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16. Abstract

Vehicle speed is among the key attributes that make a difference in the injury severity outcome of a crash. This project started by reviewing the literature and existing toolkits to identify countermeasures to manage vehicle speeds and to improve safety especially for vulnerable road users on arterial street. A companion document, *Speed Countermeasures for Arterial Streets Guide*, provides information for implementation. Those countermeasures with the largest knowledge gaps were selected for additional investigation as part of this research project and included rest in red (RIR), roadway lighting, sidewalks, roundabout corridors, and reallocation of the cross section within a corridor. For the RIR countermeasure, the finding indicates the possibility of a reduction in crash rates and a slight increase in operating speed during nighttime conditions; however, the findings were not statistically significant perhaps due to the small sample size. For roadway lighting, a small increase in nighttime speed was indicated, which was not statistically significant. In contrast, the analysis indicates a statistically significant reduction in nighttime crash rates at treated sites relative to control locations. On lower-speed corridors, sidewalk implementation is associated with a slight reduction in operating speeds, suggesting a modest traffic-calming effect. In contrast, higher-speed corridors exhibit increases in operating speeds relative to comparison corridors after implementation, indicating that sidewalks alone do not substantially influence driver behavior in roadway environments that continue to support higher-speed travel. Sidewalk installation was associated with a reduction in fatal and injury crashes, suggesting potential safety benefits at the corridor level. Implementing a series of roundabouts is associated with a statistically significant reduction in operating speeds. For safety outcomes, treated corridors exhibit lower crash frequencies compared to control corridors; however, the estimated treatment effects for both total and pedestrian crashes are not statistically significant. The case study of the corridor cross-section reallocation found three of four zones had a speed reduction (business 3.2 mph, park 8.5 mph, and residential 4.3 mph) and fourth zone had a nominal speed increase of 0.4 mph, all statistically significant.

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INVESTIGATION OF SPEED COUNTERMEASURES FOR ARTERIAL STREETS

by

Kay Fitzpatrick, PhD, PE, PMP
Senior Research Engineer
Texas A&M Transportation Institute

Kara Kockelman, PhD, PE
Professor of Transportation Engineering
Department of Civil, Architectural, and Environmental Engineering
The University of Texas at Austin

Boniphace Kutela, PhD, PE, PMP
Associate Research Engineer
Texas A&M Transportation Institute

and

Keya Li
Graduate Student of Transportation Engineering
Department of Civil, Architectural, and Environmental Engineering
The University of Texas at Austin

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The Texas A&M University System
College Station, Texas 77843-313

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 Kay Fitzpatrick, PE #86762.

The United States Government and the State of Texas do not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the object of this report.

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CHAPTER 1: INTRODUCTION

BACKGROUND

Vehicle speed is among the key attributes that make a difference in the injury severity outcome of a crash. Lower speeds tend to come with lower crash severities, while deadly and disabling outcomes are much more likely at higher speeds (*1*). Considering that fact, traffic safety researchers and practitioners have developed and applied several countermeasures to lower vehicle speeds. The applications and effectiveness of such countermeasures vary greatly. Further, the extent of the documented evidence of the effectiveness of the countermeasures, the approaches used to evaluate such countermeasures, and the level of effectiveness differ significantly.

PROJECT OBJECTIVE

Texas Department of Transportation (TxDOT) Project 0-7220 investigated the effectiveness of arterial-focused speed management countermeasures for application across Texas. The research team considered roadway design, traffic control devices, vehicle design, operations, enforcement, and other countermeasure types across a range of settings for uncontrolled-access arterials under different traffic, road type/context, and land-use conditions. The research generated two documents:

- This research report, *Investigation of Speed Countermeasures for Arterial Streets*.
- *Speed Countermeasures for Arterial Streets Guide* (2).

The project started with reviewing documents to summarize the effectiveness of the countermeasures. Those countermeasures with the largest knowledge gaps were selected for additional investigation as part of this research project. This research report documents the findings from those evaluations. The guide presents a summary of the identified relationships of countermeasures with speed and crashes.

REPORT ORGANIZATION

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

- Chapter 2 reviews existing toolkits that include material on speed management countermeasures.
- Chapter 3 starts with an overview of RIR and roadway lighting countermeasures and then presents the evaluation conducted as part of this TxDOT project.
- Chapter 4 documents an evaluation of sidewalk corridors with a focus on their impact on operating speeds and associated safety implications.

- Chapter 5 documents an evaluation of roundabout corridors with a focus on their impact on operating speeds and associated safety implications.
- Chapter 6 documents the impact of corridor cross section reallocation on operating speed using a case study of William J. Bryan Parkway (FM 158) in Bryan, Texas.
- Chapter 7 summarizes researchers' findings and provides recommendations for future action.

CHAPTER 2: REVIEW OF EXISTING TOOLKITS

TOOLKITS

The assessment began by reviewing the recently updated TxDOT *Roadway Design Manual* (RDM) (*3*) along with documents from the Federal Highway Administration (FHWA), Institute of Transportation Engineers (ITE), National Cooperative Highway Research Program (NCHRP), and National Association of City Transportation Officials (NACTO). The following toolkits were also reviewed with findings included in this document, where relevant:

- TxDOT RDM (*3*). This document provides design guidelines for roadways in Texas.
- Commonwealth of Massachusetts, Massachusetts Department of Transportation (MassDOT) Safe Speeds website (*4*). The website describes roadway treatments, with "cut sheets" to "highlight quick facts and cost estimates, advantages and considerations, typical locations and experiences from around the Commonwealth".
- FHWA's *Speed Management Toolkit* (*5*). The toolkit provides information on key resources, like the Crash Modification Factors Clearinghouse, along with tables summarizing appropriate area and location types, documented effects, and details on crash count and speed reductions.
- FHWA's *Engineering Speed Management Countermeasures: A Desktop Reference of Potential Effectiveness in Reducing Speed*, updated 2014 (*6*). The document discusses speed management countermeasures and provides their potential effectiveness in reducing crashes and speed.
- ITE's *Traffic Calming Measures* (*7*). The website provides links to several traffic calming measures including vertical deflections, horizontal shifts, roadway narrowing, and closures.
- NCHRP Report 613 (*8*). The report summarizes findings in the published literature for several treatments.
- NACTO's Speed Reduction Mechanisms (*9*). The website provides links to several speed reduction countermeasures such as medians, speed humps, roundabouts, signal progression, street trees, on-street parking, and others.

The following websites were reviewed early in the project; however, they were modified during the project and currently do not include details about specific speed management treatments:

- City of Austin's *Austin Transportation and Public Works, Speed Management* (*10*).
- City of Dallas' *Traffic Calming* (*11*).

COUNTERMEASURES DISCUSSED IN THE TOOLKITS

Table 1 lists the countermeasures discussed in these key reference documents, while Table 2 lists the countermeasures available on websites. Some of these documents and websites call the same

treatment by different names. For example, the treatment that extends the sidewalk into a parking lane is called a curb extension in the TxDOT RDM and is called a corner extension or bulb-out in the ITE Traffic Calming website. Some of the countermeasures discussed in these reference documents are not of interest to this TxDOT project because the countermeasure may only be appropriate on roads with speed lower than what is relevant to this TxDOT project. TxDOT Project 0-7220 focuses on arterial speed management countermeasures. Therefore, several countermeasures with known impacts on operating speed that are only appropriate for local or residential streets, such as speed humps or street closure, are not included in this document or are provided only within a broader category. This document also does not include countermeasures that would prevent movement such as forced turn islands.

Table 1. List of Countermeasures Discussed in Key Reference Documents.

Reference	Countermeasures Discussed in the Reference
TxDOT RDM (*3*) 2024	• Linear pedestrian facilities ("sidewalks") (TxDOT RDM section 19.3). • Curb ramp design (TxDOT RDM section 19.4). • Driveway design (TxDOT RDM section 19.5). • Pedestrian refuge island (TxDOT RDM section 19.6.3.1). • Curb extension (TxDOT RDM section 19.6.3.2). • Truck aprons (TxDOT RDM section 19.6.3.3). • Raised crosswalk (TxDOT RDM section 19.6.3.4). • Lower speed limits (TxDOT RDM section 19.6.3.5). • Hardened centerlines (TxDOT RDM section 19.6.3.6). • Marked crosswalks (TxDOT RDM section 19.6.4.1). • Advance "stop here for pedestrians" sign and stop line (TxDOT RDM section 19.6.4.2). • In-street pedestrian crossing sign (TxDOT RDM section 19.6.4.5). • Rectangular rapid flashing beacon (TxDOT RDM section 19.6.4.6). • Signals (TxDOT RDM section 19.6.5.1). • Pedestrian hybrid beacon (PHB) (TxDOT RDM section 19.6.5.3). • Pedestrian signal faces (TxDOT RDM section 19.6.5.4). • Actuation (TxDOT RDM section 19.6.5.5). • Signal timing considerations (TxDOT RDM section 19.6.5.6). • Supportive signs (TxDOT RDM section 19.6.5.7). • Midblock pedestrian crossing (TxDOT RDM section 19.6.6). • Pedestrian facilities at alternative intersections (TxDOT RDM section 19.6.7). • Pedestrian treatments at railroad crossings (TxDOT RDM section 19.6.8). • Overcrossings and underpasses (TxDOT RDM section 19.7).
FHWA *Speed Management Toolkit* (*5*) 2015	• Road design and traffic-calming countermeasures. • Pavement treatments, markings, and signs. • Traffic speed management and operations measures. • Enforcement and publicity measures.
ITE *Traffic Calming Measures* (*7*) 2018	• Chicane. • Choker. • Closure. • Corner extension/bulb-out. • Diagonal diverter. • Lateral shift. • Median barrier/forced turn island. • Median island. • Mini roundabout.

Reference	Countermeasures Discussed in the Reference
	• On-street parking. • Raised intersection. • Realigned intersection. • Road diet. • Roundabout. • Speed cushion. • Speed hump. • Speed table. • Traffic circle.
NCHRP Report 613 (*8*) 2008	• Dynamic warning signs. • Transverse pavement markings. • Transverse rumble strips. • Longitudinal rumble strips. • Wider longitudinal pavement markings. • Roundabouts. • Approach curvature. • Splitter islands. • Speed tables and plateaus. • Reduced lane width. • Visible shoulder treatment. • Roadside design features.

Table 2. List of Countermeasures Discussed on Websites.

Reference	Countermeasures Discussed in the Reference
Safe Speeds website, MassDOT (*4*) 2024	• **Vertical deflection measures:** Speed humps, raised pedestrian crossings, or raised intersections that raise roadways for various lengths to slow drivers. • **Horizontal countermeasures:** Median islands, chicanes or curves, or curb extensions that change the horizontal cross section of a roadway. Chicanes are a series of curb extensions that alternate from one side of the street to the other, forming S-shaped curves that essentially narrow the roadway width and create an environment that slows down drivers. • **Mini roundabouts and neighborhood traffic circles:** Small-scale circular islands that act as a kind of intersection, offering yield-controlled entries and counterclockwise circulation in order to improve safety and reduce delays. • **Road diets and marking measures:** Narrowing or eliminating travel lanes to calm traffic speeds and increase safety of all roadway users, and strategies such as perceptual speed markings. Road diets do not automatically impact throughput or cause congestion, and safety is the preferred tradeoff. • **Speed transition zones, advisory, and feedback signage**: Slowing drivers traveling from a rural to an urban environment via signage, texture, and striping that communicate recommended speed information and feedback to drivers.
NACTO website (*9*) 2025	• Median. • Pinch point. • Chicane. • Lane shift. • Speed hump. • Two-way street. • Roundabout. • Diverter. • Signal progression. • Building lines. • Street trees. • On-street parking.

MASSDOT WEBSITE

An example of a cut sheet developed by MassDOT for the centerline hardening countermeasure is available at https://www.mass.gov/doc/speed-management-cut-sheets-centerline-hardening/download. The document is one page. The list of countermeasures with a MassDOT cut sheet includes crossing tables, raised intersections, speed cushions, speed humps, median crossing islands, neighborhood traffic circles, and road diets. The MassDOT website does include typical speed reduction values for select countermeasures.

The MassDOT website makes the following statement with regards to safe design for higher speed roadways:

> In some instances, a target speed may be high and cannot be reduced. In these instances, separation of users is needed to make it safe. Some examples of design features that can both protect all road users include: separated bike lanes, protected intersections, side paths, and safer crossings for pedestrians.

CITY OF AUSTIN

The City of Austin's *Austin Transportation Traffic Calming Toolkit* focuses on photos and descriptions of traffic-calming devices that are associated with lower-speed facilities (e.g., 35 mph and less). The toolkit provides data on where to use the devices in a table, reproduced in this document as Table 3. As of the date of this report, the toolkit is no longer available on the website.

Table 3. City of Austin Guidance for Traffic Calming Devices (*10*).

Devices	Roadway Characteristics	Speed Limit Compatibility	Vehicle Volume	Considerations
Type 1 Devices Horizontal Deflection	Typically installed on roadways over 36 ft wide	30 – 35 mph	Typically, under 10,000 vehicles a day	Horizontal deflection devices may require removal of parking opportunities. Devices such as curb extensions must take into consideration existing drainage.
Type II Devices Vertical Deflection	Typically installed on roadways under 36 ft where existing design speed of 30 mph may want to be reduced	25 – 30 mph	Typically, no more than 6,000 vehicles a day	Vehicles may park adjacent to devices. Devices are designed such that drainage is not impacted. Not recommended for steep grades.
Type III Devices Speed Monitoring and Awareness Tools	Any	Any	Any	Informational and driver feedback signage is self-enforcing

CITY OF DALLAS

The City of Dallas had a website that provided photos and descriptions (*11*). In addition to the traditional traffic-calming treatments, other treatments discussed included the following: signal light progression (timing), building lines, presence of street trees, and the materials and appearance of pavement. As of the date of this report, the toolkit is no longer available on the website.

CHAPTER 3: EVALUATION OF RIR AND STREET LIGHTING COUNTERMEASURES

INTRODUCTION

This chapter provides an overview of RIR and roadway lighting countermeasures. These two strategies are designed to enhance safety for all types of travelers during dark conditions. RIR focuses on signal control to manage vehicle speeds during nighttime and low-traffic periods, while roadway lighting improves visibility for all road users.

RIR

RIR is a traffic signal control strategy designed to encourage drivers to reduce speed when approaching signalized intersections (*12*). Under this treatment, traffic signals display red lights in all directions during late-night and early-morning hours when traffic volumes are low, instead of cycling through traditional green, yellow, and red phases. As drivers approach an intersection, they encounter a red signal, which makes them slow down instead of passing through the intersection at higher speeds. Once an approaching vehicle is detected by the signal system, the signal transitions from red to green, allowing the vehicle to proceed through the intersection. By requiring drivers to approach the intersection more cautiously and reducing the likelihood of uninterrupted green signals along a corridor, the RIR strategy helps discourage speeding and promote safer driving behavior during low-traffic periods. To date, only a handful of U.S. cities appear to have adopted this strategy as part of their road safety plans. They include Albuquerque, New Mexico (*13*); Los Angeles, California; Portland, Oregon; and Austin, Texas. Notably, Portland's Vision Zero Action Plan includes RIR as one of the traffic control strategies that can maximize signal operations for safety by slowing down traffic on wide corridors and protecting people (*12*).

However, limited research has quantified the effectiveness of this signal strategy in reducing vehicle speeds and crashes (*14*). Conner demonstrated that RIR operations significantly and safely reduced average speeds by 0.5 to 5 mph within 600 ft of approaching and departing a traffic signal in New York City, though the reduction in crashes was insignificant in locations with low crash rates (*14*).

In Texas, the City of Austin launched a pilot project along Cameron Road between East 51st Street and Mckie Drive (2.6 miles northwest of the state Capitol building) on May 31, 2023, by displaying red signals on all approaches until a vehicle is detected between midnight and 5 a.m. (*15*). This strategy stopped on October 13, 2025, due to multiple upcoming Traffic Control Plan projects and ongoing construction in this area.

Lighting

Roadway lighting is widely used as a safety countermeasure to reduce the incidence of nighttime crashes. The decision to install lighting and the appropriate lighting level are two key considerations in the design of lighting systems. The *FHWA Lighting Handbook* provides guidelines for policymakers and the design community when considering roadway or street lighting system (*16*). In Texas, roadway lighting can only be installed on eligible highways, as defined by state rules (*17*). City, county, and state engineers rely on the American Association of State Highway and Transportation Officials *Roadway Lighting Design Guide* (*18*) to justify the need for lighting.

Many past studies (e.g., *19*, *20*, *21*, *22*) have examined the relationship between roadway lighting, vehicle speeds, and road safety. For instance, Assum et al. compared 273,780 vehicle speeds three weeks before and four weeks after the installation of roadway lighting on a highway section in Norway and found that vehicle speeds rose 3 to 5 percent (as compared to speeds along unlighted, nearby control sections, at the same time, under the same weather and traffic load conditions) (*21*). In contrast, Reed and Woodard's look at the average speeds of 80 vehicles with highway lighting turned on and off along a 0.75-mile section of a state highway in Colorado found that lighting did not significantly change mean speeds (*22*).

While past studies report mixed speed effects, roadway lighting has been found to reduce crash counts and severities, especially pedestrian- and cyclist-related crashes (*23*, *24*, *25*, *26*). Elvik summarized 37 studies across 11 countries and concluded that adding road lighting reduces fatal crashes by 65 percent and injury crashes by 30 percent (*23*). Bruneau et al. (*25*) analyzed crash records from 1990 to 1998 for 213 roadway sections along 500 miles of four-lane rural freeways in Canada and found that continuous lighting was associated with 33 percent fewer total crashes than roads without lighting and 32 percent fewer than roads with interchange-only lighting. While roadway lighting may increase some drivers' speeds, it enhances visibility so much that it tends to improve nighttime safety for all road users. It not only makes it easier for drivers to see pedestrians but improves pedestrians' abilities to see their surroundings and detect trip hazards (*27*). Høye found that road lighting reduced fatal pedestrian crashes in darkness by 78 percent and injury crashes by 51 percent, based on 53 meta-analyses of research from around the globe (*28*). Using pedestrian crossing injury data, Siddiqui et al. constructed an ordered-probit model based on data from 1986 to 2003 and found that street lighting lowered the probability of fatal pedestrian injuries by 42 percent at midblock crossings and 54 percent at intersections, compared to dark conditions without street lighting (*29*). For cyclist injuries, Kim et al. analyzed police-reported crashes in North Carolina over five years and found that darkness without streetlights more than doubled the probability of fatal injuries in cyclist accidents compared to accidents occurring in daylight or darkness with streetlights (*30*). Li et al. studied 242 intersections across Virginia and estimated the benefit-cost ratio of lighting additions at unsignalized intersections to range from 2.6 to 5.6, and 2.8 to 7.9 at signalized intersections, assuming one injury nighttime

crash per year at such locations and no time savings included (*31*). Li et al. estimated that the total cost for a new pole, including installation, construction engineering inspection, annual electricity, and maintenance, is nearly $45,000, compared to $19,000 for extending an existing pole.

To enhance road safety, cities like Austin and Rowlett, Texas, have installed or upgraded lighting on roads that are prone to crashes (*32*, *33*). For example, in 2025, the City of Austin invested $1.7 million to improve street lighting across 14 intersections, focusing on areas with high crash frequencies and pedestrian activity. The following section describes study segments across Texas, with and without RIR and lighting treatments.

STUDY SITES

The research team collected detailed information on 108 Texas corridors (including location, roadway design attributes, traffic volumes, speeds, and crash counts by type) for further analysis. Sixty-three of these received no RIR or lighting treatment, two sites (both in Austin) began using a RIR strategy, and 43 sites or corridors added lighting across the state. For all lighting sites, the start of the before period was defined as January 1, 2018, and the end of the after period was defined as December 31, 2025. For all RIR sites, the end of the after period was defined as September 30, 2025. Thus, speed data and crash data were collected for seven years.

Treated Sites

Installation dates for each treated study site were obtained from local agency personnel and allowed the team to distinguish pre- and post-treatment periods. Sites with posted speed limits (PSLs) of 60 mph or higher and sites with unknown construction or installation dates were excluded from this study. As shown in Figure 1, most treatment installations occurred between 2021 and 2023, guaranteeing sufficient before and after durations. Table 4 lists all treated sites and their key characteristics, including the number of lanes, PSL, and annual average daily traffic (AADT), which are used to identify corresponding control sites. AADT values were extracted from the TxDOT Roadway Inventory dataset (*34*), while the number of lanes and PSL were obtained from Google Street View imagery. Notably, when a treatment is implemented along a continuous corridor, but roadway characteristics (like PSL) vary across segments, the corridor was divided into multiple segments. This ensures that each study site has consistent values for PSLs and the number of lanes. Because some treatments were installed between 2021 and 2023, traffic volumes during the study period may be affected by post-pandemic changes in travel patterns. However, the most recent available AADT values were used for treated–control site matching, so temporary traffic anomalies during the pandemic and immediate post-pandemic period are not expected to substantially affect the matching results. In addition, treated and corresponding control sites were evaluated over the same study periods, helping account for broader temporal changes in traffic conditions in the before-and-after analysis.

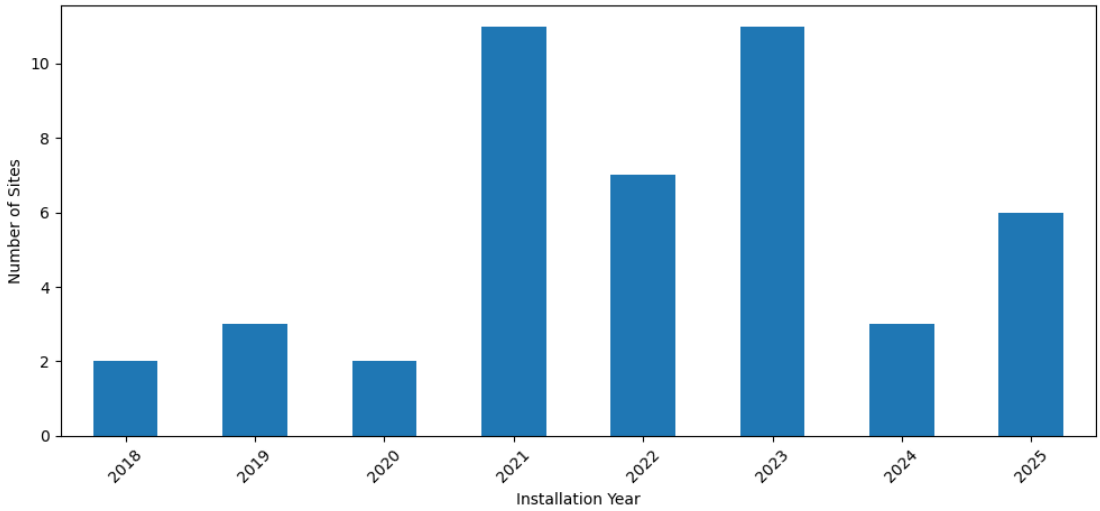


Figure 1. Installation Years for RIR and Lighting-Treated Study Sites.

Table 4. Summary of Treated Sites and Key Characteristics.

Site ID	End of Before Period	Start of After Period	Location	Length (Miles)	Install Year	No. of Lanes	PSL	AADT	No. of Signals
RIR-1	5/31/2023	6/1/2023	Cameron Rd., Austin	1.17	2023	4	30	14,699	8
RIR-2	5/31/2023	6/1/2023	Cameron Rd., Austin	0.63	2023	6	35	27,478	3
Light-1	6/15/2022	5/21/2023	S. 1st St., Abilene	1.05	2023	4	40	15,935	3
Light-2	8/15/2024	12/15/2024	Redwater Blvd., Maud	0.65	2024	2	55	5,049	1
Light-3	5/9/2020	12/15/2021	Hwy. 90, Beaumont	1.14	2021	6	45	26,671	2
Light-4	5/9/2020	12/15/2021	Hwy. 90, Beaumont	2.17	2021	6	45	26,671	4
Light-5	2/20/2020	4/15/2021	J. M. Lindsay Blvd., Lindsay	0.37	2021	4	55	11,386	0
Light-6	2/20/2020	4/15/2021	J. M. Lindsay Blvd., Lindsay	0.39	2021	4	50	12,922	0
Light-7	5/15/2022	8/15/2022	TX 331/Southeast Dr., Lubbock	0.40	2022	2	55	4,757	0
Light-8	5/28/2018	11/28/2018	US 84/Avenue Q, Lubbock	0.47	2018	6	35	19,791	1
Light-9	5/28/2018	11/28/2018	US 84/Avenue Q, Lubbock	1.86	2018	6	45	14,565	6
Light-10	9/15/2022	6/15/2023	US 80/W Main St, Hallsville	0.50	2023	4	50	16,614	2
Light-11	9/15/2022	6/15/2023	US 80/W Main St, Hallsville	0.50	2023	4	50	16,614	1
Light-12	2/19/2019	3/15/2021	US 181, Falls City	0.66	2021	2	55	7,133	0
Light-13	12/29/2019	10/7/2021	W. University Dr., McKinney	0.49	2021	6	40	51,482	3
Light-14	6/29/2022	11/20/2022	US 54 BUS (Dyer St.), El Paso	2.92	2022	6	40	21,700	12
Light-15	6/29/2022	11/20/2022	US 54 BUS (Dyer St.), El Paso	1.15	2022	6	45	23,236	6
Light-16	6/29/2022	11/20/2022	US 54 BUS (Dyer St.), El Paso	0.65	2022	6	50	19,948	3
Light-17	1/31/2020	3/23/2022	Hwy. 35S, Rockport	0.30	2022	2	55	9,160	0
Light-18	9/15/2022	8/15/2023	TX 49 (Broadnax St.), Daingerfield	0.50	2023	4	55	9,942	0
Light-19	5/15/2024	2/23/2025	N. Veterans Blvd., Eagle Pass	2.20	2025	4	45	27,650	2
Light-20	12/15/2018	5/15/2019	Hwy. 77, Riviera	0.38	2019	4	45	13,022	1
Light-21	1/31/2020	12/15/2021	US 77, Sinton	0.30	2021	2	40	5,061	0
Light-22	9/15/2022	7/15/2023	TX 154 (W Tyler St.), Gilmer	0.70	2023	2	45	10,311	2
Light-23	10/9/2023	3/16/2025	Lloyd Bentsen Hwy., Laredo	1.10	2025	6	50	41,796	3
Light-24	12/6/2019	5/15/2021	FM 88, Edcouch	0.77	2021	2	50	7,386	1
Light-25	12/6/2019	4/15/2021	Texas Blvd., Weslaco	0.56	2021	4	55	400	1
Light-26	5/13/2019	10/15/2019	FM 439 (S. Fort Hood St.), Killeen	0.93	2019	4	40	28,683	5
Light-27	12/6/2019	10/28/2021	FM 490 (Jesus Flores Rd.), Edcouch	0.47	2021	2	55	939	0
Light-28	6/15/2024	3/13/2025	McNeil Dr., Austin	1.1	2025	4	40	21,451	5
Light-29	6/15/2024	3/13/2025	McNeil Dr., Austin	0.63	2025	4	40	19,591	3
Light-30	9/15/2023	3/15/2025	Winters Mill Pkwy., Wimberley	0.25	2025	2	45	3,050	1
Light-31	12/15/2024	3/18/2025	Industrial Blvd., McKinney	1.04	2025	4	40	25,674	0

Site ID	End of Before Period	Start of After Period	Location	Length (Miles)	Install Year	No. of Lanes	PSL	AADT	No. of Signals
Light-32	10/15/2019	2/6/2021	San Jose Ranch Rd., San Benito	0.36	2021	2	55	7,543	1
Light-33	3/15/2016	11/22/2019	E. Martin Luther King Jr. Blvd., Austin	0.49	2019	4	45	40,290	1
Light-34	8/31/2023	2/17/2024	FM 1464, Richmond	3.22	2024	4	50	18,896	5
Light-35	10/15/2019	11/10/2024	FM 1479 (Rangerville Rd.), San Benito	0.45	2024	2	55	1,905	0
Light-36	1/18/2019	1/31/2020	FM 1069 (Main St.), Ingleside	0.28	2020	4	45	11,175	0
Light-37	1/15/2022	3/23/2022	FM 24, Robstown	0.50	2022	2	45	2,039	0
Light-38	1/15/2020	10/5/2020	Hwy. 6, Houston	2.92	2020	6	55	55,061	2
Light-39	12/15/2021	6/2/2023	S. TX 6, Houston	0.36	2023	6	45	51,912	2
Light-40	12/15/2021	6/2/2023	S. TX 6, Houston	0.78	2023	6	45	57,048	2
Light-41	4/6/2022	6/2/2023	S. TX 6, Houston	1.17	2023	6	45	56,337	2
Light-42	4/6/2022	6/2/2023	S. TX 6, Houston	1.82	2023	6	50	51,595	5
Light-43	4/15/2021	3/23/2022	TX 361 (W. Avenue G), Port Aransas	0.30	2022	2	35	9,136	0

Unlike RIR, which operates during fixed hours (e.g., midnight to 5 a.m. along Cameron Road in Austin), lighting treatments are active only during nighttime periods. Sunrise and sunset times were determined for study sites based on each site's geographic coordinates (latitude and longitude) and using the Python language's Astral package for each day and year. For instance, at the RIR-1 site, the segment centroid coordinates are 30.314884 and −97.702756, so sunrise on January 1, 2018, was at 07:27:42 CST, and sunset was at 17:41:23 CST. Therefore, the lighting treatment was effective or active only during that 10.24-hour period.

