THE UNIVERSITY OF TEXAS AT AUSTIN
CENTER FOR TRANSPORTATION RESEARCH

TECHNICAL REPORT 0-7209-1
TxDOT PROJECT NUMBER 0-7209

Traffic Signal Operations Supporting All Users

Isabelle Reynolds
Yue Qi
Randy Machemehl
Bunny Neible

August 2025

Published September 2025

https://library.ctr.utexas.edu/ctr-publications/0-7209-1.pdf

Technical Report Documentation Page

1. Report No.
FHWA/TX-26/0-7209-1

2. Government Accession No.

3. Recipient’s Catalog No.

4. Title and Subtitle
Traffic Signal Operations Supporting All Users

5. Report Date
Submitted: August 2025

6. Performing Organization Code

7. Author(s)
Isabelle Reynolds, MS, https//orcid.org/0009-0000-1431-9299
Yue Qi, MS, https//orcid.org/0009-0002-3161-9685
Randy B. Machemehl, P.E., PhD, https:orcid.org/0000-0002-4045-2023
Bunny M. Neible, MBA, https:orcid.org/0009-0006-3679-3665

8. Performing Organization Report No.
0-7209-1

9. Performing Organization Name and Address
Center for Transportation Research
The University of Texas at Austin
3925 W. Braker Lane, 4th Floor
Austin, TX 78759

10. Work Unit No. (TRAIS)

11. Contract or Grant No.
0-7209-1

12. Sponsoring Agency Name and Address
Texas Department of Transportation
Research and Technology Implementation Division
125 E. 11th Street
Austin, TX 78701

13. Type of Report and Period Covered
Technical Report
September 2024 – August 2025

14. Sponsoring Agency Code

15. Supplementary Notes
Project performed in cooperation with the Texas Department of Transportation and the Federal Highway Administration.

16. Abstract
Common complete street traffic signal timing strategies include leading pedestrian intervals, exclusive bicycle and pedestrian phasing, transit and bicycle queue jumps, and more. These countermeasures are utilized to curb pedestrian and bicycle crashes with vehicles, however, they often come at the expense of decreased travel efficiency. Safety and congestion management can sometimes conflict with each other. The objective of this document is to provide TxDOT with a catalogue of commonly used operation strategies including safety benefits and applicability to TxDOT roadways.

17. Key Words
Pedestrian safety countermeasures, bicycle safety countermeasures, complete streets, traffic signals, pedestrian crashes, bicycle crashes

18. Distribution Statement

19. Security Classif. (of report)	20. Security Classif. (of this page)	21. No. of pages	22. Price
Unclassified	Unclassified	TBD [Total count excl. cover]	

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Isabelle Reynolds, MS
Yue Qi, MS
Dr. Randy B. Machemehl, PE, PhD
Bunny M. Neible, MBA

CTR Technical Report:	0-7209-1
Report Date:	Submitted: August 2025
Project:	0-7209
Project Title:	Traffic Signal Operations to Support All Users
Sponsoring Agency:	Texas Department of Transportation
Performing Agency:	Center for Transportation Research at The University of Texas at Austin

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Center for Transportation Research
The University of Texas at Austin
3925 W. Braker Lane, 4th floor
Austin, TX 78759

http://ctr.utexas.edu/

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Project Engineer: Dr. Randy Machemehl
Professional Engineer License State and Number: Texas No. 14921
P.E. Designation: Research Supervisor

Acknowledgments

The authors greatly acknowledge the financial support for this project provided by the Texas Department of Transportation (TxDOT). The authors express appreciation to Danny Souraphath, Research and Technology Implementation Division Project Director.

The authors also wish to thank the Research and Technology Division Project Monitoring Team members for their support and constructive advice throughout the project: Champions and Technical Leads Ugonna Ughanze and Suzanna Set, Houston District; Subject Matter Experts Jesus Taboada, El Paso District; Milad Kiaee, Design Division; Luz Robledo Valdez, Abilene District; Danielle Carson, Design Division; Mark Baker, Design Division.

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Chapter 1. Introduction

Complete Streets are roadways designed to provide safe mobility to all users, including drivers, pedestrians, cyclists, and transit users as well as people of all ages and abilities. Common complete street traffic signal timing strategies include leading pedestrian intervals, exclusive bicycle and pedestrian phasing, transit and bicycle queue jumps, and more. These countermeasures are utilized to curb pedestrian and bicycle crashes with vehicles. Repeatedly proven to enhance safety for pedestrians and bicyclists, these improvements often come at the expense of decreased travel efficiency. Safety and congestion management are two primary elements transportation agencies consider when evaluating projects, and these goal areas can sometimes conflict with each other. The objective of this document is to provide TxDOT with a catalogue of commonly used operation strategies including safety benefits and applicability to TxDOT intersections. Furthermore, this document will also expose the deficiencies and challenges found within the current research and complete street implementation process, specifically regarding the balance of safety and travel efficiency.

Chapter 2. Literature Review

There were 3,000 pedestrians and 1,927 cyclists struck at TxDOT intersections over the last five years, between January 1, 2020 and December 15, 2024 (TxDOT, n.d.). Of these people, 234 pedestrians and 50 cyclists were killed. Walking is the second most prevalent mode after driving in the United States (Ryus et al. 2022). Yet, infrastructure to support walking in the United States is often inadequate and unsafe. Complete Streets and other movements that promote infrastructure aiming to serve all users safely gained traction in the past couple of decades as road fatalities increased. TxDOT Project 0-7209 aims to develop strategies to support all intersection users at signalized intersections, using a Complete Streets approach. This literature review outlines findings related to the current state of practice in how sites with high crash risk are selected, how appropriate countermeasures are selected, and how sites are evaluated after installation. Thirty-seven countermeasures are analyzed, and their applicability to TxDOT roadways is discussed.

This section is going to discuss all the literature by countermeasure; talking about 1. Safety, 2. Delay, and 3. Implementation (including required materials and costs).

2.1. Complete Streets Signal Operations

Complete Streets are designed to provide safe use and mobility to all users regardless of age or ability (FHWA). When implementing Complete Streets, the context and needs of a given area are the main focus as opposed to implementing a generic design in every location. Even though intersections are a small portion of all the roads in the United States about 40% of crashes happen at intersections, making them an important area to analyze when implementing Complete Streets policies (Choi 2010). At signalized intersections, safe crossings have minimal conflicts between pedestrians and bicyclists, short crossing distances for pedestrians, and work to make pedestrians and bicyclists visible to drivers.

Since the initiative was launched in 2004, streets that have incorporated Complete Street designs have been proven to have significant safety benefits in numerous studies (Smart Growth America 2024; Dumbaugh 2005; Litman 2013). After Rhode Island widely implemented road diets, they found a 37% reduction in fatal and injury crashes for all modes on these streets (Zhou and et al 2022). In California, it was shown that dense and well connected street patterns are strongly correlated with increased safety (Marshall and Garrick 2010). Intersection signal operations have also been proven to have a major impact on the safety of an intersection (Chen et al. 2012). At the 10 intersections in State College, Pennsylvania where leading pedestrian intervals were implemented, the pedestrian-vehicle crash rates fell by 58% (Fayish and Gross 2010a).

2.2. Identifying Potential Candidates

Traditional methods for identifying and treating high-risk areas in need of Complete Streets and other safety installations typically follow the six-step process of the Highway Safety Manual (AASHTO 2010): (1) Network screening, (2) Diagnosis, (3) Countermeasure selection, (4) Economic appraisal, (5) Project prioritization, and (6) Safety effectiveness evaluation. The objective of the hotspot approach is to address sites with the highest potential for improvement, often without regard to the overall strategic safety needs of the system. The following is an overview of these steps with respect to the hotspot approach.

1. *Network screening:* Identify sites based on site-specific, crash-based performance measures. For example, analysts may seek to identify candidate locations for safety projects with the highest frequency of crashes using a high injury network (Ryus et al. 2022).
2. *Diagnosis:* Diagnostic analyses hone in on safety concerns at sites identified in Step 1. Diagnosis involves a review of site-specific crashes and characteristics (e.g., geometry, traffic operations, road users, and adjacent land use) to understand collision patterns and common crash contributing factors. This provides the foundation for the identification and selection of appropriate countermeasures to mitigate the specific safety issues (e.g., crash patterns and contributing factors) at each site.
3. *Countermeasure selection:* The next step is to select appropriate countermeasures targeting the underlying crash contributing factors, which may include engineering, education, enforcement, and emergency medical service (EMS)-related countermeasures (i.e., the 4E approach).

Steps 4, 5, and 6 are aimed at determining which projects to prioritize, typically based on an analysis of benefits and costs associated with each project.

2.2.1. The Proactive Approach

Unfortunately, for Step 1, network screening, transportation planners typically utilize historical crash data, meaning planners are reactively responding to the problem (FHWA 2018a). Additionally, pedestrian crashes are rare events and so past crashes at a location are not necessarily indicative of future risk to pedestrians. This approach also will tend to neglect areas with unsafe conditions but low pedestrian activity (Ryus et al. 2022). Pedestrian fatalities occur at similar or higher rates in rural areas compared to urban ones when population is controlled for (Wolfgram 2021; Xu et al. 2019). Some hotspot approaches control for this issue, but the low numbers of pedestrian crashes especially at rural intersections with low pedestrian activity makes focusing solely on crashes inadequate for many areas.

To avoid the accumulation of accidents, the Federal Highway Administration (FHWA) has provided an alternative approach to identify potential Complete Streets. FHWA recommends that safety, along with connectivity, and equity concerns be identified within the network in order to target candidate locations. These recommendations include (FHWA 2023b):

1. Engage with community members, particularly individuals in underserved communities.
2. Analyze crash risk using data driven safety analysis (DDSA).
3. Assess the need for new safety infrastructure elements.
4. Evaluate impacts by monitoring and measuring success.

In step 1, by engaging with the public, planners will be able to collect humane insight to better understand the area's needs, as well as fill the gaps that data may not provide. In step 2, FHWA recommends that instead of simply collecting crash data, planners should utilize the DDSA to analyze both crash and roadway data to identify high-risk areas. The DDSA is a proactive, data-driven approach to identify high-risk roadway features. Through round four of Every Day Counts (EDC-4), this effort focuses on both predictive and systemic analyses—two types of data-driven approaches that state and local agencies can implement individually or in combination (FHWA 2023b).

Predictive Analysis identifies roadway sites with the greatest potential for improvement and quantifies the expected safety performance of different project alternatives. Predictive approaches combine crash, roadway inventory, and traffic volume data to provide more reliable estimates of an existing or proposed roadway's expected safety performance. The data not only helps agencies make better decisions, but also informs the public as to what safety benefits they can expect from their investment (FHWA 2023b).

Systemic Analysis uses crash and roadway data to identify high-risk roadway features that correlate with particular crash types. Agencies have traditionally relied on crash history data to identify "hot spots," or sites with high crash frequency. However, severe crashes are widely dispersed over road networks, and their location and frequency fluctuate over time. Systemic analysis identifies locations that are at risk for severe crashes, even if there is not a high crash frequency by first identifying characteristics that are associated with crash risk (Ryus et al. 2022). Practitioners can then apply low-cost countermeasures to those locations. The benefit is wider, but more targeted, safety investment (FHWA 2023b).

Once the collected intersection issues have been diagnosed via predictive or systemic analysis, potential Complete Street strategies can be implemented and assessed for their associated benefits and costs in Step 3. This step, aimed at evaluating the need for a new safety infrastructure element, mirrors Steps 4-5 of the HCM hotspot approach. Lastly, in Step 4, planners are advised to continually monitor the safety success of the chosen project, similar to Step 6 of the HCM. While this methodology is more data and analysis intensive, it provides a more consistent and equitable process of project selection (Ryus et al. 2022). The following sections will adhere to the order of the FHWA approach, beginning with the identification of potential Complete Street countermeasures, followed by their ranking and assessment against other projects, and concluding with methods for measuring the project's success.

2.3. Issues with Balancing Safety and Congestion

What Step 2 of the FHWA Complete Street implementation process does not mention is that congestion management along with safety is another common primary consideration for transportation agencies when evaluating projects. However, they often conflict with each other depending on the metric used to measure congestion. The conventional metric for safety change is predicted crash rates and fatalities of bicycle and pedestrians, whereas for measuring the transportation system performance, or congestion, indictors typically include vehicular Level-of-service (LOS), average traffic speed, and congestion delay. Although the majority of Complete Street strategies are proven to increase safety (Goughnour, D. L. Carter, et al. 2018; Ma'en Mohammad et al. 2020), if the project is predicted to show a significant reduction in vehicular level-of-service (LOS) that is not fit to support projected vehicular demand, then the project has a high likelihood of being rejected (FHWA 2022). This occurs because non-motorized links of trips that include motorized travel are often ignored, so a bike-transit-walk trip is coded simply as a transit trip, and pedestrian trips from parked cars to destinations are often not counted even if they involve walking several blocks on public sidewalks.

2.4. Signal Timing Basics

Many countermeasures involve altering signal timings. It is imperative to first discuss the signal timing terminology utilized in this report.

Traffic signals are used to safely increase traffic flow. Signal timing is made up of phases, where each phase consists of a green-yellow-all red sequence. Each signal has a cycle length, which is the amount of time it takes from the start of one phase to the start of the next phase. Yellow and all-red times are dependent on the intersection width and street speed limits, whereas green times are provided on the traffic volume from each approach.

Signals can either be actuated or fixed time (Chandler et al. 2013). Actuated signals involve detection of some kind to identify when a vehicle or pedestrian approaches and respond accordingly. At actuated signals, pedestrians can sometimes be accommodated only when they press a button to indicate they are present and the signal will resultingly adjust the green time to account for them. At fixed time signals, pedestrians are typically accounted for every cycle. Accommodating pedestrians every cycle can be beneficial along corridors where signals are coordinated (Tian and Xu 2006).

Movements at signalized intersections can either be protected only, permissive only, or protected-permissive/permissive-protected (Chandler et al. 2013). Protected only movements indicate vehicles can move unopposed and are typically indicated with a flashing green arrow in modern signal systems (FHWA 2023a). Permissive left turns are often indicated with a green ball, sometimes accompanied by a sign instructing vehicles to yield on green (FHWA 2023a). Protected-permissive or permissive-protected phasing provides a protected phase and a permissive phase, sometimes with a green arrow indicating the protected only phase and a flashing yellow arrow or a green ball indicating the permissive part of the phase.

Cycle length is typically based on Webster's equations (cite from 1958). However, literature points to this equation overestimating the required cycle length when looking to minimize delays or emissions (Calle-Laguna et al. 2019).

Characteristics that improve vehicle flow through signalized intersections often have adverse impacts on pedestrians and bicyclists trying to traverse the intersection. Wider intersections, faster speeds, and longer cycle lengths all contribute to decreased perceptions (Chandler et al. 2013).

2.5. Crash Modification Factors

Safety is paramount. There have been many studies evaluating how countermeasures change the safety of a given intersection or segment. While measures such as delay are concrete, safety does not have a measure that is as easy to conceptualize and compute. Observing past crashes at intersections is the most commonly used measure of safety; however, yielding rates, observed conflicts, and more qualitative methods, such as ranking systems, are also used.

Crash-based measures are solely quantitative and, therefore, do not take into account people's actual comfort and experience at the intersections. However, they are currently the best-practice way of calculating safety benefits at intersections. This study will use existing crash modification factors to determine safety benefits of studied countermeasures but will discuss further in Chapter 2 the drawbacks and problems with this methodology.

Crash Modification Factors (CMFs) are the most commonly used way to predict safety benefits from installing a countermeasure. They represent the expected proportion of crashes that would be expected after implementing a countermeasure (FHWA, n.d.-d). Historically, CMFs were referred to as AMFs (Accident Modification Factors). When multiplied by the number of crashes currently occurring at an intersection, a CMF can be used to produce the expected number of crashes, called a Crash Reduction Factor (CRF). A CRF is the percentage decrease in crashes and is related to the CMF in the following way:

$$CMF = (1 - \frac{CRF}{100})$$

This section discusses different ways CMFs are calculated in studies as a background for the safety data collected for the countermeasures.

2.5.1.1. Regression To The Mean

When an intersection experiences a high number of crashes it is partially due to unsafe design and partially due to random chance. When a countermeasure is installed at a location with a high crash rate, part of this high crash rate was due to random chance. Therefore, following the countermeasure treatment, the number of crashes will be reduced solely due to that intersection's number of crashes returning to the average number of crashes. This phenomenon is called regression to the mean.

Simple methodologies for computing CMFs do not account for regression-to-the-mean bias. Areas with high crash rates are more likely to be flagged as a location that requires countermeasures to be implemented; however, high crash rates are likely due in part to random variability. This is exacerbated with pedestrian or bicyclist crashes since they are relatively rare. Following a period of high crashes, it is statistically likely that the number of crashes will return to the average, or regress to the mean, which may seem to indicate a countermeasure implemented after this period of high crashes was due to the implementation of the countermeasure when it could just be due to random variability. Therefore, the amount of regression-to-the mean bias depends on a given study and will be less influential at locations where countermeasures are implemented as part of a system-wide implementation as opposed to using a crash-based hot-spot identification method.

2.5.1.2. Naïve Before-After

The easiest way to calculate a CMF is simply using a before-after methodology. This involves measuring the number of crashes before and after a treatment is installed, and calculating the CMF as:

$$CMF = \frac{crashes\ after}{crashes\ before}$$

While the simplest, this does not account for regression to the mean bias or changes in user volumes or other site changes and is typically looked at as inadequate.

2.5.1.3. Before-After with Comparison Group

The before-after with comparison group method for calculating CMFs involves designating a comparison group, in addition to the treatment group, where the countermeasure was implemented (Hauer 1997). Crashes are measured for all the intersections in each group during a before period and after period. The before-after analysis with comparison group methodology assumes the comparison group is a perfect representation of the crash reduction in the treatment group if no countermeasure were applied (Morris et al. 2010).

The methodology to calculate a CMF from a before-after with comparison group study outlined in FHWA's A Guide to Developing Quality Crash Modification Factors is based on the methodology developed by Hauer (Morris et al. 2010; Hauer 1997). First, an initial calculation of a sample-odds ratio is performed to determine that the comparison group and the treatment group are sufficiently similar. Then, the following equations are used to calculate the CMF and the variance of the CMF. The variables are defined as:

$$N_{observed,TB} = the\ observed\ number\ of\ crashes\ in\ the\ before\ period\ for\ the\ treatment\ group$$

$$N_{observed,TA} = the\ observed\ number\ of\ crashes\ in\ the\ after\ period\ for\ the\ treatment\ group$$

$N_{observed,CB}$
$= the\ observed\ number\ of\ crashes\ in\ the\ before\ period\ for\ the\ comparison\ group$

$N_{observed,CA}$
$= the\ observed\ number\ of\ crashes\ in\ the\ after\ period\ for\ the\ comparison\ group$

First, the expected number of crashes at the treatment sites without any countermeasure is calculated:

$$N_{expected,TA} = N_{observed,TB}(\frac{N_{observed,CA}}{N_{observed,CB}})$$

Next, the variance of this expected number of crashes at the treatment site is calculated:

$$Var(N_{expected,TA}) = N_{expected,TA}^2(\frac{1}{N_{observed,TB}} + \frac{1}{N_{observed,CB}} + \frac{1}{N_{observed,CA}})$$

Finally, the CMF and the variance of the CMF are calculated:

$$CMF = \frac{(N_{observed,TA}/N_{expected,TA})}{(1 + Var(N_{expected,TA})/N_{expected,TA}^2)}$$

$$Var(CMF) = \frac{CMF^2(1/N_{observed,TA} + Var(N_{expected,TA})/N_{expected,TA}^2)}{(1 + Var(N_{expected,TA})/N_{expected,TA}^2)^2}$$

This methodology is commonly used in the literature; however, recognized limitations include it does not account for the regression to the mean bias and it does not take into account differences between the treatment group and the comparison group in traffic volume or geometry (Gross et al. 2010).

2.5.1.4. Empirical Bayes

Currently seen as the gold-standard of CMF calculations, the Empirical Bayes methodology accounts for regression to the mean and differences between site characteristics. The difference in the Empirical Bayes methodology is how the expected number of crashes at the treatment sites is calculated. Typically, this is done using Safety Performance Functions (SPFs). An SPF is a mathematical model that predicts the mean crash frequency for sites based on their characteristics (Gross et al. 2010). The variables used are defined as:

$$N_{expected,TB} = the\ unadjusted\ empirical\ Bayes\ estimate$$

$N_{predicted,TB}$
$= the\ predicted\ number\ of\ crashes\ estimated\ by\ the\ SPF\ in\ the\ before\ period$

$N_{predicted,TA}$
$= the\ predicted\ number\ of\ crashes\ estimated\ by\ the\ SPF\ in\ the\ after\ period$

The Empirical Bayes estimate of the expected number of crashes without treatment is:

$$N_{exp,TB} = (SPF\ weight)\left(N_{predicted,TB}\right) + (1 - SPF\ weight)(N_{observed,TB})$$

From here, the number of expected crashes in the after period can be calculated similarly to before.

$$N_{exp,TA} = N_{exp,TB}\left(\frac{N_{o,CA}}{N_{o,CB}}\right)$$

The variance is then estimated from the expected number of crashes in the after period:

$$var\left(N_{exp,TA}\right) = N_{exp,TA}\left(\frac{N_{predicted,TA}}{N_{predicted,TA}}\right)(1 - SPF\ weight)$$

Empirical Bayes finishes computing the CMF in the same way as before-after studies. The main drawback with the Empirical Bayes methodology is that it is very data-intensive since it requires pedestrian or bicyclist and vehicle counts to compute a corresponding CMF.

2.5.1.5. ANCOVA Regression

The ANCOVA regression approach is a before-after crash methodology used to account for regression to the mean. It accounts for a difference in crashes in the before periods of the treatment and comparison groups. There is a base assumption the treatment and comparison intersections are assumed exactly equal in the before and after scenarios. Instead of finding the expected value using the traditional method (Hauer 1997):

$$E(X_{t1}) = X_{t0} * E\frac{X_{c1}}{X_{c0}}$$

The expected value is calculated using the following equation, per location (Chen et al. 2013):

$$E(X_{t1}) = const + \alpha(X_{t0})$$

Where $const$ and α are calculated using the following regression equation:

$$posttest = const + \alpha(pretest) + \beta(group)$$

Where:

$posttest$ = the crashes in the after period

$pretest$ = the crashes in the before period

$group$ = 1 for the treatment group and 0 for the comparison group

$const$ = the constant from the model

This methodology then calculates a CMF using the same methodology as in the before-after with comparison groups method.

One limitation of this method is it only uses crash frequencies, which requires assuming the comparison and treatment groups should have the same number of crashes in the before period. Therefore, it corrects for regression to the mean by adjusting the final CMF to account for these groups not being constant in the before period, when these differences could be a result of exposure or site characteristic differences. Although the only methodology that explicitly discusses accounting for the regression to the mean bias, the ANCOVA regression method is used infrequently compared to the Empirical Bayes method.

2.5.1.6. Cross-Section Regression

Cross-section regression studies gather data from multiple locations with and without a given countermeasure installed, and perform a regression to determine the changes in mean predicted crash count when the countermeasure is present (Gross et al. 2010). The main issues with these studies are that it is difficult to gather enough sites with similar characteristics to see a statistical difference in the number of crashes and unknown factors not accounted for in the regression may be influencing the results.

2.5.1.7. A Caveat

One issue with CMFs is the sample size required in order for a CMF to be statistically significant is largely dependent on the value of the CMF itself (Goughnour, D. Carter, et al. 2018).

Therefore, it is likely CMFs that show a larger reduction in the number of crashes due to a countermeasure will be rated higher and, therefore, seen as more accurate.

2.5.1.8. CMFs in This Study

All of the aforementioned methods to calculate CMFs are employed in the literature, and therefore many of the methods mentioned are used to calculate CMFs in studies cited in the literature review for this study. Since multiple methods are employed throughout the literature, the validity of CMFs found for different countermeasures are different and may each harbor different sources of error. The method, number of intersections studied, location characteristics, and number of crashes identified all contribute to error within the CMFs despite methodologies that aim to minimize error.

2.6. Countermeasures

In this project, 37 countermeasures were recommended and therefore relevant literature was collected on them. The following countermeasures were also found and analyzed but not included as a recommendation after initial study either due to inapplicability to TxDOT roadways or unlikely benefits:

- Pedestrian detection: adding automatic detectors to an intersection to eliminate the need for pedestrians to press a push button.
- Protected/permissive left turns: changing a permissively signalized intersection to instead use signalization that provides an exclusive movement for left-turning vehicles followed by a period where the vehicles may turn if a gap in the oncoming traffic is identified.
- Reservice: allowing the same pedestrian phase to be serviced more than once within a single cycle.
- Two-stage turn queue boxes: green boxes that guide bicyclists on where to queue in the middle of a two-part left turn. This enables bicyclists to complete a left turn easily without merging into vehicular traffic.
- Bike boxes: a green box designated for cyclists to wait in ahead of cars at an intersection during the red phase.

For all countermeasures in this section, an overview, safety, delay, and costs are provided. Additional information in the form of a table summarizing the studies used to determine safety information can be found in Appendix A.

2.6.1. Sidewalks

Sidewalk installation is typically a countermeasure for an entire roadway segment, including intersections. When sidewalks are added at an intersection, pedestrian mobility and access increase.

2.6.1.1. Safety

Installing sidewalks provides a place of refuge for pedestrians while they wait to cross the street, increasing their safety. FHWA's "Toolbox of Pedestrian Countermeasures and Their Potential Effectiveness" claims a CMF of 0.12 for pedestrians, citing McMahon et al.'s 1999 paper. Using a binary logistic model, this paper analyzed walking along the roadway crashes for 141 segments of road. While this study is not directly applicable to signalized intersections, their stated CMF of 0.12 was determined to be the best guess available at a CMF for installing sidewalks at intersections (McMahon et al. 1999).

No literature was found discussing the increase in safety for bicyclists after sidewalks were installed, and therefore a CMF of 1 is assumed.

2.6.1.2. Delay

It can be assumed that no delay will be added from providing sidewalks at an intersection.

2.6.1.3. Costs

Installing a sidewalk is an average of $90 per square yard based on recently built TxDOT projects.

Line Items:

- $90 per square yard | **Sidewalk** | [6038-] (TxDOT 2025)

Complimentary items are curb ramps and pedestrian crosswalks.

2.6.2. Pedestrian signal heads

Pedestrian signal heads are installed to direct pedestrians crossing at a traffic signal and may be installed in conjunction with a crosswalk (FHWA 2023a). Pedestrian signal heads should be included in a new signal installation under the MUTCD guidelines if it meets warrant 4, which studies the amount of pedestrian traffic, or warrant 5, which studies the number of school children crossing at the intersection (FHWA 2023a).

Figure 1. Pedestrian countdown signal head (taken: Guadalupe Street & W 39th Street in Austin, Texas, December 2024).

Pedestrian signal heads can be accompanied by push buttons, detection, or recall signal phasing. When push buttons have been installed, pedestrians push the button and a request is sent to the traffic signal cabinet. On the next cycle, a phase is included for pedestrians to cross the street in the direction indicated by the corresponding push button. Pedestrian detection uses a sensor automatically detect the pedestrian within a defined area and sends a recall to the signal controller. Some pedestrian detectors may also be capable of removing a call once the pedestrian has crossed (Lin et al. 2019). This is a new technology, and reliability varies, especially with poor weather and darkness; pedestrian detectors will be discussed further in the next section. Recall is where the pedestrian phase is called every cycle. This includes cycles where no pedestrians are present, which may increase delay at locations where only few pedestrians cross. The benefits and applicability of recall signal timing to TxDOT roadways will be discussed later, in the “Recall” section. It will be assumed in this section that push buttons are the default to be installed with pedestrian signal heads.

2.6.2.1. Safety

Markowitz et al.’s 2006 study sought to investigate the difference in safety from traditional pedestrian signal heads versus countdown timer signal heads. While they did not prove that there was a difference, they did find a reduction of 52% in pedestrian injuries with a confidence interval of 24.8-93.3 percent after installing pedestrian signal heads with countdown timers. They found a similar number for the intersections without a countdown timer and a pedestrian signal installed. Fourteen intersections were analyzed making this study not statistically significant. However, an estimated CMF of 0.48 can be used for installation of pedestrian signal heads.

There were no studies found evaluating the improvement in bicyclist safety after pedestrian signals were installed. While there may be some safety improvements as bicyclists often are allowed to follow pedestrian signal indications, a conservative CMF of 1 was chosen to represent the safety improvements for bicyclists upon installation.

2.6.2.2. Delay

Adding pedestrian signal heads requires signal operations to account for pedestrian clearance times, which can alter the green time splits for opposing traffic (FHWA, n.d.-n). This can, therefore, effect vehicles, potentially increasing delays. These delays are typically not studied or reported likely because the alternative may prohibit pedestrians from using intersections.

2.6.2.3. Implementation

Accessible pedestrian signals should be considered at all locations (NCHRP, n.d.). Push buttons were found to be most accessible to visually impaired study participants when each push button was mounted on its own pole and each pole was placed away from the center of the intersection (Scott et al. 2005). In this arrangement, a fast tick at 10 repetitions per second worked best, but when the push buttons were mounted on the same pole, a verbal message indicating the street able to be crossed provides the most accuracy (Scott et al. 2005). However, it should also be considered that pedestrian push buttons are challenging for people with reduced mobility to operate and alternatives, such as pedestrian detection or recall signal timing, may provide additional accessibility for people unable to reach or press a push button unassisted (Sulmicki 2016).

2.6.2.4. Costs

The total estimate cost to install just pedestrian countdown signal heads on existing poles per intersection is $6,000 plus wiring costs. If pedestrian push buttons and poles need to be added, the cost will increase up to $22,800.

Line Items:

- $2.04 per foot | **Wire and Cable** | [684-] (TxDOT 2025)
- $750 each | **Pedestrian signal countdown** | [682-6018] (TxDOT 2025)

  OR $750 each | **Pedestrian signal head** | [690-6026] (TxDOT 2025)

- $600 each | **Pedestrian push button** | [688-6001] (TxDOT 2025)
- $2,600 each | **Pedestrian signal pole** | [687-7001] (TxDOT 2025)

  OR $3,000 each | **Pedestrian push button pole** | [687-7002] (TxDOT 2025)

The total cost is therefore estimated at $6,000 - $22,800. The $6,000 estimate assumes only eight pedestrian signal heads are installed. The $22,800 estimate is obtained by assuming eight pedestrian signal heads, eight push buttons, and four pedestrian push button poles are required. Costs may be even greater if unusual sidewalk geometries cause push buttons to require poles separate from the pedestrian signal head pole.

A sidewalk and curb ramps along with pedestrian curb ramps are expected to already be present at the site for the cost estimate. Additionally, a vehicle signal and therefore a traffic signal controller are expected to be present. If these are not present, they will need to be added to the cost.

2.6.3. Change pedestrian signal heads to display a countdown timer

Pedestrian signals can either include or not include a countdown display (FHWA 2023a). While historically many signals did not include a countdown display, the current MUTCD guidelines are "all pedestrian signal heads used at crosswalks where the pedestrian change interval is more than 7 seconds shall include a pedestrian change interval countdown display in order to inform pedestrians of the number of seconds remaining in the pedestrian change interval" (FHWA 2023a). Signal heads where the pedestrian change interval is less than 7 seconds are also optionally allowed to include a countdown display (FHWA 2023a). Figure 2 below shows allowable pedestrian signal configurations (FHWA 2023a).

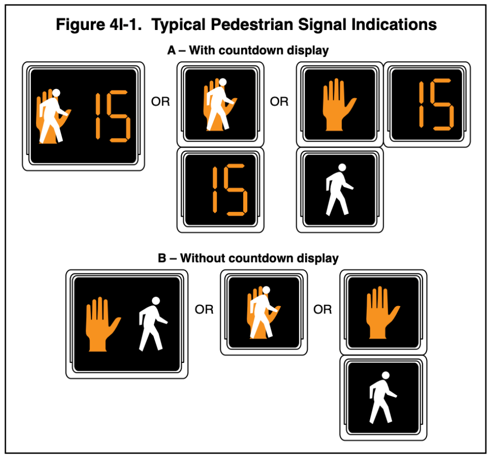

Figure 2. Typical pedestrian signal head configurations (FHWA 2023a).

2.6.3.1. Safety

Countdown pedestrian signals are stated to be safer than the traditional upraised hand or "flashing don't walk" signals because they provide pedestrians with more information to judge whether they have enough time to cross. FHWA's "Toolbox of Pedestrian Countermeasures and Their Potential Effectiveness" cites two pedestrian CMFs; 0.75 and 0.3. The first is from a study by Markowitz et al. in 2006 where a reduction of 52% was found after installing pedestrian signal heads with countdown timers. The paper cited did not develop a CMF and, instead, found the control group had a similar reduction in crashes, and therefore, the reduction in crashes for countdown pedestrian signal heads was not statistically significant. They anecdotally said countdown signal timers appeared to be effective. Van Houten et al. performed a study in Detroit where they looked at the safety increase at 362 intersections after a staggered introduction of pedestrian countdown timer signal heads (2012). They used a before-after analysis with a time-series regression to determine that the 70% reduction in pedestrian crashes they saw at the treatment intersections, compared to a "non-significant" but unstated change in the 82 control sites. Therefore, a CMF of 0.3 is used for the safety improvement of installing a pedestrian countdown signal where previously a traditional signal was.

There were no studies found evaluating the improvement in bicyclist safety after pedestrian signals were changed to display a countdown. While there may be some safety improvements as bicyclists often follow pedestrian signal indications, a conservative CMF of 1 was chosen to represent the safety improvements for bicyclists upon installation.

2.6.3.2. Delay

In a 2011 study, two intersections were observed to determine the difference in operations before and after countdown pedestrian signals were installed (Schmitz 2011). The researcher found drivers were less likely to run the red light after countdown timers were installed. They also looked at the speeds of vehicles during the yellow phase, and found increased speeds at one intersection but decreased speeds at the other, providing conflicting results.

2.6.3.3. Implementation

Pedestrian signal heads should be included at TxDOT intersection locations when pedestrians are expected to be crossing at that location.

Typical pedestrian signal phasing for a pedestrian phase includes a walk phase at least 7s long (Kittelson & Associates, Inc. 2022). When pedestrian signal heads are installed, if no crosswalks are existing, they will need to be painted and curb cuts excavated. Also, signals will need to be retimed.

2.6.3.4. Costs

The average cost of adding countdown timers per intersection is $6,000 for eight pedestrian countdown signal heads, with potential additional cable fees.

Line Items:

- $2.04 per foot | **Wire and Cable** | [684-] (TxDOT 2025)
- $750 per head | **Pedestrian signal countdown** | [682-6018] (TxDOT 2025)

It is assumed that a pedestrian signal pole, curb ramps, crosswalks, and a traffic signal controller are already present at the intersection.

2.6.4. Crosswalks

At intersections where a crosswalk is not already in place, adding one increases visibility of crossing pedestrians to drivers.

2.6.4.1. Safety

While painting crosswalks is almost undeniably determined to have a positive impact on pedestrian crashes, there was no literature found discussing this; only literature on high visibility versus traditional crosswalks was found. Therefore, the CMF chosen for painting high visibility crosswalks (0.52) is selected to represent painting crosswalks where there were none before. The selection of this CMF is discussed in the next section.

There are no studies found analyzing the impact of crosswalks on bicyclist crashes. Therefore, despite possibility for a positive effect, a conservative CMF of 1 is assumed.

2.6.4.2. Delay

Painting crosswalks alone should be assumed to not increase vehicular delays. While there could be an argument made that a crosswalk causes delays due to drivers yielding to pedestrians, this has not been quantified in the literature and could be argued that painting a crosswalk just reinforces drivers existing responsibility to yield.

2.6.4.3. Implementation

On streets with few cars (<3,000 daily), low speeds (<20 mph) and few lanes (1-2) crosswalks may not need to be provided (NACTO 2015). However, on higher-volume, higher speed, or wider streets it is typically expected crosswalks be provided (NACTO 2015).

A painted crosswalk alone should not be implemented at a multilane roadway crossing with over 10,000 Average Annual Daily Traffic (AADT) according to FHWA guidelines (FHWA, n.d.-f). However, they are commonly used on roadways exceeding these traffic volumes at signalized intersections or in conjunction with pedestrian hybrid beacons (PHBs) or rectangular rapid flashing beacons (RRFBs) at mid-block crossings.

When crosswalks are painted, oftentimes this needs to be accompanied by curb cuts, increasing the countermeasure cost. Additionally, at signalized intersections crosswalks should be accompanied by pedestrian signals.

High visibility crosswalks should typically be used at intersections where crosswalks are warranted. If vehicular speeds and volumes are high, crosswalks should be accompanied by pedestrian signal heads.

2.6.4.4. Costs

Painting a crosswalk can be estimated as $2,540 per crosswalk, with a total estimate of $10,160 for an intersection which requires four crosswalks. The City of Austin estimates $2,000 to $8,000 per crosswalk (City of Austin 2023b), with cost varying based on the length. An NHTSA research report estimates $600 - $5,700 per crosswalk with an average of $2,540 per painted crosswalk, with costs increasing to $6,000-$11,000 if thermoplastic is used (Dunlap and Associates, Inc. et al. 2023).

Line Items:

- $5.64 per foot | **Multi-polymer pavement markings** | [6038-] (TxDOT 2025)

It is assumed that curb ramps are already present at the intersection where the crosswalk will be installed and if they are not costs will increase.

2.6.5. High visibility crosswalks

High Visibility Crosswalks are defined in the MUTCD as having either of the three patterns shown in Figure 3 (FHWA 2023a). The industry standard at the moment is to paint all new crosswalks with a high visibility pattern, and typically the longitudinal bar pattern is seen.

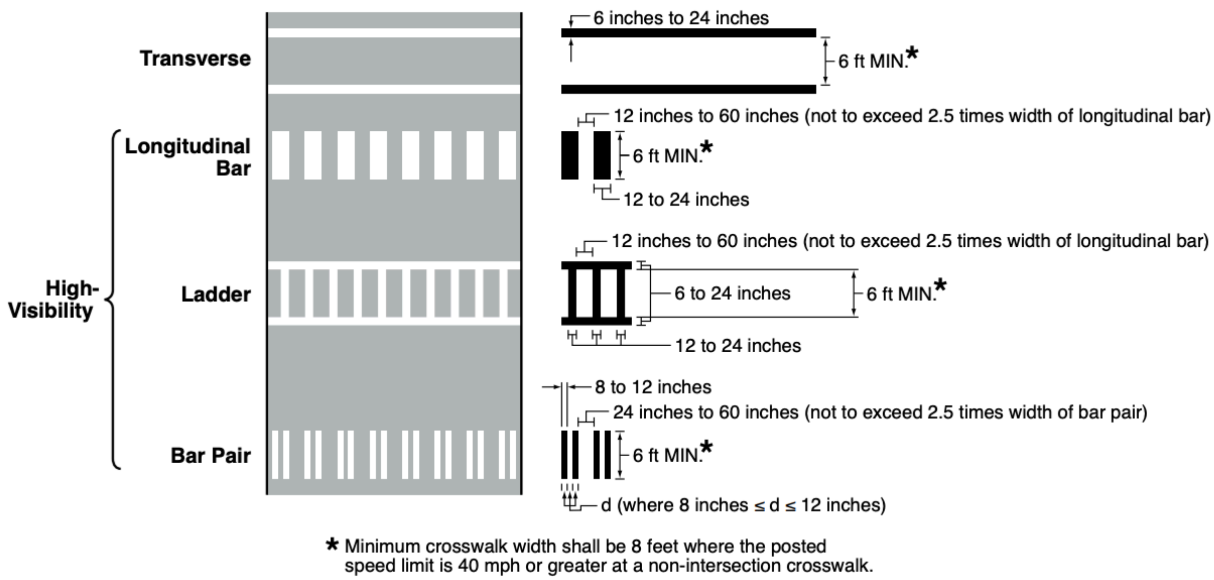

Figure 3. Allowable crosswalk markings in the MUTCD, Figure 3C-1 (FHWA 2023a).

