	Intercept	1.950	0.391	4.991	<0.001	Observation = 56, Adj R-squared: 0.01
	After period	0.373	0.517	0.722	0.313	
Nighttime	Intercept	2.489	0.526	4.730	<0.001	Observation = 22, Adj R-squared: 0.01
	After period	−0.359	0.780	−0.459	0.651	
Daytime	Intercept	1.411	0.568	2.485	0.018	Observation = 34, Adj R-squared: 0.03
	After period	0.999	0.706	1.416	0.166	

The crash rate analysis results suggest little improvement in the nighttime barrier crash rate in the after period. The observation is depicted by the statistically insignificant negative coefficient of the after-period variable for nighttime barrier crashes. The analysis was performed using only 36 observations. Such a small sample size might have contributed to the statistically insignificant results. Future studies should consider additional sites for a robust analysis.

Negative Binomial Regression Results

The research team attempted to use Negative Binomial regression models to explore the relationship between barrier crashes and barrier striping. Table 13 presents the Negative Binomial regression model results. According to the results, the coefficient for nighttime crashes is negative, indicating a decline in the number of nighttime crashes. However, such a decline is not statistically significant at a 95% confidence level. On the other hand, the positive coefficients for daytime, all barrier crashes, and all crashes indicate an increase in these types of crashes. However, only the coefficient for all crashes is statistically significant at a 95% confidence level.

Table 13. Negative Binomial Regression Analysis Results.

Crash type	Variable	Estimate	Std. Error	z value	P-value	Model summary
All crashes	Intercept	-8.777	0.1429	-61.428	<0.001	Observations = 56, AIC =307, dispersion parameter = 3.8242
	After period	0.432	0.1815	2.378	0.017	
Barrier crashes	Intercept	-10.233	0.2238	-45.715	<0.001	Observations = 56, AIC =182, dispersion parameter = 3.5893
	After period	0.147	0.2854	0.514	0.607	
Day time barrier crashes	Intercept	-11.452	0.3536	-32.391	<0.001	Observations = 56, AIC =105, dispersion parameter = 7615.907
	After period	0.651	0.4105	1.587	0.113	
Nighttime barrier crashes	Intercept	-10.481	0.307	-34.137	<0.001	Observations = 56, AIC =148, dispersion parameter = 0.9742
	After period	-0.228	0.4123	-0.553	0.581	

Traditional regression methods often assume outcomes occur immediately or within a fixed observation period, but for crashes, the timing of crashes matters just as much as whether they occur (40). Survival analysis is uniquely suited for modeling time-to-event data—in this case, the “event” being a crash (40). Thus, the research team explored the application of survival analysis to understand the safety improvements.

Survival Analysis Results

Survival analysis is used to explore the time between consecutive crashes for the before and after periods. The longer the time between consecutive crashes, the safer the location. Thus, it is assumed that for a treatment to be considered effective, the time between consecutive crashes in the after period should be longer than that of the before period.

In this analysis, the research team considered two variables: (a) AADT, and (b) before and after periods. The analysis was performed for all crashes and barrier-related crashes. For barrier-related crashes, the dataset was further divided to explore the daytime and nighttime crashes separately. The interpretation of the results was based on the coefficients or the exponential of the coefficients. A positive coefficient implied a shorter survival duration between consecutive crashes.

In addition, the Kaplan-Meier plot can be used to estimate survival over time. The plot has the survival probability on the y-axis and time on the x-axis. To understand the survival probability at any time, the analyst needs to identify that time and draw a vertical line parallel to the y-axis to intersect the curve. After intersecting the curve, the analyst draws a horizontal line parallel to the x-axis to intersect the y-axis to obtain the survival probability. For the before and after analysis, two curves are produced. The difference in the survival probability between the two curves is either the safety improvement or the worsening after the treatment.

Overall, the survival analysis results indicate that the survival time after the treatment was shorter than in the before period for all crash types except for barrier crashes in the nighttime. This result can be observed from the positive coefficients of the after-period variable for all the model results in Table 14 through Table 16 and the negative coefficient in Table 17.

All Crashes

Table 14 presents the survival analysis results for all crashes. The coefficient for the after period (0.385) is positive, implying that, on average, survival in the after period is shorter than in the before period. The results are statistically significant, as indicated by the p-value less than 0.05. To complement the results, the survival plot in Figure 50 shows that survival in the after period is shorter than in the before period.

Table 14. Survival Analysis Results for All Crashes.

Variable	Coef	Exp(Coef)	SE(Coef)	Z-stat	p-value
After period	0.385	1.469	0.114	3.376	0.001
log_AADT	0.390	1.477	0.092	4.258	0.000

Note: Model performance summary: observations = 404, likelihood ratio test = 39, Wald test = 32, score (logrank) test = 33.

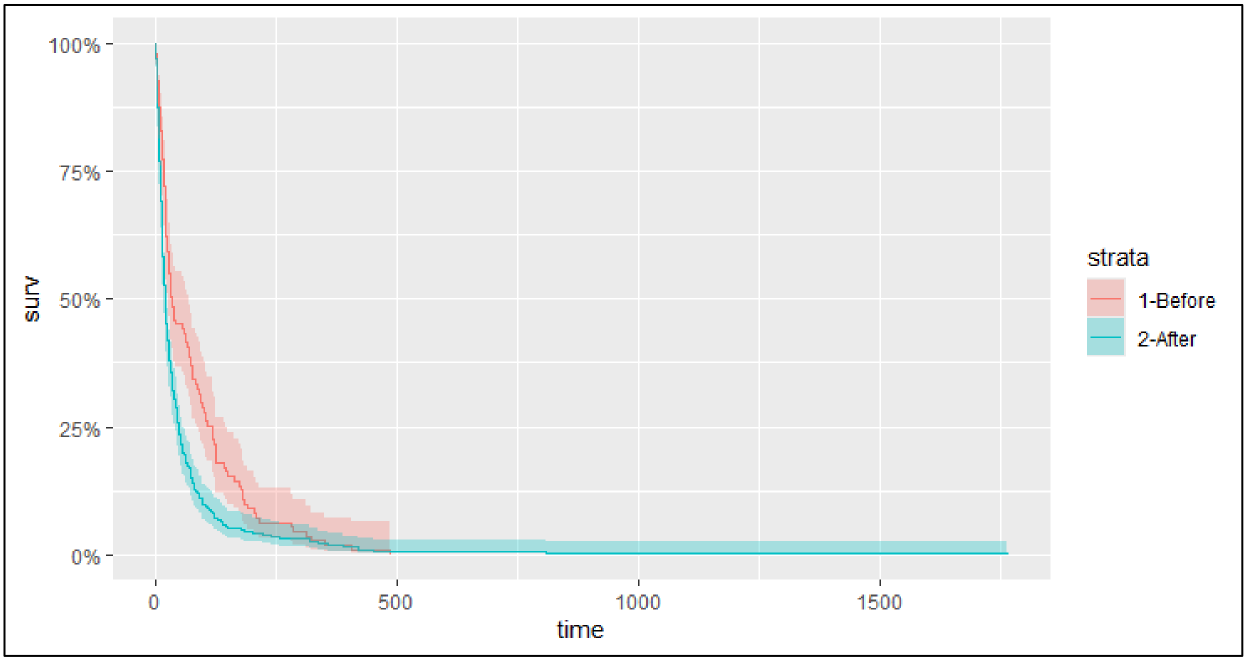


Figure 50. Survival Analysis Plot for All Crashes before and after Treatment.

Barrier Crashes

Table 15 shows the survival analysis results for all barrier-related crashes. The coefficient for the after period (0.072) is positive, implying that, on average, survival in the after period is shorter than in the before period. However, the results are statistically insignificant at a 95 percent confidence level (p-value less than 0.05). To complement the results, the survival plot in Figure 51 shows that survival in the after period is shorter than in the before period. However, the plot shows uncertainties, as revealed by the wide 95 percent confidence intervals. Since the analysis involved all barrier crashes, the results are as expected because the barrier stripes are more visible during nighttime than daytime. Thus, the need to separate the data into two portions, daytime and nighttime crashes, arose.

Table 15. Survival Analysis Results for All Barrier Crashes.

Variable	Coef	Exp(Coef)	SE(Coef)	Z-stat	p-value
After period	0.072	1.075	0.276	0.261	0.794
log_AADT	0.136	1.145	0.472	0.287	0.774

Note: Model performance summary: observations = 35, likelihood ratio test = 0.2, Wald test = 0.2, score (logrank) test = 0.2.