Control Sites

For each treated site, control sites were selected based on four criteria:

- Both sites have the same number of lanes.
- Both sites have the same PSLs.
- The AADT values of both sites are within a 20 percent range.
- The segment length is at least 0.25 miles.

Table 5 lists six control sites for RIR and 57 sites for lighting. Figure 2 summarizes key characteristics of all sites in this section (RIR sites are combined with lighting sites because there are only eight sites). Most segments have four or six lanes, and median types vary, with two-way left-turn lanes (TWLTL) and raised medians being the most common. Additionally, most sites do not have bike lanes or sidewalks, and on-street parking is also uncommon. Regarding roadway features, centerlines and edge lines are present on most segments, while curb presence varies but is generally common.

Table 5. Summary of Control Sites and Key Characteristics.

Site ID	Treated Site ID	End of Before Period	Start of After Period	Location	Length (miles)	No. of Lanes	PSL	AADT	No. of Signals
1	RIR-1	5/31/2023	6/1/2023	Enfield Rd., Austin	0.39	4	30	13,739	3
2	RIR-1	5/31/2023	6/1/2023	W. 45th St., Austin	0.31	4	30	12,840	2
3	RIR-1	5/31/2023	6/1/2023	S. Congress Ave., Austin	0.52	4	30	12,437	5
4	RIR-2	5/31/2023	6/1/2023	Cameron Rd., Austin	0.32	6	35	27,478	2
5	RIR-2	5/31/2023	6/1/2023	E. Riverside Dr., Austin	0.92	6	35	28,908	5
6	RIR-2	5/31/2023	6/1/2023	Bellaire Blvd., Austin	3.24	6	35	26,984	12
7	Light-1	6/15/2022	5/21/2023	S. 1st St., Abilene	0.50	4	40	15,935	1
8	Light-1	6/15/2022	5/21/2023	TX 36 (E. South 11th St.), Abilene	0.93	4	40	15,306	2
9	Light-1	6/15/2022	5/21/2023	Santa Fe Dr., Weatherford	1.23	4	40	16,045	4
10	Light-2	8/15/2024	12/15/2024	US 67, Maud	1.31	2	55	4,039	0
11	Light-2	8/15/2024	12/15/2024	N. Kings Hwy., Texarkana	2.78	2	55	5,114	1
12	Light-2	8/15/2024	12/15/2024	W. New Boston Rd., Hooks	7.64	2	55	5,711	2
13	Light-3	5/9/2020	12/15/2021	N. Twin City Hwy., Groves	0.77	6	50	21,082	2
14	Light-3	5/9/2020	12/15/2021	I-35 (Telephone Rd.), Houston	1.71	6	50	27,829	4
15	Light-3	5/9/2020	12/15/2021	TX 281 Loop, Longview	2.00	6	50	27,948	3
16	Light-4	5/9/2020	12/15/2021	M. L. King Jr. Pkwy., Beaumont	0.27	6	45	31,409	6
17	Light-4	5/9/2020	12/15/2021	Aldine Bender Rd., Houston	0.62	6	45	22,462	1
18	Light-4	5/9/2020	12/15/2021	TX 421 (Bandera Rd.), San Antonio	0.85	6	45	24,144	3
19	Light-5	2/20/2020	4/15/2021	J. M. Lindsay Blvd, Lindsay	1.79	4	55	12,922	1
20	Light-5	2/20/2020	4/15/2021	US 77 N. Elm St., Denton	0.82	4	55	9,985	1
21	Light-5	2/20/2020	4/15/2021	US 80 (E. Moore Ave.), Terrell	0.43	4	55	11,623	0
22	Light-6	2/20/2020	4/15/2021	N. US 377, Roanoke	0.43	4	50	13,659	2
23	Light-6	2/20/2020	4/15/2021	Parker Rd., Lucas	2.53	4	50	14,441	3
24	Light-6	2/20/2020	4/15/2021	Hillcrest Dr. N., Sulphur Springs	0.62	4	50	9,620	2
25	Light-7	5/15/2022	8/15/2022	Southeast Dr., Lubbock	1.26	2	55	4,757	0
26	Light-7	5/15/2022	8/15/2022	E. County Rd. 6900, Lubbock	0.62	2	55	4,342	0
27	Light-7	5/15/2022	8/15/2022	N. County Rd. 1800, Lubbock	0.40	2	55	3,383	0
28	Light-8	5/28/2018	11/28/2018	US 84/Avenue Q, Lubbock	0.64	6	35	21,952	6
29	Light-9	5/28/2018	11/28/2018	US 84/Avenue Q, Lubbock	0.60	6	45	14,565	2
30	Light-10	9/15/2022	6/15/2023	W. US 80, White Oak	0.96	4	50	17,492	2
31	Light-11	9/15/2022	6/15/2023	W US 80, Hallsville	0.67	4	50	15,898	0
32	Light-12	2/19/2019	3/15/2021	US 181/ N. Front St., Falls City	0.43	2	55	7,255	0
33	Light-13	12/29/2019	10/7/2021	W. University Dr., McKinney	0.96	6	40	48,573	3
34	Light-14	6/29/2022	11/20/2022	Montana Ave., El Paso	0.84	6	40	25,000	3
35	Light-15	6/29/2022	11/20/2022	Airport Rd., El Paso	0.91	6	45	25,162	3

Site ID	Treated Site ID	End of Before Period	Start of After Period	Location	Length (miles)	No. of Lanes	PSL	AADT	No. of Signals
36	Light-16	6/29/2022	11/20/2022	Global Reach Dr., El Paso	0.62	6	50	22,000	2
37	Light-17	1/31/2020	3/23/2022	TX 35 BUS, Aransas Pass	0.68	2	55	7,791	0
38	Light-18	9/15/2022	8/15/2023	US 259, Daingerfield	0.30	4	55	7,914	0
39	Light-19	5/15/2024	2/23/2025	US 277, Eagle Pass	1.00	4	45	28,140	2
40	Light-20	12/15/2018	5/15/2019	E. Rice St., Falfurrias	0.47	4	45	10,572	0
41	Light-21	1/31/2020	12/15/2021	N. Front St., Mathis	0.33	2	40	3,830	0
42	Light-22	9/15/2022	7/15/2023	S. Main St., Quitman	0.29	2	45	10,710	0
43	Light-23	10/9/2023	3/16/2025	E. Whitestone Blvd., Cedar Park	0.49	6	50	41,796	2
44	Light-24	12/6/2019	5/15/2021	N. Alamo Rd., Edinburg	0.55	2	50	7,531	2
45	Light-25	12/6/2019	4/15/2021	Texas Blvd., Weslaco	0.30	4	55	400	1
46	Light-26	5/13/2019	10/15/2019	Elms Rd., Killeen	1.14	4	40	22,521	2
47	Light-27	12/6/2019	10/28/2021	FM 1015, Edcouch	1.00	2	55	1,046	0
48	Light-28	6/15/2024	3/13/2025	Anderson Mill Rd., Austin	0.96	4	40	22,782	4
49	Light-29	6/15/2024	3/13/2025	Anderson Mill Rd., Austin	0.72	4	40	22,007	1
50	Light-30	9/15/2023	3/15/2025	Winters Mill Pkwy., Wimberley	0.32	2	45	3,050	1
51	Light-31	12/15/2024	3/18/2025	Eldorado Pkwy., McKinney	1.36	4	40	25,486	3
52	Light-32	10/15/2019	2/6/2021	FM 510 (Line M Rd.), San Benito	1.70	2	55	5,905	1
53	Light-33	3/15/2016	11/22/2019	Bee Caves Rd., Austin	0.68	4	45	30,962	1
54	Light-34	8/31/2023	2/17/2024	FM 521 (Almeda Rd.), Houston	2.39	4	50	19,453	2
55	Light-35	10/15/2019	11/10/2024	FM 800 (Jim Bowie Rd.), Harlingen	0.36	2	55	1,869	0
56	Light-36	1/18/2019	1/31/2020	Buddy Ganem Dr., Portland	0.92	4	45	11,802	2
57	Light-37	1/15/2022	3/23/2022	FM 24, Robstown	0.62	2	45	2,039	0
58	Light-38	1/15/2020	10/5/2020	S. TX 6, Sugar Land	2.12	6	55	51,595	3
59	Light-39	12/15/2021	6/2/2023	S. TX 6, Houston	0.38	6	45	57,048	1
60	Light-40	12/15/2021	6/2/2023	S. TX 6, Houston	0.25	6	45	57,048	1
61	Light-41	4/6/2022	6/2/2023	Texas Ave. S., College Station	1.24	6	45	51,135	6
62	Light-42	4/6/2022	6/2/2023	Hwy. 6, Missouri City	0.98	6	50	61,665	3
63	Light-43	4/15/2021	3/23/2022	Laredo St., Corpus Christi	0.37	2	35	8,688	2

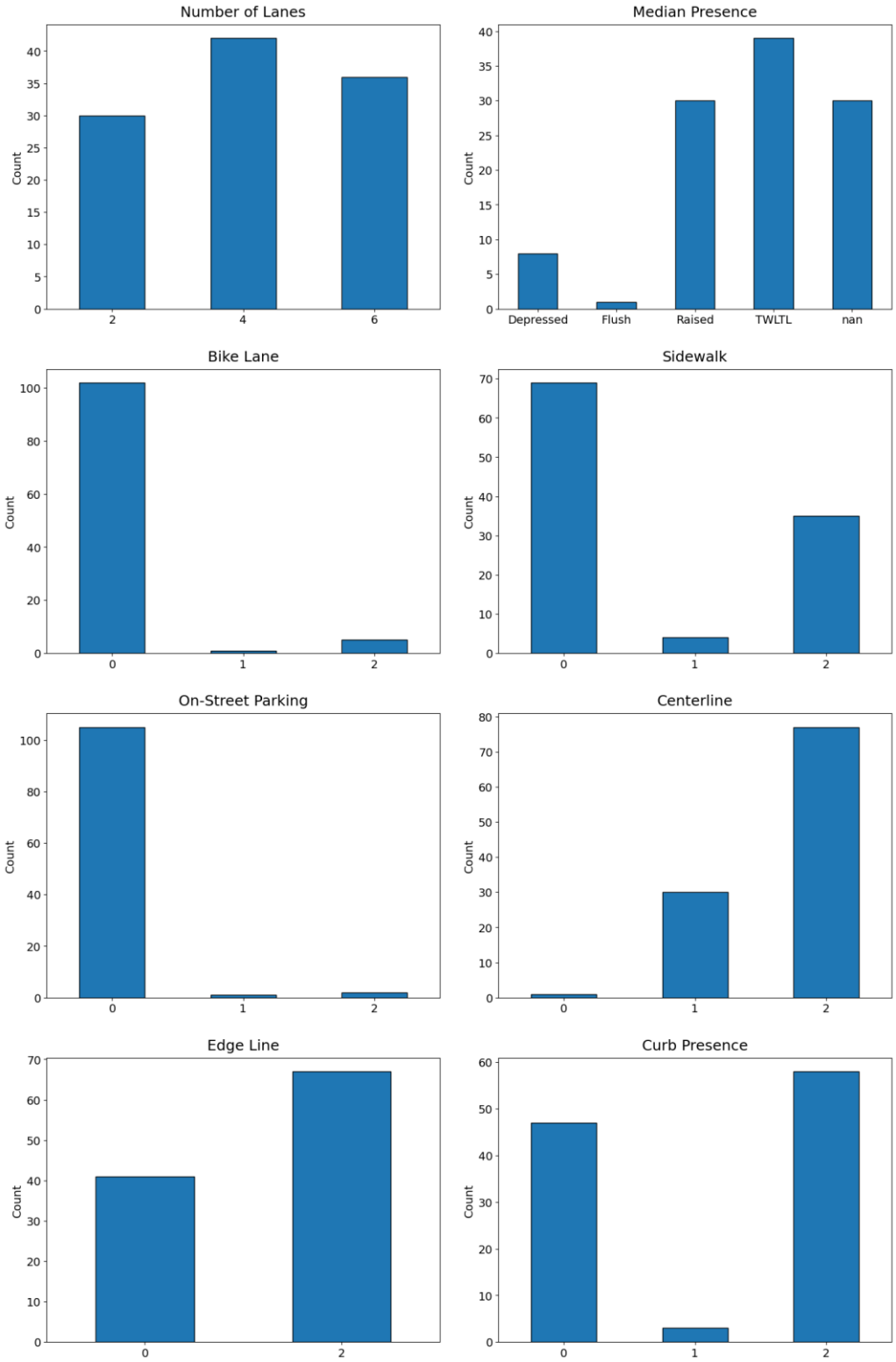


Figure 2. Key Characteristics of All Sites for RIR and Lighting.

SPEED MODEL

This section presents the analysis of before-and-after vehicle speeds at both treated and comparison sites to evaluate the operational effectiveness of RIR and lighting countermeasures. The analysis includes a description of the INRIX speed data, the statistical model specification, control variables, and key results.

Speed Data

Vehicle speed data used in this analysis were obtained from the Regional Integrated Transportation Information System (RITIS) Probe Data Analytics tool under TxDOT's license, using INRIX XD segments. XD segments are an INRIX proprietary road segmentation system that divides roadways at intersections and other key geometric points, allowing for accurate measurements of traffic conditions along different roadway segments (*35*). For each road segment, average speeds were computed as the harmonic mean of all observed speeds during the selected time period. The dataset includes both treated sites, where either RIR or lighting countermeasures were implemented, and control sites selected for comparison. The before period for all sites began on January 1, 2018, at 12:00 a.m., and the after period extended through December 31, 2025, at 11:59 p.m.

Table 6 presents an overview of the speed data used in the study. The final speed dataset during the study period for RIR includes 5.1 million hourly segment-level speeds for two treated sites and six control sites across the before and after periods. For lighting, the final dataset includes 30.8 million hourly segment-level observations for 43 treated sites and 57 control sites. Given the large size of the dataset, and because vehicle counts and speeds do not differ significantly across the same combinations of day of the week, month, and year (e.g., the first Monday in January 2018 versus the second Monday in January 2018), the data were aggregated at the segment level within each unique combination of these temporal dimensions. This results in a final dataset of 7.1 million observations for 100 sites for lighting and 1.2 million observations for eight sites for RIR.

Table 6. Example of RITIS Hourly Segment-Level Speed Data.

Xd_id	Measurement_tstamp	Speed	Historical Average Speed
485540634	1/1/2018 12:00:00	23	23
485540634	1/1/2018 1:00:00	22.74	23
485540634	1/1/2018 2:00:00	23	23
485540634	1/1/2018 3:00:00	23	23
…	…	…	…
485540634	1/1/2018 15:00:00	15.86	21
485540634	1/1/2018 16:00:00	21.77	21.74

Model Specification

To estimate the speed effects of RIR and lighting treatments, a generalized least squares regression model with site-level random effects was developed. The model quantifies changes in average speeds at treated sites relative to corresponding control sites, controlling for roadway characteristics, vulnerable road user (VRU) exposure, land use, weather conditions, and temporal patterns.

The dependent variable in the model is the average vehicle speed observed at each segment during each hourly interval aggregated by day of the week during the same month and year. Control variables include indicator variables representing the active operation of RIR and lighting treatments. Specifically, the RIR treatment was separated into two periods: from 12 a.m. to 2 a.m. (bar closing hours) and from 2 a.m. to 5 a.m. The lighting treatment was divided into three periods: from sunset to 11 p.m., from 11 p.m. to 2 a.m., and from 2 a.m. to sunrise. This temporal segmentation allows the model to capture potential differences in vehicle speeds during late-night activity and after bar closing hours, when driving risks may change. The next section discusses other control variables, including roadway characteristics, land use, and other factors. Time fixed effects capture common temporal factors affecting all sites, including year, month, day, and hour.

The general specification of the model is as follows:

For RIR,

$$Speed_{i,t} = \beta_0 + \beta_1 RIR_{12-2,i,t} + \beta_2 RIR_{2-5,i,t} + X_{i,t}\alpha + Z_i\beta + \gamma_t + u_i + \epsilon_{i,t}$$

For lighting,

$$Speed_{i,t} = \beta_0 + \beta_1 Lighting_{sunset-11,i,t} + \beta_2 Lighting_{11-2,i,t} + \beta_2 Lighting_{2-sunrise,i,t} + X_{i,t}\alpha + Z_i\beta + \gamma_t + u_t + \epsilon_{i,t}$$

Where:

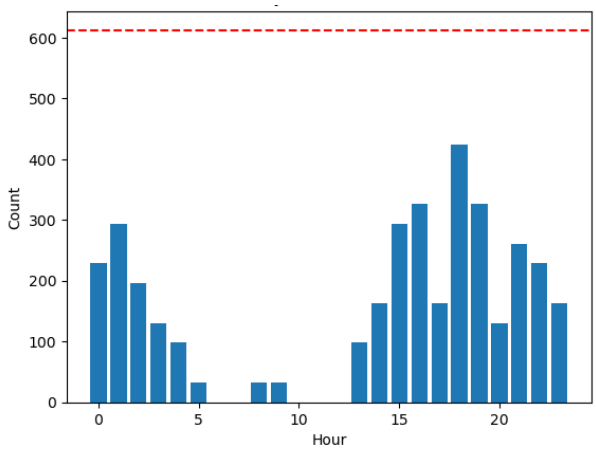
- $Speed_{i,t}$ = the hourly average speeds at segment i and time t.
- $RIR_{12-2,i,t}$, $RIR_{2-5,i,t}$, $Lighting_{sunset-11,i,t}$, $Lighting_{11-2,i,t}$, and $Lighting_{2-sunrise,i,t}$ are indicators representing the active operation of treatments during specific time periods.
- $X_{i,t}$ = vector of time-varying covariates (e.g., weather conditions, traffic flow, etc.).
- Z_i = vector of time-invariant covariates (e.g., roadway characteristics, land use, etc.).
- γ_t = time fixed effects.
- u_i = site-level random effect.
- $\epsilon_{i,t}$ = error term.

Because the dependent variable is hourly speed, the variability of observed speeds differs across hours of the day, days of the week, and road segments, leading to possible heteroskedasticity across observations. To address this issue and the possible correlation between the same treated-control pair, standard errors are clustered at the treated-control group level.

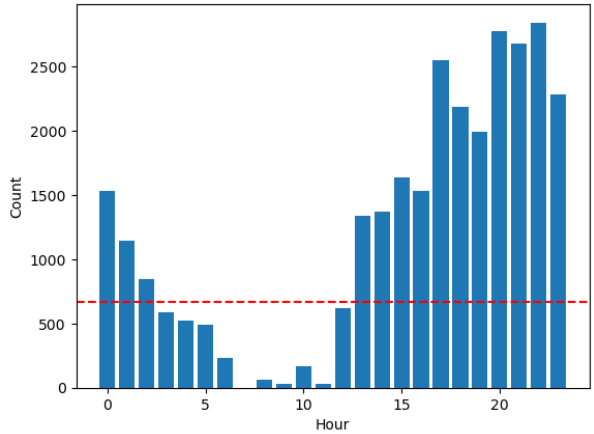
Control Variables

In addition to the treatment indicators, this model includes several control variables that capture roadway characteristics, traffic exposure, VRU exposure, land use, weather, and other factors that may affect vehicle speeds. Pedestrian and cyclist activity was represented using walk-miles traveled (WMT) and bike-miles traveled (BMT) densities, derived from tract-level estimates developed by Li and Kockelman (*36*). For segments that traverse multiple tracts, WMT and BMT values were apportioned based on the intersection area. Land use variables, such as vehicle ownership, population density, and job density for the block group to each road segment, were extracted from the U.S. Environmental Protection Agency (EPA) Smart Location Database (*37*). These values were calculated by constructing a 0.25-mile buffer around each segment and apportioning them accordingly. Weather can have a significant influence on vehicle speeds; therefore, the Analysis of Record for Calibration (AORC) dataset was used to obtain weather information by location and time (*38*). The AORC dataset provides gridded near-surface weather data with a spatial resolution of 800 meters (approximately 0.5 miles) and an hourly temporal resolution. Additional physical roadway and infrastructure characteristics were extracted from Google Street View imagery for periods before and after treatment.

The TxDOT Roadway Inventory dataset provides AADT values for each segment (*34*). However, these values remain constant throughout the day, which is unrealistic given that early-morning traffic flow is typically much lower. To address this, INRIX probe data were used here to distribute AADT values into hourly real-time traffic flows. INRIX's 2024 trip data provides 2 to 4 million vehicle trajectories per day in Texas (which represents 3 to 4 percent of all trips), along with trip distance and duration (between engine on and off points), trip start and end times, and detailed trajectory tracking by segment ID. Due to the large volume of data, this study used a one-month sample from November 1 to 30, 2024, which is the most recent period available under the TxDOT license. The total number of vehicles passing through each segment was counted hourly. Figure 3 illustrates the hourly vehicle count distributions for the RIR-1 and Light-1 sites. This figure shows distinct fluctuations during early morning and peak periods (the dotted red line represents the average hourly traffic volume estimated by dividing the AADT values by 24). Therefore, hourly traffic flow was scaled based on the ratio of hourly counts to the total sample, ensuring that the sum of the hourly flows equals the provided estimated AADT values.



a. RIR-1 site



b. Light-1 site

Figure 3. Hourly Vehicle Counts for Two Sites.

Table 7 and Table 8 presents a detailed description and summary statistics of all variables considered in the regression model and their corresponding data sources for lighting and RIR models. Notably, some variables are not included in the RIR model. This is because the RIR treatment involved only two treated sites and six control sites, and including highly correlated variables resulted in multicollinearity and a non–full-rank matrix. Consequently, variables that are nearly constant across these sites (e.g., the presence of edge lines or curbs) or highly correlated with other covariates (e.g., BMT per square mile, which is highly correlated with WMT per square mile, and population density, which is highly correlated with household density) were removed. Before model estimation, correlations among the initially collected predictors were examined to identify possible multicollinearity. Variables with absolute correlation coefficients greater than 0.8 were removed from the subsequent model specifications. The next section presents final model results.

Table 7. Variable Definition and Summary Statistics Used in the Speed Model (Lighting).

Variables	Description	Mean	Median	SD	Min	Max
Avg Speed	Average hourly speed observed at each segment aggregated by day of the week during the same month and year	38.7	37.9	10.1	1.37	84
Treat_Light_p1	Indicators for active lighting treatment from sunset to 11 p.m.	0.10	0	0.30	0	1
Treat_Light_p2	Indicators for active lighting treatment from 11 p.m. to 2 a.m.	0.03	0	0.16	0	1
Treat_Light_p3	Indicators for active lighting treatment from 2 a.m. to sunrise	0.09	0	0.29	0	1
Weekend	1 if the observation is during weekends; 0 otherwise	0.29	0	0.45	0	1
WMT/sqmi	Daily WMT per square mile	1.10	0.78	0.45	0	1
% 1-car HH	Percent of households with 1 car in block groups within 0.25-mile buffer	0.11	0.08	0.10	0.02	0.53
% 2+ car HH	Percent of households with 2+ cars in block groups within 0.25-mile buffer	0.20	0.17	0.13	0.03	0.58
Walk score	Walkability index score of block groups within 0.25-mile buffer	9.10	8.54	3.98	2.59	29.0
Job density	Jobs per acre in block groups within 0.25-mile buffer	1.85	1.01	2.71	2e-03	12.9
Network density	Total road network density per square mile in block groups within 0.25-mile buffer	12.1	12.2	7.39	1.23	28.6
Precipitation	Hourly total precipitation in millimeters	2.32	0.42	5.56	0	284
% Moisture	Percentage of moisture in the air measured 2 meters above the ground surface	0.65	0.68	0.22	0.04	1
Wind speed	Wind speed at 10 meters above ground (meter/second)	4.08	3.92	1.30	0.66	11.4
Air temperature	Air temperature at 2 meters above ground (°F)	68.2	69.3	16.3	21.2	112
Lane Width	Lane width (ft)	11.7	12	0.81	10	20
# Lanes each way	Number of lanes per direction	2.23	2	0.78	1	3
TWLTL presence	1 if the segment has a TWLTL median; 0 otherwise	0.31	0	0.46	0	1
Raised presence	1 if the segment has a raised median; 0 otherwise	0.39	0	0.49	0	1
Depressed presence	1 if the segment has a depressed median; 0 otherwise	0.06	0	0.24	0	1
Bike lane presence	1 if the segment has a separate bike lane; 0 otherwise	0.04	0	0.21	0	1
Sidewalk presence	1 if the segment has a sidewalk; 0 otherwise	0.41	0	0.49	0	1
Sidewalk * buffer	Interaction between sidewalk presence and the presence of buffer zone	0.22	0	0.41	0	1
Flow/lane	Traffic flow during that hour per lane (vehicle/lane)	200	287	175	0.41	752
On-street parking	1 if the segment has on-street parking; 0 otherwise	0.04	0	0.18	0	1
Centerline presence	1 if the segment has centerlines; 0 otherwise	1.00	1	0.06	0	1
Edge lines presence	1 if the segment has edge lines; 0 otherwise	0.54	1	0.50	0	1
Curb presence	1 if the segment has a curb; 0 otherwise	0.62	1	0.48	0	1
Tangent presence	1 if the segment has a tangent; 0 otherwise	0.62	1	0.48	0	1
PSL	Posted speed limit of the road segment (mph)	46.9	45	6.04	40	55

Note: Min = minimum, Max = maximum.

Source: Speed data are from INRIX XD dataset. WMT estimates are from Li and Kockelman (*36*). Other land-use data are from the U.S. EPA Smart Location Database (*37*). Weather attributes are from the AORC dataset (*38*). Road geometry information is from Google Street View imagery. Flow data are from TxDOT's Roadway Inventory Dataset and INRIX probe data (*34*)

Table 8. Variable Definition and Summary Statistics Used in the Speed Model (RIR).