2.6.5.1. Safety

High visibility crosswalks alert vehicles to potential pedestrian crossings but also may increase the number of pedestrians crossing and decrease pedestrian awareness when crossing (Chen et al. 2012). FHWA's "Toolbox of Pedestrian Countermeasures and Their Potential Effectiveness" estimates a CMF of 0.52 with a standard error of 0.17, which comes from Chen et al.'s study. It should be noted that in this study their high visibility crosswalk comparison group had more crashes than the treatment group locations in the before scenario, which made the CMF decrease from the raw CMF of 0.61 they calculated, and was not statistically significant. Chen, Chen, and Ewing computed a 40% crash, or a CMF of 0.6, for pedestrian crashes of all severities from data in New York City (Chen et al. 2012; FHWA, n.d.-d). This CMF was not statistically significant, however, and the comparison group also improved by 18% which would instead produce a CMF of 0.732 if accounted for using the traditional method (Chen et al. 2012). Therefore, a CMF of 0.52 was chosen for pedestrians for painting high visibility crosswalks where there were previously traditional crosswalks.

There were no studies found analyzing the impact of high visibility crosswalks on bicyclists. Chen et al. found a decrease of 61% at intersections where crosswalks were installed and a decrease of 28% at intersections where crosswalks were not installed, however they did not have enough data to compute a CMF. Therefore, a CMF of 1 is assumed.

2.6.5.2. Delay

Changing crosswalks to be high visibility only involves changing the painted design of the crosswalk and, therefore, should be assumed to not increase vehicular delays.

2.6.5.3. Costs

Repainting a crosswalk to have a high visibility pattern can be estimated as $2,540 per crosswalk, with a total estimate of $10,160 for an intersection which requires four crosswalks. The City of Austin estimates $2,000 to $8,000 per crosswalk (City of Austin 2023b), with cost varying based on the length. An NHTSA research report estimates $600 - $5,700 per crosswalk with an average of $2,540 per painted crosswalk, with costs increasing to $6,000-$11,000 if thermoplastic is used (Dunlap and Associates, Inc. et al. 2023). If there are existing markings that require removal, the final estimate will be higher.

Line Items:

- $3.45 per foot | **Eliminate pavement markings** | [677-] (TxDOT 2025)
- $5.64 per foot | **Multi-polymer pavement markings** | [6038-] (TxDOT 2025)

It is assumed that curb ramps are already present at the intersection where the crosswalk will be installed and if they are not costs will increase.

2.6.6. Curb ramps

Curb ramps are indentations in the pavement that provide a sloped surface from the sidewalk to the roadway. They are required to be installed at all pedestrian street crossings as per TxDOT design guidelines (Texas Department of Transportation 2024).

2.6.6.1. Safety

Installing curb ramps is an important practice for accessibility, however there are no studies analyzing safety impacts on either pedestrians or bicyclists. Therefore, a CMF of 1 is used for both pedestrians and bicyclists.

2.6.6.2. Delay

It can be assumed that curb ramps, which are not on the drivable area of the roadway, will not cause vehicular delays.

2.6.6.3. Costs

The estimated cost of installing a curb ramp is an average of $2,430, based on data from TxDOT existing projects. Therefore, installing eight curb ramps (at all approaches of an intersection) could be up to $20,000.

Line Items:

- $2,430 each | **Curb ramps** | [531-] (TxDOT 2025)

A sidewalk is required to be present at the intersection, and the curb ramps are cut into the existing sidewalk. If a new sidewalk is being constructed, the curb ramps should be constructed as part of the sidewalk.

2.6.7. Alter crosswalks to be perpendicular

Intersections with skewed or unusual geometry may benefit from realignment of roadway sections or crosswalks (Ryus et al. 2022).

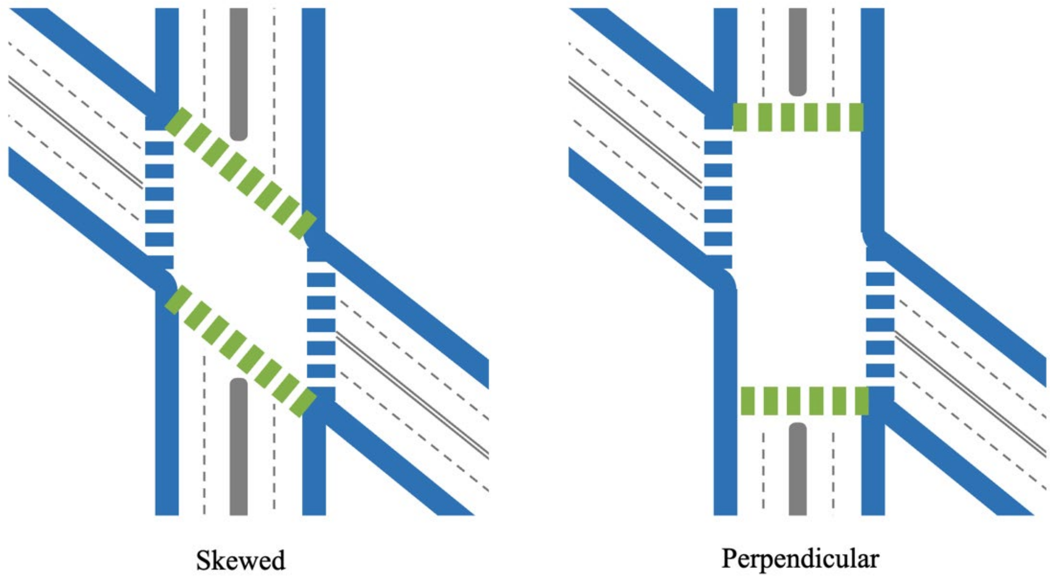

Figure 4. Crosswalk reconfiguration for a skewed intersection showing before (left) and after (right) geometries (based on: Kittelson & Associates, Inc. et al. 2021).

Perpendicular crosswalks have the shortest path across the roadway and therefore the shortest amount of time a pedestrian spends in the roadway (Kittelson & Associates, Inc. et al. 2021). Additionally, this design simplifies the placement of curb ramps.

2.6.7.1. Safety

Intersections with unusual geometry may benefit from realignment of roadway sections or crosswalks (Ryus et al. 2022). No CMFs were found in the literature relating to pedestrian or bicyclist safety from altering the geometry of an intersection to make them perpendicular. However, safety would potentially increase due to the shorter amount of time the pedestrian would spend in the roadway (Kittelson & Associates, Inc. et al. 2021). Additionally, vision of pedestrians and bicyclists would improve. Therefore, no CMF can be assumed for this countermeasure for either pedestrians or bicyclists.

2.6.7.2. Delay

The effects of altering an intersection geometry will be site-specific and cannot be generalized for all cases.

2.6.7.3. Costs

Modifying skewed intersections may include providing curb radius reduction, high visibility crosswalks and adding curb ramps. The total estimated cost of this countermeasure is about $14,800 to $55,346.

Line Items:

- $2,430 each | **Curb ramps** | [531-] (TxDOT 2025)
- $5.64 per foot | **Multi-polymer pavement markings** | [6038-] (TxDOT 2025)
- $600-$5,700 each | **High visibility crosswalks** | (FHWA, n.d.-k)

With just these modifications, the cost can be estimated to be around $14,800. Additionally, if curbs or pedestrian islands need to be reconstructed or altered, costs will increase. Installing a new pedestrian island is around $20,273 but if only modifications are needed the cost will be lower. Below is the per yard cost of constructing a pedestrian island:

- $92.4 per square yard | **Pedestrian island** | [536-6004] (TxDOT 2025)

Therefore, assuming two pedestrian island reconstructions, the cost could be as high as $55,346.

2.6.8. Recall signal timing

When a pedestrian signal phase is provided, it can either be actuated or on recall. When the phase is actuated, it is only serviced when a pedestrian is detected, either through a push-button or automated detector. Placing the phase on recall means it is served every time whether a pedestrian is present or not.

Even when a signal is operating on recall, it is possible to include pushbuttons at the intersection to increase accessibility (Kittelson & Associates, Inc. 2022).

2.6.8.1. Safety

Pedestrian recall has been theorized to improve pedestrian safety because lower delay tends to improve pedestrian compliance (Kittelson & Associates, Inc. 2022). Therefore, no CMF can be assumed for pedestrians for this countermeasure.

For bicyclists, having the pedestrian phase on recall is unlikely to increase safety and therefore a CMF of 1 is assumed.

2.6.8.2. Delay

Typically, placing pedestrian phases on recall at a location with longer crossing lengths will create more delays for all users (Jared Wall 2019).

Where signals are pretimed/fixed timing, pedestrian phases should be set on recall (Kittelson & Associates, Inc. 2022). When the signal is not fixed, guidelines or judgment should be used to determine if the pedestrian phase should be served every cycle. While fixed time signals are common in downtowns, outside these areas most signals are actuated-coordinated (Kittelson & Associates, Inc. 2022). Pedestrian volumes and relative crossing time thresholds are, therefore, needed to determine whether pedestrian recall is applicable at any given intersection.

Cesme et al developed the simplistic guidelines that pedestrian recall should be considered "when pedestrian demand is large enough that there is a pedestrian call in most cycles" (Cesme et al. 2021). This was based on VISSIM modeling that found that pedestrian recall was advantageous when the average number of pedestrians per cycle was at least 0.9.

Kittleson & Associates also developed guidelines for actuated-coordinated signals. Figure 5 shows their attempt to balance the number of pedestrians per cycle to the proportion of the time needed for a pedestrian to cross the street to the side street green time (Kittelson & Associates, Inc. 2022). The red striped section is where pedestrian recall was determined to not be advantageous, the section with large vertical alternating green and red stripes is where pedestrian recall could be considered, and the green section is where pedestrian recall was seen to be advantageous.

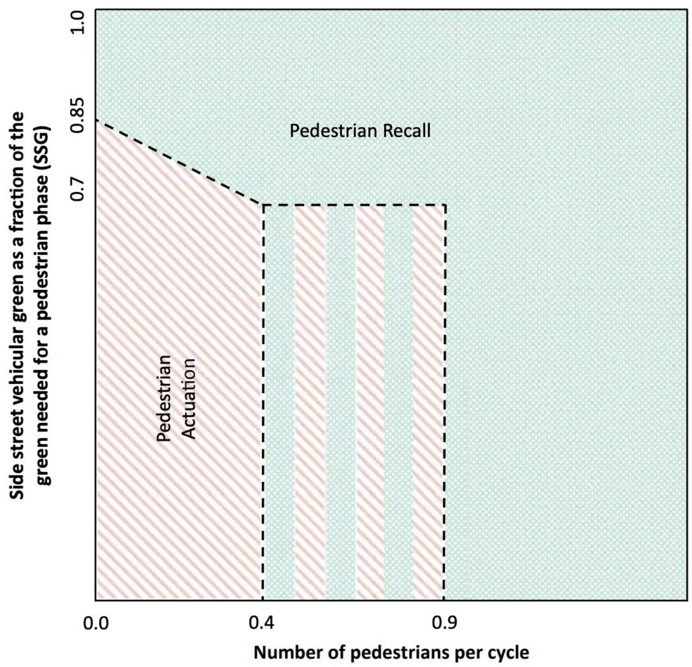

Figure 5. Criteria for the implementation of a pedestrian recall phase at an actuated-coordinated signal (Kittelson & Associates, Inc. 2022).

The basis for the guidelines in Figure 5 was a microsimulation study that analyzed the effect of pedestrian volumes on vehicular delay along a corridor in Virginia (Kittelson & Associates, Inc. 2022). Where signals are fully actuated, often it is most beneficial to reduce both pedestrian and vehicular delay to have the pedestrian phase be actuated (Kittelson & Associates, Inc. 2022).

Cho et al. also created guidelines for the implementation of the pedestrian phase on recall. They determined when the number of pedestrians total at the intersection exceeded 90 per hour, the four locations in Korea they analyzed operated as a fixed time signal despite being programed with actuated timing (Cho et al. 2007). They argued that when the pedestrian volumes were less than or equal to 90 pedestrians per hour and the vehicular volume was greater than or equal to 2,500 vehicles per hour, pedestrian push buttons should be installed. However, this study analyzed signalized mid-block locations as opposed to signalized intersections, so results may not be directly applicable to a signalized intersection in the United States. The cut-off points shown in Figure 5 are similar to the cut-off point of 90 pedestrians per hour, which is equivalent to 0.75 - 1.5 pedestrians per cycle (for 60 second – 120 second cycle lengths) (Cho et al. 2007).

Furthermore, NCHRP 969 provides a tool that suggests when pedestrian recall should be used based on pedestrian volumes and green times (Wolfgram 2022).

2.6.8.3. Costs

Signal retiming for pedestrian recall typically costs an average of $3,500 and between $1,000 and $8,000 per intersection for a signal not managed by a mobility management center that can change the signal timings remotely, in which case it would be less expensive.

Line Items:

- $3,500 ($1,000-$8,000) | **Traffic signal retiming |** (FDOT, n.d.; City of Colusa, n.d.; Texas A&M Transportation Institute 2013)

It is assumed that an intersection already has pedestrian signals before recall signal timing is implemented.

Traffic signal retiming is estimated as $1,000-$8,000 per intersection (FDOT, n.d.) with an average of $3,500 in Texas based on available literature. City of Colusa's cost table of safety projects estimates $2,500 per update (City of Colusa, n.d.) and Texas A&M Transportation Institute estimates $3,500 per intersection (Texas A&M Transportation Institute 2013).

2.6.9. Leading pedestrian interval

Leading pedestrian intervals (LPIs) give pedestrians a head start across an intersection (FHWA, n.d.-l). With an LPI, the pedestrian signal head is programmed to allow pedestrians to enter the intersection typically 3-7 seconds before vehicular traffic is allowed to move. This increases the visibility of pedestrians, reinforcing their existing right of way and increasing the likelihood of turning vehicles yielding to the crossing pedestrians (Albee and Bobitz 2021). There is also an increased benefit for pedestrians who may be slower to begin walking into the intersection (Albee and Bobitz 2021). The implementation of an LPI therefore increases pedestrian safety but may create delays for cars waiting at the intersection (FHWA, n.d.-a).

2.6.9.1. Safety

Implementing a leading pedestrian interval (LPI) is one of the better-studied countermeasures with regard to CMFs. FHWA's "Toolbox of Pedestrian Countermeasures and Their Potential Effectiveness" cites 0.413 as the CMF to be used for LPIs. This comes from a 2010 study by Fayish and Gross where LPIs were installed at 10 intersections and a 22% real reduction was seen in crashes, but corrected to be much larger accounting for the expected value of the mean. Goughnour et al. performed a study in 2018 using a before-after with Empirical Bayes methodology, at 105 intersections in Chicago, New York City, and

Charlotte. They found a statistically significant CMF of 0.87 for pedestrians at all crash severities. Therefore, it was determined that the CMF of 0.87 from Goughnour et al. was likely to be more accurate and therefore applicable to TxDOT roadways.

There are no CMFs calculated for bicyclists when LPIs are installed. When bicyclists are not permitted to use the pedestrian signal they may experience no safety benefits (New York City DOT 2019). Since LBIs are analyzed as a separate countermeasure, it is assumed bicyclists are not allowed to use the LPI and, therefore, this countermeasure is assumed to have a CMF of 1. It should be noted , bicyclists should be considered to use the LPI and, in which case, the safety benefits can be estimated using the provided CMF for LBIs.

2.6.9.2. Delay

Delays resulting from LPI implementation vary in the literature. While some studies claim an LPI results in a loss of time per car relatively equal to that of the length of the LPI, many studies claim an LPI results in minimal or no time lost (King 2000; Lin et al. 2017; Kittelson & Associates, Inc., n.d.). In his paper about calming New York City intersections, King states "… all the LPI really does is electronically enforce the legal responsibility of drivers, especially turning drivers, to yield to pedestrians in crosswalks. At corners with high pedestrian volumes, the drivers are already suffering a loss of green time as they wait for pedestrians to cross" (King 2000). It is likely delays resulting from LPI installation at an intersection with low pedestrian traffic approximate the length of the LPI, while delays at an intersection with high pedestrian traffic are closer to zero. Therefore, this study will investigate the delays of LPIs at intersections with varying pedestrian volumes.

A leading through Interval (LTI) can also be used where exclusive right-turn and left-turn lanes are present (Saneinejad and Lo 2015). This is a type of leading pedestrian interval where right-turn and left-turn vehicles are not allowed to turn for the first couple seconds to give pedestrians a head start, but straight-through traffic is allowed to proceed through the intersection as normal. This version of an LPI reduces vehicular delays with the same assumed safety benefits of an LPI.

2.6.9.3. Implementation

Factors that make an intersection a good candidate for an LPI are a high volume of turning vehicles (Albee and Bobitz 2021), a high volume of pedestrians crossing (Saneinejad and Lo 2015), visibility issues (Saneinejad and Lo 2015), and a high rate of collisions between pedestrians and turning vehicles (Saneinejad and Lo 2015).

Once it is determined an LPI should be implemented, the current conditions of the intersection will determine what improvements need to be made. When no pedestrian signal heads are present at an intersection, installation will be needed, adding to the cost of the improvement. This improvement is only a signal timing change at intersections with existing pedestrian signal heads. When LPIs are implemented, right-turn-on-red restrictions should be implemented accompanying the LPI (Saneinejad and Lo 2015). If no right-turn-on-red restriction is enabled, cars wishing to turn right may turn in front of pedestrians crossing with a signal, partially defeating the purpose of the LPI.

Additionally, curb extensions can be used in conjunction with an LPI to reduce the length that a pedestrian must cross and, therefore, decrease the required LPI time (Saneinejad and Lo 2015).

2.6.9.4. Case Studies

The optimal length of an LPI may depend on the intersection and city in which it is being implemented. The City of Austin found an LPI of five seconds worked best at all of their intersections (FHWA, n.d.-a). The City of Toronto bases LPI lengths on a formula that estimates the time it will take a pedestrian to clear at least half of the crosswalk (Saneinejad and Lo 2015). The City of New York requires the minimum LPI time of six seconds (Saneinejad and Lo 2015).

Austin has continued to implement LPIs throughout their city, and over 640 were implemented in the summer of 2024 (Austin Transportation and Public Works Department 2024).

2.6.9.5. Costs

Reprogramming the traffic signal to accommodate an advanced pedestrian phase costs between $1,000 and $8,000 per intersection with an average of $3,500.

Line Items:

- $3,500 ($1,000-$8,000) | **Traffic Signal retiming |** (FDOT, n.d.; City of Colusa, n.d.; Texas A&M Transportation Institute 2013)

It is assumed that the signal has pedestrian signals and crosswalks at the time of a leading pedestrian interval being installed.

Traffic signal retiming is estimated as $1,000-$8,000 per intersection (FDOT, n.d.) with an average of $3,500 in Texas based on available literature. City of Colusa's cost table of safety projects estimates $2,500 per update (City of Colusa, n.d.) and Texas A&M Transportation Institute estimates $3,500 per intersection (Texas A&M Transportation Institute 2013).

2.6.10. Exclusive pedestrian phase

An exclusive pedestrian phase (EPP) is also sometimes referred to by other names, including pedestrian scramble. This signal timing modification provides pedestrians with a dedicated through movement to cross the street either instead of or in addition to typical pedestrian phasing. Bicycles may also be permitted to move with the pedestrian signals.

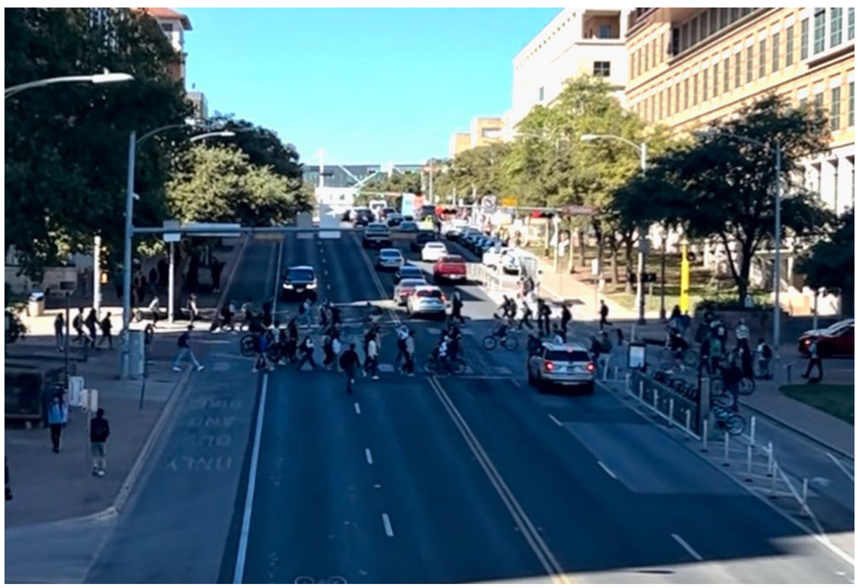

Figure 6. Exclusive pedestrian phase at Dean Keeton Street & Speedway in Austin, Texas.

There are multiple ways exclusive pedestrian phasing can be engineered (Bissessar and Tonder, n.d.). Type 1 pedestrians are not allowed to cross during the vehicular phases, and are given an entirely separate phase where they are allowed to cross in all directions. This is the most common method when pedestrian safety is the primary concern, and there is enough space to store all pedestrians waiting to cross during the exclusive pedestrian phase. Type 2 pedestrians are not allowed to cross during the vehicular phase, but during their exclusive phase they are only allowed to cross parallel to the roadways. This is the least common type of phasing and would likely only be used in circumstances where the intersection needs a short cycle length and, therefore, not enough time can be given for pedestrians to cross the street diagonally in one cycle. Type 3 pedestrians are allowed to cross while the vehicular phases are allowed to move and during their own exclusive phase. This would be used when there is a large volume of pedestrians or a lack of sidewalk space to store waiting pedestrians. These phasing patterns can be seen in Figure 7.

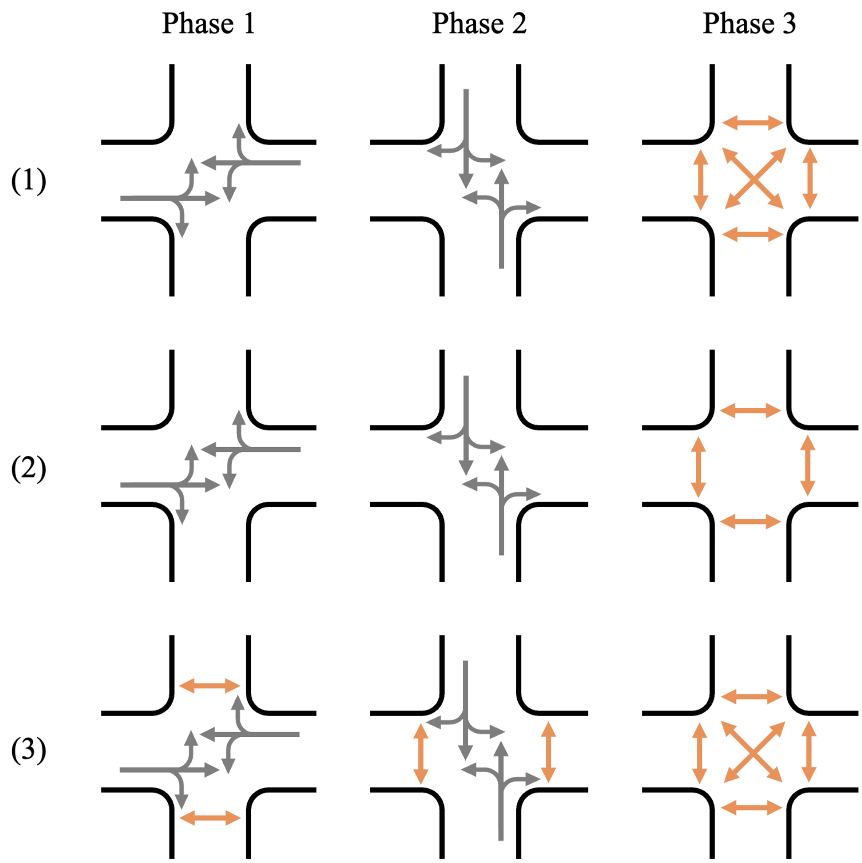

Figure 7. Three types of exclusive pedestrian signal phasing (figure based on: Bissessar and Tonder, n.d.).

The MUTCD includes an example of crosswalk markings that can be used for an Exclusive Pedestrian Phase where diagonal crossings are allowed (FHWA 2023a).

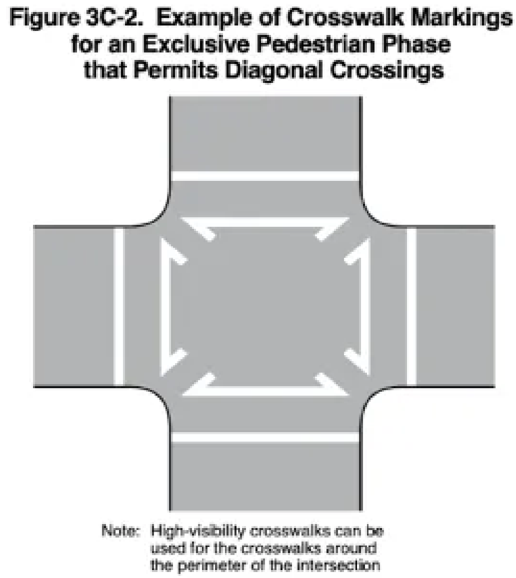

Figure 8. MUTCD guidelines for sidewalk markings when an exclusive pedestrian phase is used (FHWA 2023a).

These markings may also be used with high visibility crosswalks, which would be recommended.

2.6.10.1. Safety

Since an exclusive pedestrian phase fully separates pedestrian and vehicular traffic, it is typically always agreed upon in the literature to increase pedestrian safety (FHWA, n.d.-g). A pedestrian CMF for exclusive pedestrian phasing has been developed twice in the literature. In 2012, Chen, Chen, and Ewing used a before-after with comparison group methodology and found a CMF of 0.49. This is the CMF that is cited in FHWA's "Toolbox of Pedestrian Countermeasures and Their Potential Effectiveness". In 2013, Chen et al. looked at what appears to be the same New York City dataset using an ANCOVA regression approach to account for the regression to the mean bias. They found a statistically significant CMF of 0.65, which is the value that was determined to be most applicable to the present study.

There is no data on whether an exclusive pedestrian phase increases bicyclist safety. It is possible bicyclists using the exclusive pedestrian phase could increase their safety, but this phasing could also add additional confusion for bicyclists. Chen et al. collected very little bicyclist crash data and were unable to calculate a statistically significant CMF but did record an increase in bicyclist crashes. Therefore, a CMF of 1 (no change) will be assumed.

2.6.10.2. Delay

An EPP can increase vehicular delays due to the nature of adding an additional phase where vehicles are not allowed to move (Tu and Sano 2014; Bissessar and Tonder, n.d.; FHWA, n.d.-g).

After exclusive pedestrian phasing was implemented at three intersections in Toronto and Calgary, each intersection increased from an LOS B at both peak periods to LOS C or D during the peak periods (Bissessar and Tonder, n.d.). Substantial transit delays at an intersection which a streetcar passed through were also noticed. However, the cities considered these vehicular delays acceptable due to the high number of pedestrians.

Another study showed varying increases in delays at the eight intersections exclusive pedestrian timing was implemented, with the most substantial increase in delays occurring at the location with the highest vehicular volume (FHWA 2013).

A study also investigated the impacts of an exclusive pedestrian phase on the LOS of an intersection, concluding, for their simulated intersection with 850 pedestrians per hour, exclusive pedestrian phasing will result in more delays than concurrent phasing for any amount of vehicular traffic (Tu and Sano 2014). This highlights the importance of high pedestrian volumes and adequately weighting pedestrian delays and safety when deciding when to implement an exclusive pedestrian phase.

2.6.10.3. Implementation

Toronto established the following criteria for implementing a pedestrian scramble phase (Bissessar and Tonder, n.d.). If any one of the following criteria is met, exclusive pedestrian phasing is warranted:

- Over 3,000 pedestrians per hour on average for an eight hour period.
- Over 2,000 pedestrians per hour on average for an eight hour period and turning vehicle volumes over 35% of total approach volume.
- Over 2,000 pedestrians per hour on average for an eight hour period and over three left-turn and right-turn collisions where pedestrians had the right of way over a three year period.

Over 2,000 pedestrians per hour on average for an eight hour period and a desire by at least 15% of pedestrians to cross diagonally.

Five or more intersection legs, precluding normal pedestrian crossing operation.

While Toronto included high pedestrian volumes as a sole warrant to determine whether an exclusive pedestrian phase should be chosen, Wang et al. argued that, in order to optimize both safety and delays, both high vehicular volumes and high pedestrian volumes must be present to warrant choosing an exclusive pedestrian phase over traditional concurrent phasing (Wang et al. 2021). They determined over 500 pedestrians per hour and 1,000 vehicles per hour warranted choosing an exclusive pedestrian phase.

NACTO guidelines stated that an exclusive pedestrian phase is favorable when pedestrian volume exceeds 30% of vehicle volume during peak hour, turning traffic through any crosswalk exceeds 200 vehicles per hour, and an above average history of collisions involving turning vehicles and pedestrians (NACTO 2017).

Additionally, exclusive pedestrian phasing has been stated to work especially well for complex intersections with poor site distance (Asante and Nagle 2015).

Implementing an exclusive pedestrian phase can require adding diagonal pedestrian signal heads, signal heads parallel to the vehicular paths, signage (advance warning, overhead priority, and no right-turn-on-red), curb cuts, new crosswalk striping, and signal retiming (Bissessar and Tonder, n.d.).

Exclusive pedestrian phases are applicable at TxDOT intersections where high pedestrian or cyclist volumes are present.

2.6.10.4. Costs

The implementation of an exclusive pedestrian phase requires installation of diagonal signal heads, signal adjustments, and diagonal crosswalk markings. The total cost estimate is $11,580.

Line Items:

- $750 each | **Install pedestrian signal head** | [690-6026] (TxDOT 2025)
- $5.3 per foot | **Multi-polymer pavement markings** | [6038-] (TxDOT 2025)

- $3,500 ($1,000-$8,000) | **Traffic Signal retiming |** (FDOT, n.d.; City of Colusa, n.d.; Texas A&M Transportation Institute 2013)

The cost estimates for exclusive pedestrian phasing assume four diagonal pedestrian signal heads added, two painted crosswalks, and traffic signal retiming. The full range of traffic signal retiming costs are used to estimate a range for this countermeasure.

It is assumed that pedestrian signals and crosswalks are already present at the intersection. When exclusive pedestrian phasing is implemented, right-turn-on-red restrictions can be implemented and signage to indicate this and that pedestrians may cross on the diagonal can increase the costs.

Traffic signal retiming is estimated as $1,000-$8,000 per intersection (FDOT, n.d.) with an average of $3,500 in Texas based on available literature. City of Colusa's cost table of safety projects estimates $2,500 per update (City of Colusa, n.d.) and Texas A&M Transportation Institute estimates $3,500 per intersection (Texas A&M Transportation Institute 2013).

2.6.11. Protected-only left turns

When protected left turn phasing is implemented at an intersection with pedestrian crossings, left turning vehicles are allowed to turn only when a green arrow is shown, reducing conflict with crossing pedestrians (FHWA 2013). Phasing can be configured so left turning vehicles are allowed to turn either before or after pedestrians in the same direction are allowed to cross, and phasing can be configured so left turns from opposite directions are allowed to move at the same time, or so one approach and the corresponding pedestrian phase for which there are no conflicts goes at the same time. The way right turns are dealt with can vary among implementations.

2.6.11.1. Safety

When protected left turn phasing is implemented at an intersection with pedestrian crossings, left turning vehicles are allowed to turn only when a green arrow is shown, reducing conflicts between left turning vehicles and crossing pedestrians (FHWA 2013). Chen et al. calculated a statistically significant CMF of 0.57 after adjusting for regression to the mean using the ANCOVA regression approach (Chen et al. 2013). They analyzed 95 intersections in New York City for a 5 year pre-treatment and 2 year post-treatment period. In another study, Chen et al. found a 77% reduction in all crashes and a 67% reduction in pedestrian crashes after implementing protected only phasing at 9 intersections in NYC that had either protected phasing installed between 2000 and 2007 (Chen et al. 2015).

Raihan et al. conducted a regression cross-section analysis and determined a CMF of 0.69 with a standard error of 0.14 for bicyclists when a protected left turn phase was added (Raihan et al. 2019). This study looked at facilities in urban areas and 397 four-leg intersections. Therefore, a pedestrian CMF of 0.57 was chosen to best represent TxDOT intersections following the installation of protected-only left turns.

After implementing protected only phasing at nine intersections in NYC, Chen et al. found a 67% reduction in bicyclist crashes (Chen et al. 2015). After implementing protected only left turn phasing in NYC at 95 treatment intersections, Chen et al. found a decrease of 49% in crashes compared to a 23% decrease in crashes at untreated intersections (2013). However, due to the small sample size in both studies, no CMF was calculated. Therefore, there is likely a real reduction in bicyclist crashes after implementing protected-only left turns occurs, but a CMF cannot be quantified at this time.

2.6.11.2. Delay

Protected left turn phases are likely to increase overall intersection delay (Colorado Department of Transportation 2023). However, pedestrian presence decreases the left turning capacity of vehicles during protected-permissive, likely decreasing the impact of changing the signal timing from protected-permissive to protected only (Dey et al. 2023).

2.6.11.3. Implementation

Protected left turns can be selected as the mode of operation for varying reasons, including high pedestrian volumes or sight distance limitations (Colorado Department of Transportation 2023). It is suggested when high pedestrian or bicyclist volumes are present, protected left turns should be considered (Colorado Department of Transportation 2023).

Installing protected left turn signal phasing requires adding a signal head capable of displaying a green arrow. The cost will vary by intersection depending on whether the existing mast arm is long enough to add an additional signal and whether the intersection geometry needs to be altered to add new turn bays or other improvements.

2.6.11.4. Costs

On average the cost of implementing protected left turns per intersection range from \$5,000 to \$50,700. From FHWA, with a maximum cost potential of \$150,000, this estimate accounts for possible additional needs such as new signal equipment, turn bay additions, a new longer mast arm, or other necessary enhancements (FHWA, n.d.-j).

Line Items:

- $2.04 per foot | **Wire and Cable** | [684-] (TxDOT 2025)
- $750 each | **Signal head (with green left turn arrow)** | [690-6026] (TxDOT 2025)
- $3,500 ($1,000-$8,000) | **Traffic Signal retiming |** (FDOT, n.d.; City of Colusa, n.d.; Texas A&M Transportation Institute 2013)

When only two left turn arrow signal heads and a low signal retiming cost are estimated, the cost is $2,500. Estimating an intersection with four left turn arrow signal heads and a high cost for traffic signal readjustments, the cost is $11,000.

The cost of adding protected left turn phasing will vary depending on the current equipment. Already having signal heads capable of displaying a solid green arrow could mean this countermeasure would only require signal retiming, while requiring a new or longer mast arm, turn bays, or other enhancements will greatly increase the costs.

A new mast arm cost can be estimated as follows:

- $11,000 | **Mast arm** | [686-6033] (TxDOT 2025)

Additionally, signage explaining lefts are only permitted on green arrows (R10-5) may be included:

- $50 | **Left turn sign** | [636-] (TxDOT 2025)

Assuming with four left turn arrow signal heads, a high cost for traffic signal readjustments, four new mast arms, and four left turn signs, the cost is estimated as $50,700.

Traffic signal retiming is estimated as $1,000-$8,000 per intersection (FDOT, n.d.) with an average of $3,500 in Texas based on available literature. City of Colusa's cost table of safety projects estimates $2,500 per update (City of Colusa, n.d.) and Texas A&M Transportation Institute estimates $3,500 per intersection (Texas A&M Transportation Institute 2013).

2.6.11.5. Case Studies

In an Austin, Texas, Vision Zero initiative, 473 intersections had flashing yellow arrows, signal and sign upgrades or protected left turn phasing implemented

(Austin Transportation and Public Works Department 2024). They found a 47% decrease in opposite direction left turn crashes at the 18 intersections where safety improvements had initially been implemented in 2022. While impacts specifically to pedestrians and bicyclists were not stated, it is likely that as a part of this reduction pedestrians and bicyclists would be favorably impacted.

2.6.12. Protected-only left turns when pedestrians present

Protected left turn phasing can be implemented at only certain times of day or when specific conditions exist at an intersection in an attempt to balance delay and safety considerations (Colorado Department of Transportation 2023). When pedestrian safety is a key concern at a given intersection and due to delay concerns, it is determined a protected left turn should not be utilized all the time; a protected only left turn only when pedestrians are present may be considered.

2.6.12.1. Safety

When protected-only left turns may cause excessive delays if implemented at all time, it is possible to implement them only when pedestrians are present and detected via a push-button or other type of detector. This phasing has not been studied extensively in the literature, and, therefore, no CMFs have been found for either pedestrians or bicyclists. Since it is likely there is a real reduction in crashes from this phasing, these CMFs cannot be assumed.

2.6.12.2. Delay

Providing a protected left turn phase only when pedestrians are present incurs less vehicular delay than implementing a protected only left turn all the time.

2.6.12.3. Implementation

Installing protected left turn signal phasing requires adding a signal head capable of displaying a green arrow. The cost will vary by intersection depending on whether the existing mast arm is long enough to add an additional signal head and whether the intersection geometry needs to be altered to add new turn bays or other improvements.

2.6.12.4. Costs

On average, the cost of implementing protected left turns ranges from $5,000 to $50,700 per intersection. The difference between a protected-only left turn at all times and a protected-only left turn when pedestrians are present is a form of pedestrian detection is needed, which includes a pedestrian push button which most intersections will already have.

FHWA estimates a maximum cost of $150,000 for installing a protected left turn, which accounts for possible additional needs such as new signal equipment, turn bay additions, a new longer mast arm, or other necessary enhancements (FHWA, n.d.-j).

Line Items:

- $2.04 per foot | **Wire and Cable** | [684-] (TxDOT 2025)
- $750 each | **Signal head (with green left turn arrow)** | [690-6026] (TxDOT 2025)
- $3,500 ($1,000-$8,000) | **Traffic signal retiming |** (FDOT, n.d.; City of Colusa, n.d.; Texas A&M Transportation Institute 2013)

When only two left turn arrow signal heads and a low signal retiming cost are estimated, the cost is $2,500. Estimating an intersection with four left turn arrow signal heads and a high cost for traffic signal readjustments, the cost is $11,000.

The cost of adding protected left turn phasing will vary depending on the current equipment. Already having signal heads capable of displaying a solid green arrow could mean this countermeasure would only require signal retiming, while requiring a new or longer mast arm, turn bays, or other enhancements will greatly increase the costs.

Potentially required additional items are as follows:

- $11,000 | **Mast arm** | [686-6033] (TxDOT 2025)
- $50 | **Left turn sign** | [636-] (TxDOT 2025)
- $600 each | **Pedestrian push button** | [688-6001] (TxDOT 2025)

Assuming four left turn arrow signal heads, a high cost for traffic signal readjustments, four new mast arms, four left turn signs, and eight pedestrian push buttons the cost is estimated as $55,500.

Traffic signal retiming is estimated as $1,000-$8,000 per intersection (FDOT, n.d.) with an average of $3,500 in Texas based on available literature. City of Colusa's cost table of safety projects estimates $2,500 per update (City of Colusa, n.d.) and Texas A&M Transportation Institute estimates $3,500 per intersection (Texas A&M Transportation Institute 2013).

2.6.13. Split phase timing

Split phasing is a form of protected-only left turns where all movements on one approach are given green signals at the same time. A typical split phase signal timing diagram is shown below.