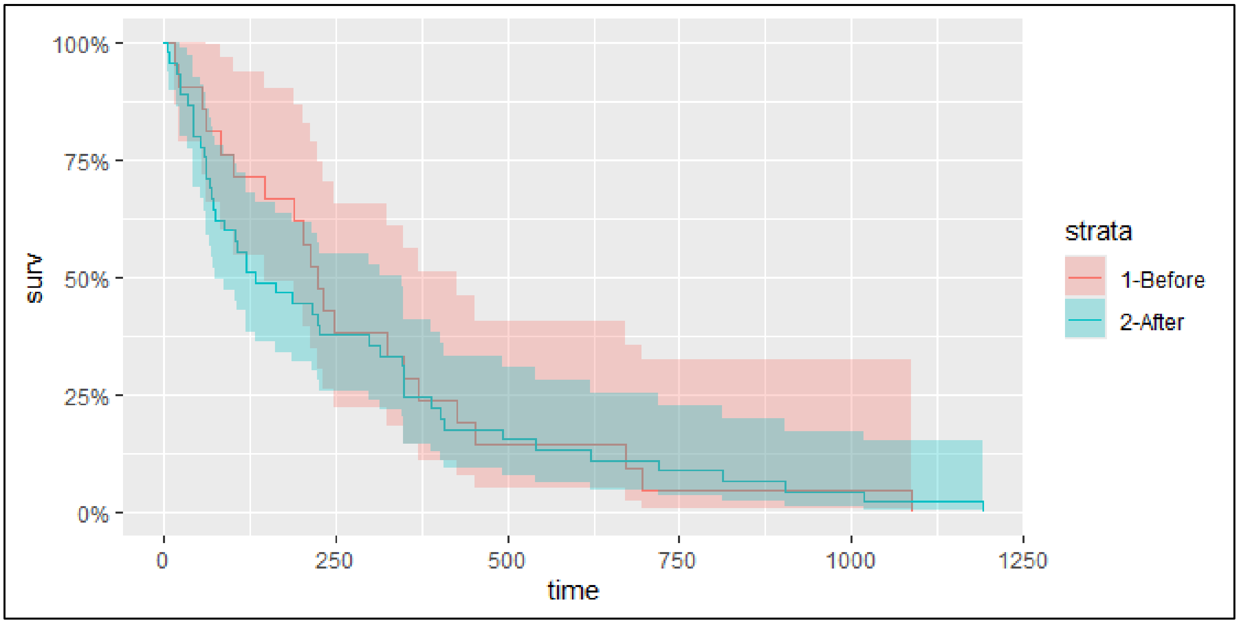


Figure 51. Survival Analysis Plot for All Barrier Crashes before and after Treatment.

Daytime Barrier Crashes

Table 16 shows the survival analysis results for daytime barrier-related crashes. The coefficient for the after period (0.255) implies that, on average, survival in the after period is shorter than in the before period. However, the results are statistically insignificant at a 95 percent confidence level (p-value of 0.649, which is greater than 0.05). Further, the survival plot in Figure 52 also shows that survival in the after period is shorter than in the before period. However, the plot shows significant uncertainties, especially in the before period, as revealed by the wide 95 percent confidence intervals. The results were expected because barrier striping works better in the nighttime than daytime.

Table 16. Survival Analysis Results for Daytime Barrier Crashes.

Variable	Coef	Exp(Coef)	SE(Coef)	Z-stat	p-value
After period	0.255	1.290	0.559	0.455	0.649
log_AADT	0.970	2.638	0.712	1.363	0.173

Note: Model performance summary: observations = 35, likelihood ratio test = 2.32, Wald test = 2.31, score (logrank) test =2.35.

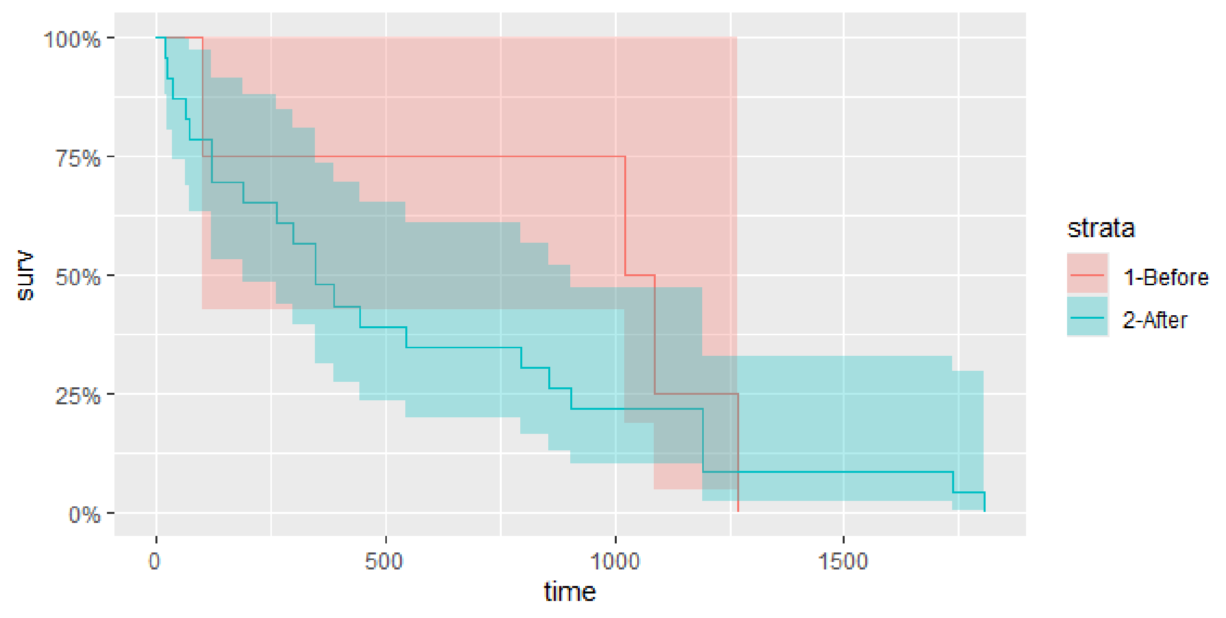


Figure 52. Survival Analysis Plot for Daytime Barrier Crashes before and after Treatment.

Nighttime Barrier Crashes

Table 17 shows the survival analysis results for nighttime barrier-related crashes. The coefficient for the after period is negative (−0.686), which implies that, on average, survival in the after period is longer than in the before period. However, the results are statistically insignificant at a 95 percent confidence level (p-value = 0.118). The survival plot in Figure 53 also shows that survival in the after period is longer than in the before period for most of the observation time. Although the results are not statistically significant, the negative coefficient signifies some improvement in the nighttime barrier crashes after installation.

Table 17. Survival Analysis Results for Nighttime Barrier Crashes.

Variable	Coef	Exp(Coef)	SE(Coef)	Z-stat	p-value
After period	−0.686	0.504	0.439	−1.562	0.118
log_AADT	0.280	1.323	0.752	0.372	0.710

Note: Model performance summary: observations = 35, likelihood ratio test = 2.58, Wald test = 2.63, score (logrank) test = 2.7.

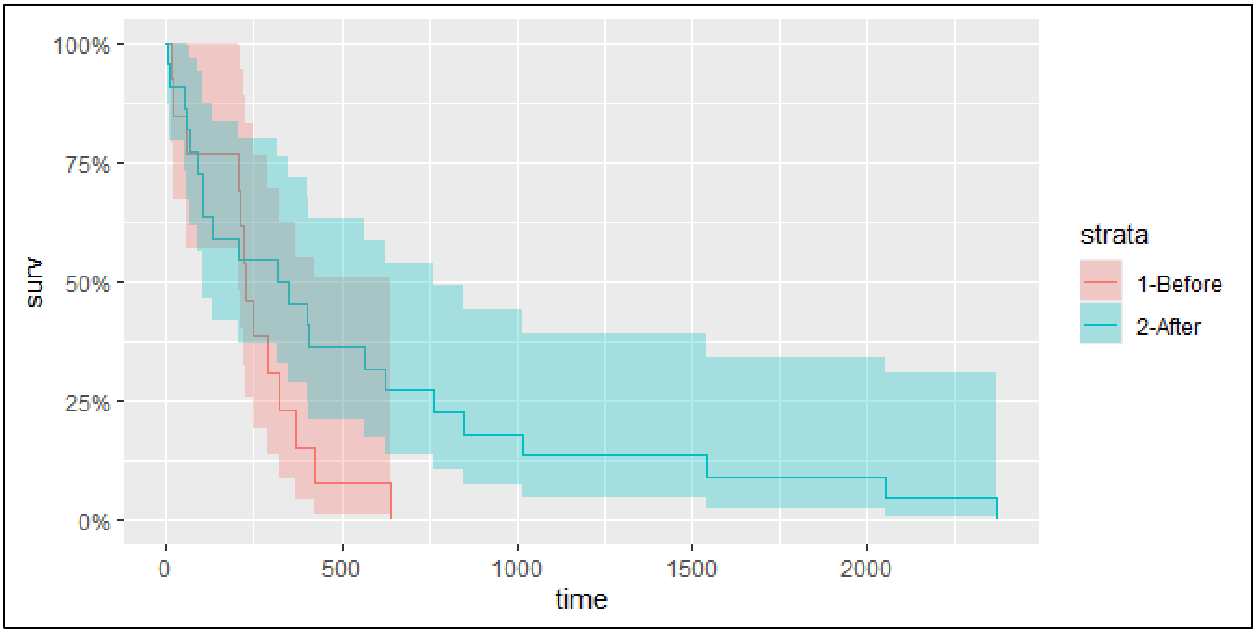


Figure 53. Survival Analysis Plot for Nighttime Barrier Crashes before and after Treatment.

In conclusion, similar to the previous two approaches, the survival analysis results show some improvements for the after period for barrier crashes in the nighttime. The improvement is statistically insignificant, similar to the crash rate analysis conclusion. An additional detail for the survival analysis is that a clear difference can be observed in the survival plots.

DESCRIPTIVE CRASH ANALYSIS FOR NEW SITES

The research team performed an exploratory analysis of 2,743 crashes at seven sites (Figure 54), as described in Chapter 3, to understand the distribution of the key variables. The sites were identified as follows: Site 1 was located at I-35E near W Twelfth Street, Site 2 was at I-30 over 1st Avenue, and Site 3 was at I-10 near I-410. Site 6 was situated at I-35E near Mockingbird Ln, Site 7 was at US 281 and Hildebrand Ave, Site 8 was at US 281 and Josephine St, and Site 9 was at I-35E near S Ewing Ave. The variables included temporal factors such as years and time of day, severity levels, lighting conditions, etc. The exploratory analysis covered barrier-related crashes that involved median barriers, guardrails, or concrete traffic barriers, as well as non-barrier-related crashes. Further, daytime and nighttime crashes were explored.