Variables	Description	Mean	Median	Std. Dev.	Min	Max
Avg Speed	Average hourly speed observed at each segment aggregated by day of the week during the same month and year	23.9	24.0	4.44	3.44	53.4
Treat_RIR_p1	Indicators for active RIR treatment from 12 a.m. to 2 a.m.	0.01	0	0.09	0	1
Treat_RIR_p2	Indicators for active RIR treatment from 2 a.m. to 5 a.m.	0.01	0	0.11	0	1
Weekend	1 if the observation is during weekends; 0 otherwise	0.29	0	0.45	0	1
WMT/sqmi	Daily WMT per square mile	5.64	5.34	1.09	3.52	7.35
% 1-car HH	Percent of households with 1 car in block groups within 0.25-mile buffer	0.07	0.06	0.05	0.02	0.18
% 2+ car HH	Percent of households with 2+ cars in block groups within 0.25-mile buffer	0.07	0.05	0.03	0.04	0.15
Walk score	Walkability index score of block groups within 0.25-mile buffer	15.0	14.6	1.15	12.1	17.0
Job density	Jobs per acre in block groups within 0.25-mile buffer	12.4	7.35	6.70	5.28	26.2
Network density	Total road network density per square mile in block groups within 0.25-mile buffer	25.6	24.7	3.07	15.1	28.9
Precipitation	Hourly total precipitation in millimeters	2.34	0.59	4.77	0	146
% Moisture	Percentage of moisture in the air measured 2 meters above the ground surface	0.69	0.73	0.20	0.18	1
Wind speed	Wind speed at 10 meters above ground (meter/second)	4.09	3.95	1.17	0.90	9.77
Air temperature	Air temperature at 2 meters above ground (°F)	70.4	71.7	15.4	29.9	109
Lane Width	Lane width (ft)	10.6	11	0.49	10	11
# Lanes each way	Number of lanes per direction	2.57	3	0.49	2	3
TWLTL presence	1 if the segment has a TWLTL median; 0 otherwise	0.35	0	0.48	0	1
Raised presence	1 if the segment has a raised median; 0 otherwise	0.57	1	0.49	0	1
Depressed presence	1 if the segment has a depressed median; 0 otherwise	0	0	0	0	0
Bike lane presence	1 if the segment has a separate bike lane; 0 otherwise	0.35	0	0.48	0	1
Sidewalk presence	1 if the segment has a sidewalk; 0 otherwise	1	1	0	1	1
Sidewalk * buffer	Interaction between sidewalk presence and the presence of buffer zone	1	1	0	1	1
Flow/lane	Traffic flow during that hour per lane (vehicle/lane)	171	190	116	12.9	353
On-street parking	1 if the segment has on-street parking; 0 otherwise	0.11	0	0.31	0	1
Centerline presence	1 if the segment has centerlines; 0 otherwise	1	1	0	1	1
Edge lines presence	1 if the segment has edge lines; 0 otherwise	0.35	0	0.48	0	1
Curb presence	1 if the segment has a curb; 0 otherwise	1	1	0	1	1
Tangent presence	1 if the segment has a tangent; 0 otherwise	0.77	1	0.42	0	1
PSL	Posted speed limit of the road segment (mph)	32.9	35	2.47	30	35

Source: Speed data are from INRIX XD dataset. WMT estimates are from Li and Kockelman (*36*). Other land-use data are from the U.S. EPA Smart Location Database (*37*). Weather attributes are from the AORC dataset (*38*). Road geometry information is from Google Street View imagery. Flow data are from TxDOT's Roadway Inventory Dataset and INRIX probe data (*34*)

Results

Figure 4and Figure 5 illustrate the distribution of site-level average speed during the before and after period for the 100-site lighting study and eight-site RIR pilot, respectively. For the lighting treatment, both the treated and control groups exhibited a slight upward trend in average speed; however, the magnitude of this increase was smaller at the treated sites. Furthermore, both groups demonstrated a negligible change in speed variance across the two periods. These results indicate that while lighting installation may not result in an absolute decrease in travel speeds, it effectively moderates speed growth, maintaining vehicle speeds within a controlled and stable range relative to the broader city-wide increase. Conversely, for the RIR pilot, the treated sites experienced a more pronounced upward shift in average speed during the after period compared to the before baseline, with the median speed rising from approximately 23.5 to 25.5 mph. In contrast, the control sites remained relatively stable, with both the median speed and interquartile range showing negligible change between periods. The observation that RIR implementation coincided with a speed increase, rather than a decrease, is likely due to the limited sample size of the pilot, which consisted of only two consecutive treated segments. Consequently, this increase may be biased by site-specific external factors or unique roadway characteristics rather than being a representative effect of the RIR treatment itself.

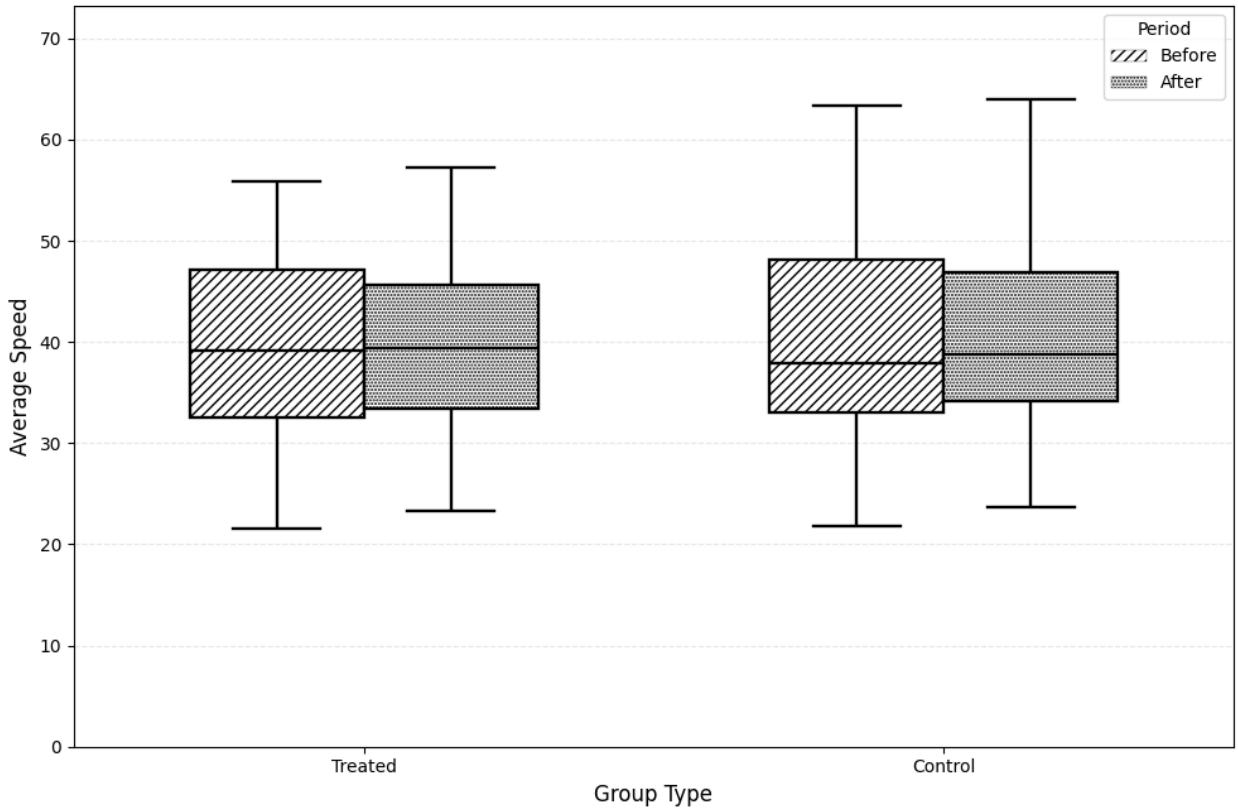


Figure 4. Average Speed Change: Treated versus Control (Lighting).

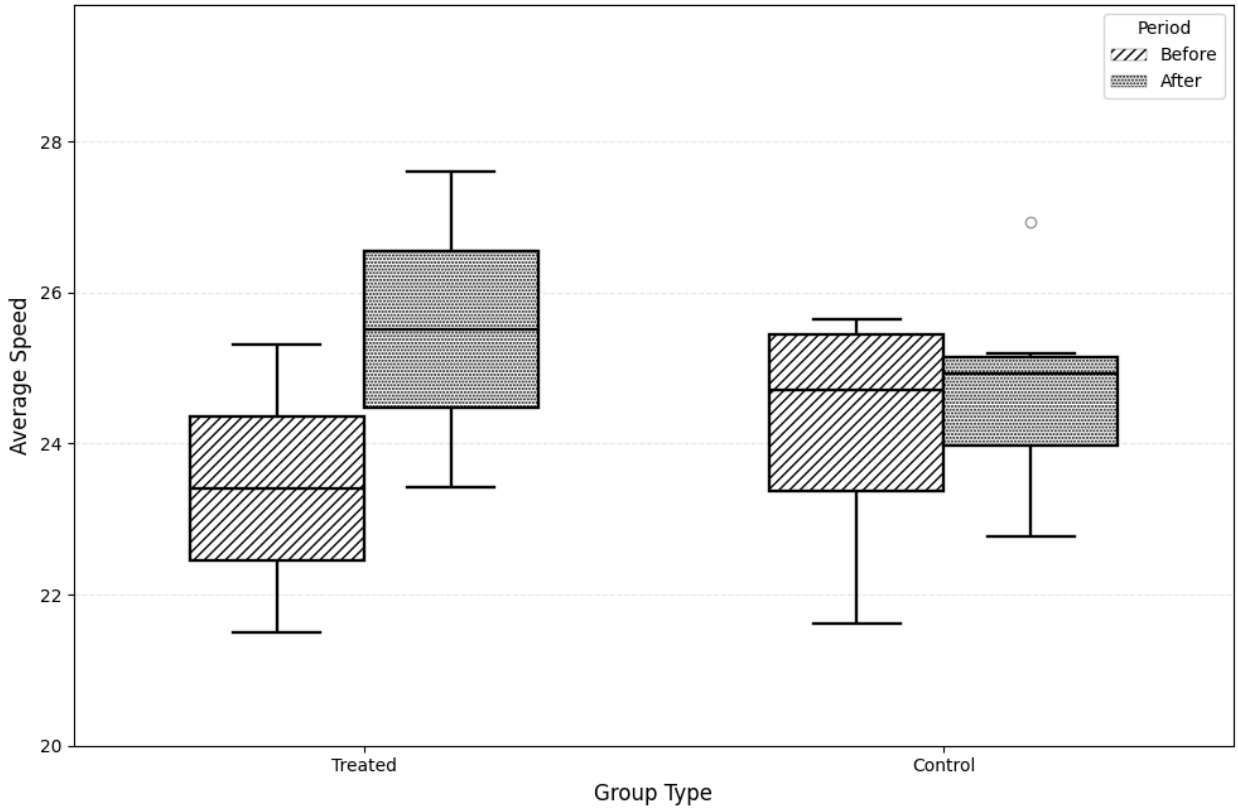


Figure 5. Average Speed Change: Treated versus Control (RIR).

Table 9 presents the regression model estimates for the lighting treatments based on 7.1 million segment-level average speed observations. The dataset includes a total of 100 sites, of which 43 are treated sites. To help evaluate the magnitude of each variable's impact, practical significance was assessed by increasing each covariate by one standard deviation (SD) in each speed record and calculating the ratio of average vehicle speeds after to that before the increase. A positive value indicates an increase in speed, while a negative value indicates a decrease.

Table 9. Model Estimates for Lighting Treatment (Y = Avg Speed).

Variable	Coefficient	T-stat	P-value	Practical Significance
Treat_Light_p1	**0.202**	1.4	0.151	0.2%
Treat_Light_p2	**0.391**	1.4	0.160	0.2%
Treat_Light_p3	**0.009**	0.1	0.954	0.01%
Weekend	0.956	12.6	0.000	1.1%
WMT/sqmi	0.167	0.2	0.831	0.5%
% 1-car HH	2.807	0.4	0.692	0.7%
% 2+ car HH	−2.722	−0.3	0.742	−0.9%
Walk score	−0.260	−1.0	0.338	−2.7%
Job density	0.293	0.9	0.373	2.1%
Network density	−0.261	−1.7	0.098	**−5.0%**
Precipitation	−0.007	−3.5	0.001	−0.1%
% Moisture	−0.376	−1.0	0.309	−0.2%
Wind speed	−0.028	−1.2	0.215	−0.1%
Air temperature	0.015	1.8	0.077	0.6%

Variable	Coefficient	T-stat	P-value	Practical Significance
Lane width	−0.004	−0.0	0.993	0.01%
# Lanes	−0.545	−0.5	0.620	−0.7%
TWLTL presence	−0.233	−0.2	0.876	−0.3%
Raised presence	2.475	1.3	0.191	3.1%
Depressed presence	2.460	1.3	0.180	1.5%
Bike lane presence	1.439	0.7	0.501	0.8%
Sidewalk presence	−1.376	−0.8	0.398	−1.8%
Sidewalk * buffer	0.858	0.4	0.694	0.9%
Flow/lane	−0.007	−7.7	0.000	**−3.1%**
On-street parking	2.103	0.6	0.530	1.0%
Curb presence	−4.324	−2.3	0.022	**−5.4%**
Tangent presence	1.161	0.9	0.363	1.7%
PSL	0.697	4.3	0.000	**10.9%**
Hour of the day - 1	−0.582	−6.4	0.000	na
Hour of the day - 2	−0.742	−4.9	0.000	na
Hour of the day - 3	−0.695	−3.9	0.000	na
Hour of the day - 4	−0.595	−2.9	0.004	na
Hour of the day - 5	−0.703	−2.6	0.008	na
Hour of the day - 6	−1.457	−4.8	0.000	na
Hour of the day - 7	−3.083	−7.7	0.000	na
Hour of the day - 8	−3.079	−6.4	0.000	na
Hour of the day - 9	−2.972	−5.8	0.000	na
Hour of the day - 10	−3.169	−5.9	0.000	na
Hour of the day - 11	−3.225	−5.9	0.000	na
Hour of the day - 12	−2.941	−5.2	0.000	na
Hour of the day - 13	−2.365	−4.4	0.000	na
Hour of the day - 14	−2.574	−4.8	0.000	na
Hour of the day - 15	−2.969	−5.8	0.000	na
Hour of the day - 16	−2.695	−4.8	0.000	na
Hour of the day - 17	−2.490	−4.3	0.000	na
Hour of the day - 18	−1.641	−3.4	0.000	na
Hour of the day - 19	−0.979	−2.6	0.000	na
Hour of the day - 20	−0.525	−1.9	0.054	na
Hour of the day - 21	−0.083	−0.4	0.680	na
Hour of the day - 22	0.417	2.9	0.004	na
Hour of the day - 23	0.584	5.3	0.000	na
Month of the year - February	−0.458	−8.4	0.000	na
Month of the year - March	−0.333	−2.7	0.006	na
Month of the year - April	−0.276	−1.5	0.123	na
Month of the year - May	−0.357	−1.4	0.162	na
Month of the year - June	−0.322	−1.0	0.295	na
Month of the year - July	−0.244	−0.7	0.461	na
Month of the year - August	−0.387	−1.2	0.233	na
Month of the year - September	−0.295	−1.0	0.303	na
Month of the year - October	−0.199	−1.0	0.327	na
Month of the year - November	0.018	0.2	0.866	na
Month of the year - December	0.174	2.6	0.009	na
Year - 2018	13.930	1.1	0.257	na
Year - 2019	14.470	1.2	0.239	na
Year - 2020	15.777	1.3	0.199	na
Year - 2021	16.408	1.3	0.182	na
Year - 2022	16.221	1.3	0.188	na

Variable	Coefficient	T-stat	P-value	Practical Significance
Year - 2023	15.755	1.3	0.201	na
Year - 2024	15.301	1.2	0.214	na
Year - 2025	15.238	1.2	0.216	na

Note: $N_{site} = 100$, $N_{obs} = 7{,}070{,}077$, $R^2 = 0.616$, Log-likelihood = −2.1e+07, and na denotes no practical significance calculated for temporal variables. In the random effects model, the first category of categorical variables (year, month, and hour) is used as the baseline and is absorbed by the entity-level random effects, so no separate intercept is shown here.
Source: Speed data are from INRIX XD dataset. WMT estimates are from Li and Kockelman (*36*). Other land-use data are from the U.S. EPA Smart Location Database (*37*). Weather attributes are from the AORC dataset (*38*). Road geometry information is from Google Street View imagery. Flow data are from TxDOT's Roadway Inventory Dataset and INRIX probe data (*34*).

Results indicate that the lighting treatment was associated with an increase in vehicle speeds during nighttime periods. Specifically, the early evening period from sunset to 11 p.m. and the late-night period from 11 p.m. to 2 a.m. corresponded to increases in average speed of 0.20 mph and 0.39 mph, respectively. The period from 2 a.m. to sunrise showed a negligible effect of 0.01 mph. However, with p-values ranging from 0.15 to 0.95, these findings suggested that the lighting countermeasure has a limited direct impact on mean speeds in these study areas. In contrast, several infrastructure and land-use variables exhibit significant influence on driver behavior. Curb presence was found to be a significant variable, associated with a 4.99-mph decrease in average speeds. Similarly, network density and traffic flow were negatively associated with speed. Weather conditions also play a critical role, with precipitation and wind speed both showing a negative correlation with speed. Among all variables, PSL was the strongest predictor of speeds, with an SD increase in PSL associated with 10.5 percent higher speeds. Time-of-day effects were substantial, with speeds lowest during morning and evening peak hours (when traffic is heaviest) and highest late at night. Monthly effects indicated slightly slower speeds in February and the spring months, while yearly coefficients suggested gradual increases in speeds over time, with increased speeds observed during the COVID period (2020–2021) and post-period.

For the RIR treatment, Table 10 shows the model estimates derived from 1.2 million speed observations across eight sites. Similar to the lighting analysis, RIR treatment led to an increase of 0.22 and 0.56 mph in average speeds during the first period (12 a.m. to 2 a.m.) and second period (2 a.m. to 5 a.m.), respectively. The estimated coefficients for the RIR treatment indicators suggested no statistically significant change in vehicle speeds, possibly due to the small sample size of treated sites. However, several other variables demonstrated statistically significant relationships with speed. Job density was associated with a 0.176-mph reduction in speeds, while WMT density was related to a 0.306-mph decrease in speeds, suggesting that higher pedestrian activity correlates with more cautious driving and lower speeds. Roadway geometry also had a significant impact on average speeds. The presence of a TWLTL was strongly associated with lower speeds, with a 1-SD increase corresponding to a 7.5 percent reduction in speeds.

Table 10. Model Estimates for RIR Treatment (Y = Avg Speed).

Variable	Coefficient	T-stat	P-value	Practical Significance
Treat_RIR_p1	**0.564**	1.7	0.092	0.2%
Treat_RIR_p2	**0.223**	0.8	0.360	0.1%
Weekend	0.522	1.8	0.071	1.0%
WMT/sqmi	−0.306	−19.2	0.000	−1.4%
% 1-car HH	15.422	35.6	0.000	**3.2%**
Job density	−0.176	−93.8	0.000	**−4.9%**
Network density	0.004	2.4	0.016	0.1%
Precipitation	−0.008	−7.3	0.000	−0.2%
% Moisture	0.932	6.3	0.000	0.8%
Wind speed	−0.057	−2.3	0.019	−0.3%
Air temperature	−0.009	−1.7	0.091	−0.6%
# Lanes	0.400	3.4	0.000	0.8%
TWLTL presence	−3.757	−89.1	0.000	**−7.5%**
Flow/lane	0.002	0.8	0.451	1.0%
Tangent presence	1.576	22.9	0.000	2.8%
Hour of the day - 1	0.041	0.3	0.772	na
Hour of the day - 2	0.060	0.3	0.790	na
Hour of the day - 3	0.031	0.3	0.793	na
Hour of the day - 4	0.353	2.7	0.007	na
Hour of the day - 5	0.837	2.8	0.005	na
Hour of the day - 6	0.387	0.7	0.483	na
Hour of the day - 7	−1.003	−0.8	0.397	na
Hour of the day - 8	−1.753	−1.4	0.152	na
Hour of the day - 9	−1.325	−1.2	0.250	na
Hour of the day - 10	−1.460	−1.5	0.138	na
Hour of the day - 11	−2.423	−3.7	0.000	na
Hour of the day - 12	−3.450	−9.7	0.000	na
Hour of the day - 13	−3.599	−36.4	0.000	na
Hour of the day - 14	−3.578	−16.3	0.000	na
Hour of the day - 15	−3.926	−14.3	0.000	na
Hour of the day - 16	−4.346	−35.7	0.000	na
Hour of the day - 17	−4.592	−358	0.000	na
Hour of the day - 18	−3.908	−316	0.000	na
Hour of the day - 19	−3.017	−32.0	0.000	na
Hour of the day - 20	−2.234	−140	0.000	na
Hour of the day - 21	−1.389	−17.6	0.000	na
Hour of the day - 22	−0.882	−5.2	0.000	na
Hour of the day - 23	−0.399	−2.2	0.031	na
Month of the year - February	−0.358	−63.8	0.000	na
Month of the year - March	−0.115	−3.27	0.001	na
Month of the year - April	0.287	5.6	0.000	na
Month of the year - May	0.321	3.6	0.000	na
Month of the year - June	0.508	3.7	0.000	na
Month of the year - July	0.620	4.0	0.000	na
Month of the year - August	0.473	1.6	0.104	na
Month of the year - September	0.266	0.9	0.347	na
Month of the year - October	0.133	0.6	0.582	na
Month of the year - November	0.098	0.7	0.471	na
Month of the year - December	−0.014	−0.2	0.872	na
Year - 2018	27.045	27.8	0.000	na
Year - 2019	25.969	32.3	0.000	na

Variable	Coefficient	T-stat	P-value	Practical Significance
Year - 2020	26.499	42.4	0.000	na
Year - 2021	26.635	179	0.000	na
Year - 2022	26.834	513	0.000	na
Year - 2023	27.333	603	0.000	na
Year - 2024	27.428	891	0.000	na
Year - 2025	27.159	183	0.000	na

Note: $N_{site} = 8$, $N_{obs} = 1{,}171{,}800$, $R^2 = 0.293$, Log-likelihood = −3.2e+06, and na denotes no practical significance calculated for temporal variables. In the random effects model, the first category of categorical variables (year, month, and hour) is used as the baseline and is absorbed by the entity-level random effects, so no separate intercept is shown here.
Source: Speed data are from INRIX XD dataset. WMT estimates are from Li and Kockelman (*36*). Other land-use data are from the U.S. EPA Smart Location Database (*37*). Weather attributes are from the AORC dataset (*38*). Road geometry information is from Google Street View imagery. Flow data are from TxDOT's Roadway Inventory Dataset and INRIX probe data (*34*).

CRASH MODEL

This section reports crash outcomes for both treated and control sites during the before-and-after periods, with the goal of assessing the safety effectiveness of RIR and lighting treatments. It covers the crash data, statistical model specification, control variables, and the main findings.

Crash Data

Crash data were retrieved from the Crash Records Information System (CRIS) query tool, maintained by TxDOT. The dataset provides comprehensive information on crash times, locations, contributing factors, vehicle types, and any injuries or fatalities involved. The system supports data-driven analyses and is widely used for traffic safety studies, roadway condition evaluations, and identification of high-risk locations.

As RIR is a signal-related countermeasure, its application is limited to intersections, and only intersection-related crashes were included in the analysis. For this study, the research team collected all crashes occurring within a 250-ft buffer around the segment corridor for the lighting countermeasure or around the intersection for the RIR countermeasure. The crash dataset categorized intersection and non-intersection crashes using the At_Intrsct_Fl attribute, while pedestrian- and cyclist-related incidents were identified via the Harm_Evnt_ID field. Figure 6 plots crash counts by intersection type for both the before and after study periods for the lighting countermeasure. One-third of all crashes are intersection-related, and non-VRU incidents account for more than 90 percent of the total (Figure 6 and Figure 7).

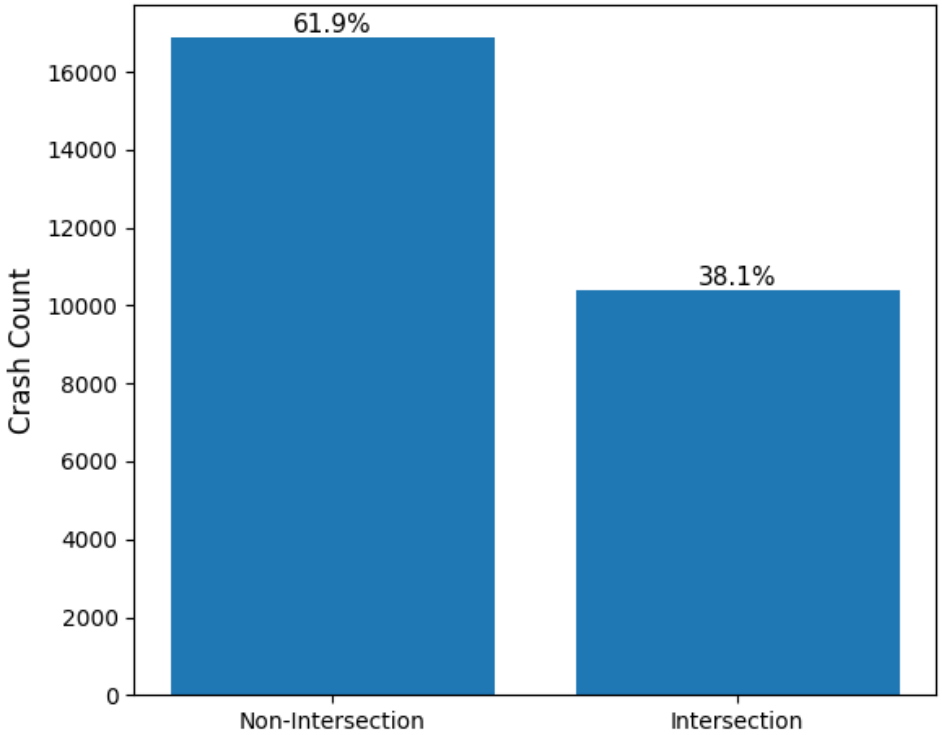


Figure 6. Intersection Crashes versus Non-intersection Crashes for Lighting.

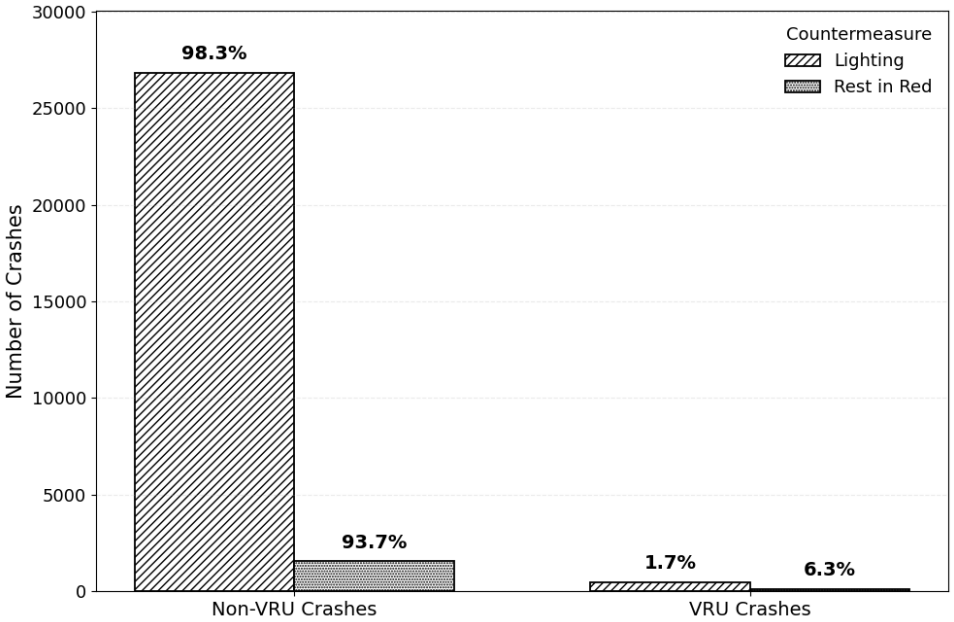


Figure 7. VRU versus Non-VRU Crashes by Treatment Type.