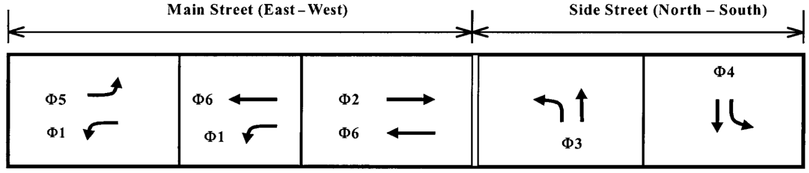

Figure 9. Split phase ring and barrier diagram, with split phasing only on the side street (Urbanik et al., n.d.).

This phasing is often used when the intersection requires protected left turns for safety reasons, but there is either a shared left turn/through lane or other geometric constraints that do not allow the left turns of the opposing traffic to both travel at the same time. Incorporating pedestrian crossings into split phasing can be challenging as the amount of time a pedestrian needs to cross is often much longer than the phase would be without providing for pedestrians (Tian et al. 2001).

The typical solution for split phasing signal timing when pedestrians are present is to provide vehicles with a green ball (indicating they should yield) as opposed to a green arrow (Urbanik et al., n.d.). The signal can also only display a green ball when pedestrians are detected (automatically or via pushbutton). In this case, safety is not increased for pedestrians compared to an intersection with permissive left turns.

2.6.13.1. Safety

Split phasing is often used when geometric constraints, such as a shared left turn/through lane, do not allow for dual phasing. However, on one-way streets using split phasing versus dual left-turns results in the same signal phasing. In the literature, using protected left turns on one-way streets has been referred to as split phasing (Chen et al. 2013). Chen et al. calculated a statistically significant CMF of 0.61 for pedestrian crashes of all severities when split phasing on a one-way street was implemented, using the ANCOVA regression methodology and a sample size of 30 intersections (Chen et al. 2013). They also found a statistically significant CMF of 0.73 for all crashes and a CMF of 0.75 for multi-vehicle crashes, showing that this countermeasure may have safety implications for all road users (Chen et al. 2013). Chen, Chen and Ewing found a reduction of 39%, compared to an 8% reduction in the comparison group for split phasing on a one-way street (Chen et al. 2012). Therefore, a pedestrian CMF of 0.61 was chosen to represent split phasing on a one-way street (Chen et al. 2013).

In the Chen et al. study, there was not a significant sample size of bicyclist crashes to identify a CMF, however, there was a 53% decrease in crashes in the treatment group and a 42% decrease in crashes in the control group. Due to a lack of claims that split phasing will increase bicyclist safety, a CMF of 1 is assumed for this countermeasure.

2.6.13.2. Delay

No literature was identified dealing with the impacts of delay from split phase timing, but since it involves adding an extra phase it likely will increase delay for all users.

2.6.13.3. Costs

Implementing splitting phase timing ranges from $1,000 to $8,000 per intersection for signal retiming with an average of $3,500.

Line Items:

- $3,500 ($1,000-$8,000) | **Traffic signal retiming |** (FDOT, n.d.; City of Colusa, n.d.; Texas A&M Transportation Institute 2013)

Assumed Existing/Complementary Items:

- Pedestrian signal

2.6.14. Flashing yellow arrow signal head for left turns

Flashing yellow arrow signal heads help to clarify when drivers are supposed to yield when making an unprotected left turn (University of Minnesota Center for Transportation Studies 2024). Traditionally, a green ball indication with a sign instructing drivers to yield on green was used, however the flashing yellow arrow has been used instead as it is thought to be more intuitive (University of Minnesota Center for Transportation Studies 2024).

Figure 10 shows a sample typical for a signal assembly with a protected-permissive left turn that uses a flashing yellow arrow.

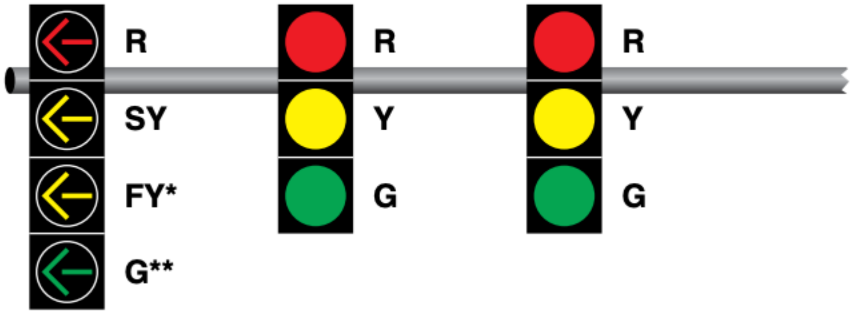

*Figure 10. Flashing yellow arrow typical assembly (FHWA 2023a). Only part of the figure is shown, * indicates shall not be displayed in the protected only mode and ** indicates shall not be displayed when operating in the permissive only mode.*

2.6.14.1. Safety

When, due to delay concerns, a fully protected phase cannot be implemented, both exclusive and unprotected parts of the phase may be used (Hauer 2004). This phasing, called protected-permissive, has been shown to have the same amount of safety as permissive-only phasing (Hauer 2004; Goughnour, D. Carter, et al. 2018). However, installing a flashing yellow arrow instead of the traditional green ball or green ball with a sign directing motorists to yield has been assumed to be safer than traditional protected-permissive phasing (Austin Transportation and Public Works Department 2024). Since implementing flashing yellow arrows, the City of Austin has found a reduction in all crashes, however since no specific pedestrian or bicyclist studies were identifies no CMFs were assumed for this countermeasure.

2.6.14.2. Delay

Researchers found flashing yellow arrows can improve traffic flow compared to traditional methods of indicating a permissive left turn, potentially reducing delays (University of Minnesota Center for Transportation Studies 2024).

2.6.14.3. Costs

On average the cost of adding a flashing yellow arrow for left turns is $6,550 per intersection. With new signal equipment, turn bay additions, or other necessary enhancements costs will increase.

Line Items:

- $750 each | **Signal head (with flashing yellow left turn arrow)** | [690-6026] (TxDOT 2025)
- $2.04 per foot | **Wire and Cable** | [684-] (TxDOT 2025)

- $3,500 ($1,000-$8,000) | **Traffic signal retiming |** (FDOT, n.d.; City of Colusa, n.d.; Texas A&M Transportation Institute 2013)
- $50 each | **Sign (left turn)** | [636-] (TxDOT 2025)

Assumed Existing/Complementary Items:

- Left turn lanes

Traffic signal retiming is estimated as $1,000-$8,000 per intersection (FDOT, n.d.) with an average of $3,500 in Texas based on available literature. City of Colusa's cost table of safety projects estimates $2,500 per update (City of Colusa, n.d.) and Texas A&M Transportation Institute estimates $3,500 per intersection (Texas A&M Transportation Institute 2013).

2.6.15. Right-turn-on-red restrictions

Prohibiting right-turn-on-red is a countermeasure that can prevent drivers from hitting crossing pedestrians and encroaching into crosswalks and inconveniencing pedestrians. When intersections have sight-distance issues, Yan and Richards found drivers will encroach into pedestrian crosswalks to maximize sight distances, creating conflicts with pedestrians and vehicles (Yan and Richards 2009).

A study found vehicles turning right on red account for a low percentage of pedestrian crashes at signalized intersections (5-15%) and are fatal in approximately 0.05% of reported cases (Houten et al. 2012). Therefore, prohibiting right-turn-on-red movements to improve pedestrian safety should be dependent on pedestrian volume.

When right-turn-on-red is prohibited, right-turn on green conflicts may increase. Therefore, using an LPI in conjunction with a right-turn-on-red prohibition can be beneficial to decrease crashes farther.

2.6.15.1. Safety

Prohibiting right-turn-on-red reduces the number of conflicts between right-turning vehicles and crossing pedestrians (Yan and Richards 2009). While some CMFs point to major improvements in safety from prohibiting right-turns on red, other literature argues right-turn-on-red restrictions only minimally affect pedestrian safety (Houten et al. 2012; Brady 2024). This is due to the fact that right-turn-on-red crashes account for a low percentage of all crashes at signalized intersections (5-15%) and are fatal in approximately 0.05% of reported cases (Houten et al. 2012; Lord 2002). FHWA's "Toolbox of Pedestrian

Countermeasures and Their Potential Effectiveness" claims a CMF of just 0.97 for implementing this countermeasure. This comes from the Harkey et al. 2008 before-after with Empirical Bayes study (FHWA, n.d.-d). Clark, Maghsoodloo, and Brown found an equation for the CMF of 0.984^N where N is the number of approaches where right turns are prohibited. This equation is also noted in the Highway Safety Manual (HSM). The Highway Safety Manual lists CMFs for pedestrian and bicyclist, pedestrian, and bicyclist mode types for allowing right-turn-on-red (American Association of State Highway and Transportation Officials 2010). For allowing right-turn-on-red, the CMFs were derived from a 1981 study by Preusser et al. The CMF for pedestrian and bicyclists is 1.69 and rated as high quality, while individual CMFs of 1.57 for pedestrians and 1.8 for bicyclists are noted as being low quality CMFs since their standard errors are both 0.2. Therefore, these results are inconclusive that there are any safety benefits, and for both pedestrians and bicyclists, a CMF of 1 is assumed, indicating effectively no change in safety.

2.6.15.2. Delay

Banning right-turn-on-reds has been shown to increase vehicle delays (Liu et al. 2025). In urban settings, higher volumes of pedestrians increase vehicular delays; however, this is mitigated when at least one straight-through lane is maintained at all intersections (Liu et al. 2025).

2.6.15.3. Implementation

Yi et al. recommended guidelines for when to install no right-turn-on-red restrictions. They determined right-turn-on-red should always be prohibited at intersections with (Yi et al. 2012):

- Limited sight distance
- More than four approaches
- Highly skewed intersections
- Exclusive pedestrian phase
- Within 200ft of a railroad crossing
- Significant conflicting U-turn movements

Additionally, they determined right-turn-on-red should be considered at intersections with:

- Significant pedestrian conflicts (50 to 100 pedestrians per hour during eight hours of an average weekday)
- Dual right- or left-turn lanes (the inside lane may be prohibited)

- High speed limits on the cross-street
- Split phasing, or the presence of an opposing protected left-turn phase
- Over one crash per year on average
- Inadequate capacity in the receiving lane
- School crossings
- Areas with large numbers of children or elderly people

The most significant finding to the present study is the guideline that right-turn-on-red should begin to be considered with over 50 pedestrian conflicts per hour on an average weekday.

Typically, implementation will only include adding a “No Turn on Red” sign (FHWA, n.d.-m). Possible signs from the MUTCD can be seen below (FHWA 2023a).

Figure 11. No right-turn signs (FHWA 2023a).

2.6.15.4. Costs

The average cost of a traffic sign is around $50, from TxDOT existing projects. To install a sign prohibiting left turns at all legs of a four-leg intersection the cost would be around $200.

Line Items:

- $50 each | **Sign (no turn on red)** | [636-] (TxDOT 2025)

2.6.16. Reduce the cycle length

Long cycle lengths often result in long pedestrian delays as pedestrians wait for their turn to cross the roadway. During off-peak periods when vehicular volumes are lower but pedestrians may still be running errands, this is a solution to minimize pedestrian delay with minimal impacts on vehicular delay (Wolfgram 2021). Even during peak periods, reducing cycle lengths, if possible, can be beneficial for pedestrians. This countermeasure is unlikely to increase pedestrian safety during the time pedestrians are permitted to cross the street but can increase pedestrian compliance at signals and therefore safety.

2.6.16.1. Safety

Reducing the cycle length can increase pedestrian compliance with the signal and reduce pedestrian delays. However, these benefits are unfounded and likely minimal. Since there are no specifically calculated CMFs for reducing the cycle length it will be assumed in this study that there are no safety benefits for both pedestrians and bicyclists, equaling a CMF of 1.

2.6.16.2. Delay

Longer signal cycle lengths can process more vehicles during congested periods due to a higher fraction of green times compared to yellow and red times (Wolfgram 2022). Therefore, reducing cycle lengths can increase vehicular delays.

2.6.16.3. Implementation

It has been recommended that 60-90 second cycle lengths be used at all possible intersection locations to provide consistent crossing opportunities for pedestrians (NACTO 2015).

2.6.16.4. Costs

Reducing the cycle length typically will only involve signal retiming. This requires $1,000 to $8,000 per intersection for signal adjustments, with an average of $3,500.

Line Items:

- $3,500 ($1,000-$8,000) | **Traffic signal retiming |** (FDOT, n.d.; City of Colusa, n.d.; Texas A&M Transportation Institute 2013)

It is assumed that pedestrian signals and other typical intersection attributes are already at the intersection.

Traffic signal retiming is estimated as $1,000-$8,000 per intersection (FDOT, n.d.) with an average of $3,500 in Texas based on available literature. City of Colusa's cost table of safety projects estimates $2,500 per update (City of Colusa, n.d.) and Texas A&M Transportation Institute estimates $3,500 per intersection (Texas A&M Transportation Institute 2013).

2.6.17. Increase the cycle length

Increasing the cycle length can provide longer time for pedestrians to cross the roadway and allow signal timings to accommodate pedestrian crossing minimum times while maintaining appropriate vehicle green splits.

2.6.17.1. Safety

Chen, Chen, and Ewing found a 50% reduction in crashes looking at 244 intersections in New York City (2012). FHWA's "Toolbox of Pedestrian Countermeasures and Their Potential Effectiveness" cites this study as a CMF of 0.49 with a standard error of 0.1. In 2013, Chen et al. analyzed presumably the same 244 intersections using the ANCOVA regression technique and found a CMF of 0.49 with a standard error of 0.1 for pedestrians at all severity levels. Therefore, a CMF of 0.49 is assumed for this study.

The Chen et al. 2013 study also looked at bicyclist crashes and found a reduction of 29% compared to 41% in the comparison group. Their sample size was too small to compute a CMF, and, since no other studies analyzing this countermeasure for bicyclists were found, a CMF of 1 is assumed.

2.6.17.2. Delay

Longer signal cycle lengths can process more vehicles during congested periods due to a higher fraction of green times compared to yellow and red times (Wolfgram 2022). Therefore, increasing the cycle length has the potential to reduce vehicular delays.

2.6.17.3. Costs

Increasing the cycle length typically will only involve signal retiming. This requires $1,000 to $8,000 per intersection for signal adjustments.

Line Items:

- $1,000-$8,000 | **Traffic Signal retiming |** (FDOT, n.d.; City of Colusa, n.d.; Texas A&M Transportation Institute 2013)

It is assumed that pedestrian signals and other typical intersection attributes are already at the intersection.

Traffic signal retiming is estimated as $1,000-$8,000 per intersection (FDOT, n.d.) with an average of $3,500 in Texas based on available literature. City of Colusa's cost table of safety projects estimates $2,500 per update (City of Colusa, n.d.) and Texas A&M Transportation Institute estimates $3,500 per intersection (Texas A&M Transportation Institute 2013).

2.6.18. Single-stage crossings

Some long crosswalks contain a median where pedestrians have to stop and wait in the middle of the street before continuing to cross the roadway (Wolfgram 2021). This can cause discomfort for pedestrians as they wait to continue across the remaining section of roadway. Instead allowing pedestrians to cross the roadway can decrease their delay and increase comfort. No claims can be made about increased safety at this time.

2.6.18.1. Safety

Retiming signals to allow pedestrians to cross in one phase removes the need for pedestrians to wait in the median. A report issued by NYC DOT discusses this retiming in New York City along Queens Boulevard in 2002, and says that the cycle length was changed from 120 seconds to 150 seconds to allow pedestrians to perform single-stage crossings (NYC DOT 2007). With this implementation, pedestrian fatalities fell from 4.7 per year during 1999-2001 to 1.5 per year after single-stage crossings were implemented (NYC DOT 2007; Kittelson & Associates, Inc. 2022). However, no pedestrian CMFs have been quantified for this countermeasure and therefore no CMF can be stated.

Bicyclists are typically not required to perform two-stage crossings, so this countermeasure likely will not apply. Therefore, the CMF for bicyclists can be assumed to be 1.

2.6.18.2. Delay

Implementing single stage crossings will typically increase vehicular delay (Wolfgram 2022). Oftentimes, simply setting the timing to accommodate a pedestrian clearance interval will not be feasible due to the amount of vehicular delay it will cause, and therefore, alternative methods, such as providing a single stage crossing but timing the clearance time only for half of the street, may be used (Wolfgram 2022).

2.6.18.3. Costs

Implementing single-stage crossings eliminates mid-crossing stops and, typically, converting a crossing to be single-stage will involve only signal retiming, costing $1,000 to $8,000 per intersection.

Line Items:

- $1,000-$8,000 | **Traffic Signal retiming |** (FDOT, n.d.; City of Colusa, n.d.; Texas A&M Transportation Institute 2013)

It is assumed that pedestrian signals and other typical intersection attributes are already at the intersection.

Traffic signal retiming is estimated as $1,000-$8,000 per intersection (FDOT, n.d.) with an average of $3,500 in Texas based on available literature. City of Colusa's cost table of safety projects estimates $2,500 per update (City of Colusa, n.d.) and Texas A&M Transportation Institute estimates $3,500 per intersection (Texas A&M Transportation Institute 2013).

2.6.19. Road diet

A road diet is generally a countermeasure where the number of vehicle lanes is reduced on a roadway and space is reallocated to other users, such as increasing sidewalk space, adding bicycle lanes, adding bus lanes, or pedestrian refuge island. A classic example of a road diet is where an existing four-lane undivided roadway segment is converted to a three-lane segment with two through lanes and a center two-way left turn lane (FHWA 2020).

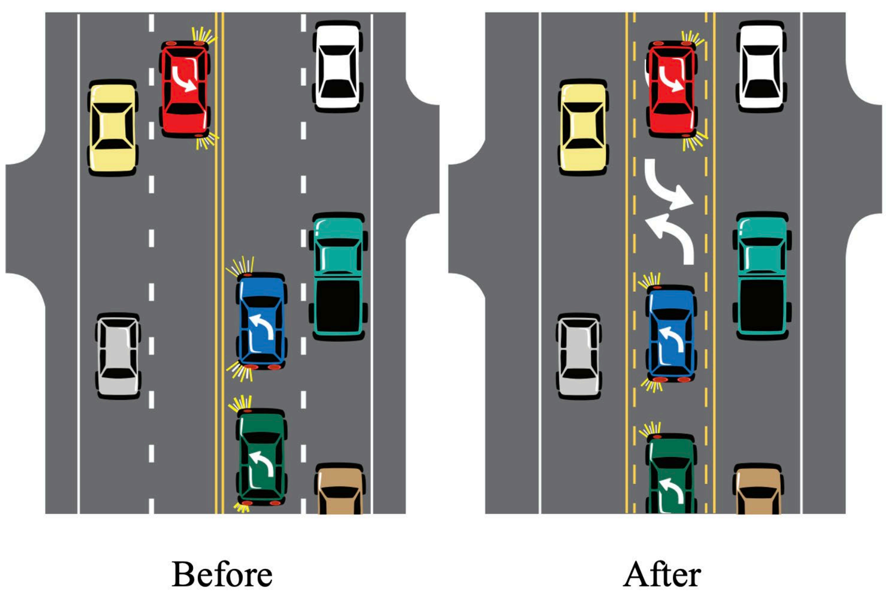

Figure 12. Illustration of a typical road diet (FHWA 2016)

2.6.19.1. Safety

A road diet removes a vehicle lane and adds pedestrian or bicyclist space. Removing a lane can slow down vehicles and lessen the distances pedestrians have to cross, therefore increasing pedestrian safety. The safety benefit of a lane reduction is dependent on specifics of the project; however, many studies have analyzed this benefit for various projects. FHWA's "Toolbox of Pedestrian Countermeasures and Their Potential Effectiveness" cites three separate CMFs for road diets: 0.71 for all users when a four lane road is narrowed to a three lane road with a center turn lane, 0.81 for pedestrians for an urban road diet and 0.53 for pedestrians for a suburban road diet. This first CMF of 0.71 is from Harkey et al.'s 2008 before-after with Empirical Bayes study from which a standard error of 0.02 was calculated (FHWA, n.d.-d). The second of these CMFs is from the Pawlovich et al. study in Iowa where 32 segments of roadway in Iowa were evaluated to find a 25% reduction in overall crashes per mile. While FHWA states this study looks at the reduction in pedestrian crashes. it is not evident in the published paper that this study does analyze pedestrian crashes. The third stated CMF is 0.53 for a suburban road diet and comes from the Persaud et al. 1997 paper entitled "Crash Reductions Related to Traffic Signal Removal in Philadelphia", which does not appear to talk about road diets and instead talks about traffic signal removal. Chen et al. also analyzed road diets in their 2013 paper. They looked at CMFs for both intersections and roadway segments. They analyzed crashes at 324 intersections using a before-after with regression approach and found a pedestrian CMF of 1.05 with a standard error of 0.16, despite the CMF for all users at intersections where a road diet was performed being a statistically significant 0.87 with a standard error of 0.05. Because the study by Chen et al. was determined to be the most accurate, a CMF of 1 was chosen to represent no change in pedestrian crashes from adding a road diet.

When lanes are removed for a road diet it frees up space to add a bicycle lane and also promotes slower speeds which can all increase the safety of bicyclists. The only study found was the Chen et al. 2013 paper which found a CMF of 1.21 at intersections. This value was not statistically significant with an error range of 0.3 and involved only a 6% increase in crashes at locations with a road diet and a -25% change in crashes at the comparison locations. Therefore, a CMF of 1 will be assumed to represent no safety improvement from removing a lane.

2.6.19.2. Delay

While it may seem road diets will increase congestion on the remaining lanes, it has been found not to be the case numerous times (Cairns et al. 2001). In many scenarios, a four-lane road is operating functionally as a three-lane road due to turning vehicles, as seen in Figure 12 (FHWA 2016). A roadway may simply not be operating at capacity and have the ability to still function acceptably without a lane or two. Finally, the most significant constraint on roadway capacity is the intersections; removing a lane throughout the corridor and instead providing dedicated turning lanes can reduce intersection delay.

However, in some instances a road diet will make congestion worse, especially in the short-term. However, in locations where vehicle delays will be increased by removing a lane, it is still often seen as a positive due to the benefits for pedestrians and bicyclists. Studies should, therefore, be done on roadways that are potential candidates for road diets to determine the impacts on all modes and whether a road diet should be implemented.

In 2012, DelDOT constructed a road diet on one mile of the Philadelphia Pike, transforming it from a four-lane roadway to a three-lane roadway with a two-way left turn lane and a bicycle lane in each direction (RK&K, LLP 2017). For one major intersection along the corridor, the vehicular LOS decreased from B to A in both the AM and PM peak, while for the other intersection the LOS increased from B to C in the PM peak but remained the same during the AM peak period.

2.6.19.3. Implementation

Road diets are especially applicable on roadways with low traffic volumes or with a high proportion of left-turning vehicles without turn bays (FHWA 2016). FHWA has determined corridors with ADT below 10,000 capacity will most likely not be affected by a road diet, whereas, for roadways over 20,000 ADT, careful studies must be conducted and capacity may be affected (FHWA 2016). However, roadways with as high as 26,000 ADT have had successful road diets (FHWA 2016).

Road diets are applicable to TxDOT intersections, following proper analysis. While the majority of a road diet will occur at locations other than intersections, intersections are where bottlenecks typically occur and where the most consideration should be taken to determine if a lane can be removed.

2.6.19.4. Case Studies

In Austin, Texas, a road diet pilot project was implemented on Barton Springs Road in August 2023 (Austin Mobility Bonds 2024). This project converted a four-lane roadway with a history of dangerous crashes to a two-lane roadway with increased bicycle lane protection and pedestrian amenities (James Rambin 2024). Framing it as a pilot project and using quick-build materials allowed the city to gain more support, with a promise to evaluate it at the year mark. After a year, it has gained support from locals (70% approval) who expected traffic to be unbearable but instead found travel times to be very similar to before the road diet was implemented (Austin Mobility Bonds 2024). Following this initial success, now the City of Austin is planning to transition the temporary improvements to more permanent solutions, in the form of concrete curbs. The Barton Springs implementation shows a pilot study can be a useful tool for implementing more drastic measures that may not win community support at first.

Figure 13. The City of Austin's Barton Springs Pilot Project, showing temporary materials used for a protected bicycle lane (James Rambin 2024).

The Barton Springs Pilot Study in Austin converted a four-lane roadway to a two-lane roadway with additional provisions for active transportation users (Austin Mobility Bonds 2024). Following this implementation, traffic volumes decreased and pedestrian and cyclist volumes increased. The number of vehicles traveling above the speed limit also sharply decreased.

2.6.19.5. Costs

The estimated cost for restriping three lanes plus bicycle lanes ranges from $25,000 to $40,000 per mile, depending on the extent of lane line repainting required (FHWA, n.d.-i). This can also be estimated as $8.75 per foot for removing old lane markings and restriping new lanes from TxDOT data, which produces a per-mile cost slightly higher than the previous estimate. However, the cost can rise significantly reaching $100,000 or more per mile with other modifications such as extended sidewalks, refuge island, and so on (FHWA, n.d.-i). So, a project of converting 4-lane to 3-lane and adding a bike lane costs from $25,000 to $100,000 per mile based on the components included in the project.

Line Items:

- $3.45 per foot | **Pavement markings removal** | [677-] (TxDOT 2025)
- $5.3 per foot | **Multi-polymer pavement markings** | [6038-] (TxDOT 2025)

Complimentary items include extending the sidewalks, adding refuge islands, adding bicycle lanes, and adding curb extensions.

2.6.20. Curb extensions

Also called bulb-outs or neckdowns, the curb can be extended into the street to reduce the distance pedestrians have to cross and improve sight distance between pedestrians and drivers (City of Austin 2023b). This also adds space for street furniture, benches, foliage, and street trees (NACTO 2015). Typically, curb extensions are used when there is a parking lane on the roadway. An example of a curb extension can be seen in Figure 14.

Figure 14. Curb extension with quick-build materials in Philadelphia (taken: Bainbridge Street & S 11th Street, July 2024).

Extending the curb also decreases the curb radius, which has been proven to have positive impacts on safety by decreasing speeds (Federal Highway Administration et al. 2022). Figure 15 shows this relationship.

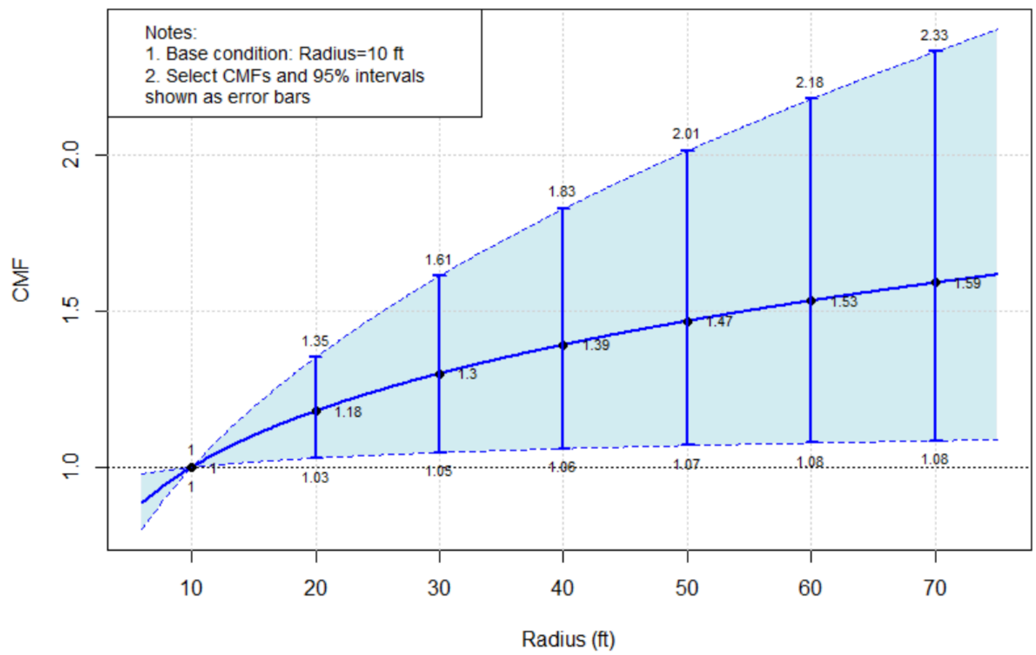

Figure 15. A diagram estimating the increase in CMF for each additional foot of corner radius (Federal Highway Administration et al. 2022).

Compared to a baseline of 10ft, a corner with a radius of 70ft is expected to experience 59% more pedestrian crashes if all other conditions are the same (Federal Highway Administration et al. 2022). On the contrary, if a corner with a radius of 70ft is then reduced to 10ft, the intersection could be expected to experience 59% fewer pedestrian crashes.

2.6.20.1. Safety

Adding curb extensions allows a space for pedestrians to wait to cross the road that is more visible than otherwise and reduces the distance they must cross (City of Austin 2023b; NACTO 2015). They are typically implemented where a roadway has existing parking and include removing parking by the intersection and adding extra curb space. There were no CMFs found for adding curb extensions, but FHWA's "Toolbox of Pedestrian Countermeasures and Their Potential Effectiveness" provides a CMF of 0.7 for prohibiting parking near intersections. This CMF comes from the Gan et al. survey of all states. It can be assumed this CMF of 0.7 represents the safety of a bulb-out conservatively.

No CMFs were found in the literature for bicyclists when curb extensions were added. There are likely some benefits from increased sight distance due to less parking, but also sometimes safety risks are created as cyclists are forced to alter their path. Therefore, no CMF can be assumed for this countermeasure.

2.6.20.2. Delay

It is likely that there are no vehicular delay impacts from adding curb extensions.

2.6.20.3. Implementation

Curb extensions should be installed only after evaluating their impact on cyclists. While they increase pedestrian safety, they can also force bicyclists to alter their path into the line of vehicles (Maria Sworske 2025).

2.6.20.4. Costs

Adding curb extensions can vary from $900-$13,000 with an average of $1,000 each when quick-build materials are used (Dunlap and Associates, Inc. et al. 2023). Storm water impacts, transit stops, or having to move utility or traffic signal poles can all increase the cost to up to $20,000 (FHWA 2013).

Line Items:

- $1,000 ($900-$13,000) each | **Curb extensions** | (Dunlap and Associates, Inc. et al. 2023)

2.6.21. Remove channelized turn lane

A channelized turn lane, also referred to as a "slip-lane", can be replaced with a conventional turn lane when the channelized turn lane poses safety issues to pedestrians (Kittelson & Associates, Inc. et al. 2021). This removal can alter a multiple-stage crossing to be only one stage, reduce total pedestrian crossing distance, and consolidate pedestrian-vehicle conflict points (Kittelson & Associates, Inc. et al. 2021; Rosas et al. 2023).

Figure 16. An example of a channelized turn lane before removal at W 38th Street and W 35th Street, Austin, Texas (Google, n.d.).

Figure 17. An example of a removed channelized turn lane transformed into a bike path at W 38th Street and W 35th Street, Austin, Texas (Google, n.d.).

The space from a removed channelized turn lane can be reallocated to pedestrians and bicyclists through increased sidewalk space or additional protected bicycle lanes, as shown in Figure 16 and Figure 17.

However, removing the channelized turn lane can also have undesirable effects for pedestrians as the main crosswalk length may increase and conflicts for bicyclists on the road as drivers turn should be considered (Kittelson & Associates, Inc. et al. 2021).

2.6.21.1. Safety

In recent years, it has become clear that channelized turn lanes can pose safety threats to pedestrians and bicyclists (Hallmark and Hawkins 2014; van Haperen et al. 2018). In these instances a channelized turn lane can be replaced with a conventional turn lane (Kittelson & Associates, Inc. et al. 2021). This removal can additionally alter a multiple-stage crossing to be only one stage by reducing total crossing distance and consolidate pedestrian-vehicle conflict points (Kittelson & Associates, Inc. et al. 2021). No pedestrian or bicyclists CMFs were found for removing a channelized right-turn lane; therefore, they cannot be assumed for this study.

2.6.21.2. Delay

Channelized turn lanes allow drivers to reduce their speed less than they would when making a typical turn. Therefore, removing channelized turn lanes can increase vehicular delays (Jiang et al. 2020).

2.6.21.3. Costs

The basic removal of a channelized turn lane normally includes restriping, and minor curb modification. The estimated cost of curb radius reduction ranges from $5,000 to $40,000 (FHWA, n.d.-b). The basic cost of line repainting ranges from $0.1 to $0.25 per foot (FHWA 2008). But with additional modifications, the cost may be up to $1 per linear foot (City of Wichita, n.d.).

Implementing removal of one channelized turn lane includes removal of pedestrian islands, removal of pavement markings, removal of pedestrian signal assembly, and performing curb extension and pedestrian signal reinstallation. From LADOT, the total estimated cost of channelized turn lane removal ranges from $5,000 to $10,000 (LADOT 2023).

Line Items:

- $42 per foot | **Replace curbs** | [690-6055] (TxDOT 2025)

Bicycle lanes can also be added through a removed channelized turn lane.

2.6.22. Alter channelized turn lane

When removing a channelized turn lane is not an option due to high proportions of vehicular turning traffic and subsequent delays, the channelized turn lane can be altered to improve visibility of pedestrians and increase decision-making time (Kittelson & Associates, Inc. et al. 2021). Drivers may be looking ahead at traffic they will merge into and maintaining relatively high speeds through channelized turn lanes (Rosas et al. 2023). Therefore, alterations can reorient the angle of the turn lane and vehicles to place potentially crossing pedestrians in drivers direct line of sight and provide them with enough time before the crosswalk to look for pedestrians and enough time after the crosswalk to look for vehicles in the upcoming lane (Kittelson & Associates, Inc. et al. 2021).

2.6.22.1. Safety

Schattler et al. evaluated channelized right-turn lanes with an increased angle and found a 59% reduction in all crashes from the treated approach using an Empirical Bayes methodology (Schattler et al. 2016; Gemar et al. 2016). Other research came to similar conclusions, but no studies were found that explicitly looked at the safety impacts on pedestrians or bicyclists; therefore, no CMFs can be assumed for this study (Gemar et al. 2016).

2.6.22.2. Delay

No literature was found discussing the impacts on delays vehicles will experience of altering channelized turn lane geometry. However, it can be assumed that altering a channelized turn lane to optimize safety instead of speed will produce some delays.

2.6.22.3. Implementation

The angle of the right-turn lane can be altered to improve visibility, as shown in Figure 18 (Kittelson & Associates, Inc. et al. 2021).

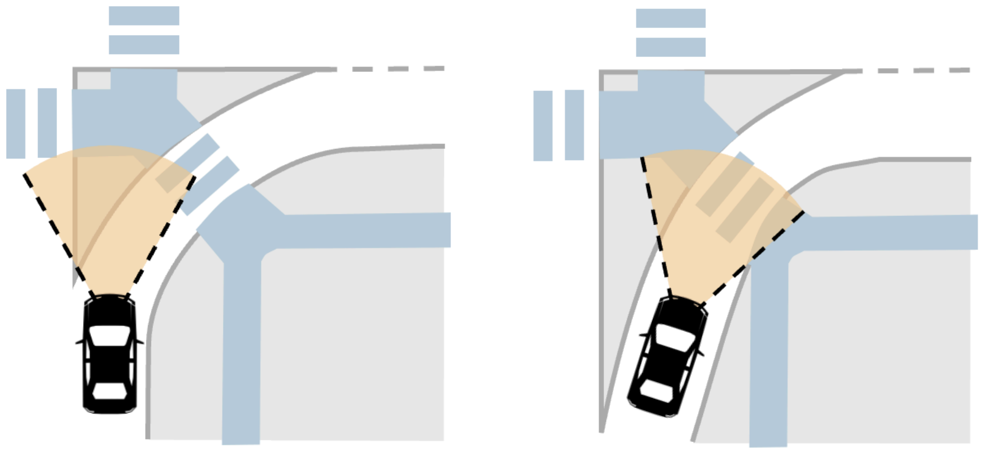

Figure 18. Channelized right-turn lane design (figure based on Kittleson & Associates, Inc. et al. 2021, car icon created by Stone from Noun Project).

When a vehicle is entering or exiting a channelized turn lane, there should be sufficient space before the driver has to worry about the next vehicle-vehicle or vehicle-pedestrian conflict point (Kittelson & Associates, Inc. et al. 2021). Typically, one vehicle length should be provided between these conflict points.

Furthermore, right-turn-on-red restrictions, adding a stop or yield line before a pedestrian crossing, or adding a raised crosswalk in a channelized turn lane can increase pedestrian safety (Kittelson & Associates, Inc. et al. 2021).

2.6.22.4. Costs

The basic reconstruction of a channelized turn lane normally includes restriping and minor curb modification. The estimated cost of curb radius reduction ranges from $5,000 to $40,000 (FHWA, n.d.-b). The basic cost of line repainting ranges from $0.1 to $0.25 per foot (FHWA 2008). But with additional modifications, the cost may increase to $1 per linear foot (City of Wichita, n.d.).

Altering a channelized turn lane normally includes restriping and potentially curb and pedestrian island modification. The estimated costs range from $50,000 to $200,000 to reconfigure an intersection with channelized turn lanes and add striping and raised islands (FHWA 2002). So, an estimate of $12,500-$50,000 per corner can be assumed for altering a channelized turn lane.

Line Items:

- $42 per linear foot | **Replace curbs** | [690-6055] (TxDOT 2025)
- $0.1-$0.25 per foot | **Restriping** | (FHWA 2008)

2.6.23. Reduce the curb radius

The radius of a curb can increase the distance that pedestrians have to cross and increase turning vehicle speeds (Chandler et al. 2013). Therefore, decreasing this turn radius may decrease vehicle speeds and help increase pedestrian safety (Potts et al. 2006).

2.6.23.1. Safety

A study in Virginia looked at crashes at intersection corners from 2013-2018 using regression models (Federal Highway Administration et al. 2022). They determined the CMFs shown in Table 1 for increasing the corner radius, which can be looked at in reverse to estimate the reduction in crashes from decreasing it.

Table 1. CMFs for increasing corner radius on pedestrian crashes, based on a baseline 10 ft corner radius (Federal Highway Administration et al. 2022).

Corner Radius (ft)	CMF	CMF Standard Error Range
10	1.00	--
20	1.18	1.03 - 1.35
30	1.30	1.05 - 1.61
40	1.39	1.06 - 1.83
50	1.47	1.07 - 2.01
60	1.53	1.08 - 2.18
70	1.59	1.08 - 2.33

Compared to a baseline of 10ft, a corner with a radius of 70ft is expected to experience 59% more pedestrian crashes if all other conditions are the same (Federal Highway Administration et al. 2022). On the contrary, if a corner with a radius of 70ft is then reduced to 10ft, that intersection could be expected to experience 59% less pedestrian crashes. Therefore, the assumed CMFs for pedestrians come from this study and vary with the current corner radius.

Corner radius can also be assumed to affect bicyclist safety; however, no studies have been carried out to test this effect and produce a CMF. Therefore, no CMF can be assumed.

2.6.23.2. Delay

Decreasing corner radii has been assumed to decrease vehicular delays, although the thought process was not explained (Federal Highway Administration et al. 2022). No studies were found in the literature testing the delay impact of various corner radii.

2.6.23.3. Costs

Reconstructing a curb to have a tighter radius can vary from $5,000-$40,000 depending on site characteristics (FHWA 2013).

Line Items:

- $42 per linear foot | **Replace curbs** | [690-6055] (TxDOT 2025)

2.6.24. Truck apron

A truck apron is where there is a painted, raised, or otherwise delineated area used by trucks and other heavy vehicles typical vehicles are not allowed to use(Alta Planning and Design 2020).

2.6.24.1. Safety

A truck apron is assumed to increase pedestrian safety due to the slower speeds of turning vehicles. It should be noted there is less assumed safety than decreasing the curb radius because the gained space is unusable for pedestrians, unsafe for them to wait in, and does not decrease crossing distances. There are no CMFs in the literature identifying the safety benefits of this countermeasure; therefore, none can be assumed.