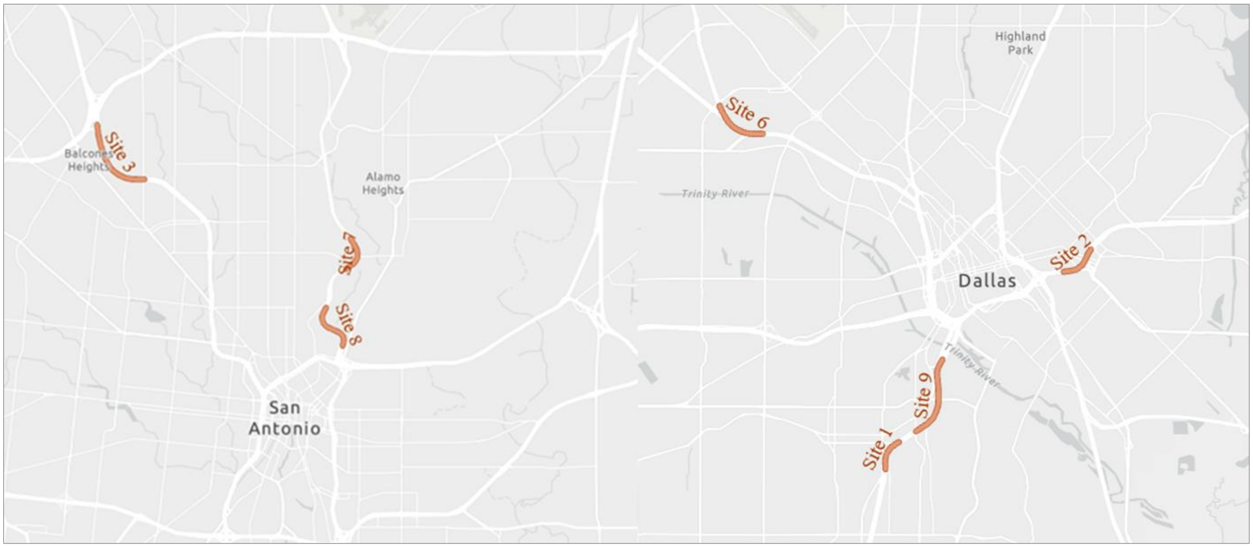


Figure 54. Study Site Map.

Crash Distribution per Site

Figure 55 presents crash distribution by study site. As shown, I-35E near Mockingbird Ln had the highest total number of crashes, followed by I-35E near S Ewing Ave, while I-35E near W Twelfth St reported the lowest crash counts. Non-barrier-related crashes consistently outnumbered barrier-related crashes at all study sites. The proportion of barrier-related crashes appeared relatively small compared to non-barrier-related crashes across all locations. This variation suggests that crash risk factors differ among sites, potentially influenced by roadway design, traffic volume, or environmental conditions.

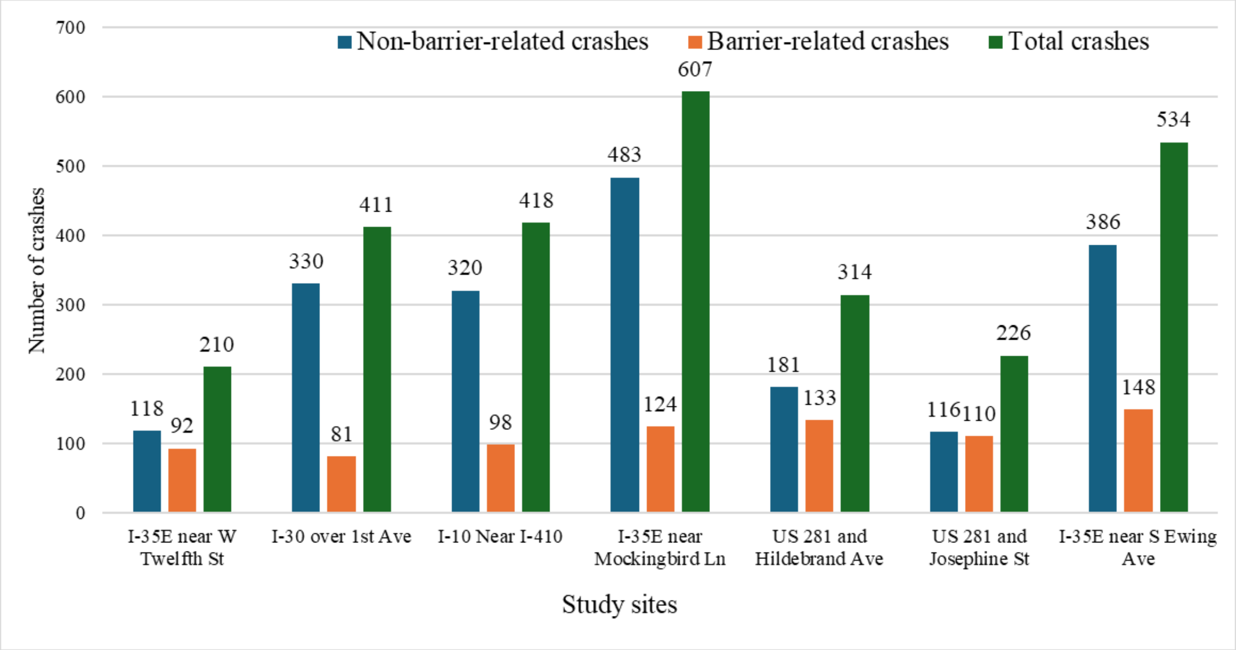


Figure 55. Crash Distribution by Study Site.

Weather and Lighting Conditions

Lighting conditions play a significant role in barrier-related crashes since striped barriers are more visible at night and in adverse weather conditions. Thus, the research team was interested in exploring the correlation between weather conditions and lighting conditions to determine the impact of striping on barrier-related crashes.

Figure 56 and Figure 57 present crash distribution by lighting conditions and weather conditions, respectively. Figure 56 shows that most of the barrier-related crashes occurred in dark lighting conditions, which include dark lighted, dark not lighted, dawn, and dusk conditions. Figure 57 shows that there were many barrier-related crashes during cloudy and rainy weather conditions, although most occurred when it was clear.

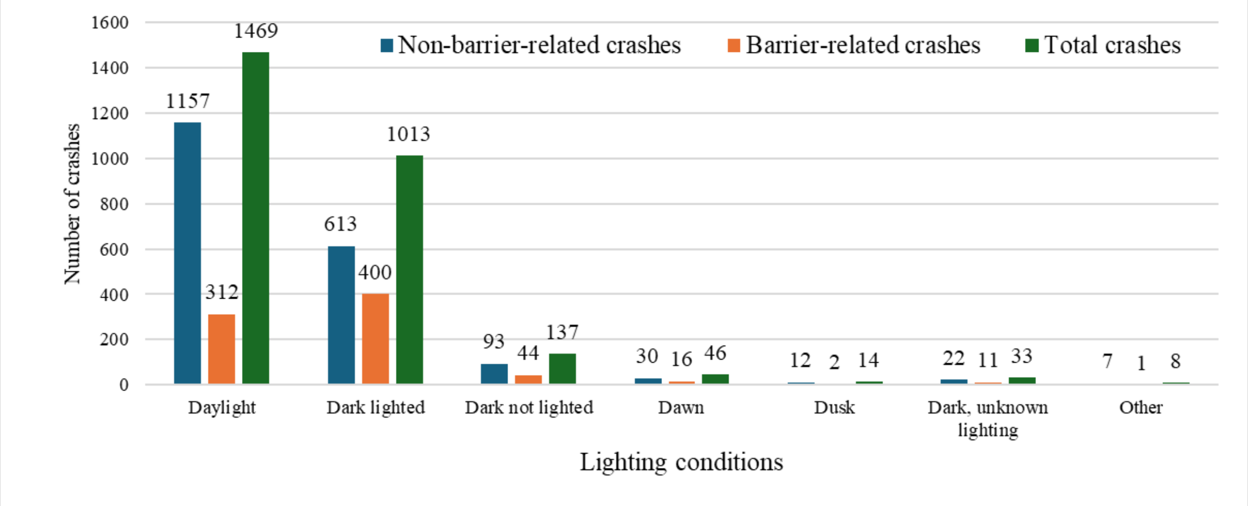


Figure 56. Crash Distribution by Lighting Conditions.

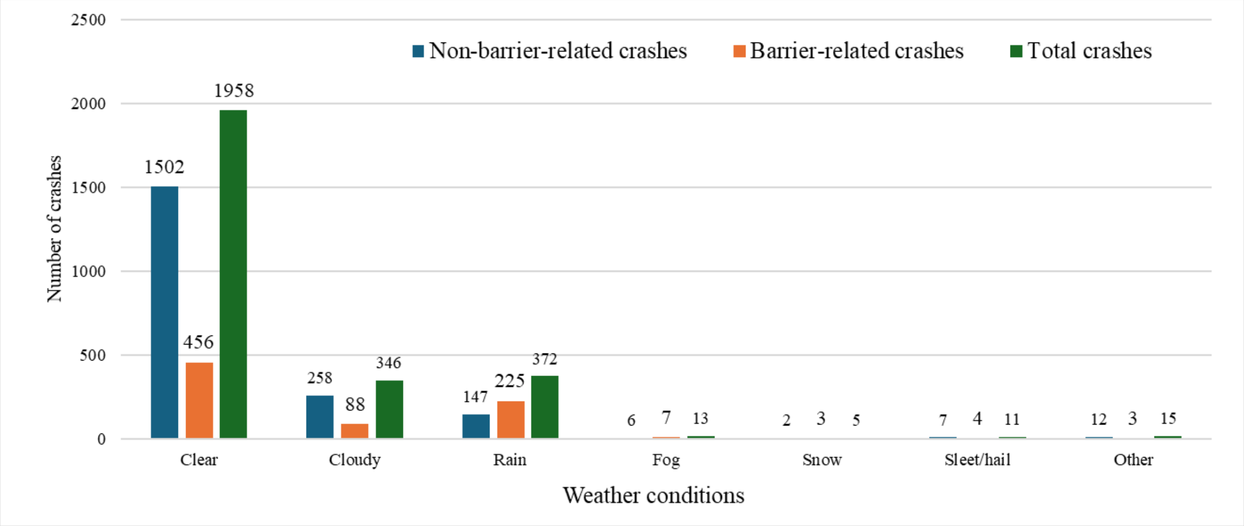


Figure 57. Crash Distribution by Weather Conditions.