Model Specification

To evaluate the safety impacts specifically related to VRUs, a generalized linear mixed model was developed. Unlike the millions of hourly speed observations in the speed model, the crash data consist of crash rates aggregated over the before and after periods, resulting in two rows per

site. Therefore, this model incorporates site-level random effects to account for baseline site heterogeneity and clustered observations within treated-control pairs. Additionally, the model includes a random intercept for each site to capture unobserved site-specific factors that are constant over time. Baseline site heterogeneity is further controlled by roadway and land-use variables.

The expected number of crashes is modeled as:

$$\ln(\mu_{i,t}) = \beta_0 + \beta_1 \text{Treatment}_{i,t} + \beta_2 \text{Treated}_i + \beta_3 \text{After}_t + \beta_4 \ln(\text{Exposure}_{i,t}) + Z_i\beta + u_i + \epsilon_{i,t}$$

Where:

- $\mu_{i,t}$ = crash rate.
- $\text{Treatment}_{i,t}$ = binary indicator representing treatment (one if the site is treated and in the after period).
- Treated_i = treated or control groups.
- After_t = before or after period.
- $\text{Exposure}_{i,t}$ = vehicle miles traveled × days during the operational period to account for variations in traffic volumes and the duration of the before and after periods.
- Z_i = vector of time-invariant covariates (e.g., roadway characteristics, land use, etc.).
- u_i = site-level random effect.
- $\epsilon_{i,t}$ = error term.

Similar to the speed models, Table 11 summarizes the basic statistics used in the crash model for lighting. Table 12, Table 13, and Table 14 list the final variables and model results.

Table 11. Variable Definition and Summary Statistics Used in the Crash Model (Lighting).

Variables	Description	Mean	Median	SD	Min	Max
Total night	Total number of crashes within 250 ft of the corridor (lighting) or intersection (RIR) during the before or after period	42.8	15	61.1	0	304
VRU night	Number of VRU-involved crashes within 250 ft of the corridor (lighting) or intersection (RIR) during the before or after period	1.16	0	2.47	0	19
Intersection night	Number of intersection-related crashes within 250 ft of the corridor (lighting) or intersection (RIR) during the before or after period	26.2	8	40.2	0	196
Non-intersection night	Number of non-intersection-related crashes within 250 ft of the corridor (lighting) or intersection (RIR) during the before or after period	16.7	6	23.5	0	120
Treatment	Indicators for active treatment	0.22	0	0.41	0	1
Treated	1 if the segment is treated; 0 control	0.44	0	0.50	0	1
After	1 if it is after period; 0 before period	0.50	1	0.50	0	1
WMT/sqmi	Daily WMT per square mile	0.87	0.33	1.21	0	5.33
% one-car HH	Percent of households with 1 car in block groups within 0.25-mile buffer	0.13	0.11	0.10	0.02	0.53
% two+ car HH	Percent of households with 2+ cars in block groups within 0.25-mile buffer	0.24	0.21	0.15	0.03	0.58
Walk score	Walkability index score of block groups within 0.25-mile buffer	8.49	7.72	3.65	2.59	29.0
Job density	Jobs per acre in block groups within 0.25-mile buffer	1.44	0.50	2.45	0	12.9
Network density	Total road network density per square mile in block groups within 0.25-mile buffer	10.0	7.93	7.46	1.23	28.6
Lane Width	Lane width (ft)	11.8	12	1.03	10	20
# Lanes each way	Number of lanes per direction	2.02	2	0.79	1	3
TWLTL presence	1 if the segment has a TWLTL median; 0 otherwise	0.64	1	0.48	0	1
Raised presence	1 if the segment has a raised median; 0 otherwise	0.74	1	0.44	0	1
Depressed presence	1 if the segment has a depressed median; 0 otherwise	0.92	1	0.28	0	1
Bike lane presence	1 if the segment has a separate bike lane; 0 otherwise	0.04	0	0.19	0	1
Sidewalk presence	1 if the segment has a sidewalk; 0 otherwise	0.31	0	0.46	0	1
Sidewalk * buffer	Interaction between sidewalk presence and the presence of buffer zone	0.17	0	0.37	0	1
Ln(Exposure)	Natural log of exposure (vehicle miles traveled × days during the nighttime period)	15.6	15.8	1.57	10.8	19.0
On-street parking	1 if the segment has on-street parking; 0 otherwise	0.02	0	0.14	0	1
Centerline presence	1 if the segment has centerlines; 0 otherwise	0.99	1	0.10	0	1
Edge lines presence	1 if the segment has edge lines; 0 otherwise	0.66	1	0.48	0	1
Curb presence	1 if the segment has a curb; 0 otherwise	0.53	1	0.50	0	1
Tangent presence	1 if the segment has a tangent; 0 otherwise	0.59	1	0.49	0	1
PSL	Posted speed limit of the road segment (mph)	47.6	45	5.98	35	55

Source: Crash data are from TxDOT CRIS dataset. WMT estimates are from Li and Kockelman (*36*). Other land-use data are from the US EPA Smart Location Database (*37*). Road geometry information is from Google Street View imagery.

Table 12. Total Nighttime Crash Model Estimates for Lighting Treatment (Y = Ln[Crashes]).

Variables	Coefficient	T-stat	P-value
Intercept	−321.2	−6.1	0.000
Treatment	5.511	0.6	0.531
Treated	15.986	2.5	0.014
After	6.275	1.1	0.281
WMT/sqmi	14.733	3.7	0.000
Walk score	2.280	1.9	0.055
Lane Width	−4.445	−1.5	0.125
Depressed presence	20.162	1.5	0.133
Bike lane presence	−31.913	−1.6	0.097
Sidewalk presence	−17.628	−2.0	0.045
Ln(Exposure)	22.726	9.8	0.000
Tangent presence	10.624	1.8	0.073

Note: N_{obs} = 193, and Log-likelihood = -928.5. Random effects: variance for site name = 780.3, and std. dev = 9.091.
Source: Crash data are from the TxDOT CRIS dataset. WMT estimates are from Li and Kockelman (*36*). Other land-use data are from the U.S. EPA Smart Location Database (*37*). Road geometry information is from Google Street View imagery. Variables with high p-values were excluded from the final model.

Table 13. VRU Nighttime Crash Model Estimates for Lighting Treatment (Y = Ln[Crashes]).

Variables	Coefficient	T-stat	P-value
Intercept	−5.647	−1.6	0.104
Treatment	0.426	0.8	0.449
Treated	0.407	1.0	0.316
After	0.093	0.3	0.802
WMT/sqmi	0.610	3.4	0.001
Walk score	−0.012	−0.2	0.842
Lane Width	−0.212	−1.3	0.190
Depressed presence	0.292	0.4	0.663
Bike lane presence	−1.488	−1.5	0.131
Sidewalk presence	0.864	2.0	0.051
Ln(Exposure)	0.486	2.9	0.004
Tangent presence	0.799	2.4	0.018

Note: N_{obs} = 193, and Log-likelihood = -410.1. Random effects: variance for site name = 0.479, and std. dev = 0.369.

Table 14. Intersection Nighttime Crash Model Estimates for Lighting Treatment (Y = Ln[Crashes]).

Variables	Coefficient	T-stat	P-value
Intercept	−109.8	−4.8	0.001
Treatment	−0.280	−0.1	0.942
Treated	7.279	2.6	0.010
After	2.785	1.1	0.271
WMT/sqmi	5.558	3.4	0.001
Walk score	0.885	1.8	0.072
Lane Width	−1.886	−1.5	0.122
Depressed presence	8.675	1.5	0.125
Bike lane presence	−9.770	−1.2	0.215
Sidewalk presence	2.394	0.7	0.500
Ln(Exposure)	7.656	7.8	0.000
Tangent presence	5.939	2.4	0.018

Note: N_{obs} = 193, and Log-likelihood = -772.3. Random effects: variance for site name = 100.8, and std. dev = 3.241.

Results

Figure 8 compares nighttime crash rates between treated and control groups before and after lighting interventions. While both groups experienced an increase in crash rates (crashes per vehicle miles traveled), the increase at treated sites was notably smaller than that observed in the control group. In contrast, Figure 9 shows a clear reduction in crash rates for the RIR treated group, while the corresponding control group witnessed an increase. The median total nighttime crash rate at the treated sites decreased by approximately 7% following implementation, compared to an approximate 50% increase at the control sites. In addition, the interquartile range for treated sites shifted downward and became more compressed, indicating that the treatment not only reduced average crash rates but also made safety performance more consistent across sites.

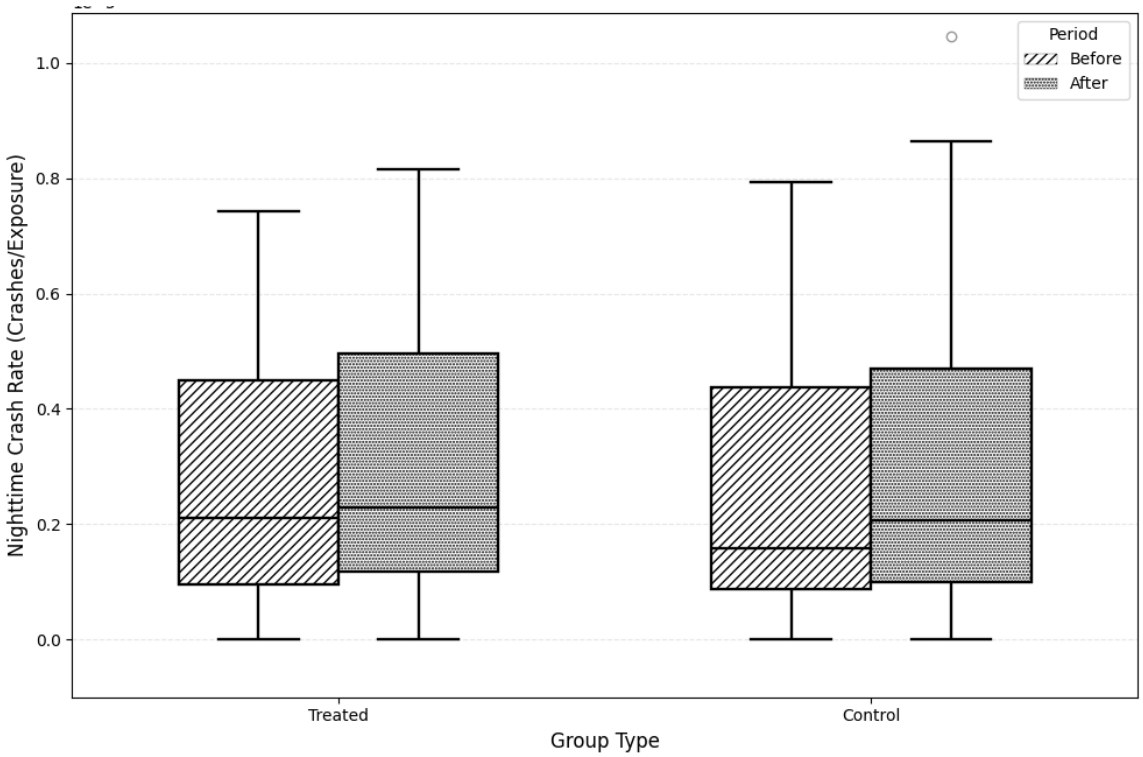


Figure 8. Total Nighttime Crash Rate: Treated versus Control (Lighting).

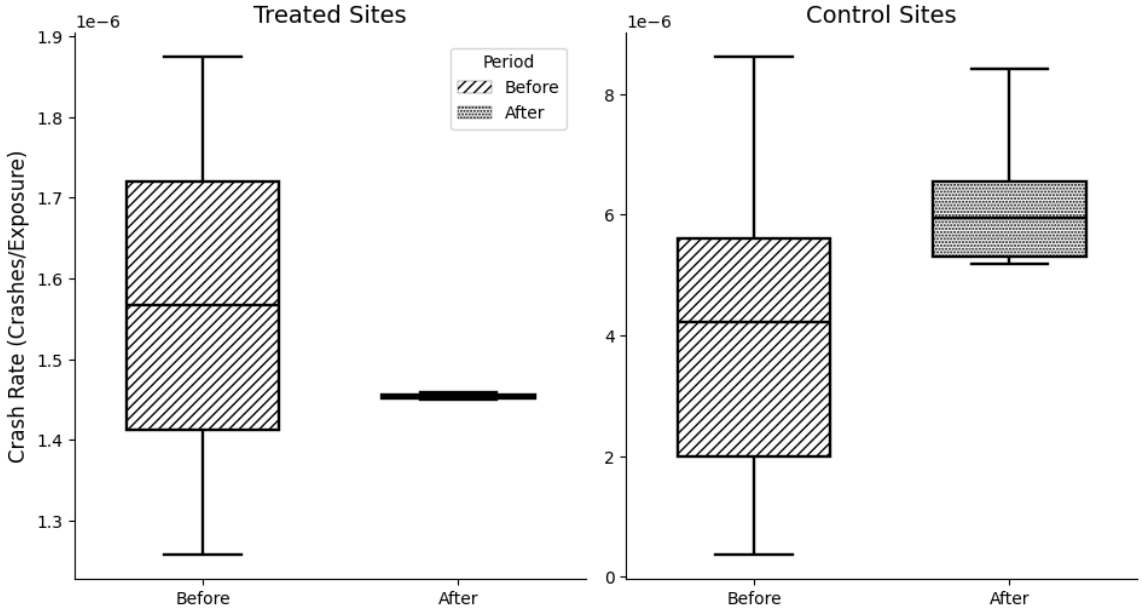


Figure 9. Total Nighttime Crash Rate: Treated versus Control (RIR).

Table 12 and Table 13 present the total and VRU-related nighttime crash model results for the lighting treatment, respectively. For the lighting intervention, the model indicates that the treatment was associated with a 53.1 percent increase in VRU-related crashes but a 24.4 percent reduction in intersection-specific nighttime crashes. However, neither estimate showed statistical

significance, suggesting that the observed changes may be attributable to random fluctuation or site-level variance rather than the treatment effect. Among roadway covariates, traffic exposure and WMT density were the most significant variables affecting crashes, both showing strong positive correlations with crashes. Besides, the presence of a separate bike lane was associated with a reduction in nighttime crashes. Due to the limited number of observations for the RIR treatment (n = 16), a crash model was not estimated here.

DISCUSSION

This section evaluates the speed and safety effectiveness of RIR and roadway lighting using a difference-in-differences (DiD) framework. The research team examined two treated sites and six control sites for RIR, and 43 treated sites and 57 control sites for lighting, comparing both speed and safety outcomes across these locations.

For the RIR treatment, the analysis includes 1.2 million hourly average speed observations across eight sites. The findings indicate increases of 0.22 mph and 0.56 mph in average speeds during the first period (12 a.m. to 2 a.m.) and the second period (2 a.m. to 5 a.m.), respectively. However, the estimated coefficients for the RIR treatment indicators were not statistically significant, possibly due to the small number of treated sites. While descriptive analyses suggest a reduction in crash rates at treated intersections, the limited sample size (n = 16) restricts statistical power and does not necessarily imply ineffectiveness. Future research incorporating more sites or longer observation periods may help better assess the treatment's effectiveness.

For roadway lighting, the results indicate that the treatment was associated with increases in vehicle speeds during nighttime periods. Specifically, the early evening period from sunset to 11 p.m. and the late-night period from 11 p.m. to 2 a.m. correspond to increases in average speed of 0.20 mph and 0.39 mph, respectively. However, with p-values ranging from 0.15 to 0.95, these findings suggest that the lighting countermeasure has a limited direct impact on mean speeds in the study areas. In contrast, the analysis indicates a statistically significant reduction in nighttime crash rates at treated sites relative to control locations, despite an overall upward trend in crashes across both groups. This suggests that while external factors (e.g., increased exposure) may have contributed to rising crash rates, the lighting intervention mitigated this increase.

Several control variables were found to be statistically significant in the speed and crash models, providing insights into contextual factors influencing driver behavior. For example, higher job density and PSLs were associated with lower speeds, while the presence of a separate bike lane was associated with a reduction in nighttime crashes. These findings underscore the importance of accounting for surrounding land use and traffic conditions when evaluating the impacts of safety interventions.

Overall, the research suggests that roadway lighting is an effective countermeasure for improving nighttime safety, particularly in terms of crash reduction, even though its influence on

decreasing vehicle speeds appears limited. While preliminary evidence for RIR treatments is promising, further investigation is needed to derive conclusions. These findings provide practical implications for transportation agencies, supporting continued investment in lighting improvements while emphasizing the importance of robust data collection for RIR.

CHAPTER 4: EVALUATION OF SIDEWALKS

INTRODUCTION

Sidewalks are among the most widely implemented pedestrian infrastructure designed to improve accessibility, encourage walking, and enhance pedestrian safety. By physically separating pedestrians from moving vehicles, sidewalks reduce pedestrian exposure to traffic and support broader transportation objectives related to complete streets and multimodal mobility.

Previous research has focused on the safety benefits of sidewalks, with most studies reporting that sidewalks reduce pedestrian crash risk. For example, Alluri et al. found that sidewalks significantly improve pedestrian safety by reducing pedestrian exposure to traffic (*39*), while Osama and Sayed reported that greater sidewalk continuity and coverage were associated with fewer pedestrian crashes (*40*). Similarly, Abou-Senna et al. found that pedestrian crashes per mile were three times more likely at locations without sidewalks, highlighting the importance of continuous pedestrian facilities (*41*). However, not all studies report consistent findings. Minas-Alexander et al. observed greater pedestrian injury severity at locations with sidewalks, particularly on multilane and higher-speed roadways, suggesting that the safety benefits of sidewalks depend on roadway context (*42*).

Compared with pedestrian safety, considerably less attention has been given to the operational impacts of sidewalks. The limited studies available suggest that sidewalks can influence driver behavior by altering the roadside environment although the direction and magnitude of these effects vary across roadway settings (*43*, *44*, *45*). These mixed findings indicate that the relationship between sidewalks and operating speeds is highly context dependent and remains insufficiently understood.

Despite the growing body of research, important gaps remain. Most previous studies have relied on cross-sectional analyses or evaluations of isolated locations, making it difficult to distinguish the effects of sidewalk installation from broader temporal changes. In addition, relatively few studies have evaluated operational and safety outcomes simultaneously using corridor-level before-and-after data with appropriate comparison corridors. To address these gaps, this study evaluates the operational and safety impacts of sidewalk installation along arterial corridors in Texas using a matched control DiD framework. The INRIX XD probe speed data and corridor-level segment (non-intersection) crash data are used to quantify changes in operating speeds, fatal and injury (FI) crashes, and pedestrian FI crashes while accounting for roadway characteristics and temporal trends.

LITERATURE REVIEW

This section reviews the existing literature on the operational and safety effects of sidewalks. The review first summarizes studies evaluating the relationship between sidewalks and

pedestrian safety, focusing on their study designs, analytical approaches, and key findings. The section then examines the limited body of research investigating the influence of sidewalks on operating speeds. By synthesizing the existing evidence, this review provides the foundation for understanding the current state of knowledge and identifying areas where additional research is needed.

Previous Safety Research

Several previous studies employed cross-sectional study designs, in which locations with different sidewalk characteristics were compared using crash and roadway data collected during the same study period rather than evaluating conditions before and after sidewalk installation. The studies were conducted at different spatial scales, including 347 roadway segments in Florida (*41*), statewide roadway segments and intersections in Florida using crash data from 2008–2010 and 2011–2013 (*39, 46*), 134 traffic analysis zones in Vancouver (*40*), and 426 pedestrian crash cases in Bakersfield, California (*42*). Despite differences in study area and sample size, each study evaluated existing roadway environments by comparing locations with varying sidewalk characteristics rather than following the same locations over time.

A variety of statistical approaches have been used to evaluate the relationship between sidewalks and pedestrian safety. Abou-Senna et al. applied a zero-inflated negative binomial regression model to account for the large number of roadway segments with no pedestrian crashes (*41*). Alluri et al. employed generalized linear models with a negative binomial distribution to estimate the effects of roadway and pedestrian infrastructure characteristics on crash frequency and develop crash modification factors (*39, 46*). Osama and Sayed developed pedestrian collision prediction models and validated the results using a full Bayesian approach to account for spatial heterogeneity and improve model reliability (*40*). In contrast, Minas-Alexander et al. used multivariable regression models to examine the association between roadway characteristics and pedestrian injury severity (*42*).

Overall, previous studies have reported mixed findings regarding the relationship between sidewalks and pedestrian safety. Most studies found that sidewalks are associated with improved safety outcomes by reducing pedestrian exposure to moving traffic. Abou-Senna et al. reported that pedestrian crashes were substantially more frequent at locations without sidewalks (*41*), while Alluri et al. found that sidewalks significantly improved pedestrian safety and recommended providing sidewalks or, at a minimum, paved shoulders on both sides of the roadway (*39*). Similarly, Osama and Sayed observed that greater sidewalk continuity, coverage, and total sidewalk length were associated with lower pedestrian crash frequencies (*40*). These findings consistently suggest that well-designed and continuous sidewalk infrastructure can contribute to safer pedestrian environments. Despite this general agreement, several studies indicate that the safety benefits of sidewalks are not universal. Alluri et al. reported that the effects of sidewalks on bicycle safety varied by roadway type, with sidewalks associated with

higher crash severity on six-lane roadways but lower severity on two-lane facilities (*46*). Likewise, Minas-Alexander et al. found that pedestrians struck at locations with sidewalks experienced more severe injuries than those at locations without sidewalks (*42*). Rather than attributing these outcomes to sidewalks themselves, the authors noted that sidewalks were commonly located along high-speed, multilane arterial corridors where severe crashes were more likely.

Previous Speed Research

In contrast to safety studies, literature examining the relationship between sidewalks and operating speeds remains limited and presents inconsistent findings. Several studies have found that sidewalks contribute to lower operating speeds by creating a more pedestrian-oriented roadway environment. Thiessen et al. reported that sidewalks located closer to the travel lane were associated with lower operating speeds than sidewalks separated from the roadway by a boulevard (a buffer space between the sidewalk and driving surface that is usually filled with some type of greenery that may or may not include trees) (*45*). Similarly, Lian and Lee found that greater sidewalk visibility was associated with reduced vehicle speeds on low-speed urban streets (*47*). Both studies suggested that sidewalks increase roadside friction, create a stronger sense of enclosure, and enhance driver awareness of pedestrian activity, encouraging motorists to adopt more cautious driving behavior. These findings suggest that sidewalks can function as a traffic-calming element, particularly in urban environments where pedestrian activity is more prevalent and the roadside environment has a greater influence on driver speed choice.

In contrast, other studies have reported that sidewalks are associated with higher operating speeds under certain roadway conditions. Eluru et al. found that the relationship between sidewalks and speed varied across urban roadway types (local or arterial), with sidewalks associated with higher operating speeds on some local roads (*44*). Likewise, Dinh and Kubota observed that residential streets with sidewalks on both sides of the roadway experienced higher operating speeds than streets without sidewalks (*43*). The authors argued that sidewalks physically separate pedestrians from the travel lane, increasing drivers' perception of safety and reducing the need to moderate their speed. Together, these findings indicate that the influence of sidewalks on operating speeds is not uniform but varies according to roadway function, sidewalk configuration, surrounding roadside characteristics, and driver perception of the roadway environment.

Literature Review Summary

Although previous studies have improved the understanding of the relationship between sidewalks, pedestrian safety, and operating speeds, several important gaps remain. Most existing research has relied on cross-sectional analyses that compare locations with different sidewalk characteristics rather than evaluating changes before and after sidewalk installation. In addition, relatively few studies have simultaneously examined operational and safety outcomes at the

corridor level using matched comparison corridors. As a result, the causal effects of sidewalk installation on both operating speeds and crash occurrence remain insufficiently understood. This study addresses these gaps by evaluating the operational and safety impacts of sidewalk installation along arterial corridors in Texas using a matched control DiD framework with high-resolution speed and crash data.

STUDY DATA DESCRIPTION

Identification of the Treated and Comparison Corridors

To identify projects involving sidewalk installation, the TxDOT Design and Construction Information System (DCIS) was used. This database, which contains over 69,000 records, was screened for several potential countermeasures. Based on the "TYPE_OF_WORK" attribute, projects with "Construct Pedestrian Infrastructure," "Bicycle and Pedestrian Improvements," "Construct Sidewalk and Bike Lanes," and other entry values containing the terms *pedestrian* and/or *sidewalk* were selected. The next step involved screening the projects' start and end dates. In this case, projects with estimated start dates before 2014 or after 2025 were removed. Further, corridors shorter than 0.25 miles were removed. Google Earth and Google Street View were used to review the remaining corridors to confirm the presence of sidewalks and to determine whether construction was in progress.

Comparison corridors were identified using a systematic, data-driven approach grounded in the TxDOT Roadway Inventory database and supported by geographic information system (GIS)–based spatial analysis. Treated corridors were first identified within each county. Using these corridors as reference points, potential comparison corridors were then identified within the same counties to ensure consistency in regional and operational characteristics. Corridors with between 80 to 120 percent of the traffic volume of the treated corridors and a similar number of lanes were retained for further screening. Google Maps and Google Street View were used to visually confirm the presence or absence of sidewalks at potential comparison locations with those corridors with sidewalks being removed.

For each treated corridor, between one and five comparison corridors were selected based on similarity in key roadway attributes, including AADT, PSL, and number of lanes. Additional consideration was given to spatial proximity and surrounding land use, with preference for comparison corridors located near treated locations or within similar development contexts. This approach was intended to ensure that comparison corridors closely resemble treated corridors except not having a sidewalk, thereby strengthening the validity of subsequent before-and-after analysis. To this end, 181 corridors were available for evaluation, which include 56 treated and 125 comparison corridors.

The installation date for each sidewalk corridor was first determined using the TxDOT DCIS database. Where installation dates were unavailable, they were estimated from historical Google

Maps and Google Street View imagery by identifying the earliest date on which the completed sidewalk was visible. These dates were then used to define the before period (January 1, 2018, to the installation date) and the after period (the installation date to December 31, 2025). The before period ranged between 165 and 2239 days, with an average of 1392 days. On the other hand, the after period ranged from 301 to 1854 days, with an average of 870 days

Speed Data Collection and Reduction

This study uses probe-based traffic data to assess the operational effects of sidewalk implementation at the corridor level. Speed information was obtained from the INRIX XD dataset, which provides high-resolution, time-stamped estimates of average vehicle speeds derived from a distributed sample of probe vehicles. A key advantage of this data source is its continuous temporal coverage, enabling evaluation of speed patterns across all times of day and operating conditions, in contrast to traditional spot-speed studies, which are limited in both spatial and temporal scope. Although probe data represent a sample of the traffic stream, multiple validation studies have shown that INRIX probe data provide reliable estimates of roadway speeds and travel times that closely agree with measurements from floating-car surveys and fixed traffic detectors (*48*, *49*, *50*).

Given that INRIX XD data are structured at the roadway segment level, all relevant segments for the treated and comparison corridors were identified and mapped using GIS tools. Speed data were subsequently extracted using the RITIS Probe Data Analytics Suite for the analysis period spanning 2018 through 2025. The following data screening and quality control procedures were applied to ensure analytical rigor. Observations collected during active construction periods were excluded to avoid capturing transitional traffic conditions. Very short segments (≤0.06 miles) were removed due to their proximity to intersections, where deceleration, queuing, and stop-related effects can bias speed measurements. Additionally, only records with high reliability (a confidence value ≥ 90) were retained, and observations with missing or low-confidence indicators were discarded. Following these procedures, the final dataset comprised 33,360,263 observations across 889 INRIX XD segments, providing a robust basis for subsequent statistical analysis.

Crash Data Collection and Reduction

This study used statewide crash data from Texas for 2018 through 2025 to evaluate safety outcomes associated with sidewalk implementation. The analysis focused on FI crashes and pedestrian FI crashes. The study focused on the non-intersection crashes since sidewalks primarily separate pedestrians from moving traffic along roadway segments rather than at intersections. For safety assessment, crashes were aggregated at the corridor level to align with the study design and to facilitate consistent comparisons between treated and comparison corridors.