No studies were identified in the literature discussing development of a CMF for bicyclists after installing a truck apron; therefore, none can be assumed.

2.6.24.2. Delay

No literature was identified discussing the delay impacts of adding a truck apron to a corner.

2.6.24.3. Costs

Reconstructing a corner to have a painted corner or a raised area can range from $2,000 to $20,000 depending on the methodology used (NACTO, n.d.).

Line Items:

- $9 per foot | **Mountable Curb** | [529-6024] (TxDOT 2024)
  OR $5.3 per foot | **Multi-polymer pavement markings** | [6038-] (TxDOT 2025)

2.6.25. Continue painted bicycle lanes through the intersection

Bicycle lanes can be continued into intersections to improve bicyclist safety (Deliali et al. 2021). Bicycle lanes can either be simply painted or colored green, as shown in Figure 19 (FHWA 2023a).

Figure 19. Bicycle lane at T-intersection in Austin, Texas (taken: W Guadalupe Street & W 46th Street, December 2024).

Creating a refuge island and crossing set back from the corner can increase the visibility and reaction time for motorists, as shown in Figure 20.

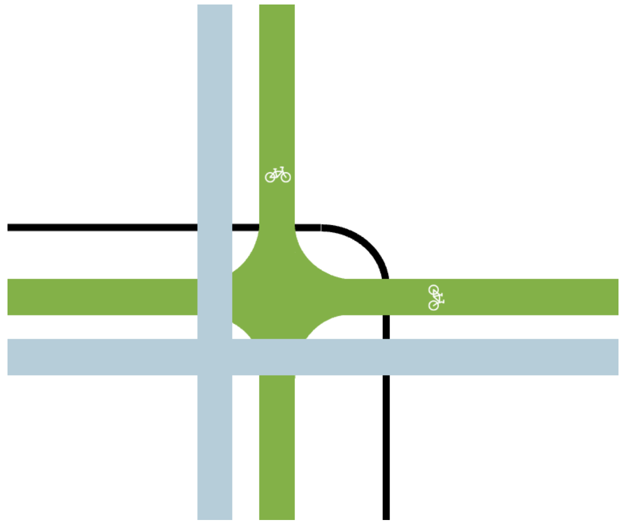

Figure 20. Example of a protected bicycle lane at a median U-turn intersection (figure based on: Kittelson & Associates, Inc. et al. 2021).

Protected bicycle lanes require more space than a painted bicycle lane, and therefore, may be infeasible at certain intersections.

2.6.25.1. Safety

No CMFs for continuing painted bicycle lanes through the intersection were found in the literature. For pedestrians, a CMF of 1 can be assumed for this countermeasure.

For bicyclists, no CMF can be assumed because there is likely an increase in safety yet none found in the literature.

2.6.25.2. Delay

When adding bicycle lanes, vehicle delays might be produced from reduced or narrowed lanes (Jaffe 2014). However, there have also been examples, such as in New York City, where adding a bike lane provided the opportunity to reconfigure the roadway and vehicle operations actually improved (Jaffe 2014).

2.6.25.3. Costs

The estimated cost of adding a bicycle lane to an existing roads is $5,000 to $50,000 per mile for basic striping, excluding any major infrastructure changes (Norte Youth Cycling, n.d.). Costs will increase if the bicycle lane is painted green or bicycle symbol markings or arrows are added.

Line Items:

- $5.3 per foot | **Multi-polymer pavement markings** | [6038-] (TxDOT 2025)
  OR
  $4 per square foot | **Green Bike lane paint** | (INCOG, n.d.)
- $140 | **Bicycle symbol markings** | [666-] (TxDOT 2025)
- $100 | **Bicycle arrow markings** | [666-] (TxDOT 2025)

2.6.26. Continue protected bicycle lanes up to the intersection

Instead of removing protected bicycle lanes near the intersection to make room for turn lanes, it is safer to continue them through to the intersection (NACTO 2012). An example of a protected bicycle lane through a T-intersection can be seen in Figure 21.

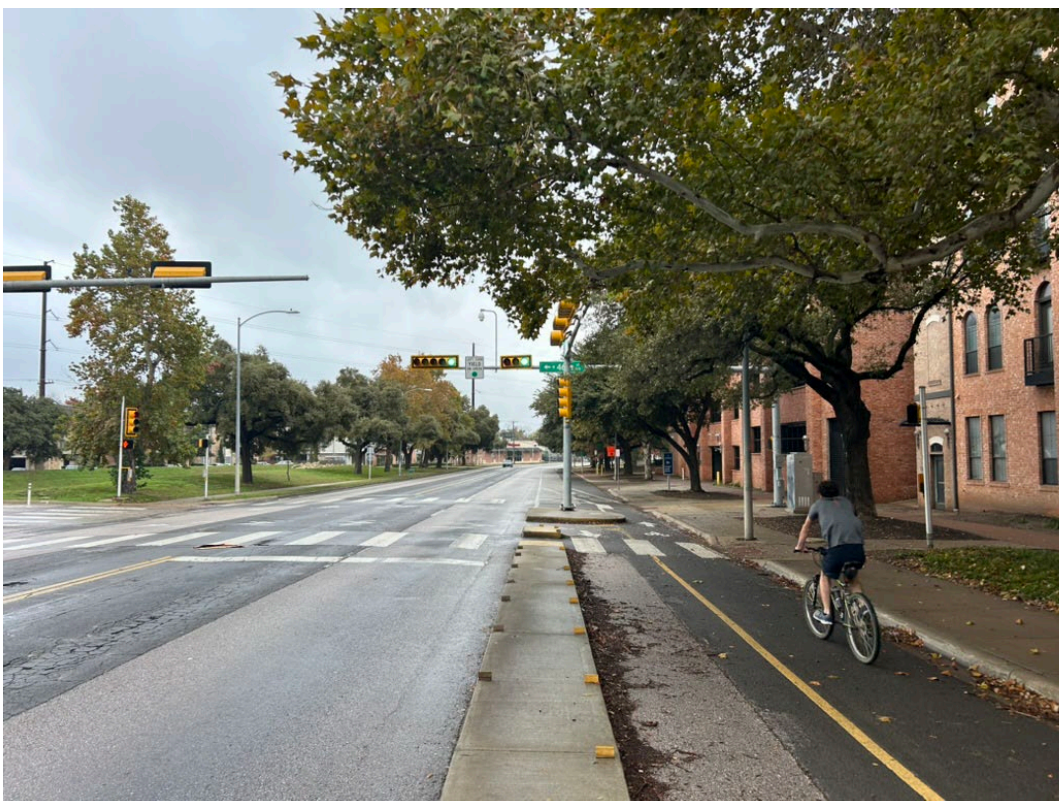

Figure 21. Protected bicycle lane at T-intersection in Austin, Texas (taken: W Guadalupe Street & W 46th Street, December 2024).

2.6.26.1. Safety

No CMFs for continuing protected bicycle lanes into the intersection were found in the literature for pedestrians or bicyclists. Protected bicycle lanes likely have no impact on pedestrian safety, and therefore, a CMF of 1 is assumed.

For bicyclists, no CMF can be assumed since there were no studies found analyzing CMFs for this countermeasure. Observational studies have shown an increase in safety from continuing protected bicycle lanes up to the intersection (Preston and Pulugurtha 2021; Donald, n.d.; Lyons et al. 2019).

2.6.26.2. Delay

When adding bicycle lanes, vehicle delays might be produced from reduced or narrowed lanes (Jaffe 2014). However, there have also been examples, such as in New York City, where adding a bike lane provided the opportunity to reconfigure the roadway and vehicle operations actually improved (Jaffe 2014).

2.6.26.3. Costs

The estimation of adding a bicycle lane to an existing roads costs $5,000 to $50,000 per mile for basic striping, excluding any major infrastructure changes (Norte Youth Cycling, n.d.). But the cost would be varied when including curb ramps or other physical separation products.

Line Items:

- $50,000-$90,000, per mile | **Flexible bollards** | (City of Austin 2023a)
  OR
  $80,000-$220,000, per mile | **Narrow cast-in-place curb** | (City of Austin 2023a)

Additionally green paint and bicycle symbol markings can be used to further emphasize the bicycle lane.

2.6.27. Protected Intersections

A fully protected intersection is sometimes referred to as a “Dutch style intersection,” where curbs are situated at each corner to provide a protected area for bicyclists to wait, as can be seen in Figure 22.

Figure 22. Fully protected intersection in Austin, Texas (taken: Shoal Creek Blvd & Foster Ave, July 2025).

2.6.27.1. Safety

No CMFs for protected intersections or “Dutch style intersections” were found in the literature for pedestrians or bicyclists. For this study it is assumed that pedestrians will have a CMF of 1 since there are only loose claims this will make pedestrians safer. For bicyclists, no CMF can be assumed since there were no studies found analyzing CMFs for this countermeasure.

2.6.27.2. Delay

There was no literature found discussing delays from altering an intersection to be fully protected.

2.6.27.3. Costs

Fully protected intersections include curbs to protect bicyclists while they wait to cross and painted bicycle lane markings. One has been stated to cost around $1,000,000 (Holeywell 2016; City of Davis, n.d.).

Line Items:

- $42 per linear foot | **Replace curbs** | [690-6055] (TxDOT 2025)
- $140 | **Bicycle symbol markings** | [666-] (TxDOT 2025)
- $100 | **Bicycle arrow markings** | [666-] (TxDOT 2025)
- $4 per square foot | **Green Bike lane paint** | (INCOG, n.d.)

2.6.28. Bicycle lane lateral shift

A lateral shift moves bicyclists to the left of the right-turn lane prior to vehicles being able to move right (Goodman et al. 2015). This geometry reinforces the vehicle's responsibility to yield (Adriazola-Steil et al. 2021). A representation of the geometry can be seen in Figure 23.

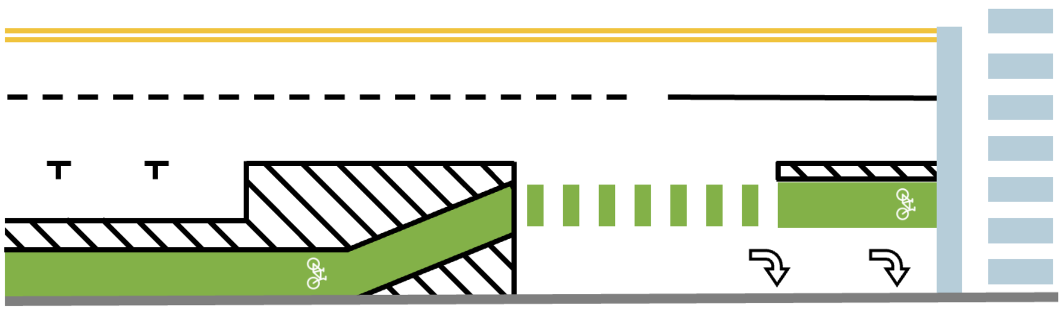

Figure 23. A depiction of a bicycle lane lateral shift at one approach (based on Goodman et al. 2015, bicycle icon by Joe Harrison from the Noun Project).

2.6.28.1. Safety

No literature has been found discussing safety for pedestrians for this countermeasure; therefore, a CMF of 1 can be assumed.

There is likely a safety benefit to bicyclists from a bike lane lateral shift, yet no CMFs have been developed in the literature; therefore, none can be assumed.

2.6.28.2. Delay

No literature has been found discussing vehicular delay impacts from adding a bicycle lane lateral shift.

2.6.28.3. Costs

Bicycle lane lateral shifts involves restriping and adding curbs or paint and flexi posts to delineate areas where cars cannot cross the bicycle lane.

- $50,000-$90,000, per mile | **Flexible bollards** | (City of Austin 2023a)
  OR
  $80,000-$220,000, per mile | **Narrow cast-in-place curb** | (City of Austin 2023a)
- $5.3 per foot | **Multi-polymer pavement markings** | [6038-] (TxDOT 2025)
- $4 per square foot | **Green Bike lane paint** | (INCOG, n.d.)

2.6.29. Raised bicycle/pedestrian crossings

A raised crossing is a bicycle and/or pedestrian path raised above the normal pavement surface, forcing vehicles to slow down as they drive over it. An example of one can be seen in Figure 24.

Figure 24. Raised pedestrian and bicycle crossing at Lamar Boulevard & Airport Boulevard.

Furthermore, at some locations entire intersections can be raised to provide increased safety to pedestrians and bicyclists.

2.6.29.1. Safety

Adding raised pedestrian crossings can slow down vehicular traffic and encourage more awareness of potential crossing pedestrians. Bahar et al. studied the safety effects of raised pedestrian crossings in an unpublished 2007 study. They found a CMF of 0.7 for all users and severities, as cited in FHWA’s “Toolbox of Pedestrian Countermeasures and Their Potential Effectiveness”. Bahar et al.’s 2008 “Desktop Reference for Crash Reduction Factors” cites a standard error of

0.67 for this CMF. Elvik and Vaa performed a meta-analysis in 2004 and found a CMF of 0.51 for pedestrian injury and fatality crashes. None of these CMFs are rigorous, but all seem reasonable. Therefore, the more conservative CMF of 0.7 was chosen as the best option (Bahar et al. 2007).

Adding a raised bicyclist crossing can reduce vehicle speeds and increase visibility of bicyclists. A 2011 study in the Netherlands looked at 852 site-years of data using a regression cross-section and found a statistically significant bicyclist CMF of 0.49 with a standard error of 0.11. The Elvik and Vaa 2004 meta-analysis also found a CMF of 1.09 for raised bicyclist crossings. The Netherlands study was more rigorous, however; therefore, the CMF of 0.49 was chosen to represent bicyclist CMFs from adding a raised crossing.

2.6.29.2. Delay

Raised crossings reinforce slow speeds (NACTO 2015), therefore moderately decreasing vehicle operations. Delays may likely be more extreme where speeding exists and minimal where speed limits are followed.

2.6.29.3. Implementation

A schematic depicting this type of crossing from an aerial view can also be seen in Figure 25.

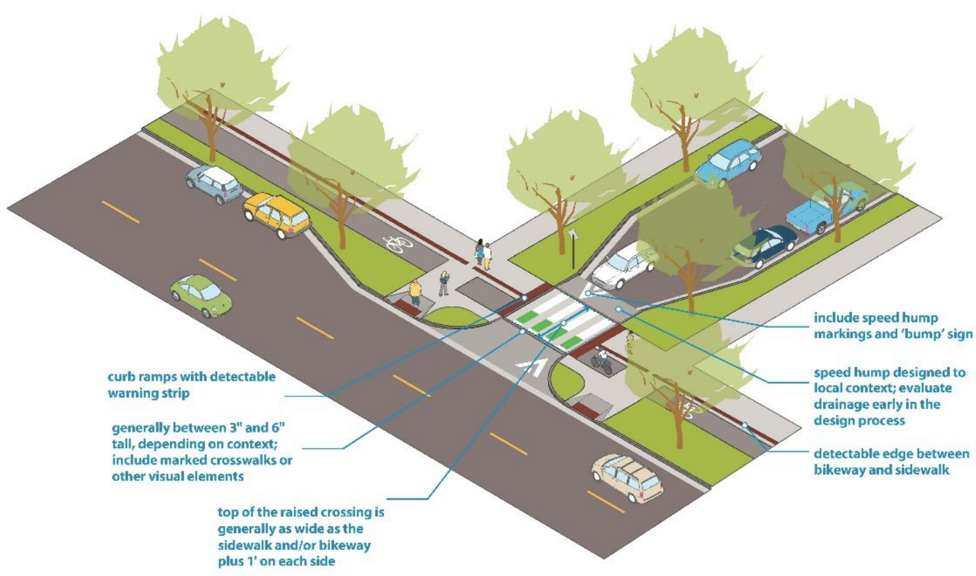

Figure 25. A depiction of a raised bicycle crossing (and pedestrian crossing) (City of Minneapolis, n.d.).

The inclined plane of the raised crosswalk should include speed hump markings and a ‘bump’ sign (City of Minneapolis, n.d.). The top of the crosswalk typically should be raised 3-6” and be the width of the sidewalk or bikeway plus 1’ (City of Minneapolis, n.d.). Typical crosswalk or bikeway symbols can be painted atop the raised crosswalk, and curb ramps should be included if the elevation is not level with the sidewalk (City of Minneapolis, n.d.).

2.6.29.4. Costs

The total estimate cost of installing raised bicycle/pedestrian crossings can be estimated as $2,400 plus $5.3 per foot for pavement markings. And from cases in the City of Portland, the cost analysis estimates $3,500 per raised crosswalk (Lynn Weigand et al. 2013).

Line Items:

- $2,400 | **Speed Table** | [5041-6001] (FHWA, n.d.-c)
- $5.3 per foot | **Multi-polymer pavement markings** | [6038-] (TxDOT 2025)

2.6.30. Bicycle signals

For bicyclists, a “right-hook” crash is where the right turning driver does not see the bicyclist and turns into them. Typically at intersections, drivers have been found to be more focused on the oncoming traffic than bicyclists approaching from behind them (Jannat et al. 2018). Bike signals give bicyclists a head-start into the intersection and improve visibility for drivers before the drivers are allowed to turn.

Figure 26. Bicycle signal at W Guadalupe Street and W 46th Street in Austin, Texas.

2.6.30.1. Safety

For pedestrians, there is likely no benefit from adding a bicycle signal; therefore, a CMF of 1 is assumed.

Bike signals can be used to separate bicycle through movements from vehicle right turning movements, which may increase safety and reduce right-hook crashes (Goodman et al. 2015). However, on their own without special signalization, bike signals can be assumed to have a CMF of 1. The safety benefit would come from other signalization techniques with the bike signal, such as adding a leading bicycle interval.

2.6.30.2. Delay

A bicycle signal alone likely would not have an impact on vehicular delays. However, oftentimes bicycle signal implementation is accompanied by adding another phase for the bicycle signal, in which case vehicular delays will likely increase (Keita and Shindgikar 2024).

2.6.30.3. Costs

Installing a bicycle signal is estimated as $5,100-$50,000 per intersection (Keita and Shindgikar 2024; TxDOT 2025). The price may vary depending on installing different numbers of bicycle signal heads, different types of bicycle detection, and different number of buttons for active detection.

Line Items:

- $750 | **Signal head (bicycle)** | [690-6026] (TxDOT 2025)
- $2.04 per foot | **Wire and Cable** | [684-] (TxDOT 2025)
- $3,500 ($1,000-$8,000) | **Traffic Signal retiming |** (FDOT, n.d.; City of Colusa, n.d.; Texas A&M Transportation Institute 2013)
- $50 | **Sign (for bicycle signal)** | [636-] (TxDOT 2025)

In their 2024 study, D. Y. Keita and Shindgikar estimated a range of $2,500-$49,999 for installation of bicycle signals. They noted that the cost rises with more signal heads installed, depends on the type of bicycle detection used, and can increase with older existing equipment. Since our estimate for the cost of a signal is $750 and the assumed median cost of signal timing is $3,500, in this study the low cost of the range is assumed to be for two signal heads, two signs, and signal retiming, which is estimated as $5,100.

It is assumed that separate bicycle lanes are present at the intersection before bicycle signals are installed. New signal poles may need to be added which would increase the costs.

2.6.31. Leading bicycle interval

Also called a bicycle queue jump, a leading bicycle interval functions similarly to an LPI. Where a leading pedestrian interval is used and a bike signal is present, a leading bike interval may also be used.

Figure 27. Bicycle signal at W Guadalupe Street and W 46th Street in Austin, Texas displaying a pedestrian and bicycle leading interval concurrently.

2.6.31.1. Safety

A leading bicycle interval (LBI) will likely not have an impact on pedestrian safety; therefore, a CMF of 1 is assumed.

Sometimes, bicyclists are unallowed to use the LPI. Therefore, this countermeasure is considered separate and assumed LBI safety benefits for bicyclists is in contrast to not being permitted to use the pedestrian signal. When bicyclists are permitted to use the pedestrian signal it has been assumed they are as effective for bicyclists as pedestrians (New York City DOT 2019). Therefore, it will be assumed bicyclists are not allowed to use the LPI and the CMF of 0.87 calculated for an LPI applies to bicyclists when the LBI is allowed (Goughnour, D. Carter, et al. 2018).

2.6.31.2. Delay

Since leading bicycle intervals remove time from the vehicular green to provide an exclusive head-start for bicycles and pedestrians, they reduce the vehicular green time and decrease vehicle operations (Keita and Shindgikar 2024).

Kathuri and Kading modeled leading bicycle intervals for three intersections, each having 500-600 vph per lane on the major street and practically no traffic to over

300 vehicles per hour per lane on the minor street. There was heavy pedestrian traffic of 184 pedestrians for the highest 15 minute period at one intersection, but practically no bicyclists in the same period. They found an increase in delay approximately equal to that of the leading bicycle interval implemented.

2.6.31.3. Implementation

Leading bicycle intervals should be considered at locations with bicycle signals and leading pedestrian intervals.

2.6.31.4. Costs

Installing a leading bicycle interval typically will only involve signal retiming if a bicycle signal is already present at the intersection. This requires $1,000 to $8,000 per intersection for signal adjustments, with an average of $3,500.

Line Items:

- $3,500 ($1,000-$8,000) | **Traffic signal retiming |** (FDOT, n.d.; City of Colusa, n.d.; Texas A&M Transportation Institute 2013)

It is assumed that bicycle signals and separate bicycle lanes are present at the intersection when the leading pedestrian interval is installed.

Traffic signal retiming is estimated as $1,000-$8,000 per intersection (FDOT, n.d.) with an average of $3,500 in Texas based on available literature. City of Colusa's cost table of safety projects estimates $2,500 per update (City of Colusa, n.d.) and Texas A&M Transportation Institute estimates $3,500 per intersection (Texas A&M Transportation Institute 2013).

2.6.32. Pedestrian refuge islands

Pedestrian refuge islands are placed in a median to dedicate a safe resting space within a crosswalk (FHWA et al. 2018). A width of 8-10 feet is preferred to accommodate all pedestrians, but six feet is possible when there are space constraints (NACTO 2013). An important characteristic of a pedestrian refuge island is a "nose" on either side of the crosswalk consisting of a curb, bollards, or another feature to protect people waiting and encourage drivers to slow down. An example can be seen in Figure 28.

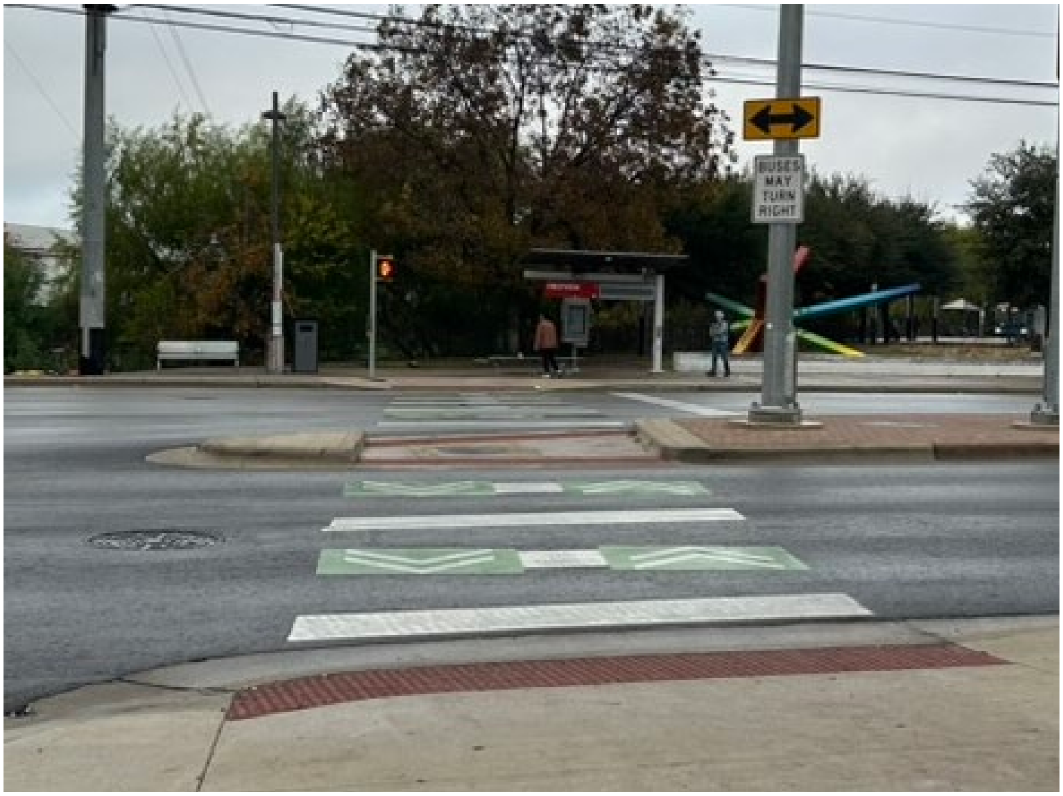

Figure 28. An example of a pedestrian refuge island at an intersection in Austin, Texas (taken: N Lamar Blvd & Airport Blvd, December 2024).

2.6.32.1. Safety

Pedestrian refuge islands are a median with curb-cuts, enabling pedestrians to safely rest in the middle of an intersection. FHWA's "Toolbox of Pedestrian Countermeasures and Their Potential Effectiveness" cites the Gan, Shen, and Rodriguez 2005 study where they found a CMF of 0.75 for installation of a raised median for all users and severities. This was developed using a study surveying states, and Montana and Kentucky each used a CRF of 15. Another study by Alluri, Gan, and Haleem (2016) found a 15% reduction in pedestrian crashes at 10 segments in Florida after a median replaced a two-way turn lane. In 2012, Alluri et al. determined a CMF of 0.711 (0.14) for installing a median where a two-way turn lane was previously based on a before-after study of 18 segments. Elvik and Vaa performed a meta-analysis and determined a CMF of 0.82 (0.15) for pedestrian refuge islands. It should be noted that none of these studies specifically studied signalized intersection crashes. Since none of these studies created a statistically significant CMF, it was determined that the Gan, Shen, and Rodriguez 2005 pedestrian CMF of 0.75 should appropriately represent the installation of a median/pedestrian refuge islands.

Studies also analyzed the impact on bicyclist crashes from installing a median. Park and Abdel-Aty (2016) developed a table of CMFs for increasing the median width beyond 10 ft, claiming that increasing the median width to 50 ft from 10 ft resulted in a bicyclist CMF of 0.564 (0.056). In 2012, Alluri et al. analyzed installing a median and found a non-statistically significant CMF of 0.955 (0.19). Miranda-Moreno, Strauss, and Morency analyzed the presence of a median using a regression cross-section methodology and found a CMF of 0.97, also not statistically significant, for the presence of a median. From this data, it cannot be determined that there is a positive improvement in safety for bicyclists after installing a median/pedestrian refuge island at a signalized intersection; therefore, a conservative CMF of 1 is used.

2.6.32.2. Delay

Raised medians have been shown to increase the capacity of roadways over 30% and decrease delays over 30% while simultaneously reducing vehicle speeds on the roadway (Redmon 2013).

2.6.32.3. Implementation

As the number of travel lanes increases, pedestrians feel more exposed when crossing an intersection; therefore, the pedestrian refuge island utility is hypothesized to increase. NACTO recommends implementation of a median when pedestrians must cross three or more lanes of traffic in one direction. FHWA recommends consideration when traffic volumes exceed 9,000 vehicles per day and speeds are 35 mph or greater (FHWA, n.d.-h).

2.6.32.4. Costs

From TxDOT project data, the estimated construction cost for each refuge island ranges from $4,417 to $36,900, with an average cost of $20,273 each. The median cost of refuge island per square yard is $92.4.

Line Items:

- $92.4 per square yard | **Directional island** | [536-6004] (TxDOT 2025)

2.6.33. Centerline hardening

Centerline hardening is where barriers are placed in the center of an intersection, forcing the path of turning vehicles to be less of a sweeping turn and therefore slowing vehicles down (Insurance Institute for Highway Safety 2020).

Figure 29. An example of centerline hardening at an intersection in Austin, Texas (taken: Airport Blvd & St. Johns Ave, July 2025).

A hardened centerline can be made of concrete curbing, rubber blocks, rigid or flexible posts (City of Austin 2023b). In Figure 29 the hardened centerline is made of what appears to be a rubber block without flexi posts. Typically centerline hardening is not as desirable as a median or pedestrian refuge island but can serve a similar function in less space (City of Austin 2023b).

2.6.33.1. Safety

A study analyzed the conflict points at locations with and without centerline hardening treatments in Washington, DC and determined they reduced left-turning vehicle speeds and reduced conflicts between left turning vehicles and pedestrians (Hu and Cicchino 2020). Therefore, no pedestrian CMF can be assumed for centerline hardening.

Since there have been no claims that centerline hardening increases bicyclist safety, it is assumed the CMF is 1.

2.6.33.2. Delay

While the purpose of centerline hardening is to slow down left turning traffic, no studies have been identified that assess the impact of this countermeasure on vehicle delays; therefore, it cannot be determined whether there is an impact.

2.6.33.3. Costs

Installing centerline hardening typically ranges from $2,500 to $3,800 (TxDOT 2025), typically costing $3,000 per approach (MASSDOT 2024).

Line Items:

- $3,000 ($2,500-$3,800), each | **Centerline hardening kit** | (MASSDOT 2024)

2.6.34. Intersection lighting

In 2022, 77% of pedestrian fatalities in the United States happened at night (Governor's Highway Safety Association 2023). Pedestrians and bicyclists are especially at risk in poor lighting conditions (TxDOT, n.d.). Lighting can improve driver detection of pedestrians when it is dark, subsequently improving pedestrian safety (Albee and Bobitz 2021). Three types of lighting will be discussed in this section: crosswalk lighting, overhead street lighting, and in-pavement lighting.

2.6.34.1.1. Crosswalk Lighting

Patell et al. showed that average vehicle speed decreased 20.6% when approaching a crosswalk with LED lighting and no pedestrian present, compared to only 4.3% when approaching a crosswalk with lighting off and no pedestrian present (Sergio Maria Patell et al. 2020). When the LED lighting was on and a pedestrian was present, this speed decrease was 34.4% compared to a 20.7% decrease when the lighting was off but a pedestrian was present. While this study was conducted at a midblock, unsignalized crosswalk it may still be applicable to signalized intersection crosswalks as it increased driver compliance in yielding to pedestrians.

2.6.34.1.2. Overhead Lighting

Used for both pedestrians and vehicles, overhead street lighting illuminates roadways and, by association, pedestrians on the roadways (Mitran et al. 2020). Overhead lighting placed at least 10ft ahead of the crosswalk has been claimed to be sufficient for drivers to detect the pedestrian while eliminating silhouetting (Ronald B. Gibbons et al. 2008).

2.6.34.1.3. In-Pavement Lighting

In-pavement lighting provides drivers with a lit path and visualization of pedestrians (Mitran et al. 2020). California first introduced this type of lighting in 1993 and has since been tested both in conjunction with automated and push-button detection (Sheryl Miller et al. 2004). A study by Gadiel showed that yielding rates and crosswalk usage increased after the installation of these lights (Gadiel 2007).

2.6.34.2. Safety

Adding overhead lighting allows drivers to better see crossing pedestrians and bicyclists at an intersection. In FHWA's "Toolbox of Pedestrian Countermeasures and Their Potential Effectiveness" a pedestrian CMF of 0.77 is stated, based on the Harkey D et al 2008 study. Wanvik et al. also did a regression cross-section study where they analyzed crash data in the Netherlands and found a CMF of 0.3 for pedestrians (2009). Elvik and Vaa calculated a CMF of 0.22 for fatal nighttime vehicle-pedestrian crashes when intersection lighting is provided, using a meta-analysis (Elvik and Vaa 2004; FHWA, n.d.-d). For nighttime A, B, and C crashes the calculated CMF is 0.58. For all vehicle-pedestrian crashes they found a CMF of 0.19 for fatal crashes and 0.41 for A, B, and C crashes. Additionally, all fatal crashes were found to have a CMF of 0.23 while all A, B, and C crashes were found to have a CMF of 0.5. While the original Elvik and Vaa 2004 Handbook of Road Safety Measures do not contain these values, they are part of an updated meta-analysis for the Highway Safety Manual (Wanvik 2009). Additionally, using data from 1996 and 1997, providing intersection illumination was found to have a CMF of 0.56 for vehicle-pedestrian crashes at rural intersections using a study size of 330 site-years across 38 counties using a regression cross-section methodology (Ye et al. 2008; FHWA, n.d.-d). Since none of the studies are very reliable, it was determined that the CMF of 0.77 from the "Toolbox of Pedestrian Countermeasures and Their Potential Effectiveness" is the best estimate of the safety benefit for pedestrians.

In their study in the Netherlands, Wanvik et al. found a CMF of 0.4 for bicyclists when intersection lighting was installed (2009). No other studies were found analyzing this; it was determined the CMF of 0.4 is the best estimate for installing intersection lighting on bicyclists, despite the fact that it is not a conservative estimate.

2.6.34.3. Delay

No literature was found directly assessing the impact of lighting on vehicle operations. However, it can be assumed that no negative impact would be experienced.

2.6.34.4. Costs

For overhead street lighting, current market prices are estimated as $2,000 to $3,000 per street light module, plus an additional $1,000 installation fee per unit to account for labor complexities (Eco Smart 2024).

Line Items:

- $3,000-$4,000 each | **Street lighting module** | (Eco Smart 2024)

For pedestrian lighting at a crosswalk, assembling one set costs around $7,500 from TxDOT data. This price is full compensation for furnishing, installing, and testing luminaires and pertinent arm, pole with additional wiring and labor fees.

Line Items:

- $7,500 each | **Pedestrian illumination assembly** | [6501-6001] (TxDOT 2025)

2.6.35. Transit signal priority

Transit signal priority (TSP) is special signal timing used to reduce transit delays at intersections, decrease travel times, and improve reliability. Almost exclusively, these techniques are used for buses. There are two main types of transit signal priority (King County 2021):

Green extension is where the length of a signal green phase is lengthened when a transit vehicle is sensed to be approaching.

Red truncation is when the length that the signal is red while a transit vehicle is waiting is shortened.

For both of these types of TSP, specialized equipment is used to sense the transit vehicles and carry out these signal operations. Less commonly, TSP can involve “full priority” where other signal phases are skipped or omitted for the transit phase to be provided a signal once it is waiting, “near side stop advance request” where once the bus arrives at a stop the signal prepares to be green after the historic typical amount of dwell time, or “cascading priority” where the bus requests priority to multiple closely spaced intersections at once (King County 2021).

2.6.35.1. Safety

Transit signal priority is not assumed to affect pedestrian or bicyclist safety and therefore the CMFs are assumed to be 1.

2.6.35.2. Delay

Studies have shown minimal impacts on vehicle operations from implementing transit signal priority (Shaaban and Ghanim 2018; Andrew Clark et al. 2018; Ali et al. 2023).

2.6.35.3. Implementation

Transit Signal Priority (TSP) systems can use radiofrequency (RF) technology, allowing transit vehicles to communicate with traffic signals and minimize intersection delays. The system operates with RF transmitters installed on transit vehicles, which send signals to RF receivers at intersections. These receivers then relay information to the Transit Priority Request Generator (TPRG), which evaluates eligibility and submits priority requests to the traffic signal controller for approved buses.

2.6.35.4. Costs

As a typical intersection, the installation contains two RF receivers and one Transit Priority Request Generator (TPRG), which costs $21,000 to $28,000 per intersection plus additional labor fees (U.S. DoT 2005). From USDOT's handbook for transit signal priority, the average cost is approximately $35,000 per intersection after adding installation fees not including bus equipment. However, these cost estimates vary with some estimating systems costing as low as $10,000 - $20,000 (Lewis 2020). Costs rise when existing infrastructure is outdated such as a lack of vehicle/pedestrian detection systems.

Line Items:

- $600 each | **RF Transmitter** | [6062-] (TxDOT 2025) (U.S. DoT 2005)
- $8,000-$9,000 each | **RF Receiver** | [6062-] (TxDOT 2025) (U.S. DoT 2005)
- $3,000 each | **Transit Priority Request Generator** | (U.S. DoT 2005)
- $3,500 ($1,000-$8,000) | **Traffic Signal retiming |** (FDOT, n.d.; City of Colusa, n.d.; Texas A&M Transportation Institute 2013)

Traffic signal retiming is estimated as $1,000-$8,000 per intersection (FDOT, n.d.) with an average of $3,500 in Texas based on available literature. City of Colusa's cost table of safety projects estimates $2,500 per update (City of Colusa, n.d.) and Texas A&M Transportation Institute estimates $3,500 per intersection (Texas A&M Transportation Institute 2013).

2.6.35.5. Case Studies

A modeling study showed benefits of up to a 43% reduction in travel time for transit vehicles with minimal effects on general traffic (Shaaban and Ghanim 2018).

In Seattle, signal delays decreased 25-34% after the implementation of TSP, in Los Angeles travel times were reduced by 19-25%, and in Vancouver variability was cut by 40-50% (Andrew Clark et al. 2018).

In Boston, transit signal priority was used for light rail lines and no negative effects to non-prioritized traffic were found (Andrew Clark et al. 2018). They used a combination of green light extensions and red light truncations.

There are challenges that come with transit signal priority, however, as pedestrians and cars also need their delay to be balanced and costs of installing and maintaining equipment can be high.

2.6.36. Bus queue jump

A bus queue jump is where buses are given both a dedicated transit facility at the intersection and a leading bus interval or transit signal priority (NACTO 2016). This allows buses to enter the traffic flow downstream of the intersection ahead of vehicles.

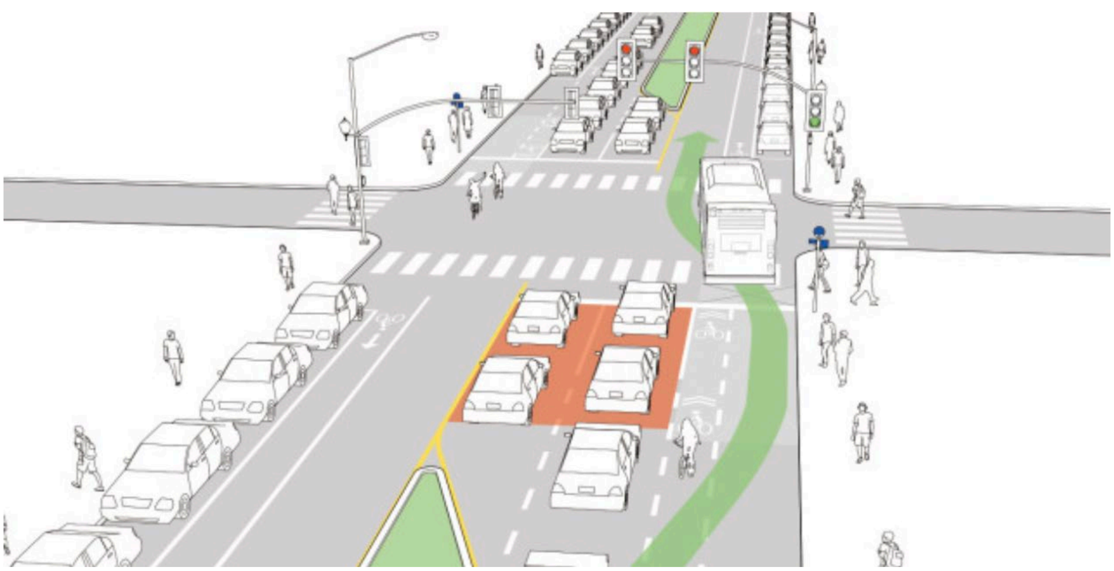

Figure 30. A depiction of a bus queue jump (NACTO 2016).