Crash Severity

Since this study focused on barrier-related crashes, the research team utilized a crash dictionary to obtain only the crashes of interest. Non-barrier crashes were also retained for further analysis if needed. It was hypothesized that barrier striping might impact non-barrier crashes, such as in a secondary crash with a non-barrier crash whose primary crash was a barrier crash. Figure 58 presents crash distribution by severity. Most crashes resulted in property damage only, and only eight barrier-related crashes were fatal. Further, injury crashes represented a substantial portion of barrier-related crashes.

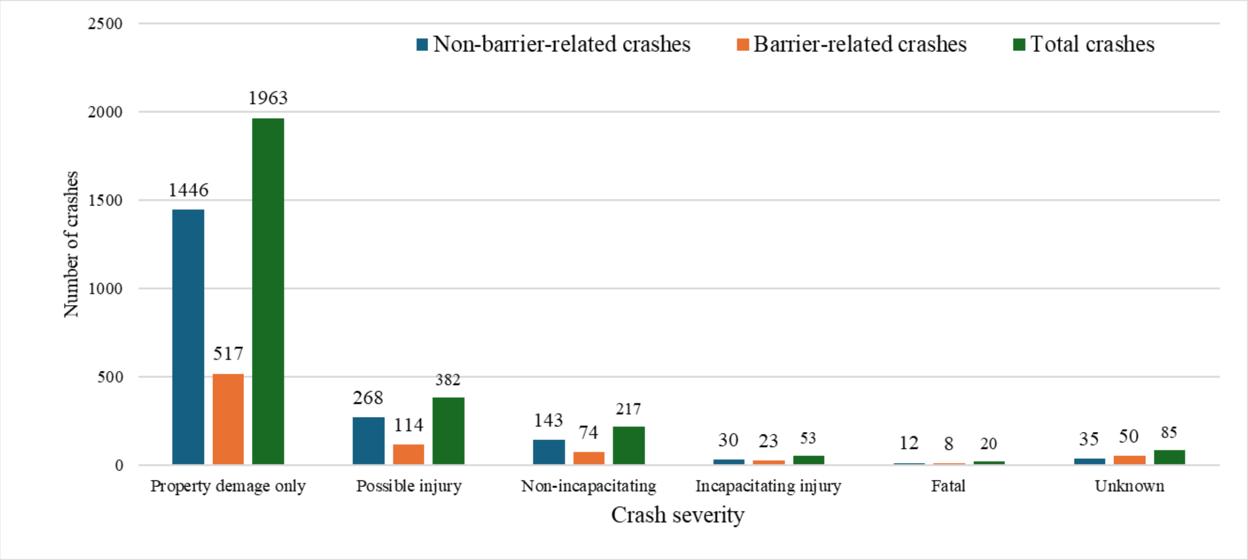


Figure 58. Crash Distribution by Injury Severity.

Temporal Crash Distribution

The research team assessed the yearly distribution of crash data by focusing on the overall and barrier-related crash distributions. The overall crash distribution covered all crashes, while the barrier-related crash distribution covered only crashes that hit the barrier.

Yearly Distribution of All Crashes

Figure 59 presents the number of crashes per year for all study sites with existing barrier stripes. The distribution suggests that crash frequency within study sites peaked in 2021. While the non-barrier-related crashes indicate a declining trend between 2021 and 2023, the figure also indicates a decline in barrier-related crashes.

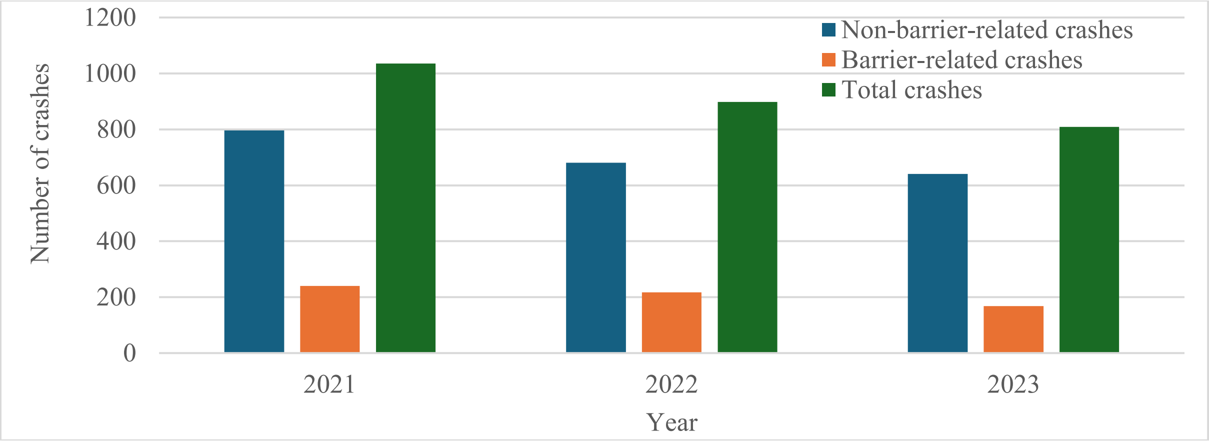


Figure 59. Crash Distribution by Year.

Yearly Distribution of Barrier-Related Crashes

Since the project focused on barrier-related crashes, the research team subdivided crash data into barrier-related crashes and non-barrier-related crashes, and then examined lighting conditions. All the crashes that occurred during daytime formed one category, while crashes that occurred in the dark lighted, dark not lighted, dawn, and dusk conditions formed a second category. Figure 60 presents the yearly distribution of barrier-related crashes by lighting conditions. As shown, total crashes exhibited a declining trend over the years. Despite the overall reduction, night/dark barrier-related crashes remained consistently higher than daytime crashes, highlighting the persistent safety concern under low-light conditions.

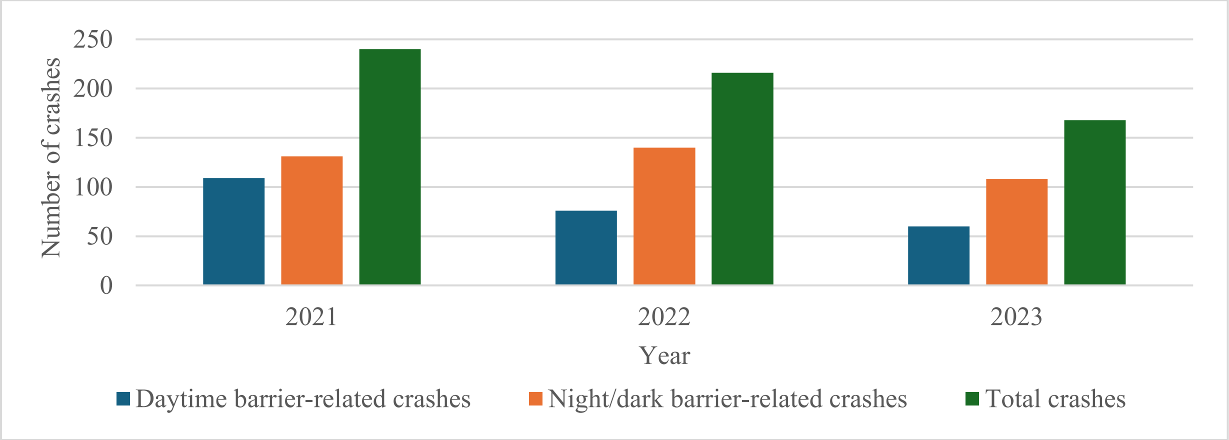


Figure 60. Barrier-Related Crash Distribution by Lighting Conditions.

Time-of-Day Distribution of All Crashes

Figure 61 presents crash distribution by time of day. As shown, total crashes showed a clear peak between 4:00 and 6:00 p.m., likely corresponding to increased traffic volumes during evening rush hours. Non-barrier-related crashes consistently outnumbered barrier-related crashes across all hours of the day. Barrier-related crashes remained relatively stable throughout the day, with minor fluctuations. Additionally, there was a noticeable increase in crashes during early morning hours (around 2:00 a.m.).