To identify crashes associated with each corridor, the research team first developed spatial representations of the study corridors using GIS tools. A 250-ft buffer was then applied to each corridor to capture crashes occurring near the roadway. Geocoded crash records were overlaid onto the buffered corridors, and all crashes located within these buffers were extracted for further processing. Additional data cleaning procedures were implemented to address potential duplication, particularly in areas where buffers from adjacent corridors overlapped.

To support the before-and-after analysis, crash records were classified based on their occurrence relative to the implementation period of the sidewalk improvements. The dataset was then structured to compute the total number of non-intersection FI crashes and the number of non-intersection pedestrian FI crashes for each corridor in both the pre- and post-installation periods. To determine non-intersection crashes, the variable "INTRSCT_RELAT_ID" from the CRIS database was used. The available codes were (1) intersection, (2) intersection related, (3) driveway access, (4) non-intersection, (5) not reported, (6) undetermined, and (7) reported invalid. In this case, only crashes labeled as (4) non-intersection were used in this study. This structured aggregation enabled a consistent and comparable evaluation of safety outcomes across corridors.

Descriptive Statistics of the Data

The descriptive analysis of the data is divided into three parts: the study site's characteristics, the distribution of speed data, and the distribution of crash data. The division intends to provide a better understanding of all the data used in this study.

Table 15 and Table 16 present the distribution of the study sites' characteristics. The treated and comparison corridors are broadly similar in corridor length, number of lanes, and lane width, indicating reasonable comparability. In contrast, treated corridors have relatively lower PSLs, higher traffic volumes, and more signalized intersections, suggesting more urban and complex traffic environments. These differences indicate that treated locations may experience higher traffic activity and operational complexity, which can influence observed speed and safety outcomes.

Table 15. Characteristics of the Study Sites (Continuous Variables).

Variable	Corridor Type	Min	Max	Average	SD
Corridor length (mi)	Comparison	0.08	7.94	0.78	0.80
Corridor length (mi)	Treated	0.19	4.27	0.80	0.68
Number of lanes	Comparison	2.00	8.00	3.35	1.12
Number of lanes	Treated	2.00	8.00	3.57	1.13
Average lane width (ft)	Comparison	10.50	19.00	11.90	0.81
Average lane width (ft)	Treated	10.00	21.00	12.30	2.10
Shoulder width (ft)	Comparison	0.00	13.00	4.23	3.79
Shoulder width (ft)	Treated	0.00	14.00	2.60	4.18
Posted speed limit (mph)	Comparison	30.00	60.00	46.00	8.38
Posted speed limit (mph)	Treated	30.00	55.00	38.80	6.32
Number of signalized intersections	Comparison	0.00	4.00	0.63	0.88
Number of signalized intersections	Treated	0.00	17.00	2.36	2.74
Average daily traffic (ADT)	Comparison	1,124	33,336	12,652	7,653
ADT	Treated	2,111	67,504	14,563	11,034

Table 16. Characteristics of the Study Sites (Categorical Variables).

Variable	Corridor Type	Count
No median	Comparison	104
Raised median	Comparison	24
TWTL median	Comparison	122
No median	Treated	41
Raised median	Treated	10
TWTL median	Treated	61
No bike lane	Comparison	247
Bike lane present	Comparison	3
No bike lane	Treated	110
Bike lane present	Treated	2
No curb	Comparison	170
Curb on one side	Comparison	6
Curb on both sides	Comparison	74
No curb	Treated	15
Curb on one side	Treated	4
Curb on both sides	Treated	93

The final speed dataset contains 33,360,263 observations. The dataset was divided into two parts; low speed (<45 mph) and high speed (≥45 mph) to explore the influence of sidewalks on operating speed. The low-speed dataset had 17,247,502 observations, while the high-speed dataset had 16,112,761 observations.

Table 17 presents the descriptive statistics of operating speeds before and after sidewalk installation. Across all roadway categories, treated corridors consistently exhibited lower average operating speeds than comparison corridors during both the before and after periods. Average speeds declined on the comparison corridors over time, while treated corridors experienced

relatively small changes following sidewalk installation. Similar patterns were observed for both low-speed and high-speed corridors although the reduction in average speed was more pronounced in the comparison corridors. Treated corridors also exhibited lower variability in operating speeds than comparison corridors, as reflected by the smaller standard deviations across all roadway categories.

Table 17. Descriptive Statistics of Speed Data.

Site Type	Period	Site Type	N	Min (mph)	Mean (mph)	Max (mph)	SD (mph)
All sites	Before	Comparison	11,424,067	2.08	42.10	76.10	12.40
All sites	Before	Treated	7,257,869	1.24	30.00	66.80	8.93
All sites	After	Comparison	9,422,710	4.74	39.90	78.70	11.80
All sites	After	Treated	5,255,617	3.93	30.50	64.90	7.72
Low-speed sites (<45 mph)	Before	Comparison	4,429,378	2.08	37.10	74.60	13.20
Low-speed sites (<45 mph)	Before	Treated	4,580,365	1.24	28.60	60.60	7.75
Low-speed sites (<45 mph)	After	Comparison	3,683,206	5.06	33.50	78.70	10.90
Low-speed sites (<45 mph)	After	Treated	3,419,812	3.93	28.90	59.80	7.00
High-speed sites (≥45 mph)	Before	Comparison	6,994,689	2.43	45.30	76.10	10.70
High-speed sites (≥45 mph)	Before	Treated	2,677,504	1.60	32.30	66.80	10.20
High-speed sites (≥45 mph)	After	Comparison	5,739,504	4.74	44.00	74.20	10.40
High-speed sites (≥45 mph)	After	Treated	1,835,805	4.28	33.50	64.90	8.08

For the safety evaluation, a total of 20,475 crashes were available. This includes intersection and non-intersection crashes and all severities. For this study, the sidewalks of interest were those constructed along the corridor (rather than focusing on sidewalk improvements at an intersection); therefore, crash data were separated by intersection/intersection-related crashes and non-intersection crashes. For this dataset, 2819 crashes were FI crashes that occurred at non-intersection locations. Further, the dataset included 122 FI crashes involving pedestrians that occurred at non-intersection locations.

Table 18 presents the descriptive statistics of the crash data before and after sidewalk installation. Across all crash categories, treated corridors experienced higher average crash frequencies than comparison corridors in both periods, suggesting that sidewalks were generally installed on corridors with greater existing safety concerns. Average crash frequencies declined from the before to the after period for all crashes and non-intersection FI crashes, with larger reductions observed on the treated corridors. In contrast, pedestrian crashes and non-intersection

pedestrian FI crashes exhibited only modest changes over time. Treated corridors also showed greater variability in crash frequencies than comparison corridors, reflecting substantial differences in crash occurrence across the study corridors.

Table 18. Descriptive Statistics of Crash Data.

Crash Type	Period	Site Type	Sum	Min	Mean	Max	SD
All crashes	Before	Comparison	5,984	0	48.70	277	59.70
All crashes	Before	Treated	6,453	2	120.00	773	169.00
All crashes	After	Comparison	4,399	1	37.90	226	50.20
All crashes	After	Treated	3,639	0	66.20	568	95.40
FI non-intersection crashes	Before	Comparison	836	0	6.69	34	8.11
FI non-intersection crashes	Before	Treated	898	0	16.00	128	24.90
FI non-intersection crashes	After	Comparison	592	0	4.74	47	7.10
FI non-intersection crashes	After	Treated	493	0	8.80	110	16.70
All pedestrian crashes	Before	Comparison	46	0	0.37	6	0.89
All pedestrian crashes	Before	Treated	83	0	1.48	15	2.82
All pedestrian crashes	After	Comparison	39	0	0.31	7	0.96
All pedestrian crashes	After	Treated	76	0	1.36	33	4.59
Pedestrian FI non-intersection crashes	Before	Comparison	26	0	0.21	3	0.51
Pedestrian FI non-intersection crashes	Before	Treated	39	0	0.70	5	1.20
Pedestrian FI non-intersection crashes	After	Comparison	21	0	0.17	4	0.58
Pedestrian FI non-intersection crashes	After	Treated	36	0	0.64	17	2.32

To perform a comparable evaluation, the research team normalized the crashes by duration and traffic volume to determine the crash rate. Figure 10 presents the distribution crash rates for non-intersection FI (per 10 million vehicle miles traveled [MVMT]) and pedestrian FI (per 100 MVMT). According to Figure 10, non-intersection FI crash rates declined on both treated and comparison corridors following sidewalk installation, with a larger reduction observed on the treated corridors. In contrast, pedestrian FI crash rates remained relatively stable over time, with a slight decrease in comparison corridors and a slight increase in treated corridors.

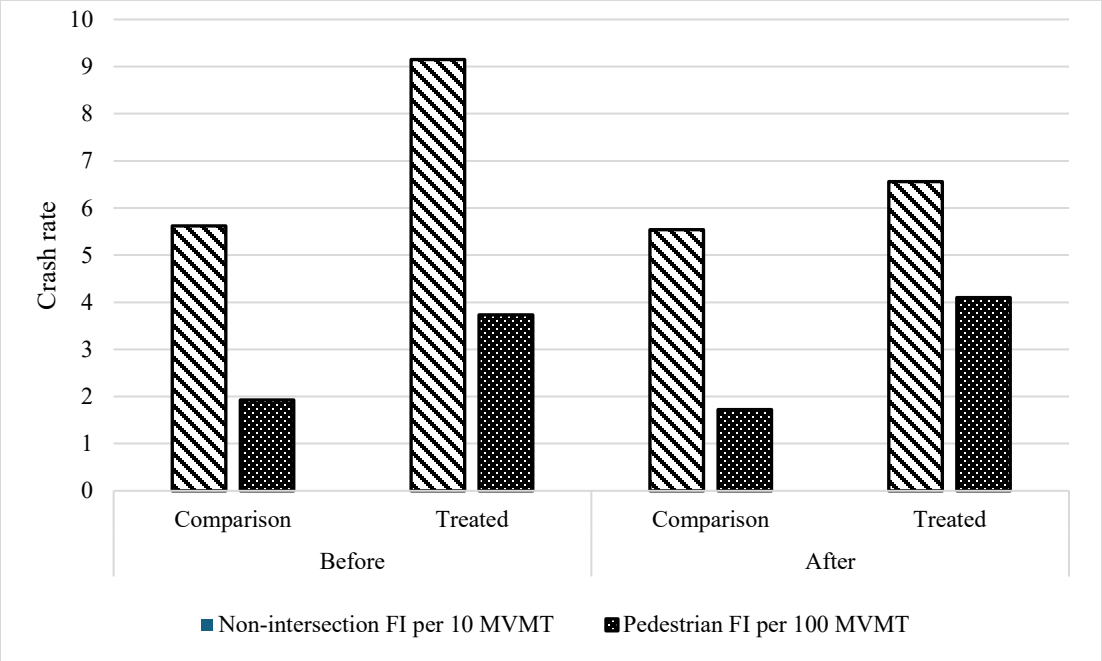


Figure 10. Distribution of Non-intersection FI and Pedestrian FI Crash Rates.

ANALYTICAL APPROACH

This study adopts a quasi-experimental DiD framework to evaluate the impact of sidewalk implementation on operating speeds by comparing temporal changes between treated and comparison corridors. Multiple mixed-effect linear regression models were used to assess the association between operating speed and other attributes. The model specification includes indicator variables for treatment status (i.e., treated or comparison) and implementation period (i.e., before and after), as well as their interaction term, which captures the net effect of the sidewalk intervention after accounting for baseline differences and common time-related trends across corridors.

Given that speed observations are repeatedly measured for the same INRIX XD segments over time, a linear multilevel mixed-effects modeling approach is employed. This structure incorporates random intercepts at both the INRIX segment and corridor levels to account for intra-segment correlation and unobserved heterogeneity across spatial units. By explicitly modeling these hierarchical dependencies, the approach improves the reliability of the estimated effects.

The model also includes a comprehensive set of explanatory variables to control for traffic, roadway design, and temporal influences on speed. These covariates include traffic volume (AADT per lane), lane width, median configuration, presence of bike lanes, PSLs, and temporal factors such as hour of the day, day of the week, and month of the year. This specification enables the isolation of the treatment effect associated with sidewalk implementation while accounting for both observable characteristics and unobserved factors that may influence

operating speeds. With the average speed ($SpdAve$) as the response variable, the DiD model can be presented in the following equation:

$$SpdAve_{ijt} = \beta_0 + \beta_1 Treated_i + \beta_2 After_t + \beta_3 (Treated_i \times After_t) + \beta_4 \mathrm{X}_{ijt} + u_i + v_j + \varepsilon_{ijt}$$

Where:

- $SpdAve_{ijt}$ = average speed for segment i, corridor j, at time t.
- $Treated_i$ = indicator for treated corridors.
- $After_t$ = indicator for after period.
- $Treated_i \times After_t$ = DiD term (treatment effect).
- $\mathbf{X}_{ijt}$ = vector of control variables (AADT per lane, lane width, median type, bike lanes, PSL, time of day, day of the week, month, etc.).
- u_i = random effect for the XD segment.
- v_j = random effect for the corridor.
- ε_{ijt} = error term.

For safety analysis, negative binomial regressions with a similar modeling framework were applied. In this case, the outcome variables were the crash counts (i.e., number of non-intersection FI crashes, pedestrian crashes, and non-intersection FI pedestrian crashes), instead of the average speed. See the following equation:

$$\log(crash\ count) = \beta_0 + \beta_1 Treated_i + \beta_2 After_t + \beta_3 (Treated_i \times After_t) + \beta_4 \mathrm{X}_{ijt} + u_i + v_j + \log(\varepsilon_{ijt})$$

Within the DiD specification, the interaction term (β_3) represents the estimated effect of the sidewalk intervention after accounting for baseline differences and common temporal trends. All analyses were conducted using the R statistical computing environment. The following section presents the results and discussion.

ANALYTICAL RESULTS

Table 19 and Table 20 presents the speed models' results for sidewalk. For lower-PSL facilities (<45 mph), the treatment effect is slightly negative (β = −0.063, t = −16.01), indicating a small but statistically significant reduction in speeds following sidewalk implementation. In contrast, for higher-speed facilities (≥45 mph), the treatment effect is positive and larger in magnitude (β = 0.930, t = 184.39), suggesting that speeds increased at treated corridors relative to comparisons in these environments.

Table 19. Speed Model Results for Sidewalk (Fixed Effects).

Fixed Effects Variable	Lower PSL (<45 mph) Estimate	Lower PSL (<45 mph) Std. Error	Lower PSL (<45 mph) t value	Higher PSL (≥ 45 mph) Estimate	Higher PSL (≥45 mph) Std. Error	Higher PSL (≥45 mph) t value
Intercept	35.380	13.179	2.69	2.755	19.690	0.14
log_AADTlane	−4.086	3.227	−1.27	−4.884	3.029	−1.61
Average lane width (ft)	−0.618	0.374	−1.66	0.554	1.389	0.40
No median	Base	Base	Base	Base	Base	Base
Raised median	2.915	2.991	0.97	1.588	2.302	0.69
TWLTL median	1.223	1.757	0.70	3.275	1.566	2.09
Signalized intersections	−0.079	0.297	−0.27	−0.819	0.693	−1.18
Shoulder width	0.720	0.204	3.53	0.194	0.167	1.16
Bike lane presence	−0.448	2.862	−0.16	−1.006	2.287	−0.44
Posted speed limit	0.533	0.185	2.88	1.009	0.130	7.74
No curb	Base	Base	Base	Base	Base	Base
Curb on one side	−1.109	4.334	−0.26	−0.661	3.252	−0.20
Curb on both sides	−3.329	1.648	−2.02	−0.659	1.814	−0.36
Hour of the day - 0	Base	Base	Base	Base	Base	Base
Hour of the day - 1	0.170	0.007	22.81	−0.105	0.008	−12.84
Hour of the day - 2	0.330	0.008	43.38	−0.109	0.008	−13.05
Hour of the day - 3	0.431	0.008	56.77	0.040	0.008	4.89
Hour of the day - 4	0.722	0.007	99.03	0.485	0.008	60.82
Hour of the day - 5	0.459	0.007	66.22	0.674	0.008	88.69
Hour of the day - 6	−0.541	0.007	−80.98	−0.422	0.007	−57.24
Hour of the day - 7	−2.222	0.007	−339.18	−2.129	0.007	−292.61
Hour of the day - 8	−2.236	0.007	−343.24	−1.983	0.007	−273.50
Hour of the day - 9	−1.995	0.006	−306.99	−1.477	0.007	−204.12
Hour of the day - 10	−2.310	0.006	−356.49	−1.685	0.007	−233.36
Hour of the day - 11	−2.765	0.006	−427.44	−2.044	0.007	−283.38
Hour of the day - 12	−3.085	0.006	−477.77	−2.242	0.007	−311.40
Hour of the day - 13	−3.073	0.006	−475.29	−2.117	0.007	−293.90
Hour of the day - 14	−3.137	0.006	−484.66	−2.305	0.007	−319.74
Hour of the day - 15	−3.612	0.006	−558.20	−2.882	0.007	−399.86
Hour of the day - 16	−3.530	0.006	−545.54	−2.802	0.007	−388.94
Hour of the day - 17	−3.248	0.006	−502.04	−2.470	0.007	−343.25
Hour of the day - 18	−2.507	0.006	−385.77	−1.644	0.007	−227.60
Hour of the day - 19	−2.027	0.007	−310.28	−1.126	0.007	−155.03
Hour of the day - 20	−1.812	0.007	−275.64	−1.055	0.007	−144.45
Hour of the day - 21	−1.495	0.007	−224.92	−0.771	0.007	−104.62
Hour of the day - 22	−0.989	0.007	−144.63	−0.303	0.008	−40.11
Hour of the day - 23	−0.428	0.007	−60.87	−0.053	0.008	−6.84
January	Base	Base	Base	Base	Base	Base
February	−0.412	0.004	−91.92	−0.452	0.005	−89.56
March	−0.193	0.004	−44.34	−0.144	0.005	−29.36
April	0.049	0.004	11.21	0.060	0.005	12.08
May	0.098	0.004	22.53	0.101	0.005	20.66
June	0.226	0.004	51.30	0.264	0.005	53.43

Fixed Effects Variable	Lower PSL (<45 mph) Estimate	Lower PSL (<45 mph) Std. Error	Lower PSL (<45 mph) t value	Higher PSL (≥ 45 mph) Estimate	Higher PSL (≥45 mph) Std. Error	Higher PSL (≥45 mph) t value
July	0.297	0.004	67.65	0.388	0.005	78.76
August	0.131	0.004	30.32	0.206	0.005	42.48
September	0.104	0.004	23.94	0.107	0.005	21.97
October	0.017	0.004	4.07	0.016	0.005	3.34
November	0.064	0.004	14.83	0.113	0.005	23.15
December	0.052	0.004	12.06	0.119	0.005	24.61
Day -Sunday	Base	Base	Base	Base	Base	Base
Day -Monday	−1.083	0.003	−323.51	−1.439	0.004	−382.83
Day -Tuesday	−1.230	0.003	−368.28	−1.616	0.004	−430.50
Day -Wednesday	−1.248	0.003	−374.13	−1.653	0.004	−441.39
Day -Thursday	−1.278	0.003	−383.06	−1.659	0.004	−442.82
Day -Friday	−1.460	0.003	−438.62	−1.666	0.004	−445.35
Day -Saturday	−0.597	0.003	−177.60	−0.572	0.004	−151.52
Before/after: treated/comparison-After	0.885	0.003	311.87	0.259	0.003	101.25
Before/after: treated/comparison-Treated	−0.113	1.530	−0.07	−4.497	1.945	−2.31
Before/after: treated/comparison-Treated*After	−0.063	0.004	−16.01	0.930	0.005	184.39

Note: Number of observations = 16,112,761 for low speed and 17,247,502 for high speed. Number of unique XD segments 442 for low speed and 447 for high speed. Number of unique corridors 85 for low speed and 96 for high speed.

Table 20. Speed Model Results for Sidewalk (Random Effects).

Grouping variable	Lower PSL (<45 mph) Variance	Lower PSL (<45 mph) SD	Higher PSL (≥ 45 mph) Variance	Higher PSL (≥ 45 mph) SD
XD Segment ID (Intercept)	19.36	4.400	33.06	5.749
Corridor name (Intercept)	25.07	5.001	23.26	4.823
Residual	12.48	3.533	16.90	4.111

The after-period effect (β_{after}) is positive in both models, indicating that speeds generally increased over time regardless of treatment status, with a larger increase observed on lower-speed facilities (β = 0.885) than on higher-speed facilities (β = 0.259). The treated corridor coefficient ($\beta_{treated}$) suggests that prior to sidewalk implementation, treated and comparison corridors had similar speeds in lower-speed environments, whereas treated corridors in higher-speed environments operated at substantially lower speeds than their matched comparisons (β = −4.497, t = −2.31).

Among the roadway characteristics, PSL was a strong and statistically significant predictor of operating speed in both models, with a larger effect observed on higher-speed facilities. Shoulder

width was positively associated with speed on lower-speed facilities, suggesting that wider roadside space may encourage higher travel speeds. Corridors with curbs on both sides experienced lower speeds than corridors without curbs in the lower-speed group, while most median, bike lane, and signalized intersection variables were not consistently significant across the two models. The random-effects estimates indicate substantial variability at both the XD segment and corridor levels, justifying the use of a mixed-effects framework to account for the hierarchical structure of the data. These results indicate that sidewalk impacts on roadway operating speed are dependent on the roadway speed environment, with slight reductions in lower-speed settings and increases in higher-speed environments.

Table 21 present the FI non-intersection crash model results for all crashes. The DiD estimate for FI crashes ($\beta = -0.365$, $p = 0.055$) is negative and marginally significant, indicating that sidewalk implementation was associated with a reduction in FI crashes relative to the comparison corridors. The after-period effect ($\beta = -0.270$, $p = 0.017$) is negative and statistically significant, showing that FI crashes declined across both treated and comparison corridors over time. The treatment coefficient ($\beta = 0.342$, $p = 0.023$) is positive and marginally significant, suggesting that treated corridors experienced somewhat higher FI crash frequencies than comparison corridors prior to sidewalk installation. Among the control variables, traffic volume (log AADT per lane) is positively and significantly associated with FI crashes, indicating that corridors with higher traffic volumes tend to experience more severe crashes. Shoulder width is negatively associated with FI crashes and is statistically significant, suggesting that wider shoulders may contribute to lower severe-crash frequencies. The presence of curbs is positively associated with FI crashes, with both one- and two-sided curb configurations showing significantly higher FI crash frequencies than corridors without curbs. The random-effects results indicate moderate variability across corridors, supporting the use of the mixed-effects modeling framework to account for differences among study corridors.

Table 21. FI Non-intersection Crash Model Results for Sidewalk Corridors.

Fixed-Effects Variable	Estimate	Std. Error	P-value
Intercept	−10.422	1.19	<0.001
log AADT per lane	2.615	0.34	<0.001
No curb	Base	Base	Base
Curb on one side	0.899	0.28	0.001
Curb on both sides	0.454	0.15	0.003
Shoulder Width	−0.045	0.02	0.007
Before/After: Treated/Comparison - Before	Base	Base	Base
Before/After: Treated/Comparison - After	−0.270	0.11	0.017
Before/After: Treated/Comparison - Treated	0.342	0.15	0.023
Before/After: Treated/Comparison - Treated *After	−0.365	0.19	0.055

Note: Random effect properties: variance = 0.246 and standard deviation 0.496. Number of observations: 362, number of unique corridors: 58.

Table 22 shows the crash model results for both pedestrian crashes (which include all severity levels) and pedestrian FI non-intersection crashes. The DiD estimate for total pedestrian crashes is negative but not statistically significant ($\beta = -0.138$, $p = 0.739$). The observation indicates that sidewalk installation was not associated with a measurable reduction in pedestrian crashes relative to the comparison corridors. Similarly, the after-period effect ($\beta = -0.176$, $p = 0.542$) is not statistically significant, suggesting that pedestrian crash frequencies did not change appreciably over time across either treated or comparison corridors. The treatment coefficient ($\beta = 1.251$, $p < 0.001$) is positive and statistically significant, indicating that treated corridors experienced higher pedestrian crash frequencies than comparison corridors prior to sidewalk installation. Among the control variables, traffic volume (log AADT per lane) is positively associated with pedestrian crashes and is marginally statistically significant ($p = 0.054$). Corridors with on-street parking experience significantly fewer pedestrian crashes than corridors without on-street parking ($\beta = -0.846$, $p = 0.039$), while the effects of median type are not statistically significant. The random-effects results indicate moderate variation across corridors, supporting the use of the mixed-effects modeling framework to account for corridor-level differences.

Table 22. Pedestrian Crash Model Results for Sidewalk Corridors.

Fixed-Effects Variable	Ped Estimate	Ped Std. Error	Ped P-value	Ped FI&NI Estimate	Ped FI&NI Std. Error	Ped FI&NI P-value
Intercept	−9.718	2.619	<0.001	−8.933	2.845	0.002
log AADT per lane	1.463	0.759	0.054	1.087	0.830	0.190
No median	Base	Base	Base	Base	Base	Base
TWLTL median	0.604	0.342	0.077	0.600	0.380	0.114
Raised median	0.483	0.481	0.315	0.681	0.518	0.189
On Street Parking	−0.846	0.409	0.039	-	-	-
Before/After: Treated/ Comparison - Before	Base	Base	Base	Base	Base	Base
Before/After: Treated/ Comparison - After	−0.176	0.289	0.542	−0.159	0.337	0.636
Before/After: Treated/ Comparison - Treated	1.251	0.294	<0.001	1.066	0.324	0.001
Before/After: Treated/ Comparison - Treated *After	−0.138	0.415	0.739	−0.074	0.466	0.873

Note: Ped = pedestrian crashes and Ped FI&NI = fatal and injury pedestrian non-intersection crashes. Random effect properties: variance = 0.584 for pedestrian crashes and 0.473 for pedestrian FI non-intersection crashes. Standard deviation = 0.764 for pedestrian crashes and 0.687 for pedestrian FI non-intersection crashes. Number of observations: 362, number of unique corridors: 58.

The results for pedestrian FI non-intersection crashes show a similar pattern (see Table 22). The DiD estimate is negative but not statistically significant ($\beta = -0.074$, $p = 0.873$), indicating no measurable reduction in pedestrian FI non-intersection crashes following sidewalk installation.

Likewise, the after-period effect ($\beta = -0.159$, $p = 0.636$) is not statistically significant, whereas the treatment coefficient ($\beta = 1.066$, $p = 0.001$) indicates that treated corridors experienced significantly higher pedestrian FI non-intersection crash frequencies than comparison corridors before sidewalk installation. None of the roadway characteristics, including traffic volume and median type, are statistically significant predictors of pedestrian FI non-intersection crashes. The random-effects results again indicate moderate corridor-level variation, supporting the inclusion of random intercepts in the model.

DISCUSSION OF THE RESULTS

The results demonstrate that the operational effects of sidewalk installation differ according to the roadway speed environment. On lower-speed facilities (<45 mph), sidewalk installation was associated with a modest but statistically significant reduction in operating speeds relative to the comparison corridors. Although the magnitude of the reduction was small, it suggests that sidewalks can influence driver behavior by creating a roadway environment that encourages slower driving. Sidewalks may be installed along either curbed or uncurbed roadway sections, and this distinction may influence how drivers perceive the roadway. Curbed sections provide a more defined edge between the traveled way and pedestrian space, whereas uncurbed sections may include shoulders, drainage areas, or other lateral separation between the roadway and sidewalk. In the present study, curbs on both sides of the roadway were associated with approximately 3.33 mph lower operating speeds than locations without curbs on lower-speed corridors. This finding suggests that the observed operating-speed environment reflects not only the presence of a sidewalk but also its surrounding roadside configuration. The distinction between curbed and uncurbed sidewalk environments is also relevant from a design perspective, as TxDOT roadway design guidance applies different roadside and clear-zone considerations to curbed and uncurbed facilities. Similar observations were reported by Thiessen et al., who found that sidewalks located closer to the travel lane were associated with lower operating speeds because they increased the sense of enclosure and driver awareness of roadside activity (*45*). Likewise, Lian and Lee concluded that greater sidewalk visibility contributed to lower operating speeds by increasing drivers' awareness of pedestrians and creating a more pedestrian-oriented streetscape (*47*). Together, these findings suggest that sidewalks can function as part of a broader traffic-calming environment on lower-speed urban roadways.