Even without a dedicated transit lane, a short bus lane can be provided at the intersection (NACTO 2016). Right turns are a major consideration with bus queue jumps. When there is a stop located before the intersection, right turns should be prohibited from the bus lane. If there is not a stop and right turns are allowed, it may be useful to provide a right-turn arrow for turning traffic (NACTO 2016).

2.6.36.1. Safety

Bus queue jumps are not assumed to affect pedestrian or bicyclist safety and therefore there both CMFs are assumed to be 1.

2.6.36.2. Delay

No studies were identified that studied the impact of bus queue jumps on personal vehicular traffic.

It has been determined that queue jumps can save a bus around 9 seconds per intersection (Cesme et al. 2015).

2.6.36.3. Costs

Bus queue jumps, a form of transit signal priority, are typically implemented on exclusive bus lanes or dedicated right-turn lanes for buses. The cost of implementing a queue jump is generally comparable to that of other transit signal priority (TSP) systems, with potential added costs for painting bus lanes if they do not already exist. For a standard intersection, the setup usually includes two RF receivers and one Transit Priority Request Generator (TPRG), costing approximately $21,000 to $28,000 per intersection, excluding labor costs (U.S. DoT 2005). According to the USDOT's handbook on transit signal priority, the average total cost, after including installation fees and excluding onboard bus equipment, is approximately $35,000 per intersection. Adding two bus signal heads to the cost, this becomes $36,500 total.

Line Items:

- $600 each | **RF Transmitter** | [6062-] (TxDOT 2025) (U.S. DoT 2005)
- $8,000-$9,000 each | **RF Receiver** | [6062-] (TxDOT 2025) (U.S. DoT 2005)
- $3,000 each | **Transit Priority Request Generator** | (U.S. DoT 2005)
- $3,500 ($1,000-$8,000) | **Traffic Signal retiming |** (FDOT, n.d.; City of Colusa, n.d.; Texas A&M Transportation Institute 2013)
- $750, each | **Signal head (bus)** | [690-6026] (TxDOT 2025)

For a bus queue jump to be installed, separate bus lanes or bus and right-turn lanes must already be present at the intersection. If they are not, additional costs to construct an additional lane or designate an existing lane to be a bus only lane will be incurred.

Traffic signal retiming is estimated as $1,000-$8,000 per intersection (FDOT, n.d.) with an average of $3,500 in Texas based on available literature. City of Colusa's cost table of safety projects estimates $2,500 per update (City of Colusa, n.d.) and Texas A&M Transportation Institute estimates $3,500 per intersection (Texas A&M Transportation Institute 2013).

2.6.37. Traffic calming

Traffic calming is a general term used to describe a host of measures used to decrease speed on roadways. Higher vehicle speeds greatly increase the probability of a severe crash, with the fatality risk at 30mph about five times as high as that at 20mph (Ryus et al. 2022).

This includes some countermeasures already discussed, such as decreasing turn radii, raised pedestrian/cyclist crossings, pedestrian refuge islands, and centerline hardening. It also can include measures implemented along a roadway segment that slow traffic down through the intersection. Design measures, such as building facades closer to the roadway and trees along the roadway, are typically used in urban areas to indicate to drivers they should travel slower through a section of roadway.

2.6.37.1. Safety

Traffic calming discusses a host of measures used to decrease speed on roadways. Therefore, depending on a given measure the safety benefits and the corresponding CMFs will vary for both pedestrians and bicyclists.

2.6.37.2. Delay

Traffic calming measures vary and, therefore, their effects on vehicular operations will also vary.

2.6.37.3. Costs

Some common traffic calming measures and their installation costs include (Victoria Transport Policy Institute 2017):

- $1,500 - $3,000 each for speed humps

- $2,500 - $3,500 each for speed cushions
- and $7,000 - $15,000 per pair for chicanes

2.6.38. Restricted crossing U-turn

Restricted Crossing U-Turn Intersections (RCUTs) are a relatively new innovative intersection. They are different from a traditional intersection because if a vehicle on the minor street wishes to proceed straight or take a left, they must make a U-turn. Therefore, instead of allowing the left-turning and straight-through traffic to proceed as normal through the intersection, all traffic must turn right.

Multiple RCUT intersections have been built in Texas, with and without pedestrian crossings. When pedestrian provisions are provided, they typically are done using a z-shaped pattern so pedestrians cross one side of the intersection, cross through the center of the intersection diagonally, and then cross the next side.

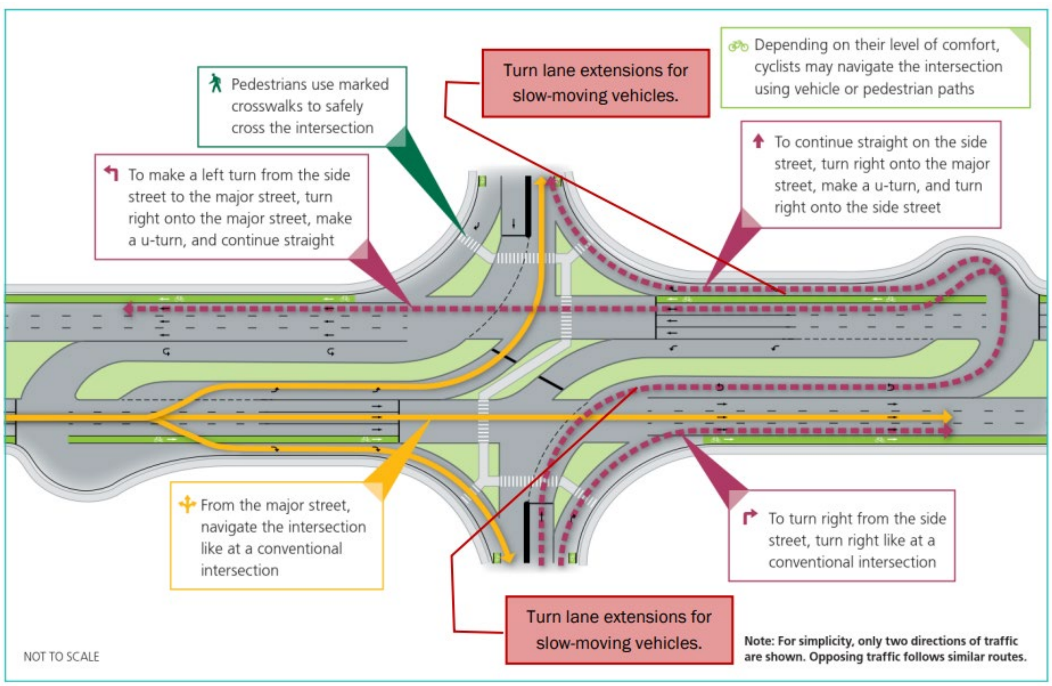

Figure 31. Typical RCUT configuration with on-street bicycle lanes (FHWA RCUT Informational Guide).

The center pedestrian crosswalk of an RCUT intersection in San Antonio can be seen in Figure 32 and Figure 31.

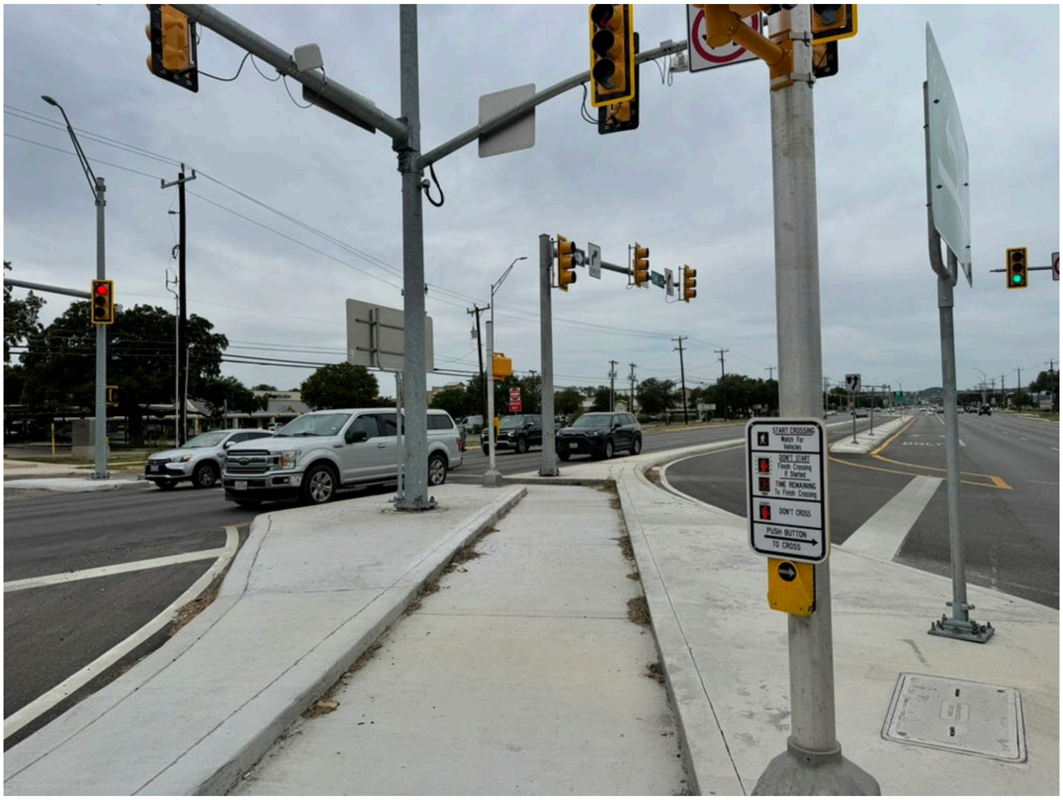

Figure 32. Image of the center pedestrian island at the RCUT (Bandera Rd & Cedar Drive, San Antonio, July 2025)

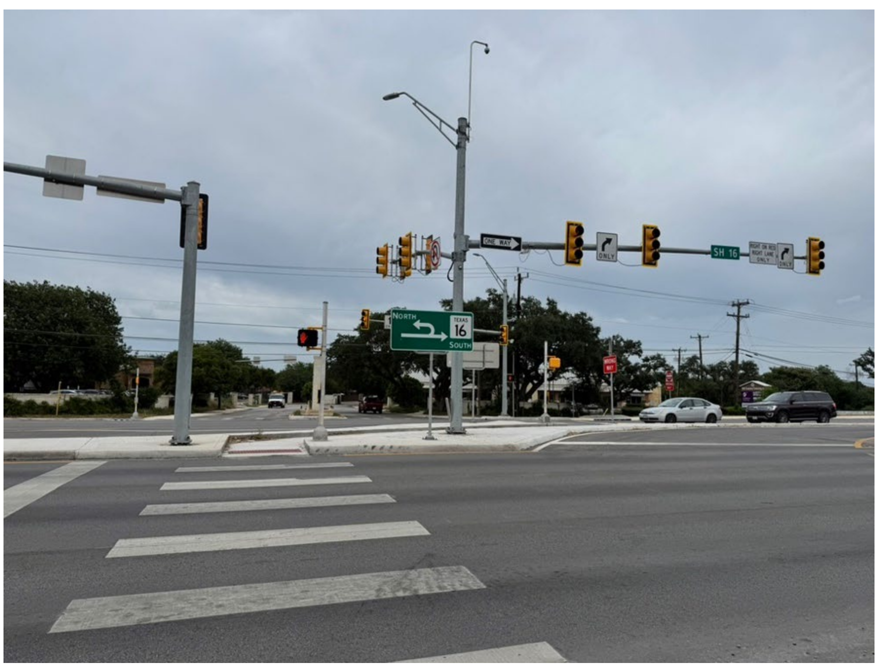

Figure 33. Image of the crosswalk at the RCUT, looking from Cedar Drive (Bandera Rd & Cedar Drive, San Antonio, Texas July 2025)

2.6.38.1. Safety

This intersection is claimed to be safer for pedestrians because it reduces the number of conflict points at the intersection. No CMFs have been developed specifically for pedestrians or bicyclists.

2.6.38.2. Delay

RCUTs have been stated to decrease overall vehicle delays by reducing the number of phases needed at the intersection.

2.6.38.3. Implementation

Right turns on red are often disallowed from one or both right-turn lanes at an RCUT, as seen in Figure 34. This helps to reduce the amount of weaving and increase safety.

Figure 34. Right On Red Signage at RCUT Intersection (taken: Bandera Rd & Cedar Trl, San Antonio, Texas July 2025)

2.6.38.4. Costs

The costs of adding an RCUT was found to vary from around half a million to $16.8 million, with roadway widening and designing for future grade separations found to increase construction costs. Costs at signalized intersections around Texas are shown in Table 2.

Table 2. Reduced Conflict U-Turn Construction Costs

Roads	City	Number of RCUTs	Cost (millions)	Cost per RCUT	Let Year	Source
Loop 1604 & Shaenfield	San Antonio	1	$2.85	$2.85	2011	(Hummer and Rao 2017)
Loop 1604 & New Guibeau	San Antonio	1	$2.85	$2.85	2011	(Hummer and Rao 2017)
US 281 & Stone Oak Pkwy/TPC Pkwy	San Antonio	1	$2.58	$2.58	2010	(Hummer and Rao 2017)
US 281 & Evans Rd	San Antonio	1	$2.58	$2.58	2010	(Hummer and Rao 2017)
FM 2818	Bryan	3	$50.4	$16.8	2019	Communication with TxDOT
US 54	El Paso	2	$1.22	$0.61	2022	Communication with TxDOT

2.7. Summary

This section presents the results of the CMFs found in the literature review as a summary table. The sources and determination of each is discussed in the corresponding section below.

Table 3. Countermeasure CMF Overviews

Countermeasure	Pedestrian CMF	Bicyclist CMF	Cost	Unit of Cost
Sidewalks	0.12	1	$90	per sq yd
Pedestrian signal heads	0.48	1	$10,800-$21,200	per intersection
Change pedestrian signal heads to display a countdown timer	0.3	1	$7,320	per intersection
Crosswalks	0.52	1	$10,160	per intersection
High visibility crosswalk	0.52	1	$10,160	per intersection
Curb ramps	1	1	$19,440	per intersection
Alter crosswalks to be perpendicular	unknown	unknown	$14,800-$55,346	per intersection
Recall signal timing	unknown	1	$3,500	per intersection
Leading pedestrian interval	0.87	1	$3,500	per intersection
Exclusive pedestrian phase	0.65	1	$11,580	per intersection
Protected-only left turns	0.57	unknown	$5,000-$150,000	per intersection
Protected-only left turns when pedestrians present	unknown	unknown	$5,000-$150,000	per intersection
Split phase timing	0.61	1	$3,500	per intersection
Flashing yellow arrow signal head for left turns	unknown	unknown	$6,550	per intersection
Right-turn-on-red restrictions	1	1	$200	per intersection
Reduce the cycle length	1	1	$3,500	per intersection
Increase the cycle length	0.49	1	$3,500	per intersection
Single-stage crossings	unknown	1	$3,500	per intersection
Road diet	1	1	$25,000-$40,000	per mile
Curb extensions	0.7	1	$4,000	per intersection
Remove channelized turn lane	unknown	unknown	$5,000-$10,000	per corner
Alter channelized turn lane	unknown	unknown	$12,500-$50,000	per corner
Reduce the curb radius	varies	unknown	$5,000-$40,000	per corner
Truck apron	unknown	unknown	$2,000-$20,000	per corner
Continue painted bicycle lane through the intersection	1	unknown	$5,000-$50,000	per mile
Continue protected bicycle lanes up to the intersection	1	unknown	$50,000-$220,000	per mile
Fully protected intersection	1	unknown	$1,000,000	per intersection
Bicycle lane lateral shift	1	unknown	$50,000-$220,000	per mile
Raised bicycle/pedestrian crossings	0.7	0.49	$2,400-$3,500	per crosswalk
Bicycle signals	1	1	$5,100-$50,000	per intersection
Leading bicycle interval	1	0.87	$3,500	per intersection
Pedestrian refuge islands	0.75	1	$20,273	per island
Centerline hardening	unknown	1	$3,000	each
Intersection lighting	0.77	0.4	$3,000-$7,500	per intersection
Transit signal priority	1	1	$35,000	per intersection
Bus queue jump	1	1	$36,500	per intersection
Traffic calming	varies	varies	$1,500-$15,000	each
Restricted crossing U-turn	unknown	unknown	$610,000-$16,800,000	per intersection

2.8. Current Roadways

As of 2022, TxDOT owns 80,905 centerline miles of roadways, including Interstate, U.S., and state highways, Farm and Ranch to Market roads, frontage roads, and a couple PASS routes, park roads, and recreation roads (TxDOT 2022a). Only 25% of roadway miles in Texas are state-owned, but 74% of all miles traveled are on state-owned roadways. State-owned facilities contain 4,457 miles of sidewalks and 447 miles of bicycle lanes or shared use paths. TxDOT also owns 2,834 transit vehicles.

TxDOT owns 7,927 miles of frontage roads, more than any other state (TxDOT 2022a; Babineck 2007). Frontage roads and diverging diamond interchanges along them present a unique challenge to Complete Streets improvements due to the many intersecting segments and vehicular movements entering and exiting the frontage roads. Additionally, about half of TxDOT's roadways are Farm or Ranch to Market roads, which are typically in rural areas and may contain Restricted Crossing U-Turn or Median U-Turn intersections. Yet, since most current Complete Streets guides are created by cities whose network contains smaller, simpler intersections, improvements for all users at these types of intersections is an understudied area.

In Austin, pedestrian and bicyclist crossings are being added across frontage roads with high levels of ped/bike traffic with pedestrian countdown signals added to cross along 4^{th} street this year (Pagano 2024). When demand exists for pedestrian or cyclist facilities across TxDOT roadways in major cities or rural areas, TxDOT can provide safe crossings for people.

2.9. Build It, and They Will Not Always Come

While countermeasures play a crucial role in enhancing safety for pedestrians and bicyclists, it's essential for planners to assess current demand, perceived comfort, and connectivity before implementing them (FHWA, n.d.-l). The notion of "build it and they will come" doesn't always hold true in the context of bicycle and pedestrian infrastructure. Location characteristics must be carefully considered. Areas with high pedestrian or cyclist demand are ideal for Complete Street treatments, as they can enhance safety and comfort and potentially increase demand. Conversely, installing Complete Street facilities in areas lacking a pedestrian or bicycle community, oriented towards high-speed vehicular traffic, or disconnected from existing networks is unlikely to boost future demand and wastes resources (Schoner and Levinson 2014; Hull and O'Holleran 2014; Ryus et al. 2022).

Therefore, bicycle demand from bike lanes should be forecast when installing new Complete Streets treatments. Since bicycle and pedestrian demand hinges on connectivity to the broader network and surrounding areas of interest, collecting data on the infrastructure in surrounding areas can be used to help estimate pedestrian demands (Kittelson & Associates, Inc. 2022). Neglecting these factors can lead to underutilized bike lanes and diminish community perceptions, thereby hindering future development. Additionally, extreme climates like the scorching summers of Texas further diminish the likelihood of future demand (Bean et al. 2021).

2.10. Existing Standards

Other states and cities have already adopted Complete Streets policies and standards, attributes of which will be discussed in this section.

There are typically two types of Complete Streets manuals. Policy documents outline an area's approach to complete streets and how existing procedures will be adapted to include Complete Streets concepts. A city's street design manual may also be updated to include Complete Streets infrastructure improvements without explicitly declaring a Complete Streets policy.

2.10.1.1. Cities Outside Texas

Cities that are well-known for their complete streets policies outside of Texas include Charlotte, North Carolina which earned the 2009 National Award for Smart Growth Achievement in Policies and Regulations from the EPA (Seskin 2009). The City of Charlotte's complete streets manual clearly outlines the City's goals, defines guiding principles for achieving a network of Complete Streets, and outlines key policies that can be used to achieve success applying Complete Streets (Charlotte Department of Transportation et al. 2007). They acknowledge that some street users will face less desirable or neutral conditions after certain countermeasures are implemented, such as transit being negatively affected by small curb radii at intersections, with trade-offs being outlined in a matrix. This matrix can be seen in Figure 35.

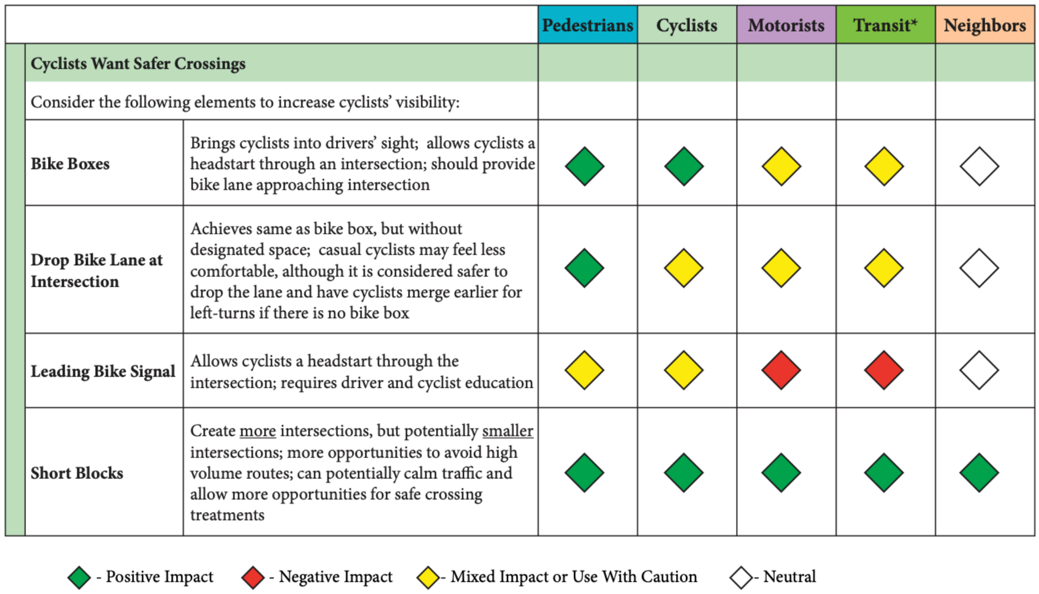

Figure 35. The City of Charlotte Design Element Matrix (Charlotte Department of Transportation et al. 2007).

The City of New York has also received acclaim over the years for its Complete Streets improvements. Instead of a policy document, they however have incorporated Complete Streets principles into their Street Design Manual and countermeasures have become routine techniques for updating roadways within their city (New York City and Department of Transportation 2020).

2.10.1.2. Texas Cities

Many large cities in Texas have their own Complete Streets design manuals. Most noticeable is the City of Dallas Complete Streets Design Manual, which combines policy and design standards including street sections for typical street types, which types of improvements should be prioritized on each type of street, and a Complete Streets vision map (City of Dallas 2016).

Houston has a Complete Streets policy that outlines ongoing efforts to increase multimodal use within the city (City of Houston 2022).

El Paso received national acclaim for their Complete Streets Policy for a strong focus on implementation, equity, and health (City of El Paso 2022). They prioritize underserved neighborhoods, ensure safety improvements for vulnerable users, and emphasize creating infrastructure to support active transportation. This policy is especially strong because it focuses on the process of implementation as opposed to specific countermeasures.

San Antonio’s Complete Streets Policy prioritizes public involvement and discusses policy implications (City of San Antonio 2024).

The City of Austin has both a general policy document and a Sidewalks, Crossings, and Shared Streets Plan (Austin Transportation Department 2016; City of Austin 2023b). While the policy document outlines case studies and relevant projects, other documents outlining technical specifications focus more on implementation and what individual countermeasures can look like in Austin.

2.10.1.3. Statewide Plans

State Complete Streets plans are typically less detailed technically, and instead focus on the processes to implement these improvements. New York State delegates Complete Streets improvements to each district while California requires cities and counties to include Complete Streets policies upon revising their plans (Cuomo and McDonald 2014; State of California, n.d.). Virginia requires that bicyclist and pedestrian accommodations be considered when network improvements are made (Virginia Department of Transportation 2004).

2.10.1.4. Regional Collaboration

Finally, the Regional Complete Streets Study examined regional strategies to create safer and more accessible transportation networks. They highlighted the importance of regional collaboration in addressing transportation challenges across jurisdictions and emphasized how integrated planning across cities and counties could enhance mobility, safety, and equity for all users (Regional Transportation Commission of Southern Nevada 2012).

2.11. Tools

Transportation agencies, including TxDOT, use tools to help assess benefits and trade-offs of implementing different alternatives. It is important to note that the usage of tools and ranking systems vary from city to city, as many states and jurisdictions have developed their own way to rank countermeasures. This results in different methodologies and no clear consensus on the best way to implement Complete Streets across the nation. Below are six tools that are relevant to implementing Complete Streets designs at intersections.

2.11.1. CMF Clearinghouse

FHWA’s CMF clearinghouse is a searchable repository of CMFs (FHWA, n.d.-d). This website includes ratings of the quality of each study along with basic information about the applicability of the CMFs.

2.11.2. Ped/Bike Safe

FHWA's Ped/Bike Safe is a predictive tool with overviews of countermeasures and case studies of applications (FHWA 2013; BikeSafe 2014). This tool is useful in determining potential effects of implementing various countermeasures including pedestrian islands, leading pedestrian intervals, exclusive pedestrian signal phasing, left turn phasing, bicycle lanes, and bicycle signals.

2.11.3. TxDOT Urban Intersections Safety Scoring Tool

The scoring tool is a systemic analysis, incorporating the effects of different design parameters of an intersection (TxDOT 2022b). This tool quantifies the effects of changes to the design parameters in the safety score it produces. With respect to Complete Streets at signalized intersections, this tool includes general site features (such as signalization, restricted crossing U-turns, etc.), geometric design elements (median widths etc.), traffic control elements (protected left turns, protected-permissive left turns, etc.), pedestrian elements (location of crossing, pedestrian flows, etc.), and bicycle elements (facility type, bicycle flows, etc.). Therefore, it is useful for determining the effectiveness of some but not all of the countermeasures previously discussed.

2.11.4. Safety Performance for Intersection Control Evaluation (SPICE)

Developed to provide practitioners with a means of evaluating anticipated control strategies, the Safety Performance for Intersection Control Evaluation (SPICE) tool is a systemic tool that provides a quantifiable basis to compare the safety performance of different intersection types (FHWA 2018b). Intersection geometry along with AADT are included as inputs to this tool, along with amount of pedestrian activity to provide the estimated number of crashes at the specific intersection from given projects. Intersection control countermeasures related to Complete Streets that can be analyzed in this tool include median U-turns and restricted crossing U-turns.

2.11.5. Multimodal Level of Service Analysis for Urban Streets

NCHRP's tool for multimodal level of service analysis is a predictive tool that provides LOS models for various transportation modes along with an integrated LOS framework across all these modes (NCHRP 2008). As it incorporates vehicles, transit, bicycles, and pedestrians, this tool is useful for evaluating the operations of Complete Street intersections for all users.

2.11.6. Signalized Crossing Pedestrian Delay Worksheet

One of the outputs of NCHRP Report 992 was a spreadsheet that calculates pedestrian delay at signalized intersections (Ryus et al. 2022). This Excel sheet handles delay for crossings across one leg with one stage, one leg with two stages, and two legs with two stages. Inputs include crosswalk lengths, average walking speed, and signal timings.

2.11.7. Northeastern University Ped & Bike Crossing Delay Calculator

The Northeastern Multistage Pedestrian and Bike Crossing Delay Calculator determines average delay at multistage crossings, two-stage diagonal crossings and two-stage left turns for bicyclists (Peter G. Furth, n.d.). This calculator is therefore useful at complicated intersections where other worksheets may be unable to determine delay.

Chapter 3. Current Safety in Texas

Crashes at intersections are defined differently depending on the analyst. The PBCAT typing defines an at-intersection crash as “Intersection—Crash occurred at or related to an at-grade junction of two or more roadways of any design or locations within 50 ft of the prolongation of the edge line or curb of the crossing street” (Thomas et al. 2022). Additionally, some studies use a definition of at an intersection that relates to a certain distance from the center (Chen et al. 2015).

Lyon and Persuad showed that increasing vehicular volume at an intersection increases the pedestrian crash frequency (Lyon and Persaud 2002).

As shown in the City of Austin Pedestrian Safety Plan, street width and number of lanes are correlated with increased probability of serious injury or fatal crashes (City of Austin 2018).

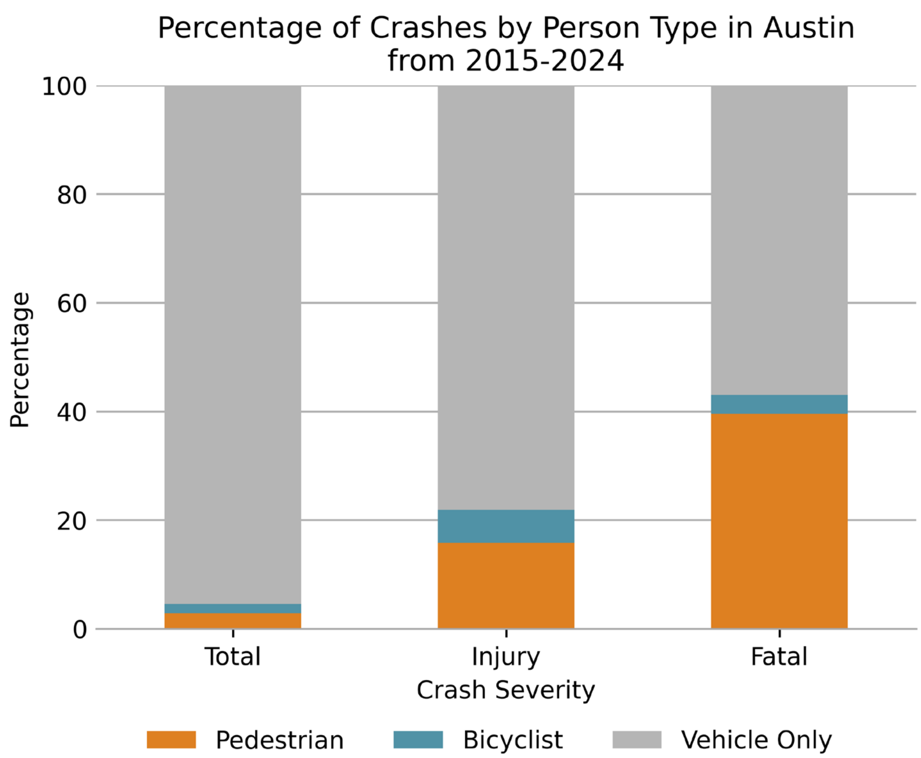

Figure 36. Percentage of Pedestrian and Bicyclist Crashes By Crash Severity, format from CMAP White Paper (Chicago Metropolitan Agency for Planning 2018) and data from (TxDOT, n.d.).

This shows that 43% of fatal crashes in the City of Austin involve a pedestrian or bicyclist, compared to just 4.5% of all crashes in the City of Austin involving a pedestrian or bicyclist.

Figure 37 shows pedestrian-related crashes were almost three times more frequent than bicyclist crashes in Texas during the period 2015 to 2024 After a decline in crash numbers in 2020 due to COVID-19, the total number of crashes involving pedestrians and bicyclists in Texas has increased year over year since 2020, and 2024 recorded the highest number of crashes in the past ten years.

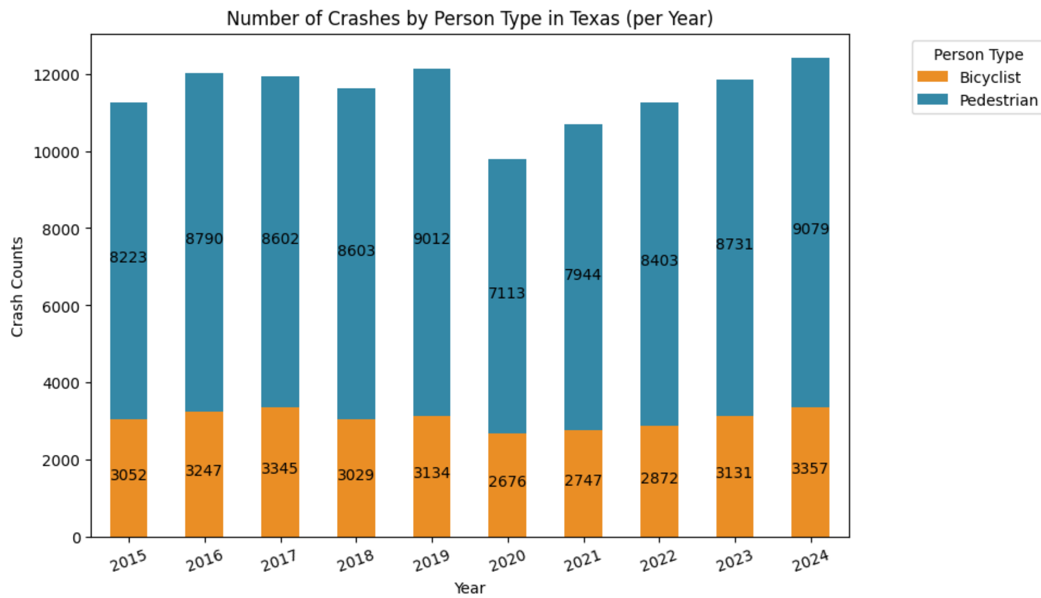

Figure 37. Number of Crashes by Person Type in Texas (per Year) and data from (TxDOT, n.d.).

In Figure 38, the percent change in these crashes relative to the date of data first available is seen. The percent change in crashes relative to 2015 is calculated as: number of crashes in a year/ number of crashes in the base year (2015) times 100.

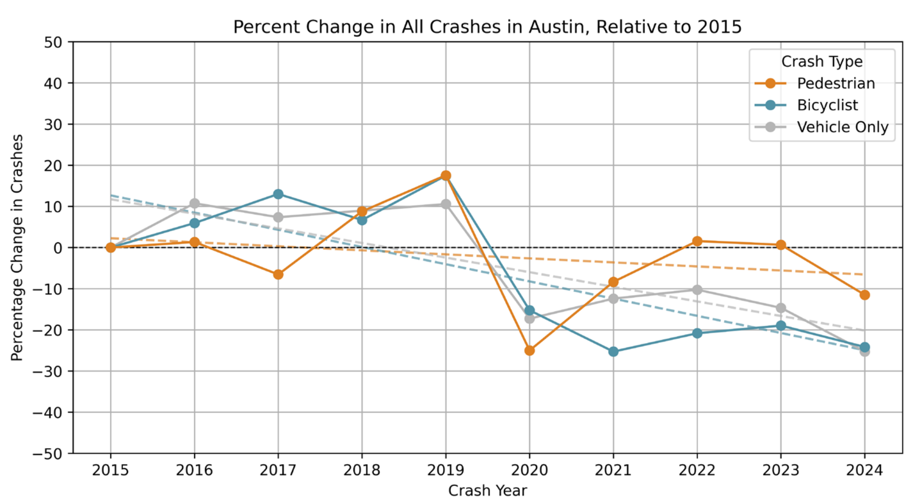

Figure 38. Percent change in crashes in Austin, relative to 2015. Data from: (TxDOT, n.d.).

While it seems that since COVID (2020) crashes have generally decreased for vehicles and bicyclists, pedestrians generally have experienced less of a decline in the past ten years than other modes.

In Figure 39 it can be seen that pedestrian fatalities are increasing while the number of fatal vehicle crashes is staying relatively constant.

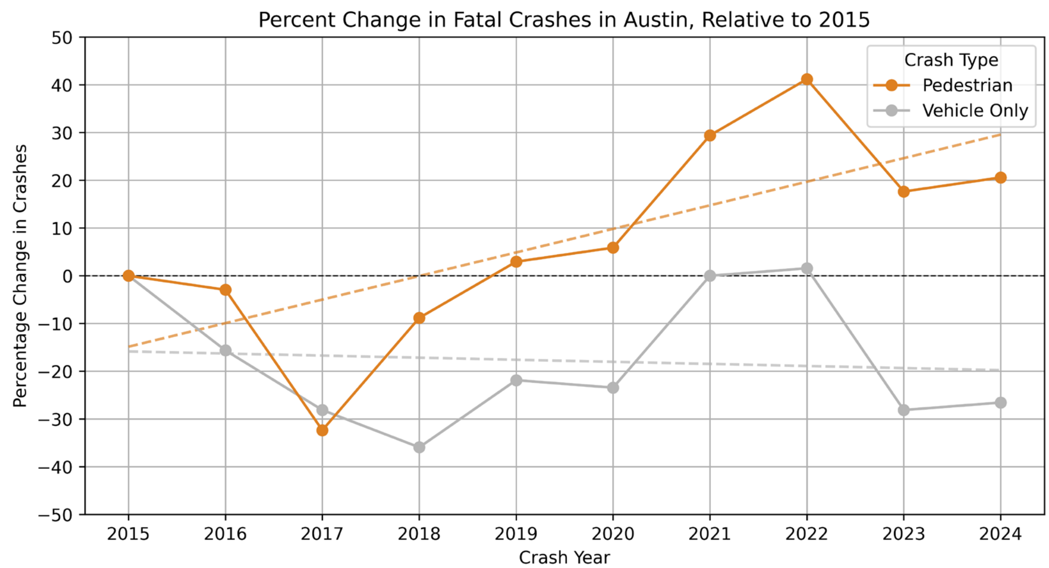

Figure 39. Percent change in crashes in fatal crashes in Austin, relative to 2015. Data from: (TxDOT, n.d.).

It should be noted that bicycle crashes were not included when looking at fatalities as they have a very small sample size.

On average over the past ten years, 36.5 pedestrians in Austin have died each year (TxDOT, n.d.). And in 2024, 41 pedestrians, 4 bicyclists, and 47 vehicle occupants died in Austin, a whopping 49% of all deaths in Austin being vulnerable road users (TxDOT, n.d.).

Despite intersections only physically representing a small portion of Texas roadways, Figure 40 shows intersection crashes account for almost a third of the total annual crashes. Additionally, intersection-related pedestrian and bicyclist crashes have increased in recent years as part of a general trend of increasing crashes.

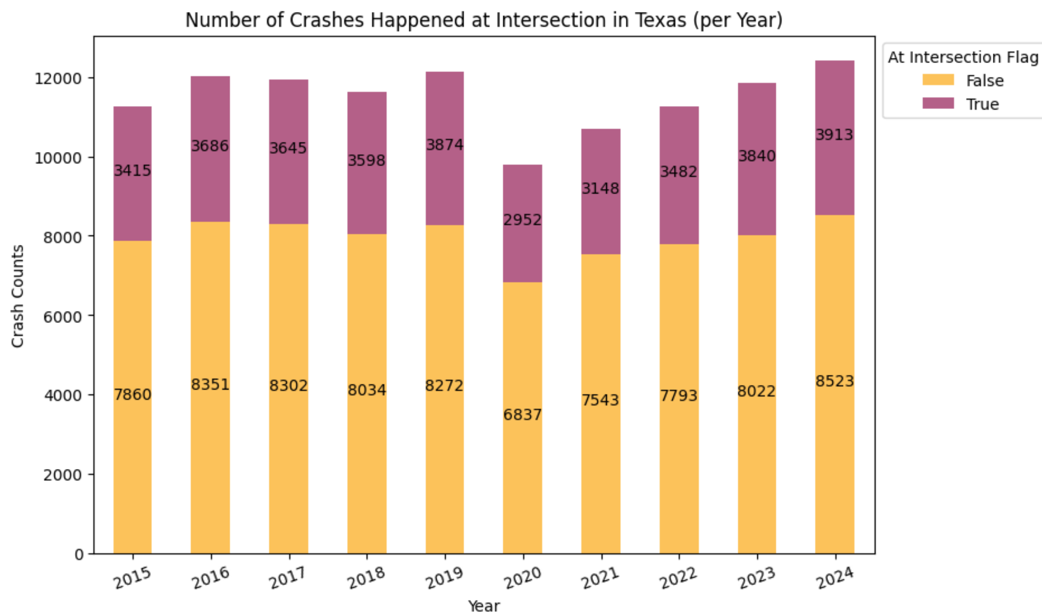

Figure 40. Number of Crashes Happened at Intersection in Texas (per year) and data from (TxDOT, n.d.).