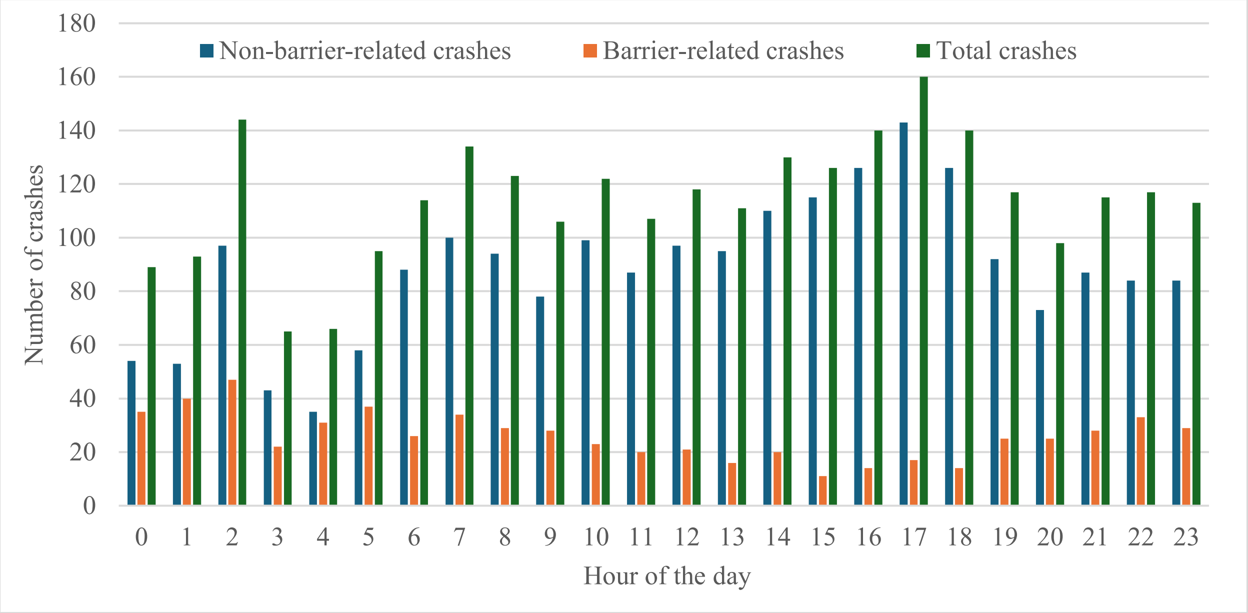


Figure 61. Crash Distribution by Time of Day.

SPEED ANALYSIS FOR NEW SITES

This section presents the examination of the impact of installing barrier striping on traffic speeds. By analyzing the speed data before and after the installation, the research team aimed to determine whether the barrier striping had a noticeable impact on traffic speed, particularly during different times of the day and in varied traffic conditions. At the time of this analysis, the barrier striping had been installed at only one site, on I-10 near I-410 (Site 3), so only this site was considered.

The research team first identified the INRIX XD segments associated with the study site. The research team then downloaded the INRIX XD speed data for the identified segments from the Probe Data Analytics Suite website. The data are part of the Regional Integrated Transportation Information System (RITIS). The installation was performed on April 8, 2025. The collected speed data spanned three months before installation (January 8, 2025–April 7, 2025) and three months after installation, with a one-week gap following the installation of the striping (April 16, 2025–July 16, 2025).

Table 18 presents an analysis of the effect of barrier striping on traffic speeds at Site 3 (I-10 near I-410), showing average speeds and the variability of those speeds (standard deviation) before and after the striping was installed. The data are broken down by overall, weekday, weekend, morning peak, evening peak, day, and night periods. The average speed increased slightly, from 66.0 mph to 66.3 mph, while the standard deviation decreased from 4.03 to 3.88. Over the weekdays, the average speed increased from 65.8 to 66.0 mph, accompanied by a slight reduction in variability (from 4.36 to 4.31), suggesting steadier driving during regular traffic conditions. A similar pattern was observed on weekends, where the average speed increased from 66.6 to 67.0 mph and the standard deviation dropped from 2.16 to 2.28. These trends suggest that after the striping was implemented, drivers tended to maintain a more uniform speed, possibly reflecting increased comfort and confidence while navigating the roadway.

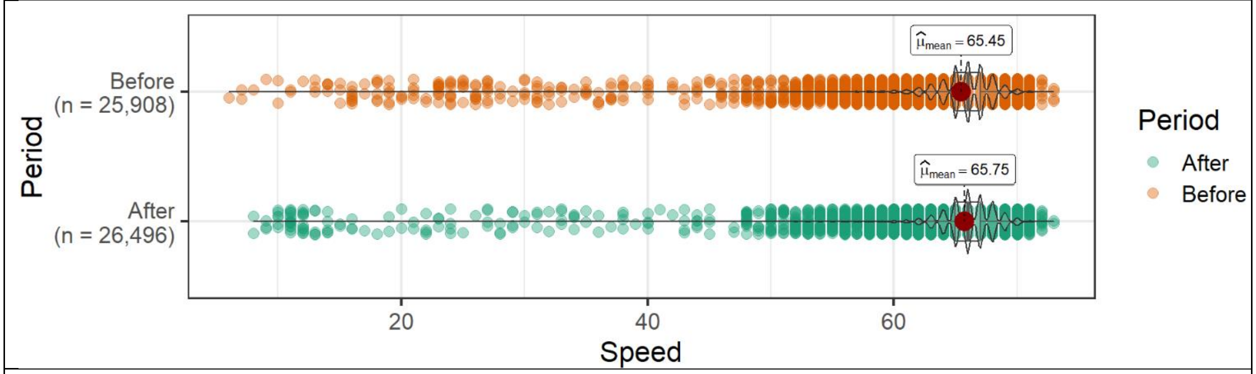
Table 18. Average and Standard Deviation of Speed Data for Site 3 (I-10 near I-410).

Speed measure	Period	Before	After
Avg spd	All	66.0	66.3
Std spd	All	4.03	3.88
Avg spd	Weekday	65.8	66.0
Std spd	Weekday	4.36	4.31
Avg spd	Weekend	66.6	67.0
Std spd	Weekend	2.16	2.28
Avg spd	Morning peak	65.9	67.1
Std spd	Morning peak	5.65	2.90
Avg spd	Evening peak	65.0	64.9
Std spd	Evening peak	5.96	7.87
Avg spd	Day	66.4	66.4
Std spd	Day	3.29	2.82
Avg spd	Night	66.0	66.3
Std spd	Night	3.15	2.80

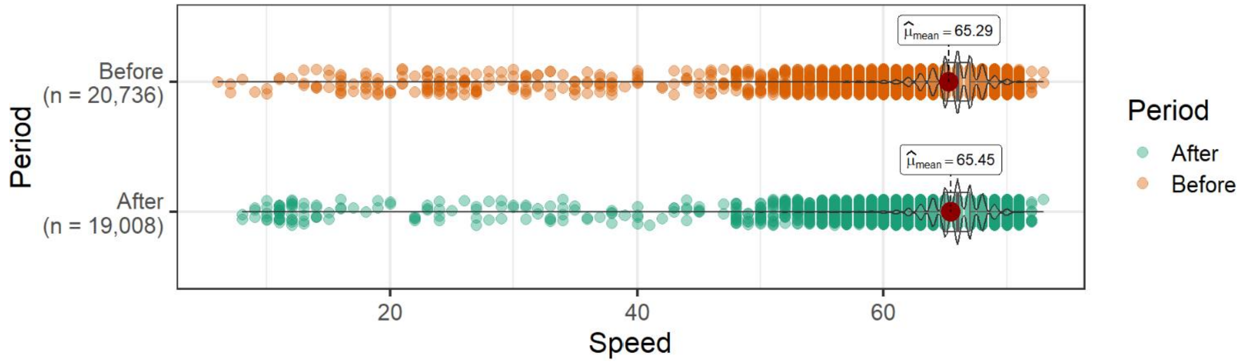
Note: Avg spd = average speed; Std spd = standard deviation of speed.

Variation in Speed Data by Weekday and Weekend

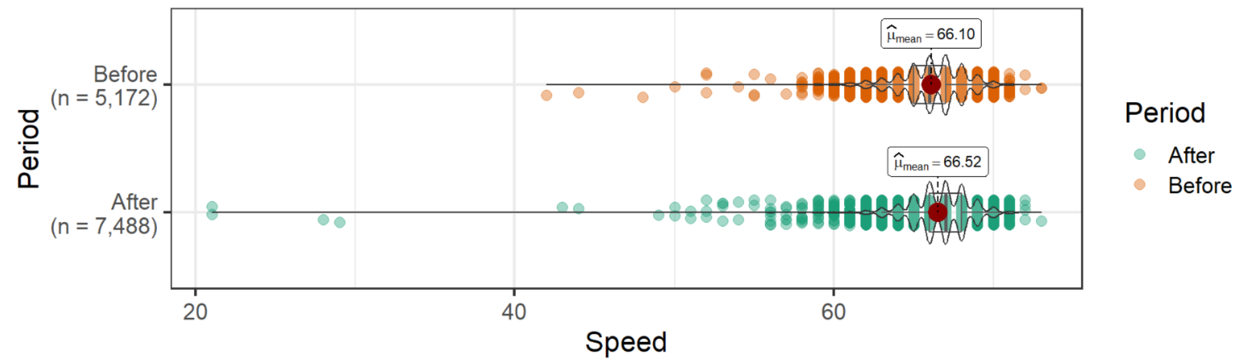
Variation in roadway speed data by weekday and weekend was evaluated and is explained in this section. Figure 62 displays the overall speed data for I-10 near I-410, representing the before period (orange dots) and the after period (green dots), segmented by overall, weekday, and weekend periods. Each subplot provides a visual comparison using dot plots and density overlays, helping to illustrate how driver behavior may have changed following the striping intervention. In the overall comparison (Figure 62[a]), the average speed increased slightly, from 65.45 mph before installation to 65.75 mph after. For weekdays (Figure 62[b]), the average speed increased from 65.29 mph before to 65.45 mph after the installation. The density plots show fairly consistent and compact speed distributions in both periods. The weekend comparison (Figure 62[c]) shows a slightly noticeable shift. The average speed increased from 66.10 mph to 66.52 mph after the striping. The plots suggest that barrier striping had a modest but consistent influence on increasing average speeds while maintaining a narrow spread in speed distributions.