The findings for higher-speed facilities (≥45 mph) paint a different picture. Sidewalk installation was associated with a slight increase in operating speeds relative to the comparison corridors, indicating that sidewalks alone were insufficient to encourage slower speeds on these facilities. This distinction between curbed and uncurbed environments was less evident on higher-speed facilities, where curb presence was not significantly associated with operating speed. On higher-speed corridors, driver speed choice is likely governed primarily by roadway geometry, PSLs, median configuration, lane arrangement, and traffic flow characteristics rather than by the presence of the sidewalk. Consistent with this interpretation, median type emerged as one of the

strongest predictors of operating speed in the higher-speed model with higher operating speeds for raised or TWLTL medians as compared to no median. These findings are consistent with Eluru et al., who reported that the relationship between sidewalks and operating speeds varied considerably across roadway types and depended on the surrounding roadway environment (*44*). The findings also differ from those reported by Dinh and Kubota, who observed higher operating speeds on low-speed residential streets with sidewalks on both sides of the roadway (*43*).

Furthermore, the results indicate that sidewalk installation was associated with a reduction in FI crashes on treated corridors relative to the comparison corridors. The negative coefficient suggests that treated corridors experienced fewer severe crashes following sidewalk installation than comparable untreated corridors. Direct comparisons with previous studies are somewhat limited because most sidewalk research has focused on pedestrian crashes and pedestrian safety rather than all crashes. Existing studies generally report that sidewalks improve safety by separating pedestrians from motor vehicle traffic and reducing conflict opportunities (*46*, *51*). However, relatively few studies have examined whether sidewalk installation influences overall severe crash outcomes at the corridor level. The findings from this study suggest that the safety benefits of sidewalks may extend beyond pedestrian-specific outcomes. One possible explanation is that sidewalks contribute to a more organized roadway environment by clearly defining the space allocated to different roadway users. The reduction in FI crashes observed on treated corridors following sidewalk installation is consistent with the broader safety objective of reducing conflicts and improving roadway operations. Although severe crashes also declined on comparison corridors during the study period, the additional reduction observed on treated corridors suggests that sidewalk installation contributed to the observed safety improvements. Given the limited literature examining the relationship between sidewalks and crashes, these findings provide valuable evidence that sidewalk installation may be associated with improved corridor safety performance.

The findings from this study indicate that sidewalk installation was not associated with a measurable reduction in pedestrian FI crashes. This result differs from much of the existing literature, which generally reports safety benefits associated with sidewalks. Some of the previous studies have consistently found that sidewalks provide a safer walking environment by separating pedestrians from motor vehicle traffic and reducing pedestrian exposure along roadway segments (*46, 51*). However, such an observation should be further explored because Raihan et at. reported that the presence of the sidewalk and sidewalk barrier is associated with the increase in bicyclist crashes (*52*). The study cautioned the interpretation of such contrasting findings because the presence of sidewalks may increase bicyclist activities and exposure to crashes. Regardless, most of these studies have focused on pedestrian crash risk, bicyclists' safety, or comparisons between locations with and without sidewalks rather than evaluating changes in pedestrian crashes following sidewalk installation. Consequently, direct comparisons with the present study are limited. One possible explanation of the statistically insignificant findings is that sidewalks primarily improve pedestrian safety along roadway segments, whereas

many pedestrian FI crashes occur at intersections, driveways, and crossing locations where pedestrian–vehicle conflicts remain. As a result, sidewalk installation alone may not be sufficient to produce meaningful reductions in severe pedestrian crashes without complementary treatments such as marked crossings, pedestrian signals, lighting, or traffic-calming measures. The findings may also suggest that sidewalks were frequently installed on corridors with existing pedestrian safety concerns, reflecting the common practice of prioritizing pedestrian infrastructure investments at higher-risk locations.

CHAPTER 5: EVALUATION OF ROUNDABOUTS

INTRODUCTION

Roundabouts are circular intersections designed to improve traffic flow and reduce crash severity by promoting continuous, low-speed movement. Vehicles entering the roundabout yield to circulating traffic, which minimizes conflict points compared to traditional signalized or stop-controlled intersections (*53*). This design reduces the likelihood of high-speed angle and head-on collisions, often resulting in fewer severe injuries (*54*). Roundabouts are also associated with operational benefits, including reduced delays, lower fuel consumption, and improved traffic efficiency under varying demand conditions (*55*). Their effectiveness depends on proper design, including geometry, signage, and accommodation for pedestrians and cyclists, particularly in urban and multimodal environments (*55*).

In Texas, the implementation of roundabouts has expanded steadily over the past decade as agencies seek alternatives to traditional signalized and stop-controlled intersections. Early applications were primarily located in suburban and rural settings, where lower traffic complexity and available right of way facilitated adoption. More recently, roundabouts have been introduced along major arterials and at high-speed intersections to address safety concerns, particularly severe angle and head-on crashes. Agencies such as TxDOT have increasingly incorporated roundabouts into project development processes, supported by evolving design guidance and growing familiarity among practitioners. Despite this progress, implementation across the state remains uneven, with variability in design practices, driver expectations, and public acceptance. In corridor settings, the use of multiple roundabouts along a single arterial remains relatively limited, and their combined operational and safety effects are not well documented.

Previous research on roundabouts primarily focused on intersection-level performance, emphasizing reductions in delay, conflict points, and crash severity at individual locations (*56, 57, 58*). While these studies provide strong evidence of the localized safety and operational benefits of roundabouts, they do not fully capture how multiple roundabouts interact along a corridor. In practice, arterial roadways often include a series of intersections where driver behavior, speed adaptation, and traffic flow are influenced by upstream and downstream conditions. As a result, evaluating roundabouts in isolation may overlook cumulative effects such as speed harmonization, platooning, or shifts in crash patterns along the corridor. In addition, many existing studies rely on short-term before-and-after analyses or lack appropriate control corridors, limiting their ability to distinguish treatment effects from broader temporal trends. This study addresses these gaps by evaluating the corridor-level safety and operational impacts of roundabouts using a matched control framework and a DiD approach, with the objective of quantifying how roundabout implementation influences speed and crash outcomes across entire arterial segments rather than at individual intersections.

LITERATURE SUMMARY

The literature review is divided into two sections—safety and operational performance—to align with the study objectives. The first section reviews prior research on crash outcomes, while the second examines the treatment's effects on operating speeds.

Safety Review

Conventional intersections controlled by stop signs or traffic signals are commonly associated with severe crash types such as right-angle, left-turn, and head-on collisions, largely due to higher approach speeds and multiple crossing conflict points. Roundabouts modify these conditions by channelizing traffic into a single circulating direction and reducing entry speeds, thereby eliminating many of the high-severity conflict types. The remaining interactions are typically merging and diverging maneuvers, which occur at lower speeds and generally result in less severe outcomes.

A substantial body of research has documented the safety benefits of converting conventional intersections to roundabouts. In the United States, studies have reported reductions in injury crashes ranging from 72 to 80 percent and total crash reductions between 35 and 47 percent following conversion (*55, 59*, *60*). At higher-speed rural intersections, reductions of 62 percent in total crashes and 85 percent in injury crashes have been observed (*61*). Similar findings have been reported internationally, with studies in Europe and Australia indicating reductions in injury crashes between 25 and 87 percent and total crashes between 36 and 61 percent (*55*). Despite these benefits, performance varies by design because single-lane roundabouts generally achieve greater safety improvements, while multilane roundabouts have shown smaller reductions or, in some cases, increases in crashes (*61, 62*). Evidence also suggests that safety performance at multilane roundabouts improves over time as drivers gain familiarity (*63*).

Roundabouts can also enhance pedestrian safety by simplifying crossing tasks and reducing vehicle speeds. Pedestrians typically cross one direction of traffic at a time over shorter distances, which reduces exposure to risk. Studies in Europe have reported approximately 75 percent reductions in pedestrian crashes after conversion to roundabouts (*64*), and single-lane roundabouts have been shown to perform better than signalized intersections in terms of pedestrian safety (*65*). However, multilane roundabouts present additional challenges because drivers are less likely to yield to pedestrians—particularly at exit legs—resulting in higher rates of driver noncompliance compared to single-lane configurations (*66*, *67*).

Recent literature continues to affirm the safety benefits of roundabouts while highlighting the importance of context-sensitive evaluation. Guidance from FHWA and research by the Insurance Institute for Highway Safety indicate that roundabouts reduce the likelihood of severe crashes by lowering speeds and eliminating high-risk conflict types such as right-angle and head-on collisions (*68*, *54*). More recent studies, however, move beyond generalized safety claims and

emphasize variability in performance across corridors. For example, recent work has developed crash-specific safety performance functions, showing that factors such as traffic volume, geometric design, and surrounding context significantly influence crash frequency and severity (*69*). Additional studies demonstrate that crash severity outcomes at roundabouts depend on roadway, environmental, vehicle, and driver-related characteristics (*57*). Emerging approaches, including traffic conflict analysis, are increasingly used to assess safety where crash data are limited, offering a proactive understanding of risk (*70*). The literature also identifies ongoing challenges, particularly for multilane roundabouts and VRUs, where lower yielding rates and more complex crossing conditions can affect pedestrian and bicyclist safety (*58, 66*). Collectively, these findings indicate that while roundabouts provide substantial safety benefits, their effectiveness varies depending on design features, operational context, and user interactions.

Operational Review

A growing body of research has documented the operational benefits of roundabouts, particularly in terms of reducing delays and improving traffic flow relative to traditional stop- or signal-controlled intersections. By allowing continuous movement and minimizing full stops, roundabouts can substantially reduce both vehicle delay and the frequency of stopping. Early studies found that converting stop-controlled intersections to roundabouts reduced delays by 13 to 23 percent and decreased the proportion of vehicles required to stop by 14 to 37 percent (*71*). More pronounced effects have been reported at corridors where signals or stop control were replaced, including an average reduction of 89 percent in vehicle delay and 56 percent in stops across locations in New Hampshire, New York, and Washington (*72*), as well as a 65 percent reduction in delays and 52 percent reduction in stops at intersections in Kansas (*73*). While most studies report overall improvements, some evidence suggests that benefits may vary by approach; for example, two-lane roundabout conversions near Bellingham, Washington, resulted in significant reductions in delay and queueing on minor approaches, but modest increases in overall intersection delay due to slower movements on major approaches (*74*).

Recent studies continue to demonstrate the operational advantages of roundabouts while emphasizing that their performance depends on traffic demand and geometric design. Empirical and simulation-based studies have shown that roundabouts can reduce vehicle delay, queue length, and stop-and-go conditions, resulting in smoother traffic flow and improved throughput under moderate traffic volumes (*58*). However, these benefits become more sensitive under high or unbalanced traffic demands, particularly at multilane roundabouts where capacity constraints and merging conflicts are more likely to occur (*75, 58*). The literature further indicates that operational performance is strongly influenced by entry geometry, lane configuration, driver behavior, and traffic characteristics, underscoring the need for context-sensitive roundabout design and evaluation (*76*). Together, these studies suggest that although roundabouts generally

improve operational efficiency compared to conventional intersections, their performance ultimately depends on site-specific geometric and traffic conditions.

Gap and Study Contribution

Existing research on roundabouts has predominantly focused on isolated intersection-level analyses, emphasizing changes in delay, stops, and crash outcomes at individual locations, with limited attention to how multiple roundabouts function collectively along a corridor. This narrow focus overlooks potential cumulative effects such as speed harmonization, traffic progression, and shifts in crash patterns that emerge when roundabouts are implemented in sequence. In addition, many prior studies rely on short-term before-and-after comparisons or lack well-matched control corridors, making it difficult to distinguish treatment effects from broader temporal trends. This study addresses these limitations by evaluating roundabouts at the corridor level using a matched-control framework and a DiD approach, integrating high-resolution probe-speed data with exposure-based crash measures. By focusing on arterial corridors in Texas, the study provides new evidence on how multiple roundabouts influence operational performance and safety outcomes in a real-world, system-level context.

STUDY DATA DESCRIPTION

This section presents the study data description, which includes the identification of treated and control corridors, the collection and reduction of speed and crash data, and descriptive statistics of the data.

Identification of the Treated and Control Corridors

To identify the treated corridors, the roundabout database developed and hosted by Kittleson Associates was used as a starting point (*77*). The database contains information such as the installation date, coordinates, traffic control type, number of approaches, etc., of most roundabouts around the globe. The roundabouts installed between 2020 and 2025 were deemed appropriate for this study because probe speed data were available. Further, since this study focuses on corridor-level evaluation, only corridors containing two or more roundabouts were selected. For a roadway to be considered as a corridor, it should have two or more roundabouts located within 0.5 miles of each other. In the case of a corridor turn, the roads should have similar characteristics, such as PSLs, landscaping, and number of lanes. The research team then collected additional corridor attributes, including corridor length, number of lanes, average lane width, shoulder width, PSL, number of signalized intersections, and traffic volume. The construction period of the roundabouts was determined using Google Maps and Google Earth Tools.

To identify the control corridors, the research team used Google Earth and Google Maps tools. To be considered a control, the corridor should have characteristics similar to those of the

corresponding treated corridor. For the PSL, the allowable difference between treated and control corridors was 5 mph. Priorities were given to corridors near the treated corridors.

Since the study uses INRIX XD speed probe data, the research team explored the availability of INRIX XD segments at the identified corridors. This process was performed in the ArcGIS platform, whereby the INRIX XD segment layer was overlaid on the identified corridor, and the corridors without INRIX XD segments were removed from the dataset. Finally, 25 study corridors, which included eight roundabout corridors and 17 comparison corridors, were available for evaluation. On average, each treated corridor had three roundabouts with a minimum of two and a maximum of six.

Speed Data Collection and Reduction

This study used high-resolution probe-based speed data to examine the operational impact of roundabouts along a corridor. INRIX XD data were selected as the primary source because they provide continuous, minute-level average vehicle speeds over extended periods (*35*). This temporal coverage allows speeds to be examined at any time of day rather than being limited to discrete observation periods. While INRIX XD probe data rely on a sample of vehicles, prior evidence suggests that they produce speed estimates comparable to those from floating-car methods.

The INRIX XD probe data are normally provided at a segment level. This requires identifying all relevant INRIX XD segments in both treated and control corridors. After obtaining all the INRIX segments, the research team extracted speed data using the RITIS Probe Data Analytics Suite for a multi-year period spanning 2018 through 2025. Several filtering steps were applied to ensure data quality and consistency. Observations recorded during the construction phase were excluded to avoid transitional effects. Very short segments (0.06 miles or less) were removed because they are typically associated with intersections where stopping behavior can distort speed measurements. Records with low reliability (confidence values below 90 or missing) were also discarded to retain only high-quality observations. After application of these criteria, the final dataset consisted of 6,317,399 hourly speed observations across 253 INRIX XD segments.

Crash Data Collection and Reduction

This study used Texas crash data collected from TxDOT's CRIS database for crashes that occurred between 2018 and 2025. The focus was on the total crashes only because they have a direct link to the roundabout treatments. For safety evaluation, corridor-level data aggregation was appropriate. To obtain crashes that occurred within the corridors, the research team first mapped the corridors and created a 250-ft buffer around each corridor. The geocoded crashes were then overlaid on the buffered corridors, and all the crashes that fell within the buffers were extracted. The team performed additional processing to remove double-counted crashes, especially at locations where the buffers of two corridors intersect. To prepare the database for

analysis, crashes occurring before and after the countermeasure installations were identified. Further, the research team counted the total number of crashes for each corridor before and after installation. To this end, the study sites experienced a total of 1587 crashes, including 163 in treated corridors before and 229 after. On the other hand, comparison corridors experienced 668 and 527 crashes for the before and after periods, respectively.

DESCRIPTIVE ANALYSIS OF THE DATA

The descriptive analysis of the study data aims to provide a clear summary of the key characteristics and distributions of the variables across treated and control corridors for the before-and-after periods. It covers the details for the study corridors, speed data, and crash data.

Study Corridors

Table 23 and Table 24 present the distribution of key continuous variables for both treated and control corridors. The average length of the treated corridors was 1.6 miles compared to 1.2 miles for the control corridors. Treated corridors generally had fewer lanes before implementation, although the average increased from 2.3 to 3.0 lanes in the after period. Average lane widths were consistently narrower on treated corridors than on control corridors, while shoulder widths were generally wider before implementation but decreased following roundabout construction. Control corridors contained substantially more signalized intersections than treated corridors in both periods, while traffic volumes were comparable, with slightly higher volumes on the control corridors. The duration of the study periods was also similar between treated and comparison corridors within each evaluation period.

Roadway characteristics differed between the two corridor groups. Control corridors had PSLs of 25 to 40 mph, whereas treated corridors had PSLs of 30 to 45 mph before implementation and 30 to 40 mph after implementation. Median presence remained relatively stable on the control corridors, while most treated corridors transitioned from having no median before implementation to having a median after construction. Bike lanes were uncommon across both groups, with only two control corridors containing bike lanes throughout the study period and one treated corridor including a bike lane after implementation. Similarly, curb presence was more common after construction on the treated corridors, increasing from four corridors before construction to all eight corridors after construction, while the control corridors remained largely unchanged, with curbs present on 15 of the 17 corridors during both study periods.

Table 23. Distribution of Corridor Characteristics for Study Corridors (Continuous Variables).

Variable	Before/ After	Treated/ Comparison	Number of Sites	Min	Mean	Max	SD
Corridor length	Before	Control	17	0.7	1.2	2.0	0.4
Corridor length	Before	Treated	8	1.2	1.6	2.3	0.4
Corridor length	After	Control	17	0.7	1.2	2.0	0.4
Corridor length	After	Treated	8	1.2	1.6	2.3	0.4
Number of lanes	Before	Control	17	2.0	2.8	4.0	1.0
Number of lanes	Before	Treated	8	2.0	2.3	4.0	0.7
Number of lanes	After	Control	17	2.0	2.8	4.0	1.0
Number of lanes	After	Treated	8	2.0	3.0	4.0	1.1
Average lane width (ft)	Before	Control	17	9.0	13.8	23.0	3.9
Average lane width (ft)	Before	Treated	8	10.0	11.2	12.5	1.0
Average lane width (ft)	After	Control	17	9.0	13.7	23.0	4.0
Average lane width (ft)	After	Treated	8	10.0	11.6	13.0	1.0
Shoulder width (ft)	Before	Control	17	0.0	0.1	1.0	0.2
Shoulder width (ft)	Before	Treated	8	0.0	0.8	1.0	0.5
Shoulder width (ft)	After	Control	17	0.0	0.1	1.0	0.2
Shoulder width (ft)	After	Treated	8	0.0	0.3	1.0	0.5
Number of signalized intersections	Before	Control	17	0.0	1.9	9.0	2.4
Number of signalized intersections	Before	Treated	8	0.0	0.4	2.0	0.7
Number of signalized intersections	After	Control	17	0.0	1.9	9.0	2.4
Number of signalized intersections	After	Treated	8	0.0	0.5	2.0	0.8
ADT	Before	Control	17	1,282.0	8,175.0	25,400.0	6,632.0
ADT	Before	Treated	8	2,364.0	6,045.0	16,367.0	4896.0
ADT	After	Control	17	252.0	8,113.0	24,887.0	6,,360.0
ADT	After	Treated	8	2,098.0	6,767.0	20,588.0	6,231.0
Study period (days)	Before	Control	17	328.0	826.0	2,022.0	503.0
Study period (days)	Before	Treated	8	328.0	829.0	2,022.0	537.0
Study period (days)	After	Control	17	286.0	1,229.0	1,872.0	554.0
Study period (days)	After	Treated	8	286.0	1,196.0	1,872.0	574.0

Table 24. Distribution of Corridor Characteristics for Study Corridors (Categorical Variables).

Variable	Before/after	Corridor Type	Variable Category	Count
PSL (mph)	Before	Control	25	1
PSL (mph)	Before	Control	30	5
PSL (mph)	Before	Control	35	6
PSL (mph)	Before	Control	40	5
PSL (mph)	Before	Treated	30	2
PSL (mph)	Before	Treated	35	3
PSL (mph)	Before	Treated	40	2
PSL (mph)	Before	Treated	45	1
PSL (mph)	After	Control	25	1
PSL (mph)	After	Control	30	5
PSL (mph)	After	Control	35	6
PSL (mph)	After	Control	40	5
PSL (mph)	After	Treated	30	3
PSL (mph)	After	Treated	35	3
PSL (mph)	After	Treated	40	2
Median presence	Before	Control	No median	7
Median presence	Before	Control	Median present	10
Median presence	Before	Treated	No median	7
Median presence	Before	Treated	Median present	1
Median presence	After	Control	No median	7
Median presence	After	Control	Median present	10
Median presence	After	Treated	No median	1
Median presence	After	Treated	Median present	7
Bike lane presence	Before	Control	No bike lane	15
Bike lane presence	Before	Control	Bike lane present	2
Bike lane presence	Before	Treated	No bike lane	8
Bike lane presence	Before	Treated	Bike lane present	0
Bike lane presence	After	Control	No bike lane	15
Bike lane presence	After	Control	Bike lane present	2
Bike lane presence	After	Treated	No bike lane	7
Bike lane presence	After	Treated	Bike lane present	1
Curb presence	Before	Control	No curb	2
Curb presence	Before	Control	Curb present	15
Curb presence	Before	Treated	No curb	4
Curb presence	Before	Treated	Curb present	4
Curb presence	After	Control	No curb	2
Curb presence	After	Control	Curb present	15
Curb presence	After	Treated	No curb	0
Curb presence	After	Treated	Curb present	8

Speed Distribution

The descriptive analysis for roundabouts examines how operating speeds vary across key roadway and corridor characteristics, with a particular focus on differences between treated and

control locations. Specifically, speed patterns are explored by corridor type (treated versus control), median configuration, presence of bike lanes, and PSLs. This analysis provides an initial understanding of how roundabout implementation is associated with changes in speed behavior across different contexts.

Table 25 presents the descriptive statistics of the speed data. Over 6.3 million speed observations were included in the analysis, with an overall average operating speed of 28.1 mph. Average speeds were slightly higher during the after period (28.2 mph) than during the before period (27.9 mph). Overall, treated corridors exhibited higher average operating speeds (29.0 mph) than comparison corridors (27.3 mph), while also showing slightly lower variability. Across the roadway characteristics examined, operating speeds generally varied with roadway design. Corridors without medians tended to exhibit higher speeds than those with medians on the treated corridors, whereas the opposite pattern was observed on the comparison corridors during the after period. Corridors without bike lanes generally operated at higher speeds than those with bike lanes, while differences associated with curb presence were relatively modest. As expected, average operating speeds increased with higher PSLs, with the highest speeds observed on corridors posted at 40 and 45 mph.

Table 25. Descriptive Analysis of Speed Data.

Before/After	Treated/Control	Variable	N	Mean	Min	Max	SD
Both	Both	All	6,317,399	2.5	28.1	60.3	5.7
Before	Both	All	1,632,935	2.5	27.9	60.0	5.8
After	Both	All	4,684,464	4.1	28.2	60.3	5.7
Both	Control	All	3,298,250	2.8	27.3	54.0	5.9
Both	Treated	All	3,019,149	2.5	29.0	60.3	5.3
Before	Control	No median	397,331	3.4	26.9	48.5	5.9
Before	Control	Median present	617,575	2.8	26.8	51.2	5.7
Before	Treated	No median	565,937	2.8	29.9	60.0	5.2
Before	Treated	Median present	52,092	2.5	26.3	42.3	5.9
After	Control	No median	829,493	6.0	23.6	51.4	3.9
After	Control	Median present	1,453,851	6.0	29.7	54.0	5.8
After	Treated	No median	2,100,129	4.1	29.0	59.2	5.1
After	Treated	Median present	300,991	6.1	28.2	60.3	6.6
Before	Control	No bike lane	670,145	3.4	28.1	51.2	5.3
Before	Control	Bike lane present	344,761	2.8	24.4	48.1	5.8
Before	Treated	No bike lane	618,029	2.5	29.6	60.0	5.3
After	Control	No bike lane	1,962,721	6.0	27.8	52.1	6.0
After	Control	Bike lane present	320,623	6.0	25.8	54.0	5.7
After	Treated	No bike lane	2,401,120	4.1	28.9	60.3	5.3
Before	Control	No curb	271,745	5.7	29.4	48.5	4.6
Before	Control	Curb present	743,161	2.8	25.9	51.2	5.9
Before	Control	No curb	252,945	3.7	29.8	48.8	4.3
Before	Control	Curb present	365,084	2.5	29.5	60.0	5.9
After	Treated	No curb	79,760	8.5	30.3	50.3	4.6
After	Treated	Curb present	2,203,584	6.0	27.4	54.0	6.0
After	Treated	No curb	983,108	4.1	29.7	56.2	5.7
After	Treated	Curb present	1,418,012	4.6	28.3	60.3	4.9
Before	Control	PSL 25	32,446	8.9	24.9	35.3	3.4
Before	Control	PSL 30	105,353	3.4	21.1	38.9	4.7
Before	Control	PSL 35	802,007	2.8	27.4	51.2	5.6
Before	Control	PSL 40	75,100	5.0	29.6	42.9	4.1
Before	Treated	PSL 30	100,142	5.0	27.6	38.7	3.6
Before	Treated	PSL 35	235,993	3.7	30.0	48.8	4.2
Before	Treated	PSL 40	61,190	2.5	26.2	42.3	5.7
Before	Treated	PSL 45	220,704	2.8	31.0	60.0	6.2
After	Control	PSL 25	382,325	9.5	23.6	51.4	2.2
After	Control	PSL 30	737,126	6.0	24.1	47.7	4.2
After	Control	PSL 35	558,423	6.0	28.1	54.0	5.7
After	Control	PSL 40	605,470	12.0	33.6	52.1	4.2
After	Treated	PSL 30	754,086	8.3	26.8	42.8	3.2
After	Treated	PSL 35	901,846	4.1	30.1	56.2	5.6
After	Treated	PSL 40	582,301	4.6	28.8	60.3	5.7
After	Treated	PSL 45	162,887	5.7	31.4	59.2	6.5

Crash Frequency and Rates

While frequency can indicate the safety effectiveness of the countermeasure, it does not account for differences in exposure durations between the before and after periods at each study site. To account for differences in exposure durations, the study used the crash rate, defined as the number of crashes normalized by the traffic volume and the number of days before and after installation. Table 26 presents the distribution of total and pedestrian crash frequencies and rates for control and treated corridors across the before and after periods. Crash frequencies declined on comparison corridors, with the average decreasing from 39.3 crashes in the before period to 31.0 crashes in the after period. In contrast, treated corridors experienced a slight increase in average crash frequency from 20.4 to 28.6 crashes, although they continued to have lower average crash frequencies than the comparison corridors in both periods. For crash rates, treated corridors exhibited lower average crash rates than comparison corridors before and after roundabout installation. The average crash rate on treated corridors decreased from 3.45 to 2.76 crashes per period, whereas the comparison corridors experienced a slight increase from 4.12 to 4.60. Comparison corridors also exhibited greater variability in both crash frequencies and crash rates than treated corridors, particularly during the after period.

Table 26. Distribution of Total Crash Frequency and Rate.

Safety Measure	Before/ After	Treated/ Comparison	Number of Sites	Crash Count	Min Crashes	Mean Crashes	Max Crashes	SD
Crash frequency	Before	Comparison	17	668	1.00	39.30	215	58.40
Crash frequency	Before	Treated	8	163	3.00	20.40	57	18.80
Crash frequency	After	Comparison	17	527	2.00	31.00	115	28.40
Crash frequency	After	Treated	8	229	1.00	28.60	74	23.40
Crash rate (crashes per MVMT)	Before	Comparison	17	NA	0.74	4.12	9.27	2.52
Crash rate (crashes per MVMT)	Before	Treated	8	NA	0.54	3.45	9.12	2.70
Crash rate (crashes per MVMT)	After	Comparison	17	NA	0.67	4.60	12.7	3.82
Crash rate (crashes per MVMT)	After	Treated	8	NA	0.65	2.76	5.42	1.60

NA = not applicable.