Figure 41 shows that the majority of crashes occur during daylight, accounting for 59.7% of crashes. This likely correlates with higher pedestrian, bicyclist, and vehicle traffic volumes during these periods.

Figure 42 shows the distribution of fatal crashes based on light conditions at the time of incident. Over 75% of fatal pedestrian and bicyclist crashes took place in the dark compared to just 37.4% of all crash severities occurring in the dark. These findings highlight the critical influence of visibility and illumination on crash severity.

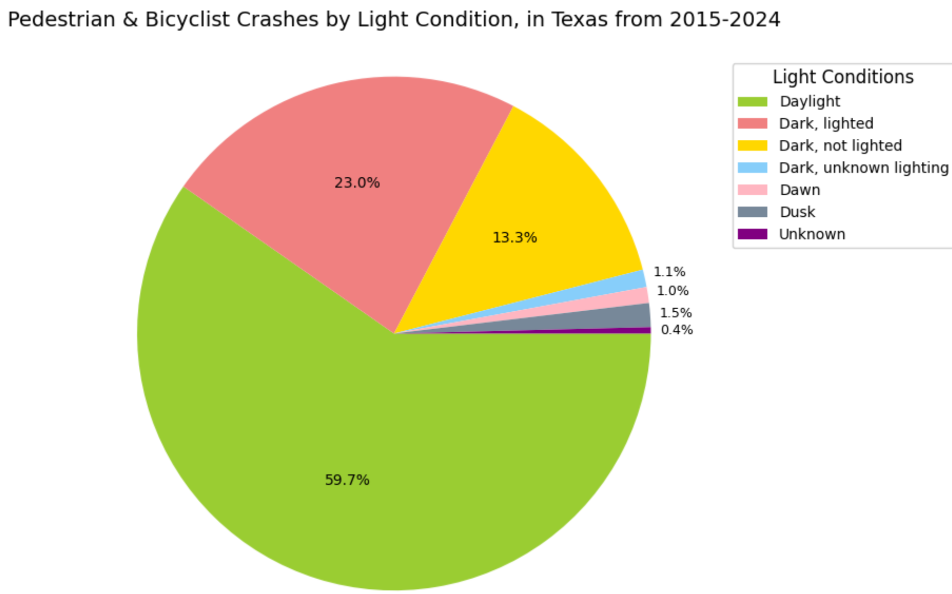

Figure 41 Pedestrian and Bicyclist Crashes Distributed by Light Condition and data from (TxDOT 2025)

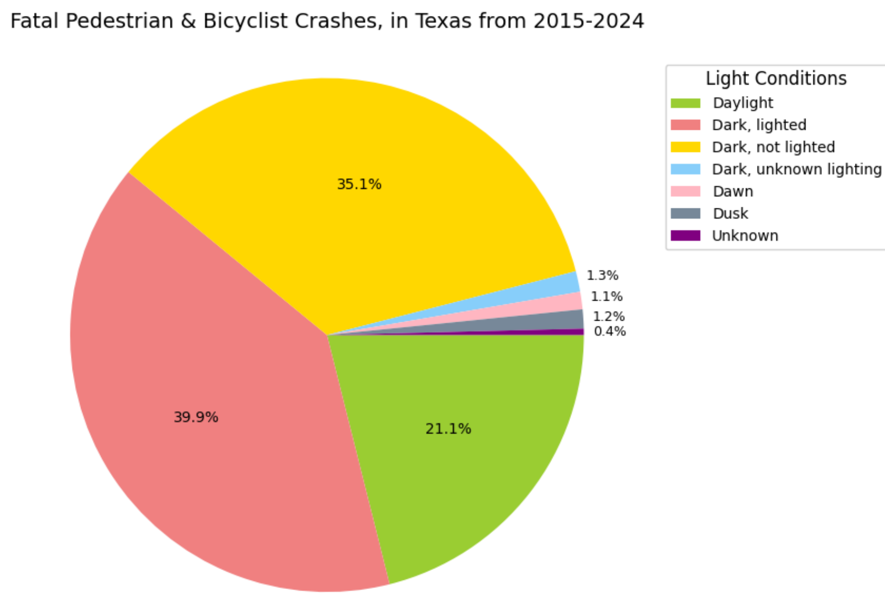

Figure 42. Fatal Pedestrian and Bicyclist Crashes Distributed by Light Condition and data from (TxDOT, n.d.)

Additionally, TxDOT owned roads often are perpetrators of many pedestrian and bicyclist crashes. Figure 43 shows where the most pedestrian and bicyclist crashes have occurred in the last 10 years in downtown Austin. It can be seen that I-35, the interstate that runs through Austin, has a hot-spot of crashes near its intersections.

Figure 43. Number of pedestrian and bicyclist crashes within 100 ft of each intersection in downtown Austin.

This is potentially due to the higher speeds on these roadways. Figure 44 illustrates the highest number of crashes, approximately 35,000, happen in areas with a speed limit range between 31 to 40 mph The second highest number of crashes, approximately 29,000, happen with a speed limit range between 21 to 30 mph, indicating that urban and suburban roadways emerge as high-risk zones for traffic accidents. Furthermore, crash counts decline steadily at higher speed limits. This trend may reflect reduced pedestrian and bicyclist presence in high-speed highway environments rather than improved safety.

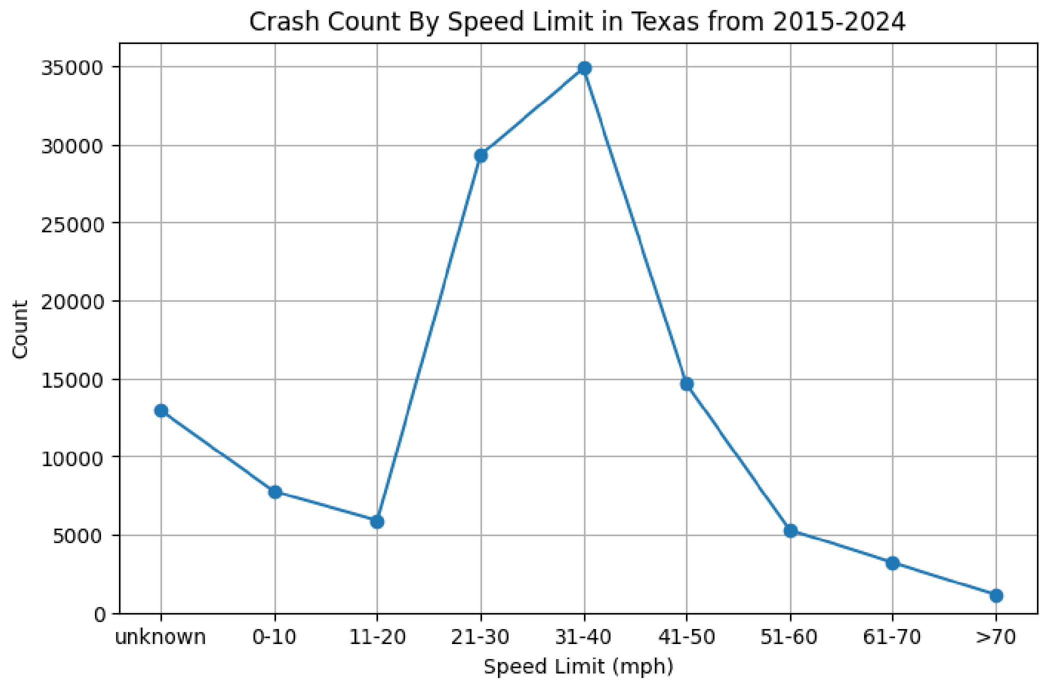

Figure 44. Crash counts based on different speed limits and data from (TxDOT, n.d.).

Figure 44 illustrates the highest number of crashes, approximately 35,000, happen in areas with a speed limit range between 31 to 40 mph The second highest number of crashes, approximately 29,000, happen with a speed limit range between 21 to 30 mph, indicating that urban and suburban roadways emerge as high-risk zones for traffic accidents. Furthermore, crash counts decline steadily at higher speed limits. This trend may reflect reduced pedestrian and bicyclist presence in high-speed highway environments rather than improved safety.

The largest number of fatal crashes and all crashes both occurred in the speed limit range between 31 and 40 mph. However, for roadways with speeds greater 40 mph, the number of fatal crashes does not decline as drastically as for all crashes. This means the proportion of fatal crashes on high speed roadways is higher, which is evident in Figure 45.

For a roadway with a 40 mph speed limit, there is around a 7% probability that a crash involving a pedestrian or bicyclist will result in a fatality, whereas for a crash on a 70 mph roadway there is almost a 40% probability that a crash involving a pedestrian or bicyclist will result in a fatality. While fewer total crashes occur on high-speed roads, the likelihood of fatal outcomes rises sharply. This highlights the strong correlation between speed and crash severity and emphasizes the importance of installing pedestrian and bicyclist countermeasures on roadways with unsafe conditions even if they are not the most heavily trafficked by these users.

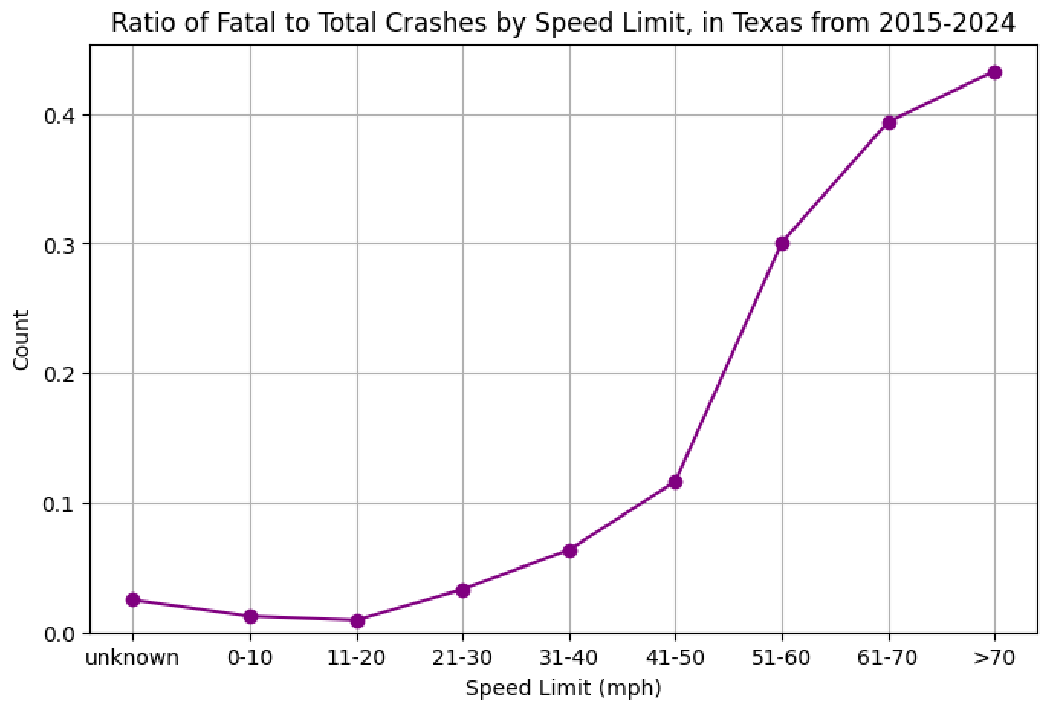

Figure 45. The ratio of fatal to total crashes based on Different Speed Limit and data from (TxDOT, n.d.)

Additionally, it is important to analyze where these crashes are occurring. Pedestrian crash frequency is significantly increased by increases in population density (Chimba et al. 2018), likely due to correlation from increased pedestrian activity. Figure 46 and Figure 47 plot crash numbers and population for each county, respectively.

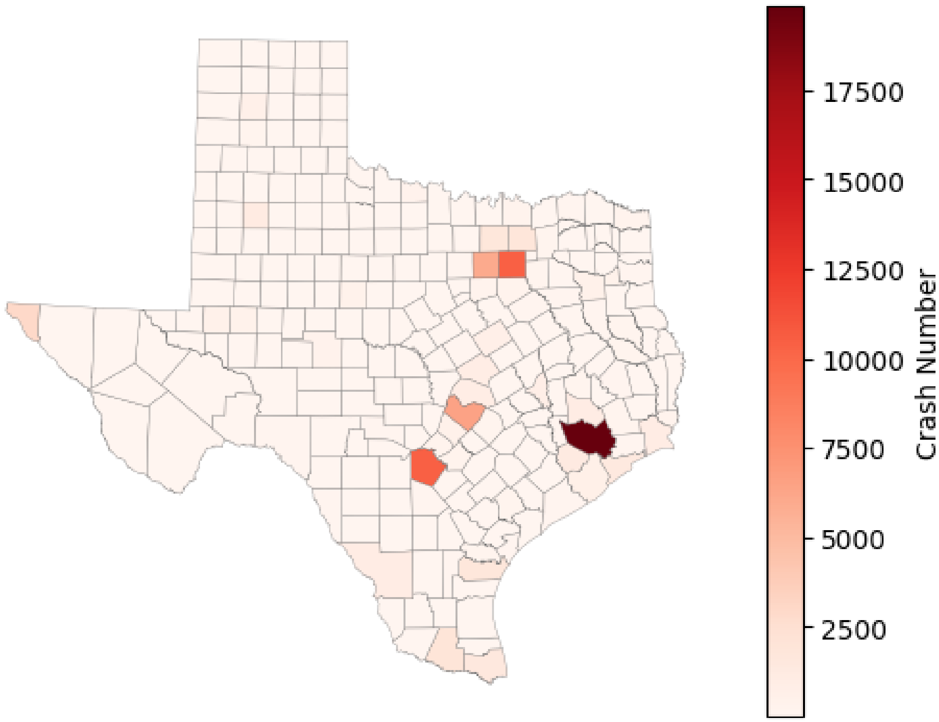

Figure 46. Crash Number per County and data from (TxDOT, n.d.).

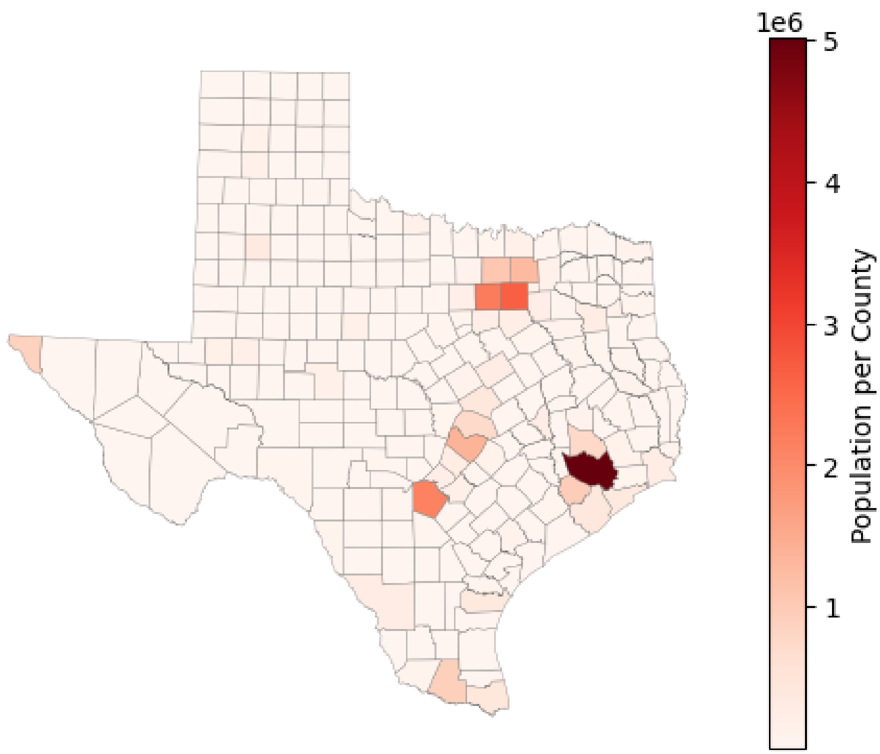

Figure 47. Population per County and data from (Bureau, n.d.)

In Figure 46 and Figure 47, as crash numbers or population increases the color intensity of each county deepens to a darker red. Here it can be seen that the counties with the darkest hues are situated in Texas's primary metropolitan districts. In both figures, the top five counties with the highest values are Harris, Dallas, Bexar, Travis, and Tarrant. This pattern demonstrates a high relationship between crash numbers and population, where regions with larger populations consistently report higher crash frequencies.

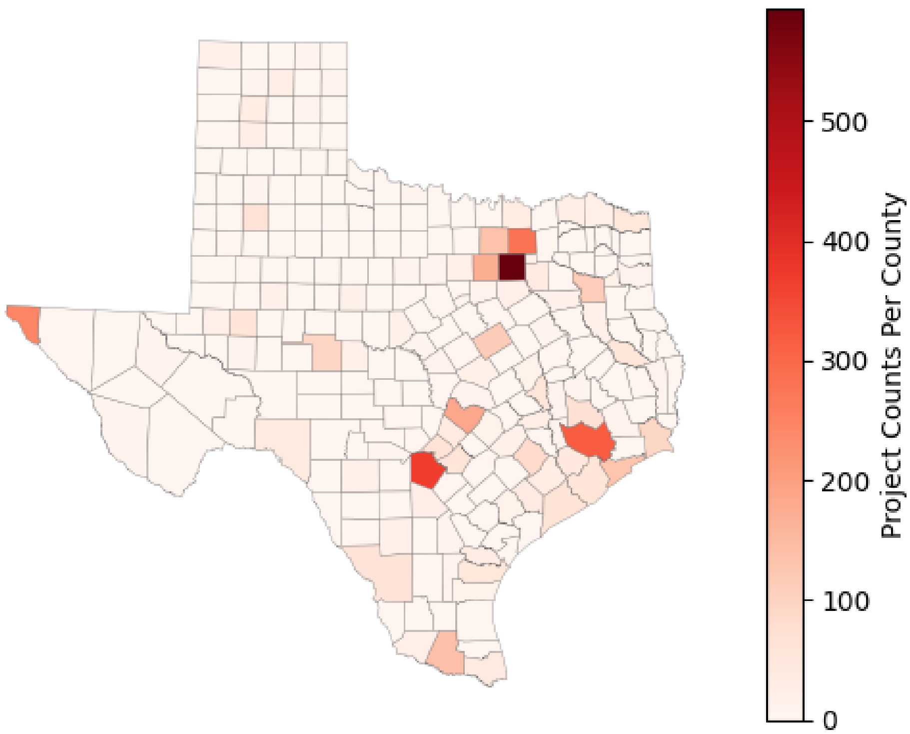

Figure 48. Project Counts Implemented per County and data from (TxDOT 2025)

Based on implementation data obtained from TxDOT pedestrian safety projects, Figure 48 was generated to visualize the distribution of projects across counties. When compared with Figure 46, it is evident that the two maps exhibit some correlation. Counties with a higher number of pedestrian and bicyclist crashes tend to have a greater number of active safety projects; however some counties, such as El Paso and Tarrant County, have a higher number of active projects than their corresponding population, indicating that these counties may prioritize this type of project.

While municipalities and TxDOT are putting in a strong effort to decrease crashes, it is clear there is much more work that needs to be done especially to curb pedestrian and bicyclist crashes.

3.1.1. Austin LPI Safety

To illustrate how a CMF is calculated and attempt (unsuccessfully) to calculate a statistically significant one, data was gathered from the City of Austin Mobility Management Center.

Leading Pedestrian Intervals (LPIs) are one of the main pedestrian-focused signalization countermeasures being implemented throughout Austin. To analyze the impact that this countermeasure has had on pedestrian safety, the date of implementation for leading pedestrian intervals was obtained and the number of crashes was analyzed.

3.1.1.1. Data

The years leading pedestrian intervals were installed were obtained from both the City of Austin Open Data Portal (City of Austin 2025b) and directly from the City of Austin (City of Austin 2025a). Both datasets contained traffic signal numbers and the date that leading pedestrian intervals were installed, and each contained some leading pedestrian intervals that the other did not so these datasets were merged to better represent all leading pedestrian intervals in Austin. If both datasets contained a different value for the date the leading pedestrian interval was installed, the date from the City of Austin Open Data Portal was used. This data was matched with another file from the City of Austin Open Data Portal to perform spatial analysis of the signals (City of Austin 2025b). The date of installation for each leading pedestrian interval in the dataset is shown in Figure 49.

Additionally, crash data was obtained from the TxDOT CRIS database for all available full years at the time of request, 2015-2024, only for crashes marked as within the City of Austin jurisdiction and labeled as either a “Pedestrian” or “Pedacyclist” crash (TxDOT, n.d.).

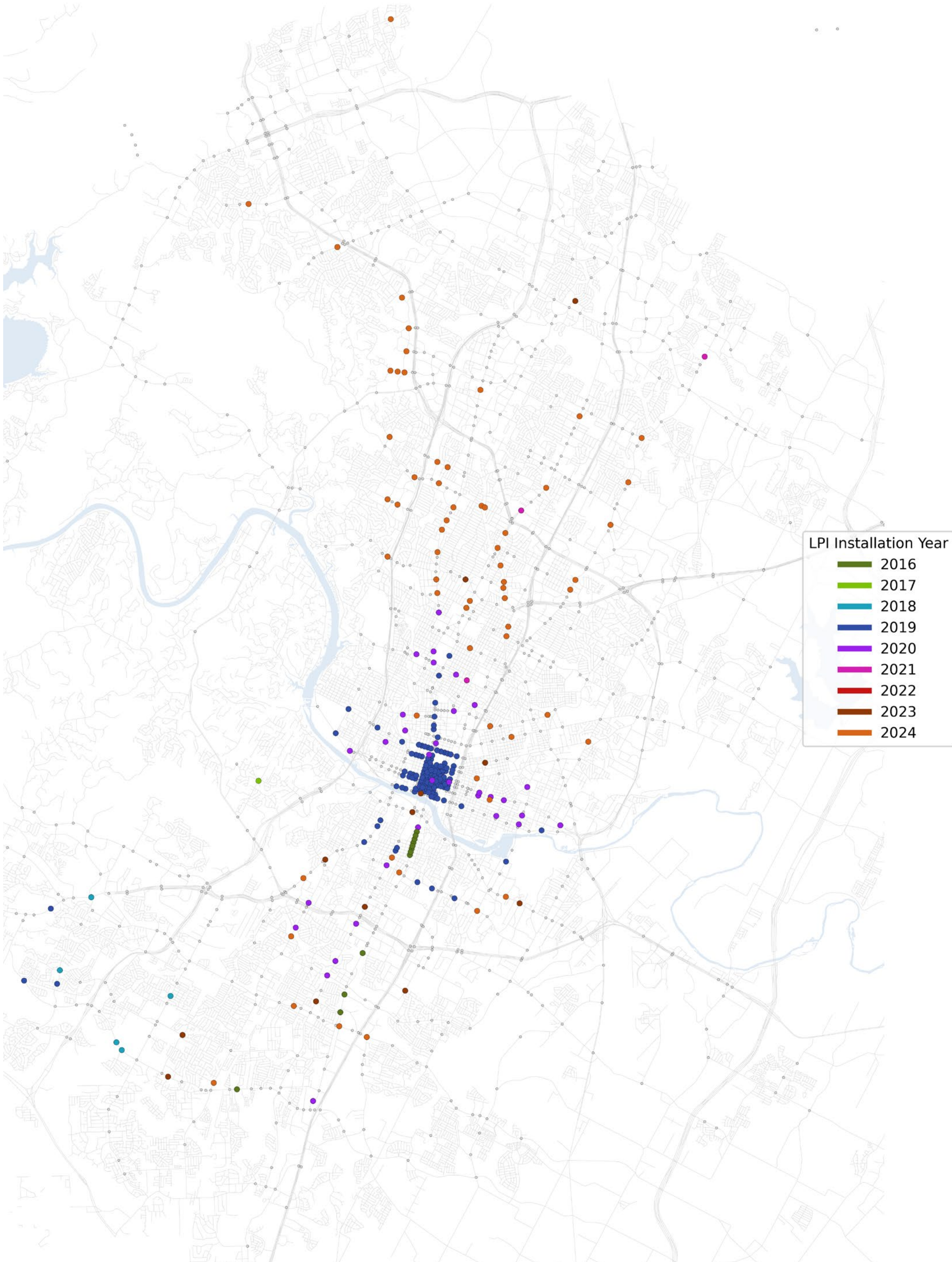

Figure 49. LPI installation years throughout Austin, TX (City of Austin 2025b; 2025a). Grey dots represent a signalized intersection without an LPI.

3.1.1.2. Methodology

Python was used for all data analysis. Crashes were defined as being associated with an intersection if they occurred within 100 ft of the center of the intersection, which is a distance used in a similar study. From here, it was possible to count the number of crashes within each year and determine crash reductions.

In 2019, a system-wide LPI implementation was conducted in Austin. This implementation was not focusing on specific hot-spot intersections and therefore reductions may be a good predictor of the actual reductions in crashes from implementing an LPI. Additionally, analyzing countermeasures implemented in 2019 allowed for four years of before data and five years of after data.

The methodology for this analysis was chosen based on available data. The empirical Bayes methodology is currently seen as the most academically rigorous in the literature. However, since pedestrian counts were not available and the present study does not have the resources to take manual counts, this methodology was unable to be used. The secondary approach typically used is a before-after with comparison group methodology. This methodology has been combined with an ANCOVA regression approach as well to reduce regression to the mean bias, which the baseline method does not do. Therefore, the crash data was analyzed using these methods.

In the case of the City of Austin implementing LPIs, in 2019 they were implemented as part of a downtown-wide approach to improve pedestrian safety as opposed to in a program that targets specific intersections with high crash rates. With this type of implementation, regression to the mean is much less likely but still a concern. In our case, it is hard to account for regression to the mean in the analysis because since LPIs were installed at almost all signalized intersections downtown, there is an inadequate reference group to pull direct comparison intersections from. However, since traffic patterns shifted following 2019 due to the COVID-19 pandemic, the crash reductions at other intersections throughout the city and near downtown should still be looked at to account for general traffic characteristic changes.

Comparison site locations were initially selected to be all sites that were not a treatment site within a mile of a rectangle drawn around the downtown area, which is where most LPIs were implemented, and then locations with the following characteristics were removed from the comparison site pool:

- Where an LPI was implemented during a different year
- On roadways that are classified as frontage roads

- Where one approach is a highway ramp
- Part of the Barton Springs road safety pilot project
- Has exclusive pedestrian phasing

All of the sites that had an LPI installed in 2019 were installed within a mile of downtown except three sites that were located on the edge of Austin in a suburban area. Since the land use and roadway type of these signals was so different than the LPIs installed in the city, these treatment sites were excluded from the analysis. They collectively had one crash in the before period and one crash in the after period. The number of sites in each category after these sites were removed are shown in Table 4.

Table 4. Number of Sites in the Study, Comparison, and Not Included Groups.

Site Type	Number of Sites
Study	129
Comparison	116
Not Included	912

Additionally, the locations of each study and comparison site can be seen in Figure 50. Any site outside of the boundaries of the figure was not included as a study or comparison site.

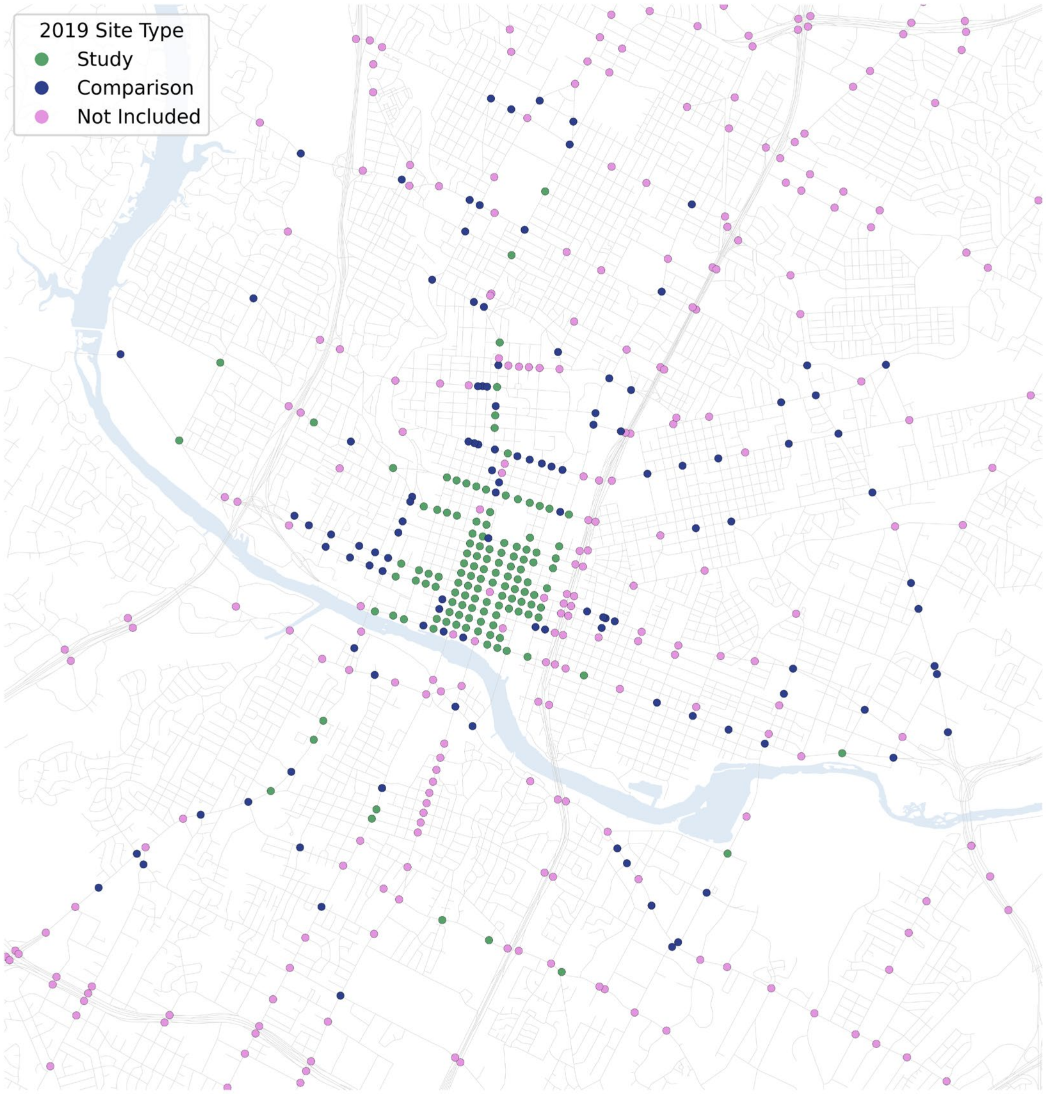

Figure 50. Locations of Study and Comparison Sites.

3.1.1.3. Crashes

The number of pedestrian and bicyclist crashes within 100 ft from the center of each intersection were determined spatially. Data was only available at this time for 2015-2024. The aggregate numbers per year for each group can be seen in Figure 51.

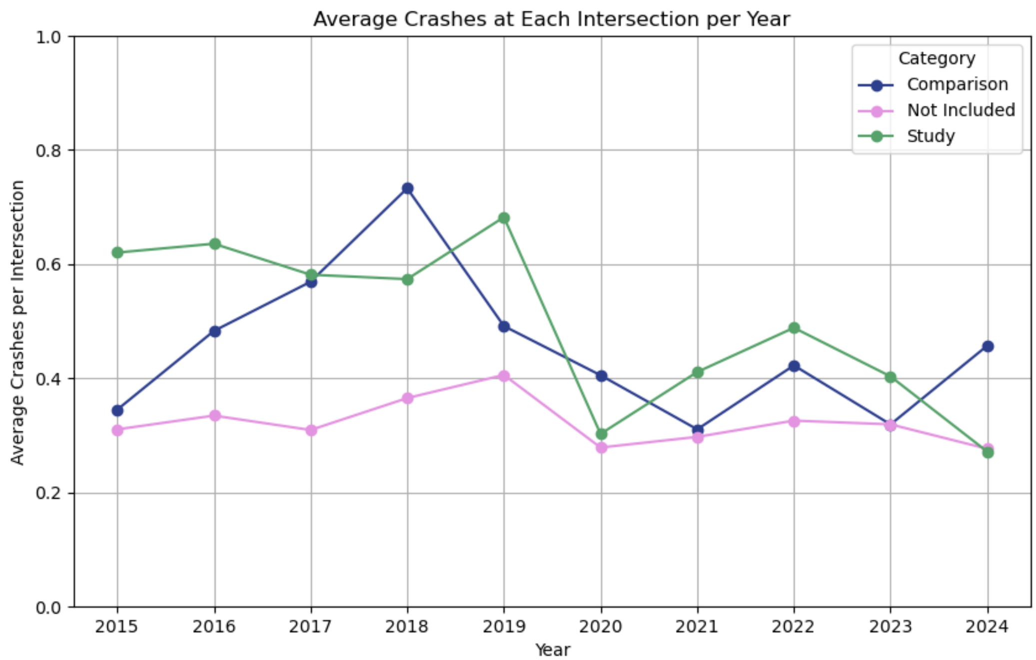

Figure 51. Average Crashes Each Year by Group

It can be seen that the Study group visibly has a decrease in crashes after 2019 when the LPIs were installed. However, due to the COVID-19 pandemic, changing transportation patterns in Austin may have led to differences in mobility. The comparison group also seems to have decreased in the number of crashes at its intersections following 2019, so at this point it is indeterminate if the LPIs increased safety.

The total number of crashes before and after 2019, as well as percent decrease in crashes can be seen in Table 5. These numbers do not include crashes during 2019.

Table 5. Crashes Before and After 2019

	Study	Comparison
Total Before (4 years)	311	247
Total After (5 years)	242	222
Percent Decrease	37.8%	28.1%

Here, it can be seen that crashes in the study group decreased about 25% more than crashes in the comparison group.

3.1.1.4. Baseline CMFs

After determining the number of crashes at each location, the baseline CMF can be calculated as 0.866:

$$CMF = \frac{(N_{o,TA}/N_{o,TB})}{(N_{o,CA}/N_{o,CB})} = \frac{(242/311)}{(222/247)} = 0.866$$

Which indicates a reduction in crashes of 13.4% from LPIs. Using Hauer's methodology to account for the expected value of a ratio, the CMF can be seen to be 0.856 with a variance of 0.0114:

$$Var(N_{exp,TA})/N_{exp,TA}^2 = \left(\frac{1}{N_{o,TB}} + \frac{1}{N_{o,CB}} + \frac{1}{N_{o,CA}}\right) = \left(\frac{1}{311} + \frac{1}{247} + \frac{1}{222}\right) = 0.0118$$

$$CMF = \frac{(N_{o,TA}/N_{o,TB})/(N_{o,CA}/N_{o,CB})}{(1 + Var(N_{exp,TA})/N_{exp,TA}^2)} = \frac{(242/311)/(222/247)}{(1 + 0.0118)} = 0.856$$

$$Var(CMF) = \frac{CMF^2(1/N_{o,TA} + Var(N_{exp,TA})/N_{exp,TA}^2)}{(1 + Var(N_{exp,TA})/N_{exp,TA}^2)^2} = \frac{0.856^2(1/242 + 0.0118)}{(1 + 0.0118)^2}$$
$$= 0.0114$$

Therefore, the 95% confidence interval of the CMF is (0.644 - 1.07) and it cannot be said that this value is statistically significant.

3.1.1.5. ANCOVA Regression CMF Approach

A reminder of the ANCOVA regression is as follows (Chen et al. 2013):

$$posttest = \; const + \alpha(pretest) + \beta(group)$$

Where:

$posttest$ = the crashes in the after period

$pretest$ = the crashes in the before period

$group$ = 1 for the treatment group and 0 for the comparison group

$const$ = the constant from the model

And the subsequent calculation of the expected value of crashes in the treatment period after is:

$$E(X_{t1}) = const + \alpha(X_{t0})$$

Where $const$ and α are calculated using the following regression equation:

In this regression, the constant represents the predicted crashes at a comparison site with no prior crashes, the alpha value represents the expected reduction per additional crash in the before period, and the beta value represents the additional effect on crashes from the treatment group compared to the comparison group.

The values from the regression model for the Austin 2019 LPIs are below:

Table 6. Austin 2019 LPI Regression Model Values

Variable	Coefficient	Standard error
const	0.8698	0.200
pretest	0.4903	0.050
group	-0.1759	0.235

Using the ANCOVA regression method, a CMF of 0.904 with a variance of 0.0127 is computed from this model:

$$N_{exp,TA} = 0.8698 + 0.4903(n_{TB}) = 264.686$$

$$CMF = \frac{(N_{o,TA}/N_{exp,TA})}{(1 + Var(N_{exp,TA})/N^2_{exp,TA})} = \frac{(242/265)}{(1 + 0.0118)} = 0.904$$

$$Var(CMF) = \frac{CMF^2(1/N_{o,TA} + Var(N_{exp,TA})/N^2_{exp,TA})}{(1 + Var(N_{exp,TA})/N^2_{exp,TA})^2} = \frac{0.904^2(1/242 + 0.0118)}{(1 + 0.0118)^2}$$
$$= 0.0127$$

These results show that the group variable has very little impact on the resulting decrease in crashes, but it does show a slight decrease which indicates a potential minor effect from regression to the mean.

The ANCOVA regression approach assumes that the comparison and treatment groups should have the same number of crashes in the before and after period and then correct for that. However, in our case LPIs were implemented at almost every intersection downtown in 2019, an area that typically will experience the highest pedestrian volumes. Therefore, this approach likely over-corrects for regression to the mean in this case.

3.1.1.6. Discussion

While this study was unable to show a statistically significant reduction in pedestrian and bicyclist safety due to the installation of LPIs, it is an important finding that the safety benefits may not be as grand as some previous literature suggests. More data points would be needed to obtain a statistically significant CMF for the installation of LPIs in Austin.

Lower CMFs require smaller sample sizes to be statistically significant (Goughnour, D. Carter, et al. 2018), and therefore it is possible that the literature is biased towards lower CMFs since they are more likely to be statistically significant. The non-statistically significant value of the CMF for pedestrians after implementing an LPI determined by this study of 0.904 is higher than the CMFs previously recorded in the literature.

From an installation of 10 LPIs in 2010, it was determined that the CMF for LPIs is 0.413. Partly due to the small sample size, the initial 22% reduction in crashes (raw CMF of 0.78) was corrected to have the CMF of 0.413 (Fayish and Gross 2010b).

Goughnour et al. used a before-after with Empirical Bayes methodology at 105 intersections, with a sample size of 507 crashes observed in the after period, and found a statistically significant CMF of 0.87 for pedestrians at all crash severities (Goughnour, D. L. Carter, et al. 2018). The later value was used to represent the CMF of an LPI in this study due to the higher sample size and more rigorous methodology.

Comparatively, in the present study despite using a similar number of study sites (129) only 222 crashes in the after period were recorded. Due to a lower total number of crashes at all the studied intersections, statistical significance is therefore more difficult to obtain. However, due to the non-statistically significant CMF of 0.904 being relatively similar to the statistically significant CMF of 0.87 obtained by Goughnour et al. it is likely that this CMF is accurate for Texas roadways.

Chapter 4. Delay Modeling

To estimate delays for various countermeasures, VISSIM models for general signalized intersections were created. This section discusses model calibration and choice of characteristics to vary between model runs.

The countermeasures chosen to be evaluated using models are:

- Right-turn-on-red restrictions
- Leading pedestrian intervals
- Lane reduction (road diet)
- Exclusive pedestrian phasing
- Add pedestrian signals
- Add protected-only phasing

This selection was based on the feasibility of evaluation and the relevance of each countermeasure.

4.1.1. Methodology

To estimate delays for various countermeasures, VISSIM models were created for general signalized intersections. This section discusses model calibration and choice of characteristics to vary between model runs.