(a) Overall



(b) Weekday

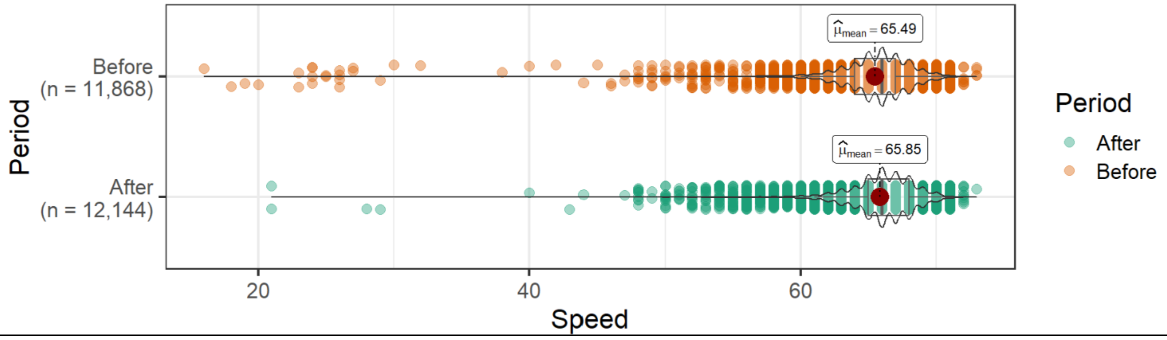


(c) Weekend

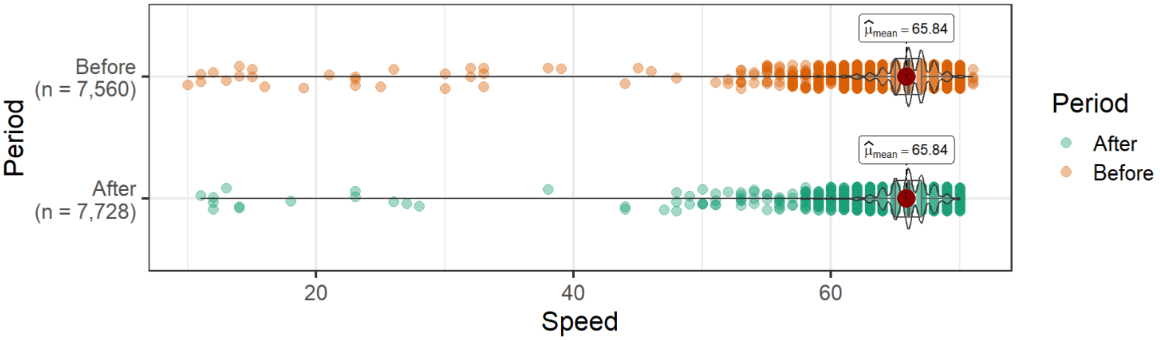
Figure 62. Distribution of Speed Measures by Installation Period and Day of Week (I-10 near I-410).

Variation in Speed Data by Time of Day

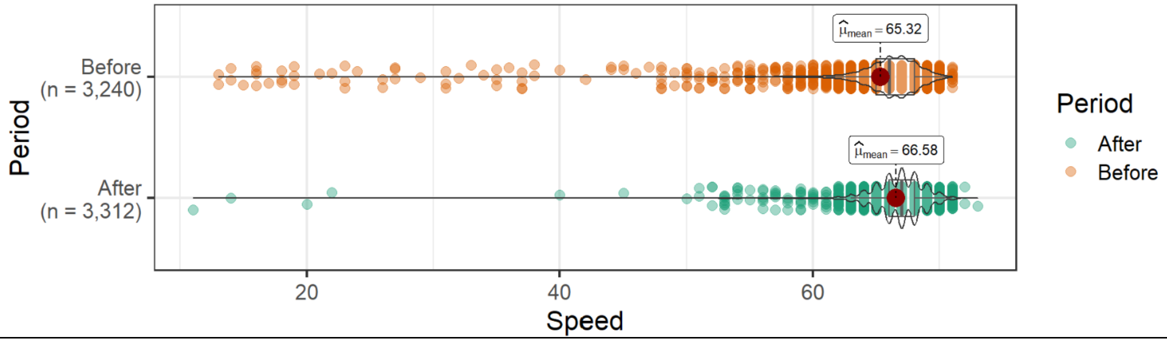
Variation in roadway speed data by hour was also evaluated. Figure 63 presents the distribution of vehicle speeds by time of day—night, day, morning peak, and evening peak—before and after the installation of barrier striping. In the nighttime period (Figure 63[a]), there was a slight increase in the average speed, from 65.49 mph before to 65.85 mph after striping. During the daytime period (Figure 63[b]), the average speed remained unchanged, at 65.84 mph before and after installation. The morning peak period (Figure 63[c]) showed a modest increase in average speed, from 65.32 mph before to 66.58 mph after striping. Last, in the evening peak period (Figure 63[d]), the average speed reduced from 64.50 mph before to 64.37 mph after installation.



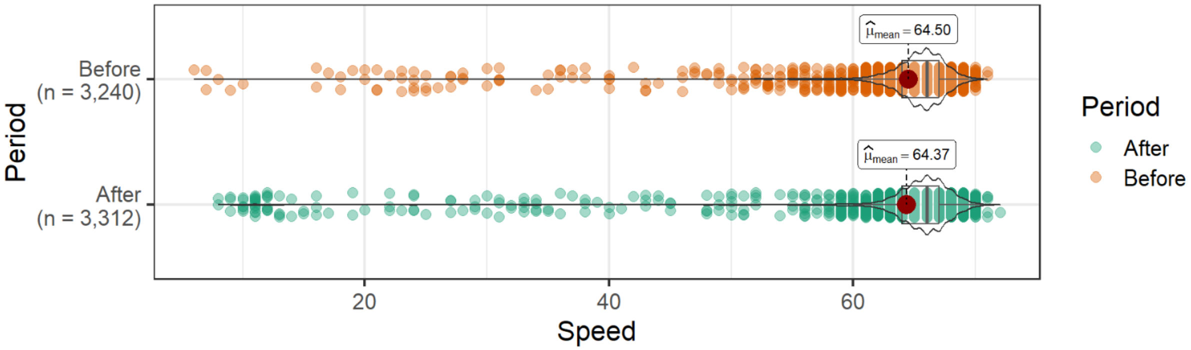
(a) Night



(b) Day



(c) Morning Peak



(d) Evening Peak

Figure 63. Distribution of Vehicle Speed by Time of Day (I-10 near I-410).

CHAPTER 6: SPECIAL SPECIFICATION GUIDELINE UPDATE

OVERVIEW

TxDOT first developed the SS for safety barrier line marking in 2023. SS 6508 – Safety Barrier Line Markings was developed as a one time use SS. The SS was finalized after reviews which included comment from the research team. Industry provided feedback to TxDOT and the research team on SS 6508. This section of the report provides additional comments from the research team to update the SS which considers industry comments and experience from the project. The update comprises two parts: proposed changes to the SS and suggested testing to improve the SS.

PROPOSED CHANGES

The research team proposed several changes and presented several questions about the SS during the initial review process in 2023. The following list presents unaddressed changes and provides additional changes and questions for consideration when updating the SS. Suggestions to improve the SS from the marking industry are also provided.

- Section 1—Description, indicates the use of traffic paint. The Section 2—Materials, indicate the use of paint and glass bead materials. There are premade stripes of retroreflective material that can be used in the same manner as the applied paint and bead marking. The SS should consider allowing these premade strips or another SS should be developed to allow their use. This would allow multiple types of systems to be used if desired
- Section 2—Materials, Subsection 2.2 indicates the use of glass beads that meet AASHTO M-247 requirements. AASHTO M-247 covers only standard refractive index glass beads (refractive index of 1.5-1.55). Higher refractive index glass beads may be required to attain the desired retroreflectivity levels as indicated in Section 4.2. The materials requirements for both the paint and beads need to be studied further to ensure the materials used are capable of meeting the desired performance levels.
- Section 4.1—There are no specifics on the placement height or width of the applied marking. At a minimum the SS should list the potential widths of the applied marking to better help with plan development. Typical widths are 6, 8, or 10 inches wide. Due to different heights in barriers, it may be best to indicate a typical height from the ground that the markings are installed unless otherwise indicated on the plans. A typical height is 18 inches to the top of the marking above the ground.
- Section 4.2—update the retroreflectivity units to millicandelas per meter squared per lux (mcd/m^2/lux). This is the typical format for marking retroreflectivity.
- Industry has indicated similar concern that the research team has with the lack of specificity in the material requirements. Specifically, that the high refractive index beads are not allowed per the SS when this type of bead may be the only way to attain the

desired performance level. Industry provided MTD with specific bead gradation and refractive index values that have proven to work in the past.

SUGGESTED TESTING

The research team recommends testing various paint and bead combinations to generate a list of approved materials that meet the performance requirements of the SS. This testing would utilize various paint products in combination with various bead products to generate the barrier stripe. The initial performance of both white and yellow markings would be evaluated to determine if the products meet the desired performance level. This testing could then be used to update the materials section of the SS. A material producer list of approved materials could be generated for the SS.

This testing is needed because the same materials that work well for horizontal pavement marking striping may not be the best materials that work well for vertical application of striping on barriers. The paint may need a specific formulation to hold the beads without running down the barrier. The beads may need a higher refractive index and specific gradation to generate the desired performance level. Utilizing inappropriate materials will likely yield less than desirable performance which will be detrimental to the contractors and require greater inspection to ensure performance levels are achieved.

CHAPTER 7: SUMMARY OF FINDINGS, CONCLUSIONS, AND RECOMMENDATIONS

OVERVIEW

Barrier striping enhances driver awareness of roadway barriers, especially under low-visibility conditions such as rain or snow. TxDOT's TRF developed a draft SS for the vertical application of retroreflective striping on concrete barriers, which was then used to guide installations at four locations. However, the safety effectiveness of these treatments had not been formally evaluated. This project addressed that gap by conducting a long-term safety analysis of the existing installations and assessing barrier striping at additional high-crash sites. Beyond evaluating safety impacts, the research team provided recommendations to improve the SS, including revised language and proposed additions of the items to support effective implementation. The updated specification, informed by this research, is intended to serve as statewide guidance for applying retroreflective barrier striping, supporting consistent and effective deployment across Texas and potentially in other jurisdictions.