ANALYTICAL APPROACH

This analysis employs a quasi-experimental DiD approach to quantify how roadway interventions influence operating speeds by tracking temporal changes across treated and comparison corridors (*78*). The specification includes binary indicators for treatment assignment and post-implementation period, along with their interaction term, which represents the incremental effect attributable to the intervention after controlling for preexisting differences and shared time trends. Because speed observations are repeatedly recorded for the same INRIX XD segments, a hierarchical mixed-effects model is adopted. This structure introduces random intercepts at both the segment and corridor levels to account for correlation within units and unobserved contextual influences. The model further incorporates a set of covariates describing roadway characteristics, traffic conditions, and temporal patterns, including traffic volume, lane geometry, median configuration, bike lane presence, PSLs, hourly variation, day-of-the-week effects, and monthly seasonality. This modeling strategy is designed to separate the treatment effect from other influencing factors while improving the robustness of the estimates.

With the average speed ($SpdAve$) as the response variable, the DiD model can be presented as:

$$SpdAve_{ijt} = \beta_0 + \beta_1 Treated_i + \beta_2 After_t + \beta_3 (Treated_i \times After_t) +$$

$$\beta_4 \mathbf{X}_{ijt} + u_i + v_j + \varepsilon_{ijt}$$

Where:

- $SpdAve_{ijt}$ = average speed for segment i, corridor j, at time t.
- $Treated_i$ = indicator for treated corridors.
- $After_t$ = indicator for after period.
- $Treated_i \times After_t$ = DiD term (treatment effect).
- $\mathbf{X}_{ijt}$ = vector of control variables (AADT per lane, lane width, median type, bike lanes, PSL, time of day, day of the week, month, etc.).
- u_i = random effect for XD segment.
- v_j = random effect for corridor.
- ε_{ijt} = error term.

A similar approach was adopted for safety analysis. In this case, the dependent variable was the number of crashes. In the DiD modeling framework, the coefficient β_3 represents the estimated treatment effect on operating speeds. The analysis was then performed in the R-statistical software environment. The next section presents the results and discussion.

STUDY RESULTS

Table 27 and Table 28 present model results for operating speed for roundabout corridors. The DiD estimate for the roundabout treatment ($\beta = -1.282$, $t = -187.74$) is negative and statistically significant, indicating that implementing multiple roundabouts along a corridor was associated with a reduction in operating speeds relative to the comparison corridors after accounting for baseline differences and common temporal trends. The positive after-period effect ($\beta = 0.872$) indicates that operating speeds increased across both treated and comparison corridors over time, whereas the treatment coefficient ($\beta = -2.363$) suggests that treated corridors had lower operating speeds than comparison corridors before construction, although the difference was not statistically significant. Among the roadway characteristics, the PSL was positively and significantly associated with operating speed, while the number of signalized intersections was negatively associated with speed. Traffic volume, lane width, median presence, shoulder width, bike lane presence, and curb presence were not significantly associated with operating speed after accounting for the other variables in the model. The random-effects results indicate substantial variability among sites, corridors, and XD segments, supporting the use of a hierarchical mixed-effects modeling framework.

Table 27. Speed Model Results for Roundabout Corridors (Fixed Effects).

Fixed Effects Variable	Estimate	Std. Error	t value
Intercept	19.854	12.113	1.64
Log AADT per lane	−0.501	2.885	−0.17
Average lane width (ft)	−0.344	0.397	−0.87
Median present	1.227	2.658	0.46
Number of signalized intersections	−1.187	0.441	−2.69
Shoulder width	−0.463	3.543	−0.13
Bike lane presence	4.342	3.667	1.18
Posted speed limit	0.560	0.220	2.54
Curb present	−1.868	3.144	−0.59
Hour of the day - 0	Base	Base	Base
Hour of the day - 1	−0.057	0.012	−4.91
Hour of the day - 2	−0.017	0.012	−1.43
Hour of the day - 3	−0.047	0.012	−3.80
Hour of the day - 4	0.376	0.011	32.86
Hour of the day - 5	0.420	0.010	40.03
Hour of the day - 6	−0.382	0.010	−38.86
Hour of the day - 7	−1.724	0.010	−181.46
Hour of the day - 8	−1.885	0.009	−199.83
Hour of the day - 9	−1.278	0.009	−135.48
Hour of the day - 10	−1.221	0.009	−129.78
Hour of the day - 11	−1.351	0.009	−144.07
Hour of the day - 12	−1.355	0.009	−144.73
Hour of the day - 13	−1.343	0.009	−143.39
Hour of the day - 14	−1.624	0.009	−173.33
Hour of the day - 15	−2.155	0.009	−230.48

Fixed Effects Variable	Estimate	Std. Error	t value
Hour of the day - 16	−2.142	0.009	−229.27
Hour of the day - 17	−1.744	0.009	−186.81
Hour of the day - 18	−1.256	0.009	−134.11
Hour of the day - 19	−0.806	0.009	−85.49
Hour of the day - 20	−0.663	0.010	−69.78
Hour of the day - 21	−0.370	0.010	−38.41
Hour of the day - 22	−0.138	0.010	−13.92
Hour of the day - 23	−0.010	0.010	−1.01
January	Base	Base	Base
February	−0.166	0.007	−24.58
March	−0.105	0.006	−16.24
April	−0.167	0.006	−26.29
May	−0.163	0.006	−26.01
June	−0.044	0.006	−6.79
July	0.025	0.006	3.86
August	−0.182	0.006	−29.31
September	−0.266	0.006	−42.54
October	−0.164	0.006	−26.67
November	−0.077	0.006	−12.38
December	0.003	0.006	0.48
Sunday	Base	Base	Base
Monday	−0.961	0.005	−204.61
Tuesday	−1.099	0.005	−234.52
Wednesday	−1.105	0.005	−236.13
Thursday	−1.140	0.005	−243.82
Friday	−1.108	0.005	−237.69
Saturday	−0.339	0.005	−72.02
Before/After: Treated/Comparison - Before	Base	Base	Base
Before/After: Treated/Comparison - After	0.872	0.005	189.11
Before/After: Treated/Comparison - Treated	−2.363	1.879	−1.26
Before/After: Treated/Comparison - Treated *After	−1.282	0.007	−187.74

Note: Number of observations = 6,317,399, number of unique corridors = 25, number of unique XD segments = 253, number of grouping corridors = 8

Table 28. Speed Models Results for Roundabout Corridors (Random Effects).

Grouping variable	Variance	SD
XD segment ID: Corridor name: Site name	11.359	3.370
Corridor name: Site name	3.681	1.918
Site name	3.971	1.993
Residual	9.576	3.094

Table 29 presents the total crash model results. The DiD estimate for total crashes ($\beta = -0.069$, $p = 0.870$) is negative but not statistically significant, indicating that roundabout corridor installation was not associated with a measurable change in crash frequency relative to the comparison corridors. The after-period effect ($\beta = -0.008$, $p = 0.972$) is also not statistically significant, suggesting that crash frequencies remained relatively stable over time across both

treated and comparison corridors. Similarly, the treatment coefficient ($\beta = -0.174$, $p = 0.601$) indicates no significant difference in crash frequencies between treated and comparison corridors prior to roundabout corridor installation. Among the control variables, log period length, traffic volume (log AADT per lane), and corridor length are positively and significantly associated with total crashes. Signalized intersections show a marginally significant positive association with crash frequency, whereas median presence and on-street parking are not statistically significant.

Table 29. Total Crash Model Results for Roundabout Corridors.

Variable	Estimate	Std. Error	P-value
Intercept	−7.470	1.903	<0.001
Log period length	0.899	0.163	<0.001
log AADT per lane	0.460	0.184	0.013
Log corridor length	1.446	0.320	<0.001
Signalized intersections	0.131	0.072	0.071
Presence of a median	−0.004	0.272	0.989
On street parking	0.072	0.174	0.677
Before/After: Treated/Comparison - Before	Base	Base	Base
Before/After: Treated/Comparison - After	−0.008	0.217	0.972
Before/After: Treated/Comparison - Treated	−0.174	0.332	0.601
Before/After: Treated/Comparison - Treated *After	−0.069	0.420	0.870

Note: Number of observations = 50, Akaike Information Criterion (AIC)= 410, Bayesian Information Criterion (BIC) = 431

DISCUSSION OF THE RESULTS

The results indicate that constructing multiple roundabouts along an arterial corridor was associated with a significant reduction in operating speeds after accounting for baseline differences and common temporal trends. This finding suggests that the speed-reducing effects of roundabouts are not limited to individual intersections but extend across the corridor, influencing driver behavior between successive roundabouts. The reduction in operating speed likely reflects repeated geometric deflection and speed adjustments as drivers encounter multiple roundabouts, resulting in a more consistent speed environment along the corridor rather than localized speed reductions at isolated intersections. Previous research has consistently shown that individual roundabouts reduce approach and circulating speeds compared with conventional intersections (*55*). Similarly, Persaud et al. attributed many of the safety benefits of roundabouts to lower impact speeds resulting from their geometric design (*79*). While these studies focused on isolated intersections, the present findings suggest that similar speed-reducing effects can be achieved at the corridor level when multiple roundabouts are implemented in sequence. This extends the existing literature by demonstrating that a series of roundabouts can influence operating speeds beyond individual intersection approaches, contributing to greater speed consistency along the entire corridor.

The results further indicate that the PSL remained an important determinant of operating speed, reflecting its role in establishing drivers' expectations of an appropriate travel speed. PSLs are generally selected based on existing operating speed, roadway function, geometry, and roadside development and therefore serve as a strong indicator of the intended speed environment. As a result, drivers tend to adjust their speed in response to the PSL even after accounting for other roadway characteristics. This finding is consistent with previous research demonstrating the relationship between operating speed and PSL on urban roadways (*80*). The number of signalized intersections was negatively associated with operating speed, indicating that corridors with more traffic signals tend to experience lower average speeds. This relationship is expected because signalized intersections interrupt traffic progression, requiring drivers to decelerate or stop, and accelerate more frequently, thereby reducing average operating speeds along the corridor. In addition to the direct effects of signal delay, a greater density of signalized intersections often reflects more developed urban environments with higher access density and greater pedestrian and turning activity, conditions that encourage more cautious driving. Similar relationships have been reported in previous studies showing that intersection density and traffic control devices substantially influence operating speeds by interrupting vehicle progression and increasing driving workload (*45*).

Other roadway characteristics, including traffic volume, lane width, median presence, shoulder width, bike lane presence, and curb presence, were not significantly associated with operating speed after accounting for the roundabout treatment and the hierarchical structure of the data. Their effects were likely overshadowed by stronger determinants of driver speed choice, particularly PSL, signalized intersections, and the cumulative influence of multiple roundabouts. In addition, several of these characteristics exhibited limited variation across the study corridors, providing little additional explanatory power once the major operational and roadway factors were included in the model. The hierarchical mixed-effects framework further accounted for site-, corridor-, and segment-level heterogeneity, suggesting that any remaining variation attributable to these roadway characteristics was relatively small.

The safety analysis indicates that installing multiple roundabouts along a corridor was not associated with a statistically significant change in total crash frequency during the study period. Although the treatment effect was negative, suggesting a reduction in crashes following installation, the magnitude of the effect was not distinguishable from natural variation. One possible explanation is that the operational benefits of corridor-level roundabouts, particularly reductions in operating speeds, may not immediately translate into measurable reductions in total crashes. Total crashes include a wide range of crash types, many of which are influenced by driver behavior, traffic demand, access density, and surrounding land use in addition to operating speed. The findings differ from much of the existing roundabout safety literature, which has consistently reported substantial crash reductions following the conversion of conventional intersections to roundabouts (*55, 79, 81*). However, these previous studies primarily evaluated individual intersections, whereas the present study examined the cumulative safety effects of

multiple roundabouts implemented along an arterial corridor. Corridor-level analyses introduce additional sources of variability, including midblock crashes, driveway-related conflicts, and interactions between adjacent intersections, which may dilute the safety effects observed at individual roundabouts. Consequently, while the speed analysis demonstrates that multiple roundabouts create a more uniform operating speed environment, the corresponding reduction in total crashes may require a longer evaluation period or additional corridor-level improvements before measurable safety benefits become evident.

Among the roadway characteristics, higher traffic volumes and longer corridor lengths were associated with greater crash frequencies, consistent with previous transportation safety research showing that increased exposure leads to higher crash occurrence. Signalized intersections also exhibited a positive association with crashes, reflecting the additional conflict points introduced by signalized control, although the relationship was only marginally significant. In contrast, median presence and on-street parking were not significantly associated with total crash frequency after accounting for the other roadway characteristics included in the model.

CHAPTER 6: THE IMPACT OF CORRIDOR CROSS-SECTION REALLOCATION ON OPERATING SPEED: A CASE STUDY OF WILLIAM J. BRYAN PARKWAY (FM 158) IN BRYAN, TEXAS

BACKGROUND

Substantially reducing operating speeds to reach a desired target speed within a residential or park area may take changing more than one roadway element. The entire cross section of the corridor needs to reflect the desired target speed. This document presents information about a corridor with several geometric roadway changes where operating speeds decreased after construction was completed.

Project Location

The William J. Bryan Parkway (FM 158) corridor between Texas Avenue and SH 6 in Bryan, Texas, needed several improvements due to traffic congestion and safety concerns caused by recent growth in the area. The joint team that included the City of Bryan, TxDOT, and the Bryan/College Station Metropolitan Planning Organization identified the following project goals:

- Provide a safer place to live, visit, work, and recreate.
- Improve storm water quality through green infrastructure and multipurpose amenities.
- Improve current mobility, functionality, and efficiency for all users.
- Create safe connectivity to parks and other amenities from intersecting systems.

The City of Bryan worked with the community to gather input. Through a series of three public meetings, a design workshop, two rounds of meetings with property owners, and two community surveys, the city developed plans to address the priorities for the corridor while reflecting community values and character. Community engagement and preliminary project design occurred between 2017 and 2019, with detailed engineering and construction plans developed during 2019 to 2021. Construction on the project started in June 2023 and was completed in November 2025. The treated area of FM 158 was divided into four contextual patterns; running from west to east, the contextual zones were historic, park, residential, and business (see Figure 11).

(Source: Google Earth with annotations by Texas A&M Transportation Institute [TTI])

Figure 11. Treated Zones.

Countermeasures

Table 30 summarizes the key traffic countermeasures implemented within each zone. The park zone had the most changes, especially with the inclusion of PHBs, roundabouts, and a new traffic control signal. The roundabouts were included to help facilitate U-turns needed to move between the one-way pairs. Providing better access to the park for pedestrians was an expectation for this project. Within the project, sidewalks were widened (or added when there was a sidewalk gap) and, for most of the project, separated from the travel way with a grass buffer area. Most of the zones had the through lane narrowed from 12 to 11 ft. Changes in the PSL were not one of the planned countermeasures. A speed study conducted before any improvements found the 50th percentile speed to be 39 mph and the 85th percentile speed to be 42 mph. Figure 12 presents an example of the pre-construction cross section for one of the one-way pairs by the park, and Figure 13 shows the cross section at the same location after implementation of the treatments.

Table 30. Characteristics and Countermeasures Installed for the Treated Zones on FM 158.

Zone, Length, and Desired Operating Speed	Existing Cross Section	Countermeasures Installed
Business 2900 ft 35 to 40 mph	4 lanes with TWLTL Narrow sidewalks	• Added raised median • Widened sidewalk • Added buffer between sidewalk and travel way
Residential 1200 ft 25 to 30 mph	4 lanes with TWLTL Narrow sidewalks	• Added raised median • Reduced lane width by 1 ft • Widened sidewalk • Added buffer between sidewalk and travel way
Park 3400 ft 25 to 30 mph	One-way pairs that go on either side of a city park, each with 2 lanes and right shoulder Narrow sidewalks	• Added roundabouts at each end of one-way pairs • Added PHBs to improve access to park • Installed traffic control signals at major cross street • Reduced lane width by 1 ft • Widened sidewalk from 4 to 6 ft when adjacent to residences or 10 ft for shared-use path adjacent to park • Added buffer between sidewalk and travel way • Removed shoulders and reallocating that space for nonmotorized users
Historic 2,200 ft 30 to 35 mph	4 lanes with TWLTL Narrow sidewalks Sidewalk gaps	• Added raised median • Reduced lane width by 1 ft • Widen or added sidewalks • Added buffer between sidewalk and travel way

(Source: Marcus Brewer, TTI)

Figure 12. Pre-construction Cross Section for FM 158.

(Source: Emma Turner, TTI)

Figure 13. Cross Section for FM 158 after Construction; Pedestrian Hybrid Beacon Added at Cross Street Along with Wider Sidewalks and Reallocation of Shoulder.

LITERATURE REVIEW

Most existing studies evaluating the impact on operating speed from roadway design interventions have focused on the effects of individual treatments, such as roundabouts, lane width reductions, or pedestrian facilities, in isolation. Following is a summary of findings from the literature.

Pedestrian Hybrid Beacon

The PHB is not installed as a speed management treatment; rather, it addresses a pedestrian crossing need. However, two studies discussed PHB and operating speed. A pilot study evaluated motorists' actions at PHB sites in Charlotte, North Carolina (*82*). The data were collected at three sites before installation, one month, three months, six months, and 12 months after the installation. While an increase in average traffic speed was observed at one site, no specific trends were observed at the other two PHB sites. Operating speed data were collected near PHBs located on higher-speed roads in several cities in Arizona (*83*). The 85th percentile speeds at nine locations were higher than the PSL by between 2 and 10 mph; however, this difference in PSL and operating speed is similar to the difference at other locations.

Roundabout

NCHRP Report 672 (*84*) notes that roundabouts lower vehicle travel speeds, which lower the severity of any possible crash. Roundabout speed observations can be grouped into three categories: entry speed, traversing/circulatory speed, and exit speed. Studies in Italy (*85*), Portugal (*86*), and Croatia (*87*) have documented slower speeds on the circulatory roadway as compared to the entry and exit sections.

Refuge Island

A study that examined speed change as a result of a median installation was not identified. A study that looked at the installation of a short refuge island considered 10 locations in Szczecin, Poland (*88*). The geometry of the refuge islands varied from site to site. Some of the refuge islands were symmetric about the carriageway centerline and deflecting the path of travel by 3.3 ft on each side, while others were 13.1 ft wide and had asymmetric lateral shifts by 3.3 to 9.8 ft. The speed data were collected during weekdays between 10:00 a.m. and 3:00 p.m. before and after the installation of the pedestrian refuge island. The study reported a significant reduction in vehicle speed as the vehicle traversed the refuge island.

Lane Width/Cross-Section Width

Narrow lane width has been reported to be one of the means of reducing vehicle speed. A study by Gattis et al. was among the earliest studies to evaluate the influence of street width on vehicle speeds and crash rates (*89*). The study used data collected from six streets in Fayetteville, Arkansas. The street width of the study sites varied between 20.1 and 31.4 ft, which were compared to their corresponding cross streets with similar land-use characteristics but different widths. The study reported that street widths have a relatively minimal impact on vehicle speed. The authors suggested that other factors, such as trip function, may be more significant determinants of the average and 85th percentile through vehicle speeds than street width.

A Ma et al. study in Hangzhou, China, evaluated the impact of lane width on arterial roadways' speed reduction (*90*). The study used over 9000 spot vehicle speed data collected at nine road segments with similar facilities and traffic conditions but different lane widths in the urban area. The lane width varied from 10.5 to 13 ft. Results indicated that both average and 85th percentile speeds increased as the lane speed increased.

Further, according to a work zone study by Chitturi and Benekohal, lane width reduction was associated with slower speed. The lane widths considered were 16, 12, 11, and 10.5 ft, whereby both passenger and heavy vehicles were observed (*91*). The study reported that a greater reduction in speed was observed for heavy vehicles compared to passenger cars. The study recommended lane widths of 10, 10.5, 11, and 11.5 ft be used to reduce work zone speed by 10, 7, 4.4, and 2.1 mph, respectively.

Cross-Section Reallocation (Road Diet)

When the cross-section reallocation results in a change in the number of lanes, it is also known as a road diet. The MassDOT Safe Speeds website reports a 4 to 9 percent reduction in speed for a road diet restriping (*4*). A study by Venegas et al. evaluated the impact of a road diet on vehicle speed at five sites that were converted from three- or four-lane to two-lane roadways with or without a center turn lane (*92*). The 85th percentile speed difference was 2.56 mph, while the difference in the average speed was 2.11 mph. Additionally, the difference in the peak- and non-peak-hour average speed was 1.73 mph and 2.81 mph, respectively. A study by Ohlms et al. evaluated four roadways, with one road having a 30-mph speed limit and the other three having a 35-mph speed limit (*93*). The changes in road configurations involved replacing a four-lane typical section with a three-lane typical section, including dedicated left-turn lanes and buffered bike lanes. The before-and-after speed data analysis revealed that the road diets studied did not result in practically significant changes in mean speeds. Furthermore, the number of drivers who drove 5 mph or 10 mph over the speed limit increased after the road diet installation. A study by Keuper in New Jersey reported a modest reduction in 85th percentile operating speed of 1 mph as a result of a road diet (*94*).

Combination of Treatments

While these studies provide valuable insights, they do not capture the combined influence of multiple, concurrent treatments implemented along a corridor. In the case of FM 158, several design changes were introduced simultaneously, including roundabouts, PHBs, narrower lane widths, expanded sidewalks, and the reallocation of shoulder space for nonmotorized users, while the PSL remained unchanged. The cumulative impact of these integrated modifications on operating speeds is not well understood in the literature. This gap highlights the need for a corridor-level evaluation to assess how multiple treatments interact to influence driver behavior. Therefore, this study aimed to evaluate the impact of corridor-level design modifications on operating speeds. The study focuses on determining whether the implemented treatments lead to measurable reductions in speeds.

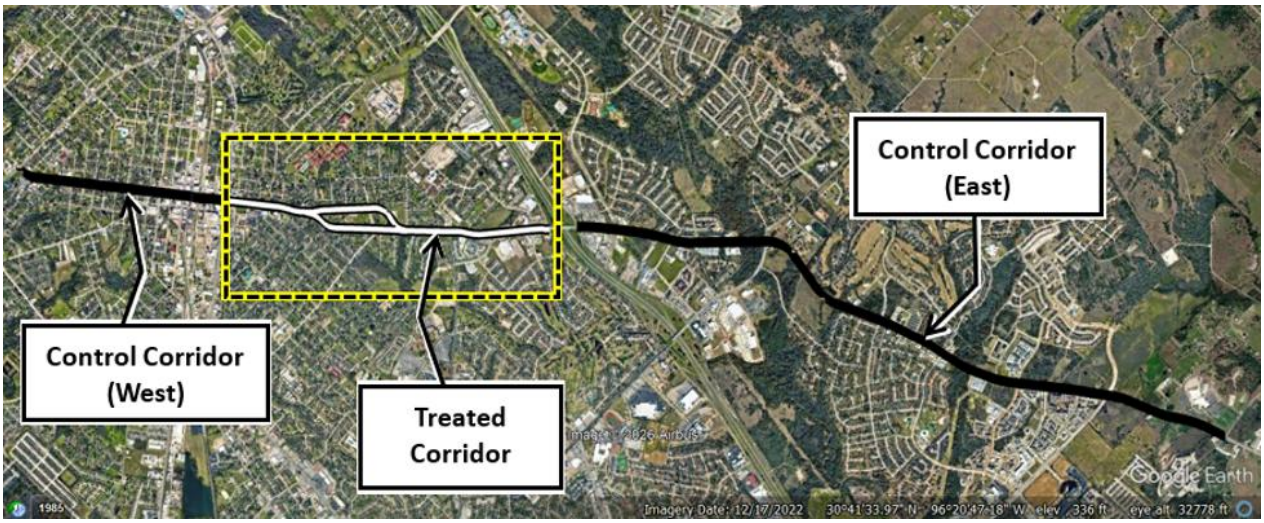
STUDY DATA DESCRIPTION

This section presents the description of the study data. It covers the identification of control corridors, how the speed data were collected and reduced, and descriptive analyses of the data.

Identification of the Control Corridors

Control sites are generally considered as sites with similar characteristics to the treated sites before treatments were applied. For the case of FM 158 reconfiguration, the geometry features of the treated corridor are unique, especially with the one-way pair around the park. Obtaining a corridor similar to this is relatively difficult. Thus, the research team focused on corridors to the

east and to the west of the treated corridor along the same road when identifying the control corridors (Figure 14). This method increases the likelihood that similar drivers will use both a control corridor along with the treated corridor.



(Source: Google Earth with annotations by TTI)

Figure 14. FM 158 Treated (Highlighted with Dashed Box) and Control Corridors (East and West of Treated Corridor).

Additionally, the research team identified several other variables for the treated and control corridors for before and after periods. These variables include the corridor length, number of lanes, lane width, shoulder width, median type, presence of bike lanes, PSL, number of signalized intersections, and traffic volume.

Speed Data Collection and Reduction

The operational effect of the corridor reconfiguration was assessed using speed data. The research team identified INRIX XD probe data as a source of speed data (*35*). The INRIX XD probe database has numerous advantages over traditional spot speed data. It permits obtaining speed data from the years prior to construction along with speed data following construction from one source. The database can also provide a greater quantity of data, such as the average speed for each hour for the periods of interest. The INRIX XD probe data represent a sample of vehicles on the segment rather than all vehicles or only free-flow vehicles. Despite the fact that the number of vehicles used for INRIX XD probe data is relatively low, the speeds could be comparable to a floating vehicle approach if that approach was used to obtain typical speed readings. Also, the availability of the probe speed data for any time of day may outweigh the shortfall of not measuring more vehicles.

The INRIX XD probe data provide speed data for each segment. Thus, in addition to identifying treated corridors and control corridors, the research team also identified the INRIX XD segments

within each study area. The research team then collected speed data for each INRIX XD segment within the study corridors (Figure 14) from January 1, 2018, to February 28, 2026.

The data reduction involved removal of the speed data collected during the construction period (June 2023 to November 2025). Furthermore, all short INRIX XD segments (0.06 miles or less) were removed from the dataset because they are likely to be at intersections, where vehicles are likely to stop, and low speeds may be more prevalent. To ensure that the speed data used represent actual measured data rather than historical data from INRIX, all observations with a confidence value below 90 or "NA" were discarded. Additionally, other INRIX XD observations, such as the ones located on the overpass of Hwy. 6, were removed due to their likely sensitivity to the diamond interchange's signal timing. To this end, a total of 1,404,466 speed readings collected from 34 INRIX XD segments were available for further analysis.