4.1.1.1. Geometries

The following geometries were chosen to represent generic TxDOT intersections, each a four-leg intersection:

- Four lanes on the major street, two lanes on the minor street
- Four lanes on the major street, four lanes on the minor street
- Six lanes on the major street, four lanes on the minor street
- Six lanes on the major street, six lanes on the minor street

A roadway with six lanes is one where there are three lanes of traffic traveling in each direction. All models were run both with right turn lanes and without right turn lanes. All lanes were modeled as 12 ft wide. The base-case scenario was assumed to allow right turns on red. Models with left turn lanes on the major street, but not on the minor street and models with left turn lanes on both the major and minor street were run for all geometries. When a left turn lane was present it was assumed to have a designated phase, as will be discussed later in this section.

For the reduced conflict U-turn, instead a base roadway with six lanes on the major street and two lanes on the minor street was modeled. For the base scenario, an intersection with all crosswalks provided was used. The layout of the pedestrian paths used in the RCUT are shown in Figure 52.

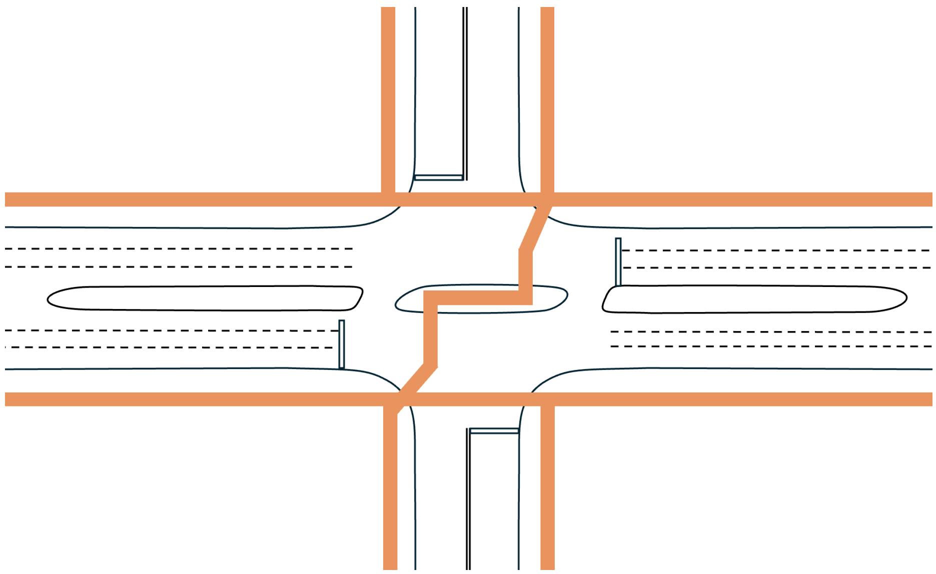

Figure 52. Pedestrian path configuration used in the RCUT model

4.1.1.2. Volumes

These models each were run for varying amounts of pedestrian and vehicular traffic. The levels of traffic were chosen to represent low, medium, and high conditions. Bicycle traffic was not considered in these models. Below the levels of vehicular traffic on the major street are listed:

- 83 vph/lane
- 167 vph/lane
- 250 vph/lane
- 333 vph/lane
- 417 vph/lane
- 500 vph/lane

Most scenarios assume 2/3 of the total traffic is on the major street and 1/3 is on the minor street. These values were derived from assuming a two lane in each direction by two lane in each direction model, using a total intersection volume of 500, 1,000, 1,500, 2,000, 2,500, and 3,000 vehicles per hour. These volume levels were then used for all geometries, but varied proportionally to the number of lanes. The comparison models for the RCUT scenarios and the RCUT scenarios themselves assume different percentages of total traffic on each roadway for some scenarios, and the percentages assumed will be outlined when discussing these models.

The levels of total pedestrian traffic at the intersection analyzed are:

- 0 pedestrians/hour
- 100 pedestrians/hour
- 500 pedestrians/hour
- 1,000 pedestrians/hour

Pedestrian and vehicles are loaded into the model at entry points, in this case the end of each sidewalk and each roadway represented within the intersection. Each pedestrian or vehicle is modeled individually and randomly entered into the network at an even rate determined by the total number of pedestrians or vehicles per hour entered.

4.1.1.3. Pedestrian Characteristics

In VISSIM, there are two approaches to modeling pedestrians. Pedestrians can either be treated as a vehicle using modified versions of the Wiedemann car-following model or use the Social Force Model (PTV Group 2025). Using the Social Force Model is not possible in the standard version of VISSIM, and the benefits were determined to be inapplicable to the current study. This is an assumption supported by past researchers (Bonneson and Pratt 2011).

The created VISSIM model consists of vehicular and pedestrian links, with pedestrian links being broken into two types: sidewalk and crosswalk. Preset modeling characteristics in VISSIM for pedestrian links using the Wiedemann car-following model involve “no interaction” between pedestrians. This essentially means that pedestrians can stack on top of each other while waiting at a signal or crossing a street. This is useful to represent an infinite queue at corners in the model, as modeling sidewalk congestion is not an aim of the given project.

This leads to the assumption that the corners of the intersections have adequate space to hold all pedestrians that are modeled.

While this approach is suitable for an analysis of sidewalks, when pedestrians cross the street, they typically create platoons. In order to model these platoons on crosswalks, a pedestrian interaction model was developed. This model was developed based off of how VISSIM models bicyclists. Pedestrians are represented as diamond-shaped and the following distances and headways were adjusted to represent a traditional pedestrian platoon visually. Since there is not much literature on modeling pedestrians using the Wiedemann model in this way and the sole goal of modeling these pedestrians is to determine the impacts of pedestrian volumes on vehicular delay, it was deemed appropriate to simply have platooning that looked accurate.

4.1.1.4. Signal Timings

Signal timings were created using best-practice equations, which are discussed in Appendix B. Only fixed-time signals were used, which conservatively estimates delay from pedestrians; with actuated signals when a pedestrian is not present no pedestrian phase will be signaled, and therefore, there will be no vehicular lost time from an LPI. In the models in this study, therefore, the same amount of time was allotted to each approach each cycle and the pedestrian phase was called each time. This assumption additionally makes sense as fixed-time comparison where pedestrian signal heads are on recall is seen as the most pedestrian-friendly. Additionally, this enabled 0 pedestrians to be modeled and the corresponding delay due solely to the signal timing change, not pedestrian platooning, to be evaluated. Drawbacks of this approach are that most State and Arterial roadways do not use fixed timing, meaning it does not represent conditions on these roadways exactly.

Additionally, all left turns were modeled as either protected or permissive, not protected/permissive. Two signalization schemes were analyzed, one where the major street left turning traffic was protected but the minor street left turning traffic was permissive and one where all left turning traffic was protected.

When a given approach contained a designated left turn lane, the left turning traffic was provided a protected phase. When a given approach was not provided a protected left turn lane, a protected left turn phase was not provided and therefore the left turning traffic was given a permissive-only phase. Based on the literature review, protected-only left turn phases are safer than protected/permissive. Additionally, due to high traffic volumes on arterial streets oftentimes left turning traffic is required to be signalized and therefore not left to simply make permissive left turns. Choosing to model only protected traffic simplified the number of signal timings and runs that had to be completed. However, as discussed in the literature review, protected left turns typically mean higher overall intersection delays.

Two cycle lengths, 120 seconds and 100 seconds were chosen to model. Signal timings were calculated for each cycle length and then an identical model was run with each cycle length. The result with the lower total vehicular delay was further analyzed.

4.1.1.5. Routing Decisions

Left-turning traffic percents modeled were:

- 10%
- 20%
- 30%

When the minor street was not provided with a protected left turn the left-turning percent was set at 20%, whereas the major street always varied the left turning percent.

Pedestrian paths were assumed to follow the routing decisions in Figure 53.

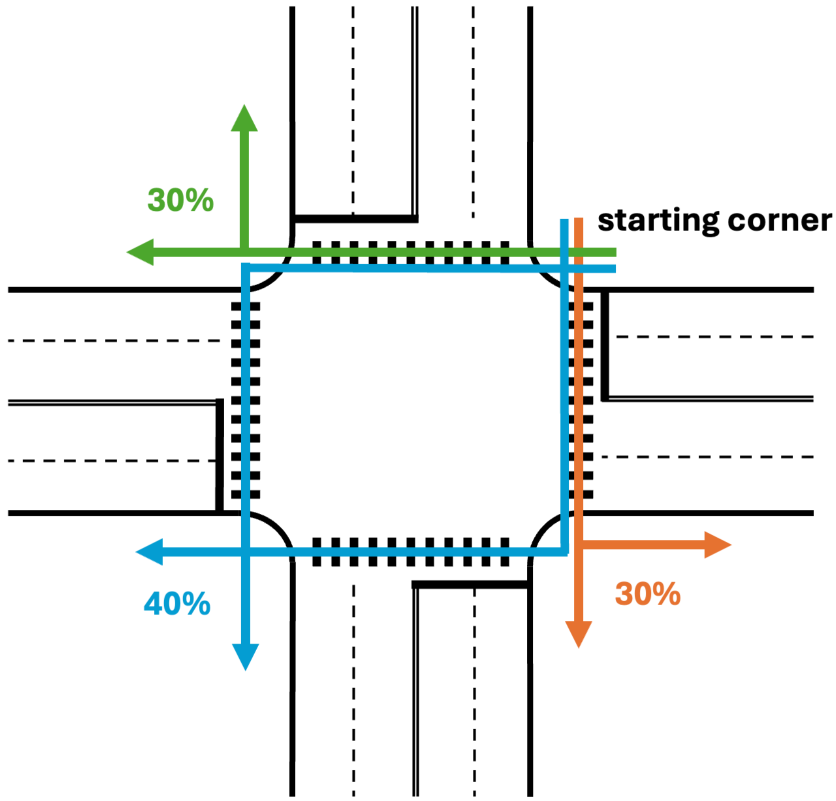

Figure 53. Pedestrian routing used in the VISSIM models.

The setting "waiting time before diffusion" was changed to over the length of a signal cycle so that vehicles were not removed from the network due to inability to change lanes before the cycle resumed and cars began to move again.

4.1.2. Scenarios

VISSIM model runs were conducted to each be composed of four individual runs that were then averaged. Each of these runs varied geometric characteristics, volume characteristics, or signal timing characteristics and were then used to analyze the differences in delay between scenarios. The characteristics of each scenario are below.

4.1.2.1. Base-Case

The base case scenarios consisted of all combinations of numbers of lanes, with right-turn lanes and without, pedestrian volumes (0, 100, 500, 1000), all vehicle volumes (83, 167, 250, 333, 417, 500), right-turn-on-red allowed, and all turning percents (10, 20, 30).

These runs established the assumed as-is conditions for the model and allowed future comparisons to be made for all countermeasures analyzed. These assumed protected-only phasing or permissive-only phasing, depending on the approach but did not use protected-permissive.

4.1.2.2. Right-Turn-on-Red Restrictions

The no right-turn-on-red scenarios consisted of all combinations of numbers of lanes, with right-turn lanes and without, 0, 100, 500, and 1,000 pedestrians per hour, all vehicle volumes (83, 167, 250, 333, 417, 500), right-turn-on-red not allowed, and all turning percents (10, 20, 30).

4.1.2.3. Leading Pedestrian Intervals

The leading pedestrian interval scenarios consisted of all combinations of numbers of lanes, with right-turn lanes and without, 0, 100, 500, and 1,000 pedestrians per hour, all vehicle volumes (83, 167, 250, 333, 417, 500), right-turn-on-red not allowed, all turning percents (10, 20, 30), and three assumed LPI lengths (3s, 5s, 7s).

The chosen three LPI lengths were assumed because those values were frequently seen in the literature.

4.1.2.4. Road Diet

The lane reduction scenarios consisted of only the two-lane in each direction on both street geometries, with right-turn lanes and without, only 100 pedestrians per hour, all vehicle volumes (83, 167, 250, 333, 417, 500), right-turn-on-red allowed, and all turning percents (10, 20, 30).

The road diet scenarios were run so that the vehicle volumes assumed for a geometry of three lanes in each direction on the major street and two lanes in each direction on the minor street were all put on to the two-lane in each direction on both street geometries. This simulated a road diet where the same level of traffic was attempting to travel on fewer lanes.

4.1.2.5. Exclusive Pedestrian Phasing

The exclusive pedestrian phasing scenarios consisted of all combinations of numbers of lanes, with right-turn lanes and without, 500 and 1,000 pedestrians per hour, all vehicle volumes (83, 167, 250, 333, 417, 500), right-turn-on-red not allowed, and all turning percents (10, 20, 30).

Only medium and high pedestrian volumes were analyzed for exclusive pedestrian phasing since low pedestrian volumes would not warrant an exclusive phase. Additionally, unique signal timings and diagonal pedestrian paths were created for these scenarios.

4.1.2.6. Add Pedestrian Signals

The pedestrian signals scenarios consisted of all combinations of numbers of lanes, with right-turn lanes and without, 0 pedestrians per hour, all vehicle volumes (83, 167, 250, 333, 417, 500), right-turn-on-red allowed, and all turning percents (10, 20, 30).

No pedestrians were assumed for these scenarios since without having pedestrian signals there was no accurate way for pedestrians to cross the road in the model. Unique signal timings were created, where the signals were retimed without accounting for minimum pedestrian crossing times.

4.1.2.7. Protected-Only Phasing

The protected-only phasing scenarios consisted of all combinations of numbers of lanes, with right-turn lanes and without, 100 pedestrians per hour, all vehicle volumes (83, 167, 250, 333, 417, 500), right-turn-on-red allowed, and all turning percents (10, 20, 30).

These scenarios involved extending the left-turn phase to represent vehicles being permitted to go if there were no opposing vehicles. A flashing yellow arrow signal head was selected to represent the signal head, although it does not appear to affect the modeling compared to a green ball.

4.1.2.8. RCUT

The RCUT scenarios consisted of an intersection with three lanes on the major street and one lane on the minor street and traditional signal timing and an intersection with three lanes on the major street and one lane on the minor street with RCUT geometry, three pedestrian volumes (0, 100, 500), eight major street vehicle volumes (100, 200, 300, 400, 500, 600, 700, 800), right-turn-on-red allowed, three turning percents on both the major and minor street (10, 20, 30), and three percentages of the per-lane major street traffic on the minor street (25,50,100).

The RCUT scenario was modeled specifically after the RCUT at Bandera Lane and Cedar Drive. This location was chosen to model because the construction has been completed and pedestrian provisions were provided. The geometry was obtained from Google Maps.

4.1.3. Analysis

A node boundary was drawn and used to analyze the delay within the intersection, and delay was output for each movement. When calculating delays, VISSIM determines the difference between the actual time it took each vehicle to travel through the intersection and the theoretical amount of time it would have taken that vehicle to travel through the intersection if no other cars were present.

Scenarios were removed that showed constantly increasing queueing throughout the simulation run. Once the queue begins to grow infinitely long, the model ceases to be an accurate representation of real-world conditions. Delay grows exponentially, which is seen to not be the case in real life. Additionally, in a network, vehicles will choose to route to other destinations or trip modes will change with growing congestion, which the model does not include. For the purposes of this study, if any approach had average vehicle delays over 80 seconds per vehicle the model run was assumed to be too congested to determine delays accurately as this corresponds with LOS F. This assumption was arbitrarily used because each approach was modeled at 1,500 ft and therefore if an average queue length was over 1,000 ft the queue can be assumed to have been over half of the link half of the time.

4.1.4. Model Results

This section shows graphs discussing the delays output by the model. First, general trends in the modeled intersections are shown, then delay from specified countermeasures. Often, 100 pedestrians per hour is used to show the graphs because this was determined to be a reasonable assumption of low pedestrian volume such as at an intersection with few pedestrian accommodations may have. This is approximately 3 pedestrians every 120 second cycle.

For each geometry, the average delays produced by the model are shown in Figure 54. Each data point includes an average of the delay for all turning percentages, and for the model with no right turns on red.

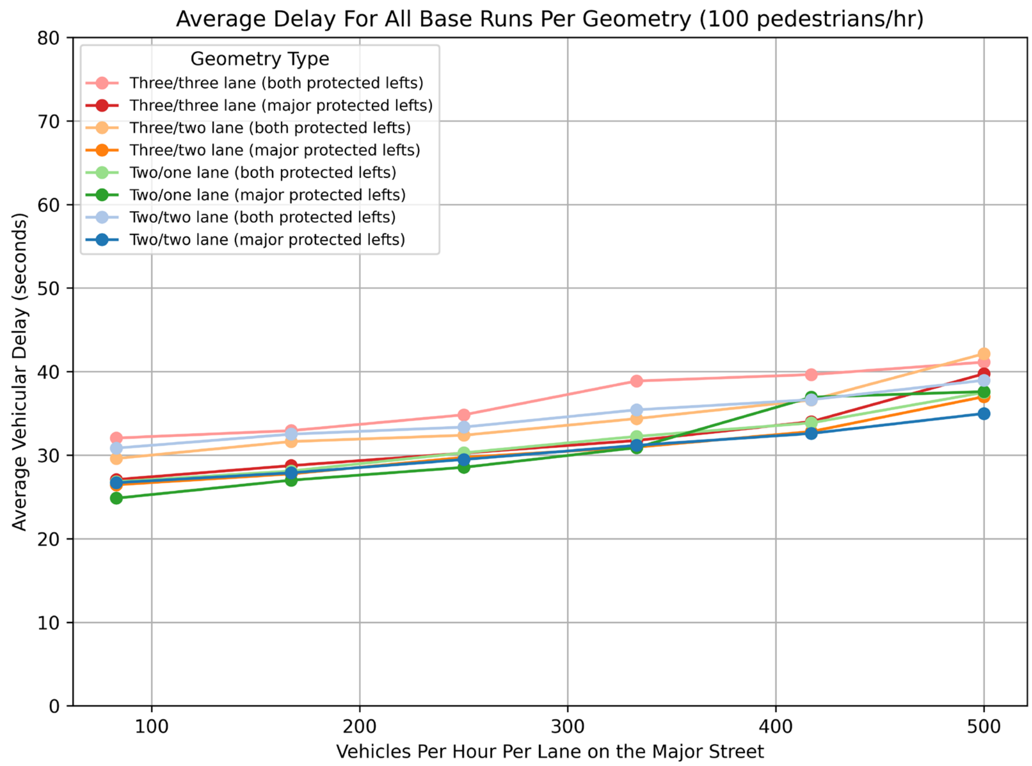

Figure 54. Base delays for 100 pedestrians per hour and no right-turn-on-red, shown per geometry.

It can be seen that geometries with more lanes tend to have higher delays, that for the signal sequencing used when both left turns are protected there tend to be higher delays, and that as the number of vehicles at the intersection increase the average delay increases.

The average delays per pedestrian volume and for all geometries can also be looked at, which is seen in Figure 55.

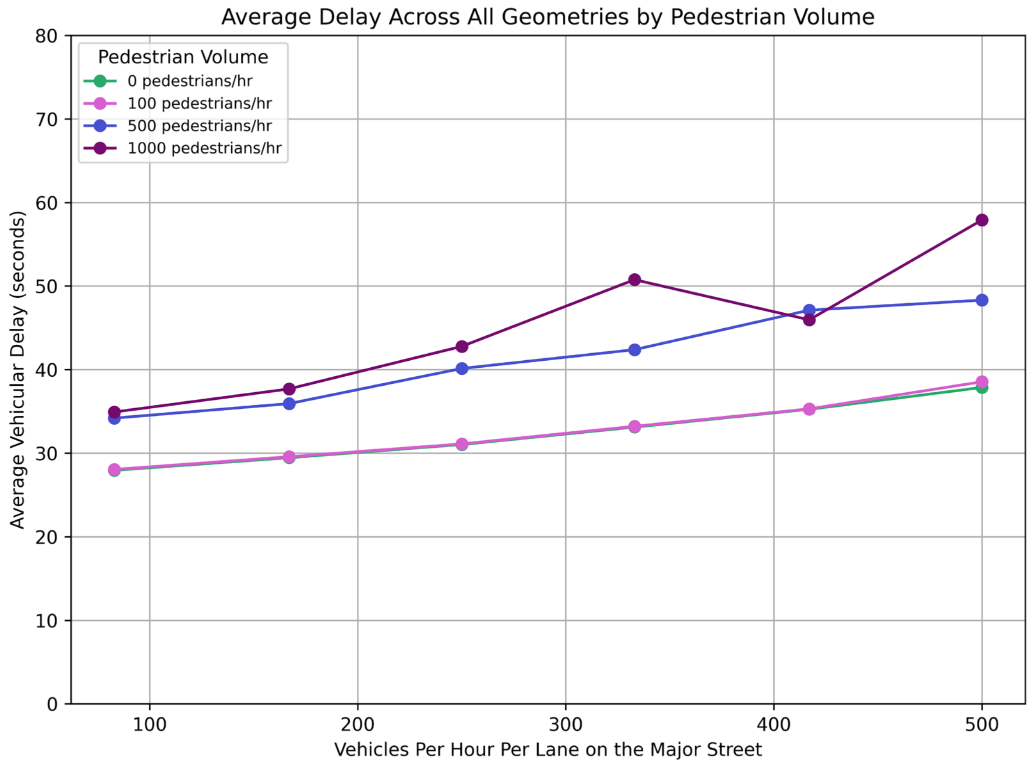

Figure 55. Base delays for all geometries, shown per pedestrian volume category.

Here, it can be seen that when there are more pedestrians present the average vehicular delay tends to be higher holding all ends constant. The one location where the delay for 1,000 pedestrians per hour is lower than for 500 is likely due to how geometries were chosen to be excluded from analysis (if their base delay was over 80 seconds).

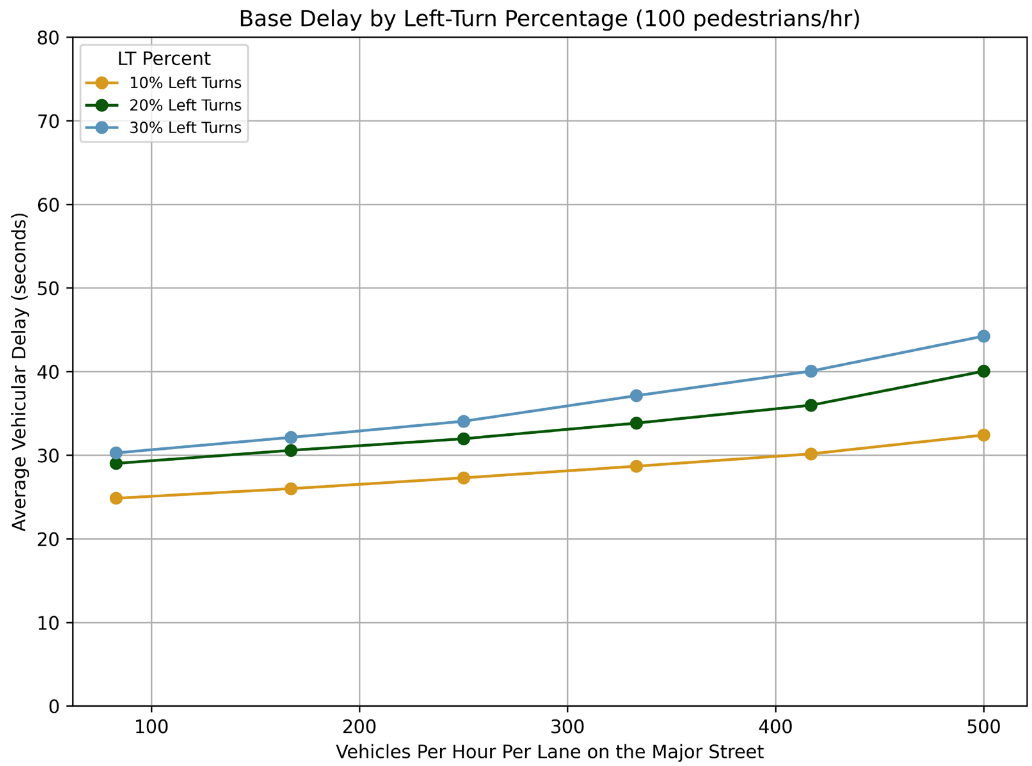

Figure 56. Base delays for 100 pedestrians per hour, shown per left turning percent volume category.

It can be seen that while the total intersection volume stays the same, as the percentage of left turning traffic increases so does the delay.

Now, the delay increases from various countermeasures will be shown in Figure 57.

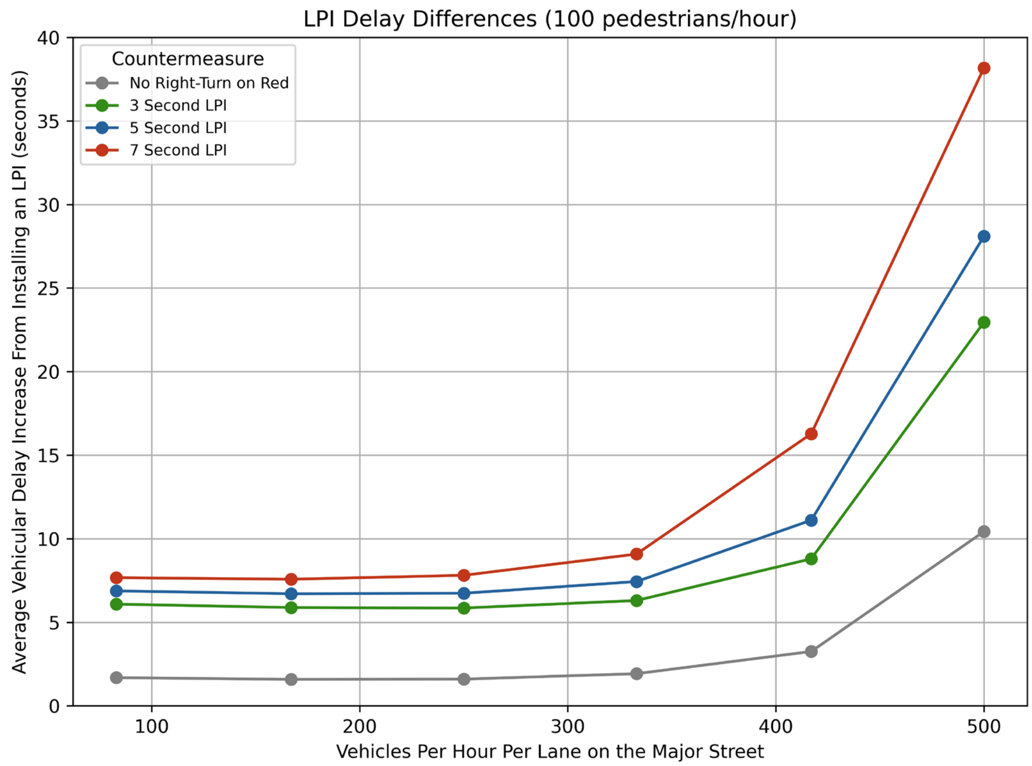

Figure 57. Increase in delay from adding a LPI of various lengths, averaged over all scenarios studied and for 100 pedestrians/hour.

Here, it can be seen that the longer the LPI, the more delay is experienced for vehicles. Additionally, the delay from implementing no right-turn-on-red is shown, as it is typically recommended that LPIs be installed with right-turn-on-red restrictions and they are therefore modeled without allowing right turns on red.

Next, the average delays across all other countermeasures modeled can be seen in Figure 58. In this figure, the protected-permissive to protected timing is based on 100 pedestrians per hour and the lane reduction countermeasure is also based on 100 pedestrians per hour. The adding pedestrian signal heads countermeasure is based on 0 pedestrians per hour, as it does not make sense to model pedestrians without signal heads, and the exclusive pedestrian phase countermeasure is based on 500 pedestrians per hour as that timing would not be warranted with only 100.

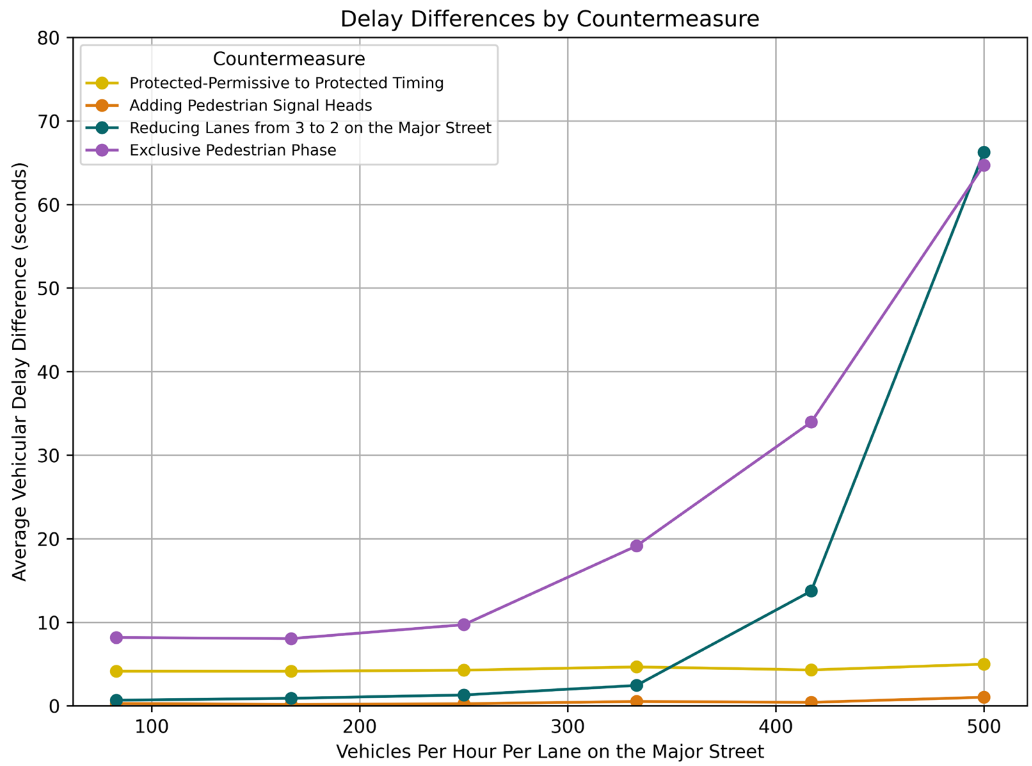

Figure 58. Increase in delay from adding four different countermeasures.

It can be seen that exclusive pedestrian phasing and lane reductions can cause severe delays at high vehicular volumes, while having only minor impacts at low volumes. Additionally, adding pedestrian signal heads had almost no impact on vehicular delays when no pedestrians were present and changing from protected-permissive to protected timing also had little impact at all volumes.

Additionally, it is important to note variations in the increase in delays between different intersection characteristics. For instance, as seen in Figure 58, exclusive pedestrian phasing causes detrimental delays when implemented at an intersection with three lanes in all directions, but much less severe delays when implemented at smaller intersections. In this case, it is because the timing of exclusive pedestrian phasing is dependent on the geometry; for an intersection with three lanes in each direction on both roadways and left turn lanes on both streets, 42 seconds were required for pedestrian clearance diagonally as opposed to 32 seconds for an intersection with two lanes in each direction on both roadways and turn lanes on both streets.

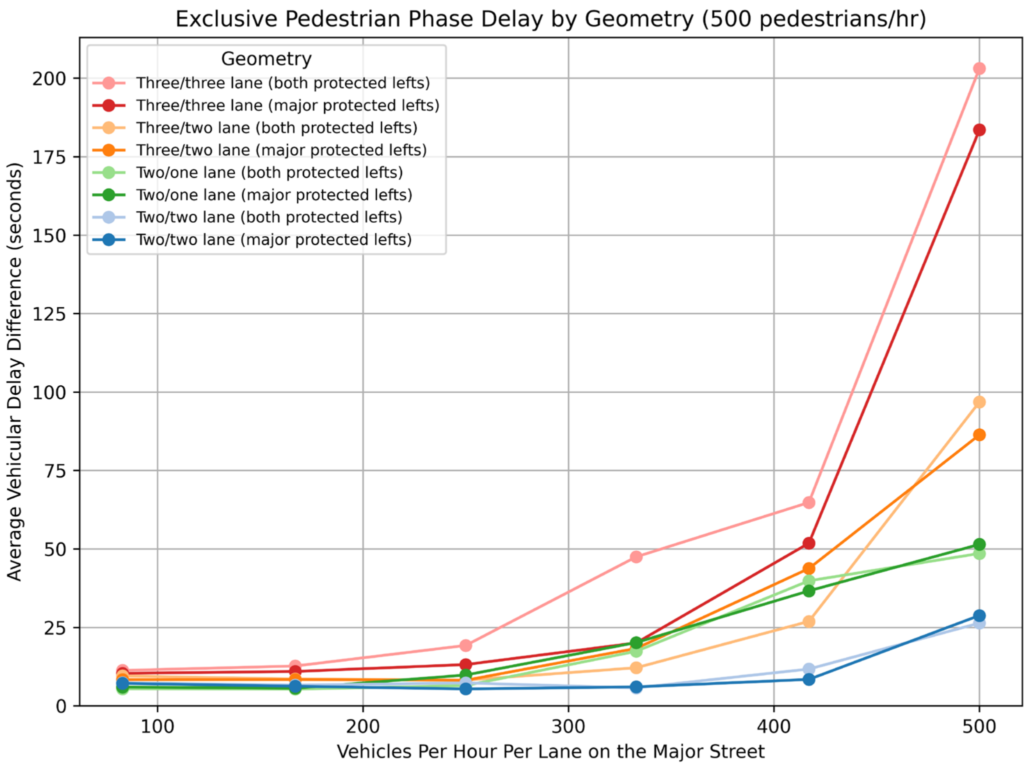

Figure 59. Increase in delay from adding an exclusive pedestrian interval, by intersection geometry and for 500 pedestrians/hour.

It is unclear why the roadway with two lanes on the major street and only one lane on the minor street experienced higher delays than the same intersection with two lanes on the minor street. There are many variables that go into each model and delays are very dependent on signal timings which vary based on many factors.

Leading pedestrian interval impact on delays also varies with geometry, as can be seen in Figure 60.

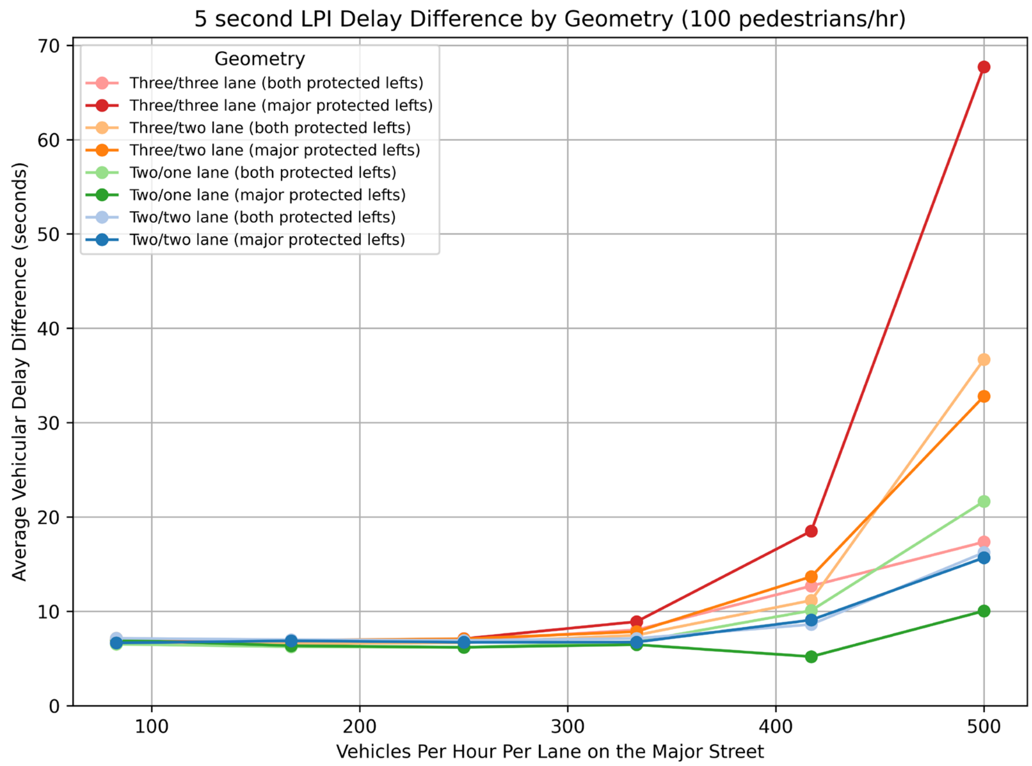

Figure 60. Increase in delay from adding a 5 second LPI, by intersection geometry and for 100 pedestrians/hour.

5 second leading pedestrian intervals are seen to have the most impact on the geometry with three lanes in each direction and protected turns for the major and minor streets at high volumes. They also have significant impacts for some other geometries at high volumes, but consistently increase the delay by about 8 seconds for all geometries at low volumes.

Figure 61 shows the changes in delay from adding protected-only instead of protected-permissive timing.

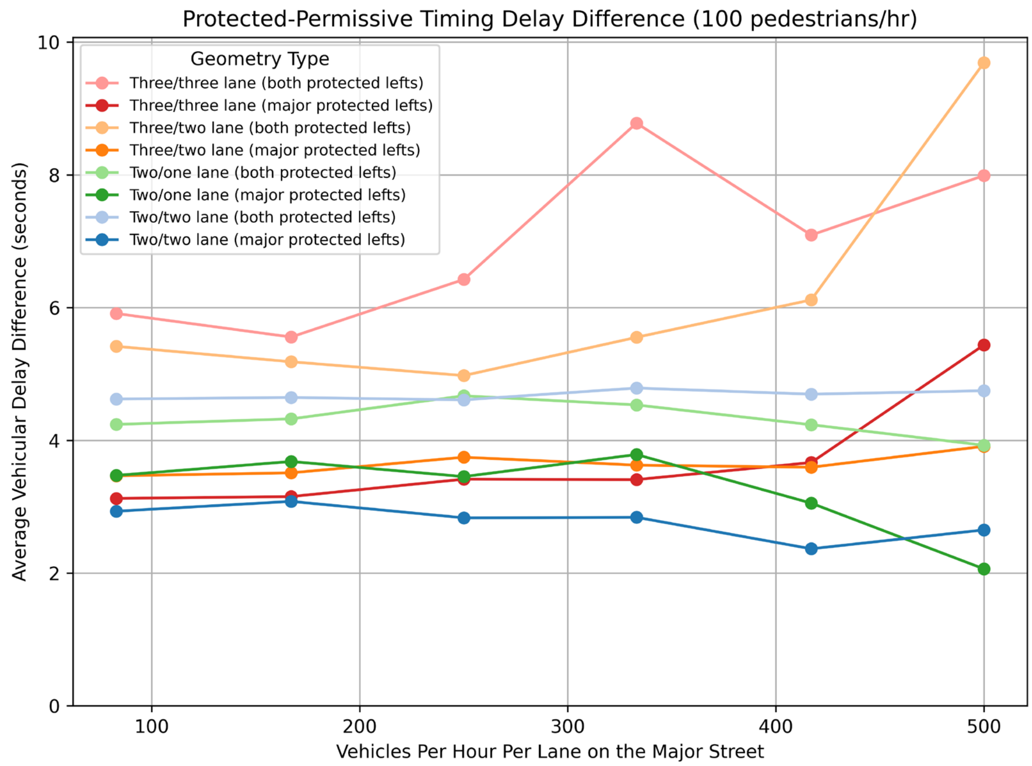

Figure 61. Increase in delay from changing from protected-permissive timing to protected only, by intersection geometry and for 100 pedestrians/hour.

Interestingly, for protected-permissive timing the change in delay does not seem to vary much based on the number of total vehicles. Logically, the increase in delay is typically larger when both streets have protected left turn phasing.