SUMMARY OF FINDINGS

This section presents a summary of the key findings regarding the impact of barrier stripes on safety and speed.

Effect of Barrier Stripes on Safety

The safety analysis evaluated the impact of barrier striping using crash data from four treated sites. The BA study approach was applied to determine the change in crash frequency. The descriptive analysis of existing sites showed 404 crashes after data cleaning, with a majority being property-damage-only cases and only one fatal barrier-related crash. Crash frequency peaked in 2016, with barrier-related crashes declining after 2019. Temporal patterns revealed that barrier-related crashes occurred more often at night, peaking around 11 p.m., while non-barrier crashes were more frequent during the day. Weather and lighting analysis indicated that most barrier-related crashes happened under dark conditions and during cloudy or rainy weather. Site-level results showed higher crash counts at larger segments, though barrier-related crashes were more evenly distributed. Overall crash rates peaked in 2016 but declined notably from 2019 onward, suggesting potential safety benefits from barrier striping

To assess the safety impact of barrier striping, the research team developed four sets of statistical models: logistic regression, linear regression, negative binomial, and survival analysis. Logistic regression results showed a 41 percent reduction in the odds of barrier-related crashes in the after period (OR = 0.59). Notably, nighttime barrier crashes declined by 62 percent (OR = 0.38), a statistically significant reduction, while daytime crash reductions (22 percent) were not significant at the 95 percent level.

Linear regression models examined crash rates while controlling for AADT and segment length. The models indicated a statistically significant increase in daytime crash rates post-treatment, while nighttime crash rates slightly declined but were not statistically significant. This mixed result suggests limited improvements during the day but potential benefits at night, when visibility enhancements from striping are more critical.

Negative Binomial regression models examined crash frequencies across crash types. Results showed a statistically significant increase in all crashes after treatment (p = 0.017), with the model producing a comparatively lower AIC value and stronger fit. Barrier and daytime crash models also indicated increases but were not statistically significant, while the nighttime crash model produced a negative coefficient, suggesting a decline that was likewise not significant. Overall, the Negative Binomial results highlight mixed effects, with only total crashes showing meaningful change after striping.

Survival analysis evaluated time intervals between crashes. Results revealed shorter crash intervals after treatment for all crashes and daytime barrier crashes, implying worse safety. However, for nighttime barrier crashes, survival time increased post-treatment, suggesting improved safety. Although statistically insignificant, the negative coefficient (–0.686) and the survival plots support this interpretation. Overall, the models consistently point to modest improvements in nighttime barrier safety after the implementation of vertical retroreflective striping.

Prediction Equation Quality

The quality of the statistical models developed to assess the effectiveness of barrier striping was evaluated using standard goodness-of-fit measures tailored to each model type. For the logistic regression models, the AIC and BIC were used to assess model fit. The models showed acceptable AIC and BIC values, with lower scores indicating better fit. Among them, the nighttime barrier crash model demonstrated the strongest performance (AIC = 145, BIC = 154), accompanied by a statistically significant treatment effect (p = 0.026), supporting the conclusion that striping reduced nighttime crashes.

In the linear regression models for crash rates, model performance was evaluated through p-values and standard errors of the estimated coefficients. While the models revealed some statistically significant results—such as an increase in daytime crash rates (p = 0.017)—the models overall suffered from limitations due to small sample sizes (n = 36) and wide standard errors, especially for nighttime crashes.

The Negative Binomial models showed acceptable but varied fit, as indicated by their AIC values. While the all-crashes model performed relatively better (AIC = 307.39) and produced a statistically significant coefficient, the barrier-specific and nighttime models lacked statistical power, with wide dispersion parameters highlighting uncertainty in estimates.

For survival analysis, model quality was assessed using the likelihood ratio test, Wald test, and Score (logrank) test. These tests confirmed statistical significance only for all crashes ($p < 0.05$), while the models for barrier-specific crashes, particularly nighttime, showed trends of improvement but lacked statistical power. The wide confidence intervals further signaled uncertainty in the estimates.

Effect of Barrier Stripes on Speed

The evaluation of barrier striping at the I-10 near I-410 site shows that barrier striping appears less effective as a direct speed-reduction tool but demonstrates potential value in enhancing consistency and driver confidence on high-volume corridors. The average vehicle speeds either remained stable or increased slightly across most conditions, with the most notable rise occurring during morning peak and weekend periods. However, barrier striping did contribute to improved consistency in driving behavior by reducing speed variability during several periods, resulting in vehicles traveling at more uniform speeds. This effect suggests that while barrier striping may not directly lower speeds, it can foster more predictable and stable traffic flow, which supports roadway safety by reducing erratic driving patterns. The exception was the evening peak period, where variability increased, indicating that the effectiveness of barrier striping may vary under heavier congestion.

CONCLUSIONS

This study evaluated the safety effectiveness of barrier striping using crash data and statistical models across multiple Texas sites. Descriptive and regression analyses indicated a general reduction in barrier-related crashes following striping installation, particularly during nighttime. Logistic regression showed a 62 percent decline in nighttime crash odds post-treatment, while survival analysis also suggested longer crash intervals at night, though not statistically significant. Linear regression results were mixed, with limited improvements observed for nighttime crashes. Negative Binomial regression results were mixed. A significant increase was found for all crashes post-treatment, while barrier-specific and daytime crashes were not significant. Nighttime crashes showed a nonsignificant decline, suggesting potential but inconclusive benefits. Despite small sample sizes, the findings support barrier striping as a low-cost countermeasure that can enhance visibility and improve safety, especially under low-light driving conditions.

RECOMMENDATIONS FOR FUTURE RESEARCH

Suggestions for future research include the following:

- Expand sample size and sites: Include a larger number of treated sites and longer observation periods to improve statistical power, especially for nighttime barrier crashes, where the effects of striping are most evident.

- Control for additional exposure variables: Incorporate more detailed roadway and environmental variables—such as curve radius, lighting conditions, and barrier type—into the models to improve explanatory accuracy and control for confounding effects.
- Explore treatment durability and maintenance effects: Assess how the retroreflectivity of striping degrades over time and its impact on safety performance to better understand long-term effectiveness and maintenance needs.
- Utilize advanced surrogate safety measures: Apply high-resolution connected vehicle data to capture near-misses, lane deviations, and hard-braking events, which can serve as early indicators of safety performance before crashes occur.
- Evaluate different bead gradations and paint types: Investigate the safety performance of alternative bead gradations (e.g., Type I, II, and III) and various paint types (e.g., water-based vs. solvent-based) under diverse environmental and traffic conditions. This would help determine the optimal combination of materials that maximize retroreflectivity, durability, and crash reduction effectiveness, especially in wet or nighttime conditions. Testing variable stripe widths may also inform standardization for future specifications.

REFERENCES

1. Ceifetz A, Yassin J, Andridge P, Kwigizile V, Oh JS, Burdick B. Evaluating Road Delineation Practices in Michigan [Internet]. Lansing, MI; 2017 Mar [cited 2023 Nov 1]. Available from: https://rosap.ntl.bts.gov/view/dot/32150
2. TxDOT. Pavement Marking Handbook. 2004.
3. MnDOT. Retroreflective Sheeting Identification Guide. 2023.
4. Haas K. Evaluation of 3M(TM) Scotchlite linear delineation system. 2004 Sep 1 [cited 2023 Oct 31]; Available from: https://rosap.ntl.bts.gov/view/dot/22946
5. Albin R, Brinkly V, Cheung J, Julian F, Satterfield C, Stein W, et al. Low-Cost Treatments for Horizontal Curve Safety. 2016 [cited 2023 Oct 15]; Available from: http://safety.fhwa.dot.gov
6. Shaffie E, Maisara N, Zin M, Shiong F, Arshad AK, Ahmad J. A Study On the Effectiveness of Rolling Barrier System at Straight Road and Curved Road: A Review. International Journal of Integrated Engineering [Internet]. 2023 Apr 4 [cited 2023 Nov 9];15(1):310–20. Available from: https://publisher.uthm.edu.my/ojs/index.php/ijie/article/view/9433
7. Lodhia V, Poojari A. A STUDY ON “ROLLING BARRIERS SYSTEM ON HORIZONTAL CURVES.” International Journal of Engineering Applied Sciences and Technology [Internet]. 2021 [cited 2023 Nov 9];5(11):243–6. Available from: http://www.ijeast.com
8. CDOT. Delineator Installations. 2019.
9. WSDOT. Guide Posts and Barrier Delineators. 2014.
10. KYTC. Delineators for Concrete Barriers. 2009.
11. CalTrans. Traffic Safety System Guide. 2019.
12. NCDOT. Guardrail and Barrier Delineator Spacing [Internet]. [cited 2025 Feb 19]. Available from: https://connect.ncdot.gov/projects/Metric%20Drawings/new12610101.pdf
13. TDOT. Delineator mounting details. 2021.
14. AASHTO. Highway Safety Manual. 2010.
15. Montella A. Safety Evaluation of Curve Delineation Improvements: Empirical Bayes Observational Before-and-After Study. Transportation Research Record: Journal of the Transportation Research Board. 2009.
16. Guo F, Klauer SG, Hankey JM, Dingus TA. Near Crashes as Crash Surrogate for Naturalistic Driving Studies. Transportation Research Record: Journal of the Transportation Research Board [Internet]. 2010 Jan 1 [cited 2023 Oct 18];(2147):66–74. Available from: https://journals.sagepub.com/doi/10.3141/2147-09
17. Johnsson C, Laureshyn A, Dágostino C. A relative approach to the validation of surrogate measures of safety. Accid Anal Prev. 2021 Oct 1;161:106350.
18. Guo F, Klauer SG, McGill MT, Dingus TA. Evaluating the Relationship Between Near-Crashes and Crashes: Can Near-Crashes Serve as a Surrogate Safety Metric for Crashes? [Internet]. 2010 [cited 2023 Oct 18]. Available from: www.ntis.gov
19. Lu C, He X, van Lint H, Tu H, Happee R, Wang M. Performance evaluation of surrogate measures of safety with naturalistic driving data. Accid Anal Prev. 2021 Nov 1;162:106403.