Descriptive Analysis of the Data

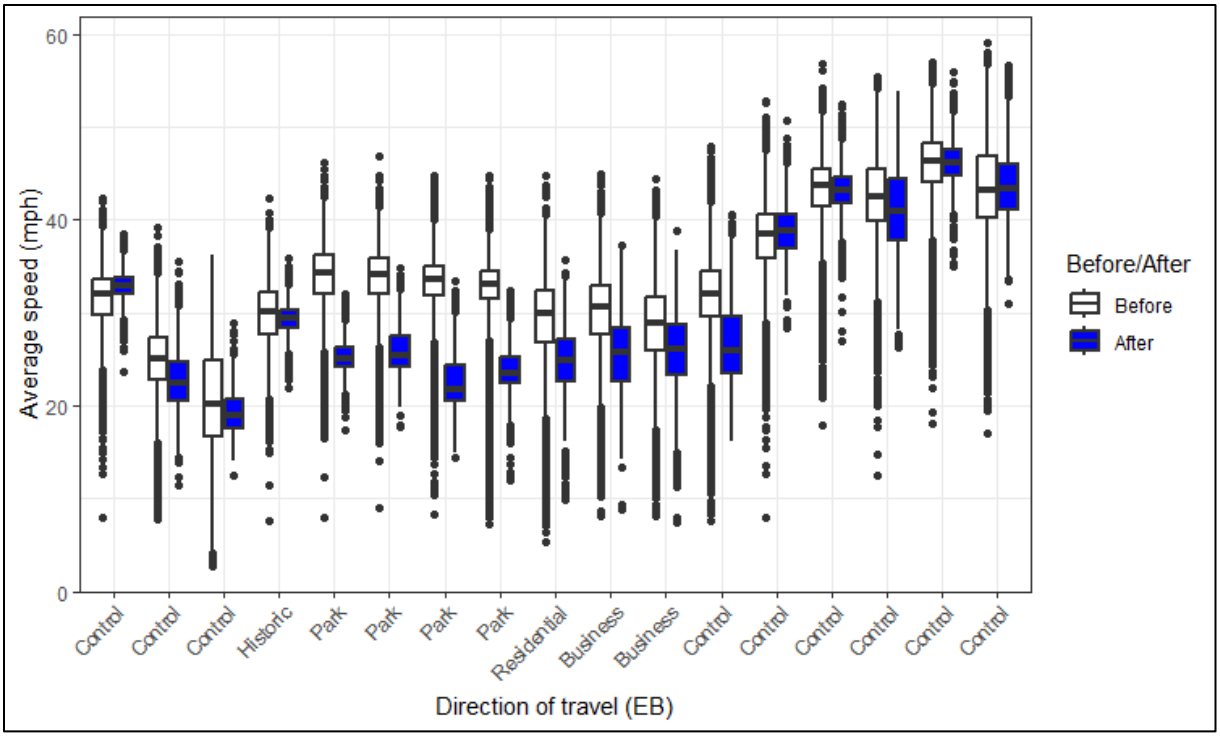
Prior to developing statistical models, the research team performed descriptive analysis to understand the distribution of various features across the study site for the before and after period. Table 31 presents the comparable key roadway characteristics and operating speeds before and after implementation across the control and treated sections, subdivided by the different land uses. The number of signalized intersections, AADT per lane, and segment lengths remain nearly unchanged between periods. Lane widths decreased in the study sections after implementation, while sidewalk widths increased substantially, particularly in the treated sections. Operating speeds show noticeable reductions in most of the treated sections after implementation, while minimal change in speed in the control sites was observed.

The research team also explored the speed distribution along the study corridor by direction of travel. Figure 15 presents the speed profile by INRIX segment for the corridor by travel direction. Across both eastbound and westbound directions, Figure 15 shows that speeds in the after period are generally lower than in the before period for the treated sections, with consistent downward shifts in median speeds across INRIX segments in the business, residential, park, and historic areas. The reduction appears across multiple segments and directions, indicating a consistent pattern of lower operating speeds in the after period. In contrast, control segments show smaller differences between before and after, with some segments exhibiting only minor changes.

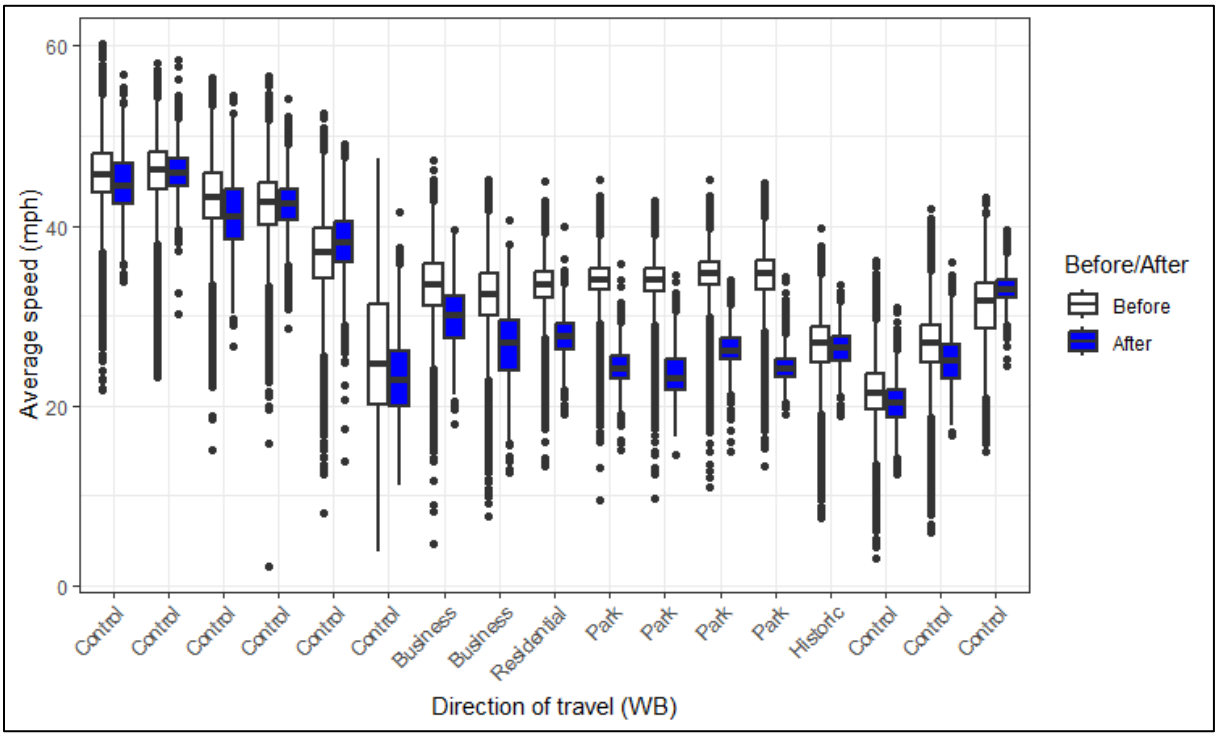
Table 31. Site Characteristics for Treated and Control Sites.

Variable	Before/ After	Control West	Treated Historic	Treated Park	Treated Residential	Treated Business	Control East
Signalized intersections (signals/mile)	Before	4.2	2.4	0	4.4	5.5	1.8
Signalized intersections (signals/mile)	After	4.2	2.4	7.8	4.4	5.5	1.8
AADT/lane	Before	4305	4688	4688	7181	8436	3616
AADT/lane	After	4295	4688	4688	7156	8426	3605
XD average segment length (mi)	Before	0.547	0.419	0.163	0.234	0.278	0.37
XD average segment length (mi)	After	0.554	0.419	0.162	0.234	0.278	0.37
Corridor length (mi)	Before	1.18	0.42	0.65	0.23	0.55	3.94
Corridor length (mi)	After	1.18	0.42	0.65	0.23	0.55	3.94
Posted speed limit (mph)	Before	30 and 40	35	35	35	40	50
Posted speed limit (mph)	After	30 and 40	30	30	30	30	50
Typical lane width (ft)	Before	12.0	11.5	11.5	11.5	11.5	13.0
Typical lane width (ft)	After	12.0	10.0	10.0	10.0	10.0	13.0
Sidewalk width (ft)	Before	5	4	4	4	4	8
Sidewalk width (ft)	After	5	6 and 10*	6 and 10	6 and 10	6 and 10	8
Operating speed, average raw data (mph)	Before	34.9	28.2	33.8	31.4	31.1	35.9
Operating speed, average raw data (mph)	After	34.6	27.8	24.5	26.3	27.1	35.6

*An average of 8 ft was used for the sidewalk width variable in the statistical models.



a. Study Site Speed Profile for the Eastbound Direction.



b. Study Site Speed Profile for the Westbound Direction.

Figure 15. Speed Profile for the Study Site by Travel Direction.

METHOD—ANALYTICAL APPROACH

This study applied a DiD modeling framework to estimate the causal effects of roadway countermeasures on operating speeds by comparing changes over time between treated and control sites. The model incorporates indicators for treatment status (treated versus control), time period (before versus after), and their interaction, where the interaction term captures the net effect of the intervention after accounting for baseline differences and common temporal trends. Since the speed values of the same INRIX XD segment are recorded over the period of time, a mixed-effects specification is used. This approach allows for random intercepts at the roadway segment and corridor levels to account for unobserved heterogeneity and repeated observations. The model also considers key roadways, traffic, and temporal variables, including traffic volume, lane width, shoulder width, median type, presence of bike lanes, PSLs, time of day, day of the week, and seasonal (month of year) effects. This approach attempts to isolate the treatment effect while improving estimation accuracy by accounting for both observed and unobserved factors that influence speed. In many cases the roadway characteristics were not significant (e.g., PSL, presences of bike lanes, etc.) and were removed from the model. Given the limited number of corridors in the evaluation and the limited range of values, it was not surprising that they were not significant.

With the average speed ($SpdAve$) as the response variable, the DiD model can be presented as:

$$SpdAve_{ijt} = \beta_0 + \beta_1 Treated_i + \beta_2 After_t + \beta_3 (Treated_i \times After_t) + \beta_4 \mathbf{X}_{ijt} + u_i + v_j + \varepsilon_{ijt}$$

Where:

- $SpdAve_{ijt}$ = average speed for segment i, corridor j, at time t.
- $Treated_i$ = indicator for treated corridors.
- $After_t$ = indicator for the after period.
- $Treated_i \times After_t$ = DiD term (treatment effect).
- $\mathbf{X}_{ijt}$ = vector of control variables (AADT per lane, lane width, median type, bike lanes, PSL, time of day, day of the week, month, etc.).
- u_i = random effect for XD segment.
- v_j = random effect for corridor.
- ε_{ijt} = error term.

In the DiD modeling framework, the coefficient β_3 represents the estimated treatment effect on operating speeds. The analysis was then performed in R-statistical software environment. The next section presents the results and discussion.

RESULTS

Table 32 presents the speed model results for the FM 158 corridor. The model structure effectively defines the treatment through land-use categories, in which business, historic, park, and residential land uses capture distinct treated contexts relative to a baseline category. As such, the after coefficient reflects the change in the baseline group, while the interaction terms (After × Land Use) indicate how the treatment effect varies across land-use types.

The results indicate a statistically significant reduction in speeds in the after period ($\beta = -0.675$, $t = -46.24$); however, this change should be interpreted in conjunction with the land-use interactions, which represent the treated conditions. The main effects for treated sections by land use—business ($\beta = 3.016$, $t = 0.19$), historic ($\beta = -4.899$, $t = -0.31$), park ($\beta = 0.811$, $t = 0.05$), and residential ($\beta = 1.656$, $t = 0.10$)—are all not statistically significant. This indicates that, in the period before, speeds across these land-use categories were not significantly different from the reference (control) group after controlling for other variables. In other words, there is no evidence of systematic baseline differences in speeds by land use, and the relatively large standard errors suggest considerable variability within each category.

The interaction terms show substantial variation in the treatment effect across land-use contexts, indicating that the impact is not uniform. The park land use exhibits the largest reduction in speeds ($\beta = -8.452$, $t = -329.44$), followed by residential ($\beta = -4.257$, $t = -95.35$) and business areas ($\beta = -3.224$, $t = -97.19$), all of which are statistically significant. When also considering the baseline after effect ($\beta_2 = -0.675$), these values indicate a pronounced decrease in speeds within park environments and a meaningful reduction in residential and business areas. The magnitude of the park effect is notably larger than the others, suggesting that these environments experience the strongest shift in driver behavior between periods. Residential areas also show a clear reduction, though less extreme, while business areas exhibit a moderate decline. In contrast, historic land use shows a small increase in operating speed ($\beta = 0.426$, $t = 9.16$). This pattern indicates that the direction and magnitude of change differ substantially by land use, with some contexts showing strong reductions and others exhibiting minimal change.

Table 32. Speed Model Results for FM 158 Corridor (Fixed Effects).

Fixed Effects Variable	Estimate	Std. Error	t value
Intercept	129.410	67.193	1.93
log_AADTlane	−21.374	8.006	−2.67
Number of signalized intersections	−3.883	15.848	−0.25
Hour of the day: 0	Base	Base	Base
Hour of the day: 1	−0.010	0.022	−0.46
Hour of the day: 2	−0.136	0.022	−6.13
Hour of the day: 3	0.162	0.022	7.27
Hour of the day: 4	0.524	0.022	24.03
Hour of the day: 5	0.878	0.021	42.67
Hour of the day: 6	−0.195	0.020	−9.72

Fixed Effects Variable	Estimate	Std. Error	t value
Hour of the day: 7	−2.645	0.020	−133.15
Hour of the day: 8	−2.539	0.020	−127.45
Hour of the day: 9	−2.323	0.020	−117.03
Hour of the day: 10	−2.640	0.020	−133.09
Hour of the day: 11	−2.952	0.020	−149.09
Hour of the day: 12	−3.113	0.020	−157.40
Hour of the day: 13	−3.114	0.020	−157.29
Hour of the day: 14	−3.075	0.020	−154.88
Hour of the day: 15	−3.401	0.020	−171.73
Hour of the day: 16	−3.498	0.020	−176.45
Hour of the day: 17	−3.995	0.020	−202.17
Hour of the day: 18	−2.853	0.020	−143.85
Hour of the day: 19	−2.197	0.020	−110.65
Hour of the day: 20	−1.964	0.020	−98.52
Hour of the day: 21	−1.537	0.020	−76.80
Hour of the day: 22	−0.910	0.021	−44.35
Hour of the day: 23	−0.284	0.021	−13.54
Month of the year: January	Base	Base	Base
Month of the year: February	−0.398	0.013	−31.69
Month of the year: March	−0.058	0.013	−4.44
Month of the year: April	0.270	0.013	20.60
Month of the year: May	0.293	0.013	22.61
Month of the year: June	0.506	0.013	37.93
Month of the year: July	0.645	0.014	47.07
Month of the year: August	0.471	0.014	34.55
Month of the year: September	0.332	0.014	24.57
Month of the year: October	0.297	0.013	23.38
Month of the year: November	0.265	0.013	20.82
Month of the year: December	0.348	0.013	27.58
Day of the week: Sunday	Base	Base	Base
Day of the week: Monday	−1.009	0.010	−96.88
Day of the week: Tuesday	−1.228	0.010	−118.10
Day of the week: Wednesday	−1.191	0.010	−114.74
Day of the week: Thursday	−1.129	0.010	−108.74
Day of the week: Friday	−1.277	0.010	−123.47
Day of the week: Saturday	−0.436	0.010	−42.00
Before_After: After	−0.675	0.015	−46.24
Treated_Control: Treated with business land use	3.016	16.054	0.19
Treated_Control: Treated with historic land use	−4.899	15.935	−0.31
Treated_Control: Treated with park land use	0.811	15.810	0.05
Treated_Control: Treated with residential land use	1.656	16.045	0.10
Before_After: After/Treated_Control: Treated with business land use	−3.224	0.033	−97.19
Before_After: After/Treated_Control: Treated with historic land use	0.426	0.047	9.16
Before_After: After/Treated_Control: Treated with park land use	−8.452	0.026	−329.44

Fixed Effects Variable	Estimate	Std. Error	t value
Before_After: After/Treated_Control: Treated with residential land use	−4.257	0.045	−95.35

Note: Number of observations = 1,404,466, number of unique corridors = 4, number of unique XD segments = 34,

Table 33. Speed Model Results for FM 158 Corridor (Random Effects).

Grouping variable	Variance	SD
XD segment ID (Intercept)	10.58	3.252
Corridor name (Intercept)	164.78	12.837
Residual	10.65	3.264

DISCUSSION

In the after period, three of the four treated sections saw a speed reduction:

- The business section had a 3.2-mph speed reduction.
- The park section had an 8.5-mph speed reduction.
- The residential section had a 4.3-mph speed reduction.

The historic land-use section experienced a nominal speed increase of 0.4 mph.

The park section experienced the largest decrease in operating speed, and it had the greatest number of countermeasures installed (see Table 30), including roundabouts, PHBs, and a traffic control signal along with reallocating the driving surface of the cross section. The business and residential sections also experienced a notable decrease in operating speed in the after period. For both sections, a raised median was added along with addition or changes to the sidewalk.

Other variables provide additional context for these results and help explain underlying patterns. Traffic volume (log_AADTlane) is negatively and significantly associated with speed, indicating that the corridors with higher volumes correspond to lower operating speeds. The number of signalized intersections does not show a statistically significant relationship in this model ($t = -0.25$), suggesting that its influence is limited once other factors are controlled for. Temporal variables for the speed readings, including hour of the day, day of the week, and month of the year, capture consistent, expected variations in speed, with lower speeds during peak daytime hours and higher speeds during off-peak periods. The random effects indicate that variability at the corridor level is substantially larger than at the INRIX segment level, suggesting that unobserved corridor-specific characteristics—such as design consistency, access patterns, or surrounding context—play an important role in shaping speed behavior. Together, these results indicate that while there is a clear temporal reduction in speeds, the magnitude and direction of change are strongly influenced by land-use context.

CHAPTER 7: SUMMARY OF FINDINGS, CONCLUSIONS, AND RECOMMENDATIONS

OVERVIEW

Vehicle speed is among the key attributes that make a difference in the injury severity outcome of a crash. Lower speeds tend to come with lower crash severities, while deadly and disabling outcomes are much more likely at higher speeds. Considering that fact, traffic safety researchers and practitioners have developed and applied several countermeasures to lower vehicle speeds. The applications and effectiveness of such countermeasures vary greatly.

TxDOT Project 0-7220 investigated the effectiveness of arterial-focused speed management countermeasures for application across Texas. The research team considered roadway design, traffic control devices, vehicle design, operations, enforcement, and other countermeasure types for uncontrolled-access arterials under different traffic, road type/context, and land-use conditions. A companion document, *Speed Countermeasures for Arterial Streets Guide* summarizes the identified relationships of countermeasures with speed and with crashes. This research report documents a review of existing toolkits along with the findings from original research on those countermeasures with the largest knowledge gaps that were selected for additional investigation as part of this research project. They included the following:

- RIR.
- Roadway lighting.
- Sidewalks.
- Roundabout corridors.
- Corridor cross section reallocation.

SUMMARY OF FINDINGS

RIR

For the RIR treatment, the research team examined two treated sites and six control sites, comparing both speed and safety outcomes across these locations. The analysis includes 1.2 million hourly average speed observations. The findings indicate increases of 0.22 and 0.56 mph in average speeds during the first period (12 a.m. to 2 a.m.) and the second period (2 a.m. to 5 a.m.), respectively. However, the estimated coefficients for the RIR treatment indicators were not statistically significant, possibly due to the small number of treated sites. While descriptive analyses suggest a reduction in crash rates at treated intersections, the limited sample size restricts statistical power and does not necessarily imply ineffectiveness. Future research incorporating more sites or longer observation periods may help better assess the treatment's effectiveness.

Roadway Lighting

For roadway lighting, the research team examined 43 treated sites and 57 control sites, comparing both speed and safety outcomes across these locations. The results indicate that the treatment was associated with increases in vehicle speeds during nighttime periods. Specifically, the early evening period from sunset to 11 p.m. and the late-night period from 11 p.m. to 2 a.m. correspond to increases in average speed of 0.20 and 0.39 mph, respectively. However, with p-values ranging from 0.15 to 0.95, these findings suggest that the lighting countermeasure has a limited direct impact on mean speeds in the study areas. In contrast, the analysis indicates a statistically significant reduction in nighttime crash rates at treated sites relative to control locations, despite an overall upward trend in crashes across both groups. This suggests that while external factors (e.g., increased exposure) may have contributed to rising crash rates, the lighting intervention mitigated this increase.

Several control variables were found to be statistically significant in the speed and crash models, providing insights into contextual factors influencing driver behavior. For example, higher job density and PSLs were associated with lower speeds, while the presence of a separate bike lane was associated with a reduction in nighttime crashes. These findings underscore the importance of accounting for surrounding land use and traffic conditions when evaluating the impacts of safety interventions.

Sidewalks

This study evaluated the operational and safety impacts of sidewalk implementation along arterial corridors in Texas using a matched control DiD framework. High-resolution probe speed data and statewide crash data were integrated to examine changes in operating speeds, FI non-intersection crashes, and pedestrian crashes before and after sidewalk implementation. The results indicate that the operational effects of sidewalks vary by roadway environment. On lower-speed corridors, sidewalk implementation is associated with a slight reduction in operating speeds (0.06 mph), suggesting a modest traffic-calming effect. In contrast, higher-speed corridors exhibit increases in operating speeds (0.93 mph) relative to comparison corridors after implementation, indicating that sidewalks alone do not substantially influence driver behavior in roadway environments that continue to support higher-speed travel.

The safety analysis produced mixed findings across the crash types examined. Sidewalk installation was associated with a reduction in FI crashes, suggesting potential safety benefits at the corridor level. In contrast, no meaningful reduction was observed for pedestrian crashes (either all severity and intersection-related levels or only FI and non-intersection-level crashes), indicating that sidewalks alone may not be sufficient to substantially improve pedestrian safety outcomes. The models further show that roadway and traffic characteristics, including traffic volume, shoulder width, median configuration, and curb presence, play important roles in influencing crash occurrence. Overall, the findings suggest that the safety benefits of sidewalks

are roadway environment dependent and may be more pronounced when combined with other roadway and pedestrian safety treatments, particularly at locations where pedestrian–vehicle conflicts occur at intersections, driveways, and crossing points.

Roundabout Corridors

This research also examined whether installing multiple roundabouts along major arterial corridors affects traffic operations and safety. As with the sidewalks, the study used high-resolution probe speed data alongside statewide crash records to evaluate changes before and after the installation of roundabout corridors. The results show that corridors with multiple roundabouts experienced an average 1.28-mph reduction in operating speed relative to comparable corridors, providing evidence that successive roundabouts create a corridor-wide traffic-calming effect rather than just isolated reductions at individual intersections. Operating speeds were also strongly influenced by PSLs and the number of signalized intersections.

In contrast, the safety evaluation revealed more modest effects. Although the estimated treatment effect corresponded to an approximate 6.7 percent reduction in total crash frequency, the change was not statistically significant after controlling for traffic exposure, corridor characteristics, and temporal trends. Traffic volume and corridor length remained the dominant predictors of crash occurrence, underscoring the importance of exposure in explaining corridor-level safety performance. These findings suggest that implementing multiple roundabouts improves speed management across the corridor, whereas measurable safety improvements may emerge more gradually as traffic patterns stabilize and drivers adapt to the new corridor environment.

Corridor Cross-Section Reallocation (Case Study of FM 158)

This study investigated the FM 158 corridor reconfiguration and found that it is associated with measurable reductions in operating speeds, with the magnitude of change varying across land-use contexts. The analysis shows a statistically significant decrease in speeds in the after period, with more pronounced reductions observed in the park and residential sections and moderate reductions in business areas. The historic section showed minimal change, indicating that responses to corridor treatments are not uniform. The absence of statistically significant baseline differences across land-use categories confirms that these changes are not driven by preexisting conditions. Instead, the variation in outcomes is linked to how different environments respond to the implemented treatments.

The results also show that control segments experience relatively small changes over time, reinforcing that the observed reductions along the treated corridor are not solely due to broader temporal trends. The average daily traffic volume for the corridors is negatively associated with speed as expected, while temporal variables capture expected variations across time of day, day of the week, and month of the year. The analysis further indicates that corridor-level characteristics contribute more to variability in speeds than individual segment-level factors.

These findings highlight that a combination of treatments applied at the corridor level can influence operating speeds, but the effect depends on surrounding context rather than a single uniform response.

CONCLUSIONS

Several reports and documents provide information about speed and safety countermeasures, as presented in Chapter 2 of this document, although most have a focus on traffic-calming treatments for local or residential streets.

Overall, safety research suggests that roadway lighting is an effective countermeasure for improving nighttime safety, particularly in terms of crash reduction. While preliminary evidence for RIR treatments is promising, further investigation is needed to derive conclusions due to the limited number of treated sites and available crash records. These findings provide practical implications for transportation agencies, supporting continued investment in lighting improvements while emphasizing the importance of robust data collection for RIR.

The speed research indicates a slight increase in operating speed during nighttime conditions for the RIR countermeasure; however, the finding was not statistically significant, perhaps due to the small sample size. For roadway lighting, a small increase in nighttime speed was observed, which also was not statistically significant.

Sidewalk installation produced different operational speed effects depending on the roadway environment. On corridors with PSLs below 45 mph, operating speeds decreased slightly (0.06 mph), indicating a modest traffic-calming effect. In contrast, corridors with PSLs of 45 mph or higher experienced an average 0.93-mph increase in operating speeds relative to comparison corridors, suggesting that sidewalks alone have limited influence on driver behavior in higher-speed environments. Sidewalk installation was also associated with a reduction in FI crashes, indicating potential corridor-level safety benefits. However, no statistically significant reduction in pedestrian crashes was observed, suggesting that the presence of sidewalks alone may not be sufficient to substantially improve pedestrian safety outcomes.

The installation of roundabouts produced a different pattern of results. Installing multiple roundabouts along an arterial corridor reduced operating speeds by an average of 1.28 mph, demonstrating a stronger and more consistent corridor-wide traffic-calming effect than that observed for sidewalks. Although corridors with roundabouts experienced lower total and pedestrian crash frequencies than comparison corridors, the estimated treatment effects for both crash types were not statistically significant during the study period. These findings suggest that the primary short-term benefit of corridor roundabouts in our study is improved speed management, whereas measurable safety benefits may require a longer post-installation period to become evident.

The case study review of the cross-section reallocation of the FM 158 corridor found reductions in operating speeds. The treated corridor was subdivided into four zones, and three of the four treated zones saw a speed reduction: the business zone had a 3.2-mph speed reduction, the park zone had a 8.5-mph speed reduction, and the residential zone had a 4.3-mph speed reduction. The historic land-use zone experienced a nominal speed increase of 0.4 mph. The park zone experienced the largest decrease in operating speed and had the greatest number of countermeasures installed, including roundabouts, PHBs, and a traffic control signal, along with reallocation of the driving surface of the cross section. The business and residential zones also experienced a notable decrease in operating speed in the after period. For both sections, a raised median was added along with addition or changes to the sidewalk.

RECOMMENDATIONS FOR FUTURE RESEARCH

Future work should include larger samples of treated sites and longer post-installation observation periods to improve the evaluation of the RIR treatment. Additional pilot deployments across various roadway types, traffic conditions, and operating schedules would help better quantify both operational and safety benefits. On the other hand, future research should improve the representation of roadway lighting by incorporating actual segment-level lighting conditions. This may include characteristics such as lamp wattage, mounting height, pole spacing, shielding, and other factors that influence roadway illumination.

Future research should examine how sidewalks interact with other roadway treatments, such as lane narrowing, cross-section reallocation (road diet), median islands, PHBs, and bicycle facilities, to influence speeds and safety outcomes. Additionally, further research is needed to incorporate pedestrian exposure measures, including pedestrian volumes and crossing activity, to provide a more comprehensive understanding of sidewalk-related safety effects. Expanding the analysis to different roadway functional classes, land-use contexts, and urban environments would also improve the generalizability of the findings. Finally, future studies should explore advanced analytical approaches, including spatial and conflict-based safety analyses, to better understand the mechanisms through which sidewalks influence traffic operations and pedestrian safety.

Future research on cross-section reallocation should focus on extending the analysis period to capture the long-term effects of corridor reconfiguration, particularly as driver behavior adapts over time. Additional studies should investigate how different combinations of treatments interact to influence speed, especially in corridors with varying land-use patterns. Incorporating exposure measures, such as pedestrian and cyclist activity, would provide a more comprehensive understanding of how infrastructure changes influence user behavior and safety outcomes. Furthermore, there is also a need to examine the transferability of the findings for FM 158 to other corridors with different geometric, operational, and contextual characteristics. Further work should explore disaggregated analyses at finer spatial scales and evaluate how specific design

elements contribute to observed changes in speed. Expanding the modeling framework to include additional behavioral and environmental factors would support the development of more context-sensitive guidance for corridor-level interventions aimed at managing speeds.

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