20. Borsos A, Farah H, Laureshyn A, Hagenzieker M. Are collision and crossing course surrogate safety indicators transferable? A probability based approach using extreme value theory. Accid Anal Prev. 2020 Aug 1;143:105517.
21. Kuang Y, Yu Y, Qu X. Novel Crash Surrogate Measure for Freeways. J Transp Eng A Syst [Internet]. 2020 Jun 12 [cited 2023 Oct 18];146(8):04020085. Available from: https://ascelibrary.org/doi/abs/10.1061/JTEPBS.0000405
22. Hu Y, Li Y, Huang H, Lee J, Yuan C, Zou G. A high-resolution trajectory data driven method for real-time evaluation of traffic safety. Accid Anal Prev. 2022 Feb 1;165:106503.
23. Moreno AT, García A. Use of speed profile as surrogate measure: Effect of traffic calming devices on crosstown road safety performance. Accid Anal Prev. 2013 Dec 1;61:23–32.
24. Ambros J, Jurewicz C, Chevalier A, Valentová V. Speed-Related Surrogate Measures of Road Safety Based on Floating Car Data. Lecture Notes in Networks and Systems [Internet]. 2021 [cited 2023 Oct 18];207:129–44. Available from: https://link.springer.com/chapter/10.1007/978-3-030-71708-7_9
25. Astarita V, Giofrè VP. Trajectory Perturbation in Surrogate Safety Indicators. Transportation Research Procedia. 2020 Jan 1;47:393–400.
26. Ma L, Yan X, Wei C, Wang J. Modeling the equivalent property damage only crash rate for road segments using the hurdle regression framework. Anal Methods Accid Res. 2016 Sep 1;11:48–61.
27. Wang J, He S, Zhai X, Wang Z, Fu X. Estimating mountainous freeway crash rate: Application of a spatial model with three-dimensional (3D) alignment parameters. Accid Anal Prev. 2022 Jun 1;170:106634.
28. Qin X, Ivan JN, Ravishanker N. Selecting exposure measures in crash rate prediction for two-lane highway segments. Accid Anal Prev. 2004 Mar 1;36(2):183–91.
29. Desai J, Li H, Mathew JK, Cheng YT, Habib A, Bullock DM. Correlating Hard-Braking Activity with Crash Occurrences on Interstate Construction Projects in Indiana. Journal of Big Data Analytics in Transportation 2020 3:1 [Internet]. 2020 Nov 16 [cited 2023 Oct 24];3(1):27–41. Available from: https://link.springer.com/article/10.1007/s42421-020-00024-x
30. Zhou Y, Liu H, Fu C. Investigating Contributing Factors of Hard-Braking Events on Urban Road Network. Smart Innovation, Systems and Technologies [Internet]. 2022 [cited 2023 Oct 24];304 SIST:112–22. Available from: https://link.springer.com/chapter/10.1007/978-981-19-2813-0_12
31. Kamla J, Parry T, Dawson A. Analysing truck harsh braking incidents to study roundabout accident risk. Accid Anal Prev. 2019 Jan 1;122:365–77.
32. Hill A, Horswill MS, Whiting J, Watson MO. Computer-based hazard perception test scores are associated with the frequency of heavy braking in everyday driving. Accid Anal Prev. 2019 Jan 1;122:207–14.
33. Park J, Abdel-Aty M, Lee J. Use of empirical and full Bayes before–after approaches to estimate the safety effects of roadside barriers with different crash conditions. J Safety Res. 2016 Sep 1;58:31–40.
34. Wood J, Donnell ET. Empirical Bayes before-after evaluation of horizontal curve warning pavement markings on two-lane rural highways in Pennsylvania. Accid Anal Prev. 2020 Oct 1;146:105734.

35. Persaud B, Lan B, Lyon C, Bhim R. Comparison of empirical Bayes and full Bayes approaches for before–after road safety evaluations. Accid Anal Prev. 2010 Jan 1;42(1):38–43.
36. Lyon C, Persaud B, Merritt D, Cheung J. Empirical bayes before-after study to develop crash modification factors and functions for high friction surface treatments on curves and ramps. Transp Res Rec [Internet]. 2020 Oct 22 [cited 2023 Oct 23];2674(12):505–14. Available from: https://journals.sagepub.com/doi/full/10.1177/0361198120957327
37. Hauer E, Harwood DW, Council FM, Griffith MS, Harwood DW. Estimating Safety by the Empirical Bayes Method A Tutorial. Transportation Research Record: Journal of the Transportation Research Board. 2002;
38. Huajing N, Yu Y, Bai L. Survival analysis of the unsafe behaviors leading to urban expressway crashes. PLoS One [Internet]. 2022 Aug 1 [cited 2023 Oct 24];17(8).
39. Xie K, Ozbay K, Yang H, Yang D. A New Methodology for Before–After Safety Assessment Using Survival Analysis and Longitudinal Data. Risk Analysis [Internet]. 2019 Jun 1 [cited 2023 Oct 24];39(6):1342–57. Available from: https://onlinelibrary.wiley.com/doi/full/10.1111/risa.13251
40. Yang D, Ozbay K, Xie K, Yang H. A survival analysis with random parameter approach for assessing temporal instability in treatment effect. Saf Sci. 2023 Aug 1;164:106182.
41. Carson JL, Powers M. Before-After Crash Analysis: A Primer for Using the Empirical Bayes Method Tutorial [Internet]. Montana. Dept. of Transportation. Research Section.; 2004 May [cited 2023 Nov 19]. Available from: https://rosap.ntl.bts.gov/view/dot/24878
42. Park ES, Park J, Lomax TJ. A fully Bayesian multivariate approach to before–after safety evaluation. Accid Anal Prev. 2010 Jul 1;42(4):1118–27.
43. Douglas I, Tan D. Global airline alliances and profitability: A difference-in-difference analysis. Transp Res Part A Policy Pract. 2017 Sep 1;103:432–43.
44. Diao M, Leonard D, Sing TF. Spatial-difference-in-differences models for impact of new mass rapid transit line on private housing values. Reg Sci Urban Econ. 2017 Nov 1;67:64–77.
45. Delgado MS, Florax RJGM. Difference-in-Differences Techniques for Spatial Data: Local Autocorrelation and Spatial Interaction. 2015 [cited 2023 Nov 13]; Available from: https://www.econstor.eu/handle/10419/125093
46. Lee M jae. Matching, Regression Discontinuity, Difference in Differences, and Beyond. Matching, Regression Discontinuity, Difference in Differences, and Beyond [Internet]. 2016 Aug 18 [cited 2023 Nov 13]; Available from: https://academic.oup.com/book/4064
47. Lord D, Qin X, Geedipally SR. Highway Safety Analytics and Modeling. Highway Safety Analytics and Modeling. Elsevier; 2021. 1–488 p.
48. Tay R. Fatal crashes involving young male drivers: a continuous time Poisson change-point analysis. Aust N Z J Public Health. 2001 Feb 1;25(1):21–3.
49. Carslaw DC, Ropkins K, Bell MC. Change-Point Detection of Gaseous and Particulate Traffic-Related Pollutants at a Roadside Location. Environ Sci Technol [Internet]. 2006 Nov 15 [cited 2023 Oct 24];40(22):6912–8. Available from: https://pubs.acs.org/doi/abs/10.1021/es060543u
50. Kidando E, Moses R, Sando T, Ozguven EE. Evaluating Recurring Traffic Congestion using Change Point Regression and Random Variation Markov Structured Model. Transportation Research Record: Journal of the Transportation Research Board [Internet].

2018 Jul 24 [cited 2023 Oct 24];2672(20):63–74. Available from: https://journals.sagepub.com/doi/abs/10.1177/0361198118787987

51. NHTSA. Fatality Analysis Reporting System (FARS) [Internet]. 2023 [cited 2023 Sep 14]. Available from: https://www.nhtsa.gov/research-data/fatality-analysis-reporting-system-fars
52. TxDOT. CRIS Query [Internet]. 2023 [cited 2023 Oct 16]. Available from: https://cris.dot.state.tx.us/public/Query/app/home
53. Wejo. Wejo | Connected Vehicle Data Solutions for Organizations [Internet]. 2023 [cited 2023 Nov 7]. Available from: https://www.wejo.com/
54. INRIX. Leading Transportation Analytics Solutions | INRIX [Internet]. 2023 [cited 2023 Nov 7]. Available from: https://inrix.com/
55. TXDOT. TxDOT Open Data Portal : TxDOT Roadway Inventory [Internet]. 2021 [cited 2021 Jul 25]. Available from: https://gis-txdot.opendata.arcgis.com/datasets/txdot-roadway-inventory/explore?location=31.170816%2C-100.081515%2C6.74
56. TxDOT. ArcGIS - Highway Curves [Internet]. 2022 [cited 2023 Nov 26]. Available from: https://www.arcgis.com/home/webmap/viewer.html?webmap=7e1523169900435588c47c9f069dc8d7&extent=-113.0357,24.7759,-87.1519,37.5526
57. NOWData. NOAA Online Weather Data (NOWData). 2022 [cited 2022 Nov 10]; Available from: https://www.weather.gov/climateservices/nowdatafaq
58. TxDOT. Special Specification 6508 Safety Barrier Line Markings [Internet]. 2023 [cited 2025 Sep 28]. Available from: https://ftp.dot.state.tx.us/pub/txdot-info/cmd/cserve/specs/2014/spec/ss6508.pdf