Other generalizations of the data could be made, however for a given scenario looking at the model results for the given characteristics of an intersection can provide a better match. Therefore, the spreadsheet tool provided with this technical memorandum will be useful for identifying delays associated with a given countermeasure and intersection geometry.

4.1.4.1. Reduced Conflict U-Turn Intersections

The next countermeasure modeled is a reduced conflict U-turn intersection (RCUT). This intersection was compared to a traditional intersection with the same number of lanes, right-turn lanes, and using the same volumes.

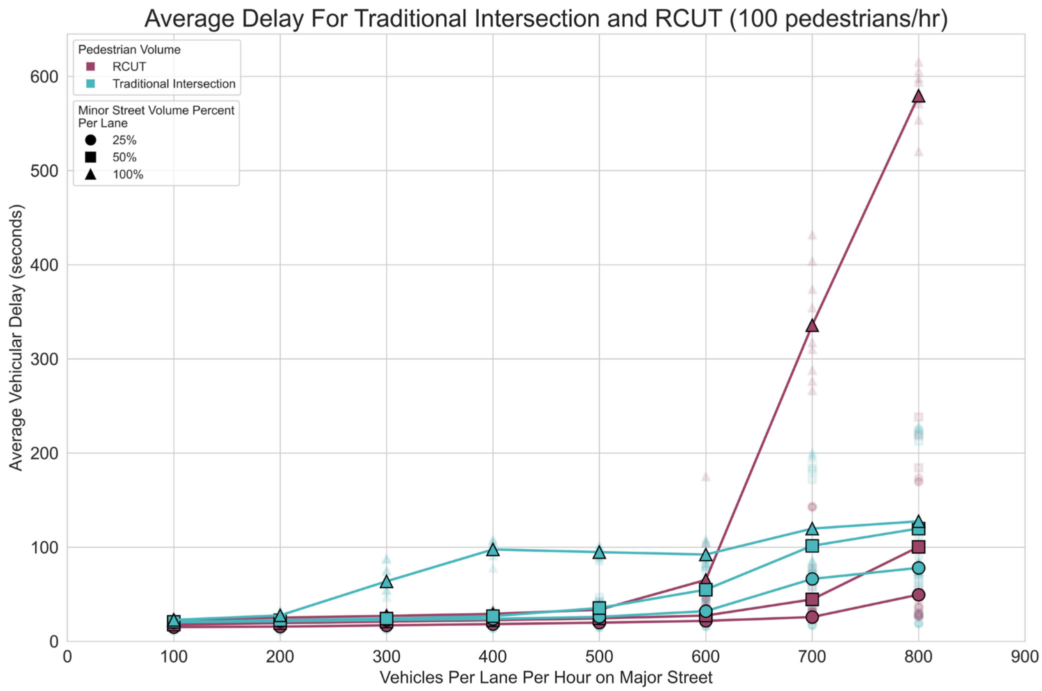

Figure 62. Reduced Conflict U-Turn Intersection Delays

As can be seen in Figure 62, the RCUT typically produces similar delays to the traditional intersection up until 600 vehicles per hour, except for the scenario where the vehicles per lane on the major street is equal to that on the major street. In this case, the traditional intersection produces more delay than the RCUT. However, when the vehicles per hour exceed 600, for this case the delay from the RCUT skyrockets, showing that the geometry is unable to handle the increase in vehicular traffic. For most other volume combinations, the RCUT out-performs the traditional intersection, however.

Next, the pedestrian delay for the RCUT vs traditional intersection were plotted in Figure 63.

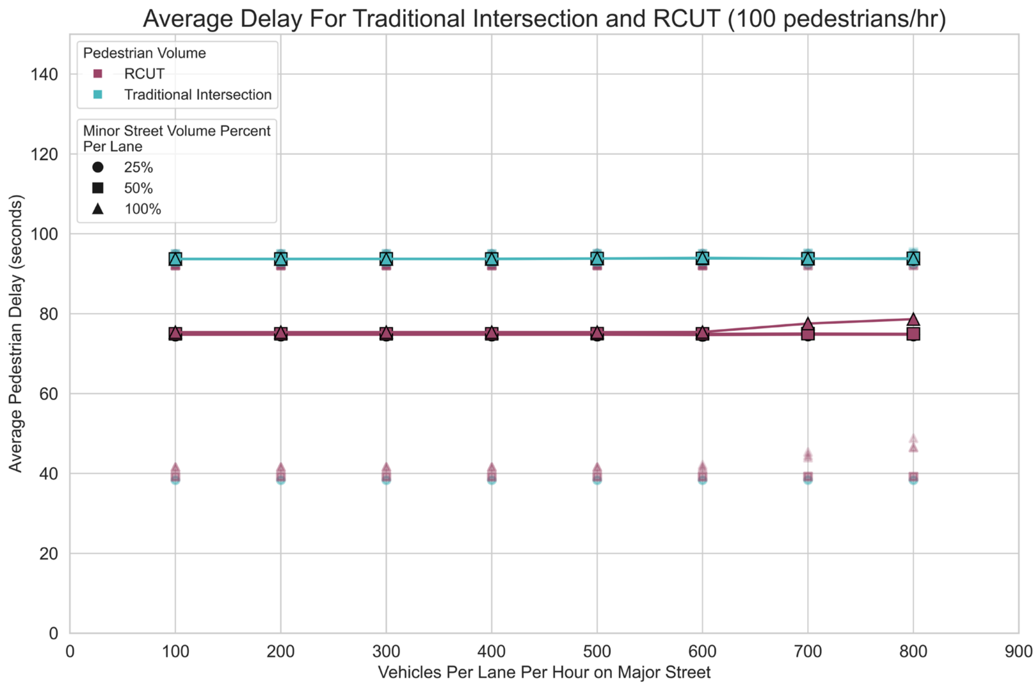

Figure 63. Average Pedestrian Delay Comparison by Minor Street Volume

Here, the average delay is typically lower than the traditional intersection for the RCUT. To investigate the contributing factors to this further, the delay by left turn percent was plotted in Figure 64.

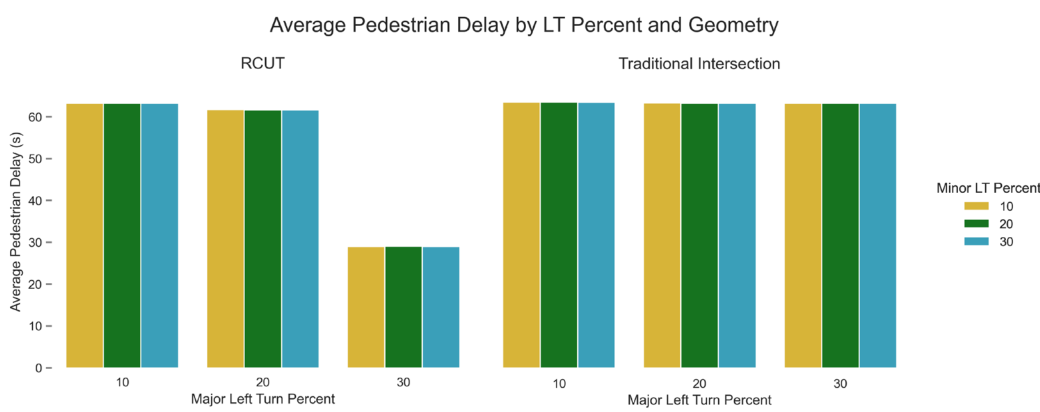

Figure 64. Average Pedestrian Delay by Left Turn Percent

By plotting the average delays in this way, it can be seen that the delay is actually the same as the traditional intersection for all scenarios except when the major street left turning percent is the highest, in which case the signal timings provide more time to the major street left turn phase which is also the phase pedestrians cross on.

Therefore, despite RCUTs reducing the number of crosswalks pedestrians can cross on they actually do not increase pedestrian delays and can be considered without adverse pedestrian effects.

4.1.4.2. Model Limitations

The modeling of pedestrian behaviors is conservative for several reasons. The entrance of pedestrians into the model is random. Typically, on a street system you will likely see groups of pedestrians and clusters of pedestrians walking near each other coming from another signal. This random entrance of pedestrians means the right turning vehicles are stopping more often than they should.

Another limitation of this study is that signal timings were not able to be adjusted individually for each scenario. At intersections controlled by a mobility management center, engineers can look at a given intersection and adjust the signal timings to match the live vehicle demands. However, many state-owned intersections are not able to be reached remotely; therefore, signal timings must be predetermined and loaded into the controller. In this case, an engineering study is done, oftentimes using software to model the intersection. While some software supports pedestrian analysis, if engineers are making a best guess at the signal timings, especially while implementing a new countermeasure, they are not likely to produce optimal signal timings. The signal timings used were deemed appropriate, however, likely represent a time higher than optimal. Additionally, many state facilities have actuated timing which this study did not model but may reduce delays in some instances.

Additionally, pedestrian volumes of 500 and 1,000 people per hour are very high compared to what is typically seen at an intersection, especially on a rural or high-speed roadway. Therefore, while large delays were measured for these scenarios, the delay for most state facilities will be closer to the number modeled with 0 or 100 pedestrians; the high values were used only as additional data points for very high pedestrian locations.

While the increases in delay and total delay can be predicted from the models, it was chosen not to provide recommendations about implementation based on traffic volumes. This is due to the predicted delays being conservative and, therefore, higher than are likely to be seen in the field. Therefore, just looking at these models, an LPI may not be implemented at a location that, in actuality, could sustain it.

Additionally, the amount of delay incurred in real life is often less than that modeled due to a phenomenon called reduced demand. Induced demand is where usage of vehicles increases and fills in excess capacity on roads during peak hours following a roadway expansion (Lee 1999). Conversely, when capacity is reduced oftentimes vehicles will find another route, change the time of day they travel, or simply not make the trip; a phenomenon called reduced demand (Steuteville 2021). However, modeling a single intersection using static route decisions means that this flexibility is not taken into account. Therefore, comparing modeled estimates to real-world countermeasure implementations would be an important future step to see how these countermeasures have impacted delays in actuality.

4.1.4.3. Summary

Conclusions can be drawn following the modeling of no right-turn-on-red, LPI, road diet, exclusive pedestrian phasing, adding pedestrian signals, protected-only phasing versus protected-permissive phasing, and RCUT countermeasures.

Variation in delays resulted from models with different turning percents, geometries, vehicle, and pedestrian volumes for some countermeasures. Since all of these factors influenced the resulting delay, simple thresholds for each countermeasure are unable to be drawn. For each countermeasure, the point at which an intersection will reach capacity is different depending on all of these factors; therefore, the data is unable to be presented clearly in a table or graphical form.

It should again be noted that each graph presented in this section is a combination of many different runs; therefore, the average does not show any meaningful values about the delays for a specific intersection with the given vehicle volume. Other characteristics, such as geometry, turning percent, and pedestrian volume, must also be evaluated to determine what delay the model estimate that will be experienced at that location.

Therefore, the presentation of the data was determined to be best accomplished in a spreadsheet format and is another byproduct of this research study. Since all aspects of the model influenced the resulting delay, and aspects that were not modeled likely also influence the delay, all estimates of delay are only approximations and are likely to vary when a countermeasure is actually implemented. However, summaries of the countermeasures qualitatively can be given.

No right-turn-on-red was found to have a quite moderate impact on delay for low vehicle volumes and low pedestrian volumes. However, when both increase, significant delays can be caused, with some intersections where pedestrian volumes were 500 or greater exceeding capacity when no right-turn-on-red was implemented. Additionally, percentage of left turning traffic can increase delays but not as significantly as pedestrian volume. This indicates that right-turn-on-red restrictions can be made at most intersections without the delay expected to increase significantly. However, when the pedestrian volumes are high or the pedestrian volumes are moderate and the vehicle volume is high, intersection capacity may be reached when right turns are prohibited from taking place on red.

Leading pedestrian intervals were modeled assuming no right-turn-on-red was implemented, and additional delays were experienced compared to just implementing no right-turn-on-red. However, similar to right-turn-on-red restrictions, leading pedestrian intervals were only found to increase delays significantly when there was a combination of high pedestrian and high vehicular traffic.

A road diet was found to have an almost exponential shape to the data, where vehicle delays greatly increased with higher vehicle volumes. This is expected, as a road diet does decrease the capacity of a roadway.

Exclusive pedestrian phasing also showed great delays with higher vehicle volumes, as does providing a phase exclusively for pedestrians effectively reduces the capacity due to a loss of green time.

Adding pedestrian signal heads, thus adjusting the signal timing to account for pedestrians, did not increase the delay significantly at any vehicle volume. Therefore, for roadways with less than 500 vehicles per hour per lane it can be assumed that pedestrian signal heads can be installed with only very minor delays expected (on average approximately one second).

Similarly, changing the signal phasing from protected to protected/permissive had a nonzero, but low, effect for all vehicle volumes. Therefore, for roadways with less than 500 vehicles per hour per lane, changing the signalization to remove the permissive part of the phase should have very little effect on the overall intersection delay (on average approximately five seconds).

An RCUT showed less delay than a traditional intersection for most scenarios except where the minor street had equal volume per lane to the major street, in which case the delay increased sharply. This indicates RCUTs should only be installed in areas where the minor street volume is unlikely to heavily increase. Additionally, the minor street volume should be much lower than the major street volume per lane.

4.1.4.4. Example

While the delays for all intersections cannot easily be compared, two sample modeled intersections can be compared side-by-side to understand how the delays incurred differ between the two.

Table 7 shows the characteristics of four sample intersections.

Table 7. Sample Intersection Characteristics

	Intersection 1	**Intersection 2**	**Intersection 3**	**Intersection 4**
Number of lanes (major)	4	4	6	6
Number of lanes (minor)	4	4	6	6
Left turning percent	20%	20%	20%	20%
Vehicle volume (per lane per hour)	250	500	500	500
Right turn lanes?	No	No	No	No
Left turn lanes	Major only	Major only	Major only	Major and minor

These intersections are all very similar to show how changing just one characteristic at a time will impact the model delay outputs. Between the first and second intersection, the vehicle volume is changed. Between the second and third intersection shown, the number of lanes is changed; between the third and fourth intersection, the left turn lanes are changed from being only on the major street to both the major and minor street.

It should be noted that even if multiple pedestrian volumes were run, only one example was used in the table below. The following pedestrian volumes were used; base delay: 0, 100, 500; adding pedestrian signals: 0; right-turn-on-red: 100; leading pedestrian interval: 100; protected-permissive phasing: 100; exclusive pedestrian phasing: 500.

It should also be noted that for the protected-permissive scenarios, the total delay should decrease; therefore, the reported delay will be positive when the protected-permissive scenario showed less delay than the base case scenario.

Additionally, it should be noted that delays much higher than 80 seconds indicate extreme congestion; therefore, the increase in delay indicated by the model is essentially meaningless, except to say that the intersection has reached capacity.

Table 8 shows the modeled delays from various countermeasures for each of the above defined intersections. For each cell in the table corresponding to a countermeasure, the change in delay is first listed, and then, in parenthesis, the average of the delay for all vehicles at the intersection is shown. For the cells that correspond to a base delay, the average of the delay for all vehicles at the intersection is listed.

Table 8. Sample Intersection Countermeasure Delays

	Intersection 1	Intersection 2	Intersection 3	Intersection 4
Base delay (0 pedestrians/hour)	31.47	37.69	40.72	45.88
Adding pedestrian signals	0.00 (31.47)	0.00 (37.69)	0.00 (40.72)	2.65 (43.23)
Base delay (100 pedestrians/hour)	31.77	38.43	42.65	46.11
Right turn on red restriction	2.10 (33.88)	3.62 (42.05)	9.08 (51.74)	34.28 (80.39)
Leading pedestrian interval (3 second)	3.28 (35.05)	5.28 (43.71)	22.57 (65.22)	35.04 (81.15)
Leading pedestrian interval (5 second)	4.50 (36.27)	8.75 (47.18)	44.63 (87.28)	27.06 (73.17)
Leading pedestrian interval (7 second)	5.36 (28.70)	16.27 (54.70)	119.25 (161.90)	39.29 (85.40)
Protected-permissive	3.08 (28.69)	2.85 (35.58)	4.52 (38.13)	7.79 (38.33)
Base delay (500 pedestrians/hour)	35.22	58.75	166.63	245.58
Exclusive pedestrian phasing	6.13 (41.34)	45.32 (104.07)	218.04 (384.667)	180.25 (425.83)

From these examples, the large delay differences between different countermeasures can be seen. Exclusive pedestrian phasing was only modeled for 500 and 1,000 pedestrians, which does result in a high base delay for some intersections, and can be seen to have a higher increase in delay than the other countermeasures analyzed. A longer leading pedestrian intervals can be seen to greatly increase the total delay in intersection 3, with a protected left turn on the minor street only, and does not have a large increasing effect in intersection 4, which has a protected left turn on both streets. The no right-turn-on-red scenario has delays under 10 seconds for scenarios 1-3, and an increase in delay of 34.28 seconds for scenario 4 where both streets are modeled as having a left turn lane and protected phase.

These examples show the variability in the modeling results and how individual characteristics of the models can greatly affect, or barely affect, resulting delays. While patterns were able to be deduced from the data, no one number or threshold can be given to represent the increase in delay from an average intersection.

Chapter 5. Spreadsheet Criteria and Development

As a part of this project, a spreadsheet tool was created to assess the applicability of the studied countermeasures of interest for a given intersection based on attributes input about the intersection. This section will discuss accessing the spreadsheet and the criteria used to determine whether to recommend each countermeasure.

5.1.1. Accessing the Spreadsheet

When downloading a spreadsheet with macros enabled from the internet (a .xlsm file), most computers will automatically disable the macros, not allowing the spreadsheet tool to work correctly. In order to unblock these macros from the sheet, the following steps can be followed:

- Right-click the downloaded file.
- Select “Properties” from the drop-down menu.
- Check the box that says “Unblock” in the “Security” section.

Once these steps are carried out, the spreadsheet should be able to be used as intended.

5.1.2. How to Use

This section will overview how to use the spreadsheet tool, which is also provided on the first page of the spreadsheet. First, answer the 60 multiple-choice questions about the intersection characteristics in the “Inputs” tab. If there is no exact match, choose the closest option. Next, look at the “Results” tab for a list of countermeasures that can be used to improve Complete Streets operations at the given intersection. These countermeasures may not be applicable at every intersection they are shown for, but will provide a starting point for further study. It should also be noted that sometimes two countermeasures will both be suggested as options, but not compatible with each other such as leading pedestrian intervals and exclusive pedestrian phasing. This is intended to be a jumping off point for future feasibility analysis of the suggested countermeasures.

5.1.3. Spreadsheet Criteria

The criteria used for selection of each countermeasure used in the spreadsheet is listed below. These criteria were input into the spreadsheet to filter which countermeasures are applicable at a given intersection based on the attributes of an intersection input. They are listed in a semi-arbitrary order where the countermeasures that typically must be implemented at an intersection are listed first. However, they are not numbered because they are not ranked.

Install sidewalks along roadway

- The intersection does not have sidewalks.

Install pedestrian signal heads

- The intersection does not have pedestrian signal heads.

Change pedestrian signal heads to display a countdown

- The intersection has pedestrian signal heads, but do not display a countdown.

Paint crosswalks

- The intersection does not already have crosswalks.

Paint high visibility crosswalk

- The intersection has crosswalks, but are not a high-visibility pattern.

Install curb-cuts

- The intersection does not have curb-cuts.

Modify skewed intersections

- The intersection is noted as being skewed so that the roadways meet at a sharp angle.

Add curb extensions

- The intersection does not have curb extensions.
- The intersection has parking leading up to the intersection.

Pedestrian phase on recall

- The intersection is fixed time (not actuated).
- Pedestrian phase is not currently placed on recall.

Add leading pedestrian intervals

- The intersection does not have leading pedestrian intervals.
- The intersection is under capacity (LOS F) and will not reach capacity with the installation of LPIs.

Add exclusive pedestrian phase

- The intersection has high pedestrian volumes (> 500 persons per hour).
- The intersection is under capacity (LOS F) and will not reach capacity with the installation of an exclusive pedestrian phase.

Implement protected-only left turns

- The intersection has at least one left-turn lane that is not already signalized with a protected-only phase.
- The roadway turns are originating from two-way (protected left turns on one-way streets are a separate countermeasure referred to as split-phasing).
- The intersection is under capacity (LOS F) and will not reach capacity by removing permissive phasing.

Implement protected-only left turns when pedestrians present

- The intersection cannot use protected-only phasing exclusively without experiencing excess delays.
- The intersection has at least one left-turn lane that is not already signalized with a protected-only phase.
- The roadway turns are originating from two-way (protected left turns on one-way streets are a separate countermeasure referred to as split-phasing).
- The intersection is under capacity (LOS F) and will not reach capacity by removing permissive phasing when pedestrians are present.

Implement split phasing

- The roadway turns are originating from one-way.

Install flashing yellow arrow signal head for left turns

- The intersection cannot use protected-only phasing exclusively without experiencing excess delays.
- The intersection has at least one left-turn lane that is not signalized with a protected-only phase.

Implement right-turn-on-red restrictions

- The intersection has sufficient pedestrian volume (>15 persons per hour).

Reduce the cycle length

- The intersection has excess capacity, and pedestrians are experiencing long wait times.

Increase the cycle length

- Pedestrians have trouble crossing during the current time provided.

Implement single-stage crossings

- Pedestrians are forced to wait in the middle of a roadway at least at one location in the intersection.

Remove a vehicle lane and add pedestrian or bicyclist space (road diet)

- There is sufficient pedestrian or bicyclist volumes (>15 of either).

- The intersection will not reach capacity (LOS F) with the removal of a lane.

R**emove channelized turn lane**

- There is a channelized turn lane present at the intersection.

Alter channelized turn lane
- There is a channelized turn lane present at the intersection.
- The channelized turn lane cannot be removed due to constraints.

Reduce the curb radius
- The curb radius is greater than 20 ft.
- Trucks or large vehicles do not frequently need to use the intersection.

Add truck apron
- The curb radius is greater than 30 ft.
- Trucks or large vehicles frequently need to use the intersection.

Install bike signals
- There is sufficient bicyclist presence at the intersection (>100 per hour).
- There are complex movements carried out that require direction.
- There are bicycle lanes at the intersection.

Add leading bicycle interval
- There is a leading pedestrian interval at the intersection.
- There is a bicycle signal at the intersection or one is recommended.

Add raised bicycle / pedestrian crossings parallel to the major street
- Speeds on the minor street are low enough (less than or equal to 30mph).

Continue painted bicycle lanes through the intersection
- There are unprotected bicycle lanes on at least one roadway before the intersection.
- The bicycle lane is not present at the intersection.

Protected bicycle lanes
- There are protected bicycle lanes on at least one roadway before the intersection.
- The bicycle lane is not protected near the intersection.

Protected intersection
- There are protected bicycle lanes on at least one roadway before the intersection.
- The bicycle lane is protected at the intersection.

Bicycle lane lateral shift

- There is a right-turn lane.
- Cars cut across the right-turn lane, as opposed to merging through it.

Add pedestrian refuge islands (add curb-cuts to median)

- There is a median with sufficient space for refuge but it does not have curb-cuts.

Add pedestrian refuge islands (increase median width and add curb-cuts)

- There is a median currently, but it does not have sufficient space for refuge.
- The median does not have curb-cuts.

Increase pedestrian refuge island width

- There is a median with curb-cuts currently, but it does not have sufficient space for refuge.

Add pedestrian refuge islands (add median with curb-cuts)

- There is no median in the roadway currently.
- The gutter space is equal to or greater than four ft.

Centerline hardening

- Currently, this countermeasure is not recommended in the spreadsheet. Applications would be for intersections which have high rates of drivers cutting across the intersection diagonally when making a left turn.

Add intersection lighting

- There is insufficient lighting noted at the intersection.

Transit signal priority

- There is a bus route that passes through this intersection.
- It is noted that delay on the bus route is sometimes a concern at this intersection.

Bus queue jumps

- There is a bus route that passes through this intersection.
- It is noted that delay on the bus route is sometimes a concern at this intersection.
- There is a right-turn lane.

Traffic calming

- If speeding is noted as a concern at the intersection.

RCUT

- If the minor street has low traffic volume (<200 vehicles per hour per lane).
- If the minor street has one or two lanes.
- If the major street has three or more lanes.

Chapter 6. Value of Research

This project has opened the door for increased implementation of pedestrian and bicyclist countermeasures on TxDOT roadways, which has the potential to save many lives.

In 2024, 803 pedestrians and 80 bicyclists died on Texas roadways, according to the CRIS database which records data from police reports and allows query of crashes from all of Texas (TxDOT, n.d.). And, of these deaths 547 pedestrian and 52 bicyclist deaths were on TxDOT roads. And, just at TxDOT intersections 87 pedestrians and 11 bicyclists were killed in 2024. This data and the numbers for severe injuries are summarized in Table 9.

Table 9. Average Crashes per Year from 2020 – 2024, in All of Texas

	Fatalities (K)			**Injuries (A,B)**		
	Pedestrian	**Bicyclist**	**Pedestrian & Bicyclist**	**Pedestrian**	**Bicyclist**	**Pedestrian & Bicyclist**
All Texas roadways	814	90	904	4,622	1,651	6,273
TxDOT roadways	568	55	623	1,540	495	2,035
All Texas intersections	626	25	651	1,356	907	2,263
TxDOT intersections	72	12	84	422	255	677

TxDOT uses a value of $4,100,000 to represent the cost of a fatality or incapacitating injury, and $340,000 to represent the cost of a non-incapacitating injury. Conservatively assuming that none of the serious injuries were incapacitating, this totals an estimated cost of $488,840,000 in 2024 just at TxDOT intersections. This number can be seen further broken down in Table 10.

Table 10. Fatalities and Severe Injuries per Year from 2020 – 2024, at TxDOT Intersections

	Count	Cost per Person	Total Estimated Cost
Fatalities	84	$4,100,000	$344,400,000
Severe Injuries	677	$340,000	$230,180,000
		Total	$574,580,000

TxDOT maintains 6,200 signalized intersections. If countermeasures were implemented at a conservative 1% of intersections each year (62 intersections), and a CMF of 0.9 was assumed, reducing just 10% of crashes at the intersection, this could be approximated as $574,580 saved each year:

$$\$574{,}580{,}000 * 1\% * 10\% = \$574{,}580$$

And, since a countermeasure implemented in 2026 will provide benefits for 2027, 2028, 2029, etc. the value of life savings over the next 10 years can be estimated as:

$$\$574{,}580 * 9 + \$574{,}580 * 8 + \$574{,}580 * 7 \ldots = \$25{,}856{,}100$$

Assuming a ten year service life and the federal discount rate of 3%, a net present value of $21,372,737 saved from these implementations can be estimated.

If a cost of $20,000 is assumed for each intersection improvement, the cost of implementation for one year would be:

$$\$20{,}000 * 62 = \$1{,}240{,}000$$

And a present value of $10,577,448 can be assumed for a lifespan of ten years. Additionally, a cost of $200,000 is assumed for the research project. Therefore, the benefit cost ratio (BCR) can be calculated as follows:

$$\frac{\$21{,}372{,}737}{\$10{,}577{,}448 + \$200{,}000} = 1.98$$

This number is greater than 1, showing a positive return on investment for this project and supplemental implementation of guidelines discussed in this report. This calculation assumes implementation only at intersections maintained by TxDOT, however, implementation by cities is likely, so the estimate is very conservative. The TxDOT VOR template is attached as Appendix C.

Chapter 7. Conclusions

Pedestrian and bicyclist safety are of the utmost importance to include when roadways are being installed or renovated. Complete Streets is a new movement that aims to enhance mobility and safety for all users. To work towards safer streets, countermeasures can be employed. However, both delay and safety are difficult to estimate before implementation and determining trade-offs between the two is a tough task, especially when investments in countermeasures can be sometimes costly.

At signalized intersections, various countermeasures can be employed that aim to address safety concerns while accommodating all modes of travel. Once potential countermeasures are identified, a Benefit-Cost Analysis can determine associated trade-offs.

In order to assess which countermeasures are best suited to a given intersection, this report performed a literature review and single-intersection VISSIM modeling. The results were used to inform a spreadsheet-based tool that analyzes user inputs pertaining to a given intersection and determines which countermeasures are applicable at that location.

First, a literature review was conducted to identify countermeasures and define them. This project recommended 37 strategies to increase safety for all users at traffic signals. Predicted safety benefits were determined from data found in the literature. Both a pedestrian and bicyclist CMF were selected for each countermeasure, or it was determined that one was not available. Additionally, estimated costs for each countermeasure were determined from a combination of TxDOT Connect database data and literature review. A summary of the findings from the literature review portion of the report can be found at the end of Chapter 2 in Table 3.

To assess expected delays, VISSIM models were run for selected countermeasures. Summaries about these runs were included graphically in Section 4.1.4. However, due to the volume of results individual delays were incorporated into the spreadsheet tool developed as a part of this project.

The spreadsheet tool includes 60 questions that inform countermeasure recommendations. The suggested countermeasures show information on the delay, safety, and cost for each countermeasure.

Considering all users in intersection design is important to ensure safety for everyone. Strategies range in cost, vehicular delay incurred, and expected safety benefits and therefore each intersection may vary in which countermeasures are best suited for that location. Continuing to research and understand the full benefits of countermeasures is vital to ensure that they are implemented correctly and as often as necessary.

This project should help TxDOT to implement more pedestrian, bicyclist, and transit-focused countermeasures at signalized intersections, which will further TxDOT's safety goals and help promote increased mobility throughout their roadway network.

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Appendix A. CMFs from the Literature

This section contains all studies identified to contain pedestrian CMFs relating to the relevant countermeasures.

Table A.1. Overview of crash-based studies found in the literature

Treatment	Mode (Severity)	Treatment Crash Change	Comparison Crash Change	CMF (Std. Error)	Study Type	Sample Size	Location	Citation
Install sidewalks	Pedestrian (All)	--	--	0.12	Regression	141 segments	Wake County, North Carolina	(McMahon et al. 1999)
Install high visibility crosswalks	Pedestrian (All)	-40	-18	0.6	Before-after with comparison group	72 intersections+	New York City	(Chen et al. 2012; FHWA, n.d.-d)
Install high visibility crosswalks	Multi-Vehicle (All)	-19	-39	--	Before-after with comparison group	72 intersections+	New York City	(Chen et al. 2012)
Install high visibility crosswalks	Pedestrian (All)	-40	-15	**0.52**	Before-after with comparison group and regression	72 intersections+	New York City	(Chen et al. 2013)
Install high visibility crosswalks	All (All)	-29	-35	0.99	Before-after with comparison group and regression	72 intersections+	New York City	(Chen et al. 2013)
Install high visibility crosswalks	Bicyclist (All)	-61	-28	--	Before-after with comparison group and regression	72 intersections+	New York City	(Chen et al. 2013)
Install high visibility crosswalks	Multi-Vehicle (All)	-19	-42	1.26	Before-after with comparison group and regression	72 intersections+	New York City	(Chen et al. 2013)
Install high visibility crosswalks	All (Injury & Fatality)	-27	-30	1.06	Before-after with comparison group and regression	72 intersections+	New York City	(Chen et al. 2013)

Install pedestrian countdown timers	Pedestrian (All)	-13	+19	**0.713**	Before-after with comparison group	107 intersections[+]	Michigan	(Boateng et al. 2018)
Install pedestrian countdown timers	Pedestrian (Injury & Fatality)	-23	+6	**0.701**	Before-after with comparison group	107 intersections[+]	Michigan	(Boateng et al. 2018)
Install pedestrian countdown timers	Pedestrian (All)	-16	0	0.808	Before-after with comparison group	96 intersections[!]	Michigan	(Boateng et al. 2018)
Install pedestrian countdown timers	Pedestrian (Injury & Fatality)	-14	-3	0.847	Before-after with comparison group	96 intersections[!]	Michigan	(Boateng et al. 2018)
Install pedestrian countdown timers	Pedestrian (All)	-70	--	**0.3**	Before-after with comparison group and regression	362 intersections	Detroit	(Houten et al. 2012).
Install pedestrian signal heads	Pedestrian (Injury & Fatality)	-52	--	--	Naïve before-after	9 intersections	San Francisco	(Markowitz et al. 2006)
LPI	Pedestrian (All)	--	--	**0.87**	Before-after with empirical bayes	105 intersections	Chicago, New York City, and Charlotte	(Goughnour, D. Carter, et al. 2018)
LPI	All (All)	--	--	**0.87**	Before-after with empirical bayes	105 intersections	Chicago, New York City, and Charlotte	(Goughnour, D. Carter, et al. 2018)
LPI	All (Injury & Fatality)	--	--	**0.86**	Before-after with empirical bayes	105 intersections	Chicago, New York City, and Charlotte	(Goughnour, D. Carter, et al. 2018)

LPI	Pedestrian (All)	-22	-74	**0.413 (0.06)**	Before-after with comparison group	10 intersections	State College, Pennsylvania	(Fayish and Gross 2010b)
LPI	All (All)	+2	+2ˆ	--	Naïve before-after	26 intersections	New York City	(King 2000)
LPI	All (Injury & Fatality)	+7	+7ˆ	--	Naïve before-after	26 intersections	New York City	(King 2000)
LPI	Pedestrian (All)	-12	+22ˆ	--	Naïve before-after	26 intersections	New York City	(King 2000)
Exclusive Pedestrian Phasing	Pedestrian (All)	-44	-9	**0.65 (0.16)**	Before-after with comparison group and regression	37 intersections	New York City	(Chen et al. 2013)
Exclusive Pedestrian Phasing	All (All)	-2	+5	0.95 (0.12)	Before-after with comparison group and regression	37 intersections	New York City	(Chen et al. 2013)
Exclusive Pedestrian Phasing	Bicyclist (All)	+71	-19	--	Before-after with comparison group and regression	37 intersections	New York City	(Chen et al. 2013)
Exclusive Pedestrian Phasing	Multi-Vehicle (All)	-3	-10	0.97 (0.13)	Before-after with comparison group and regression	37 intersections	New York City	(Chen et al. 2013)
Exclusive Pedestrian Phasing	All (Injury & Fatality)	-13	-7	0.95 (0.12)	Before-after with comparison group and regression	37 intersections	New York City	(Chen et al. 2013)
Exclusive Pedestrian Phasing	Pedestrian (All)	-51	-9	0.49	Before-after with comparison group	36 intersections	New York City	(Chen et al. 2012)
Exclusive Pedestrian Phasing	Multi-Vehicle (All)	+10	-12	--	Before-after with comparison group	36 intersections	New York City	(Chen et al. 2012)
Protected Left Turn Phase	Pedestrian (All)	-45	-11	**0.57 (0.22)**	Before-after with comparison group and regression	95 intersections	New York City	(Chen et al. 2013)

Protected Left Turn Phase	All (All)	-37	-27	**0.83 (0.07)**	Before-after with comparison group and regression	95 intersections	New York City	(Chen et al. 2013)
Protected Left Turn Phase	Bicyclist (All)	-49	-23	--	Before-after with comparison group and regression	95 intersections	New York City	(Chen et al. 2013)
Protected Left Turn Phase	Multi-Vehicle (All)	-37	-30	0.88 (0.07)	Before-after with comparison group and regression	95 intersections	New York City	(Chen et al. 2013)
Protected Left Turn Phase	All (Injury & Fatality)	-38	-28	**0.86 (0.06)**	Before-after with comparison group and regression	95 intersections	New York City	(Chen et al. 2013)
Protected Left Turn Phase	All (All)	-55	--	--	Naïve before-after	9 intersections	New York City	(Chen et al. 2015)
Protected Left Turn Phase	All, left-turn crashes (All)	-77	--	--	Naïve before-after	9 intersections	New York City	(Chen et al. 2015)
Protected Left Turn Phase	Pedestrian (All)	-67	--	--	Naïve before-after	9 intersections	New York City	(Chen et al. 2015)
Protected Left Turn Phase	Bicyclist (All)	-67	--	--	Naïve before-after	9 intersections	New York City	(Chen et al. 2015)
Protected Left Turn Phase	All, opposite-direction left turn crashes (All)	-47	--	--	Naïve before-after	18 intersections	Austin	(Austin Transportation and Public Works Department 2024)
Protected Left Turn Phase	All (All)	--	--	0.3	Macro analysis	--	--	(Hauer 2004)

“Split Phasing”	Pedestrian (All)	-39	-12	**0.61 (0.15)**	Before-after with comparison group without regression	30 intersections	New York City	(Chen et al. 2013)
“Split Phasing”	Pedestrian (All)	-39	-12	0.74 (0.24)	Before-after with comparison group and regression	30 intersections	New York City	(Chen et al. 2013)
“Split Phasing”	All (All)	-50	-36	0.83 (0.12)	Before-after with comparison group and regression	30 intersections	New York City	(Chen et al. 2013)
“Split Phasing”	Bicyclist (All)	-53	-42	--	Before-after with comparison group and regression	30 intersections	New York City	(Chen et al. 2013)
“Split Phasing”	Multi-Vehicle (All)	-56	-45	0.85 (0.10)	Before-after with comparison group and regression	30 intersections	New York City	(Chen et al. 2013)
“Split Phasing”	All (Injury & Fatality)	-45	-29	0.82 (0.19)	Before-after with comparison group and regression	30 intersections	New York City	(Chen et al. 2013)
“Split Phasing”	Pedestrian (All)	-39	-8	0.61	Before-after with comparison group	30 intersections	New York City	(Chen et al. 2012)
“Split Phasing”	Multi-Vehicle (All)	-56	-44	--	Before-after with comparison group	30 intersections	New York City	(Chen et al. 2012)
Implement protected/ permissive left turn phasing	All (All)	--	--	1.0	Macro analysis	--	--	(Hauer 2004)
Implement protected/ permissive left turn phasing	Pedestrian (All)	--	--	1.091	Before-after with empirical bayes	148 intersections^	Chicago, New York City, and Toronto	(Goughnour, D. Carter, et al. 2018)

Implement protected/ permissive left turn phasing	Multi-Vehicle (All)	--	--	1.023	Before-after with empirical bayes	148 intersectionsˆ	Chicago, New York City, and Toronto	(Goughnour, D. Carter, et al. 2018)
Implement protected/ permissive left turn phasing	Multi-Vehicle (Injury & Fatality)	--	--	**0.942**	Before-after with empirical bayes	148 intersectionsˆ	Chicago, New York City, and Toronto	(Goughnour, D. Carter, et al. 2018)
Implement protected/ permissive left turn phasing	All (All)	-33	--	--	Naïve before-after	59 intersections	New York City	(Chen et al. 2015)
Implement protected/ permissive left turn phasing	Pedestrian (All)	-38	--	--	Naïve before-after	59 intersections	New York City	(Chen et al. 2015)
Implement protected/ permissive left turn phasing	All, left-turns (All)	-17	--	--	Naïve before-after	59 intersections	New York City	(Chen et al. 2015)
Implement protected/ permissive left turn phasing	Bicyclist (All)	-52	--	--	Naïve before-after	59 intersections	New York City	(Chen et al. 2015)
Prohibit RTOR	All (All)	--	--	0.984ˆ	Naïve before-after	2,042 crashes	Alabama and South Carolina	(Clark et al. 1983; NCHRP et al. 2008)

Allow RTOR	Pedestrian and Bicyclist (All)	--	--	1.69 (0.1)	Before-after with empirical bayes	--	New York State, Ohio, Wisconsin, New Orleans, Los Angeles	(American Association of State Highway and Transportation Officials 2010; Preusser et al. 1981)
Allow RTOR	Pedestrian (All)	--	--	1.57 (0.2)	Naïve before-after	--	New York State, Ohio, Wisconsin, New Orleans, Los Angeles	(American Association of State Highway and Transportation Officials 2010; Preusser et al. 1981)
Allow RTOR	Bicyclist (All)	--	--	1.80 (0.2)	Naïve before-after	--	New York State, Ohio, Wisconsin	(American Association of State Highway and Transportation Officials 2010; Preusser et al. 1981)
Allow RTOR	All, right-turn (Injury & Fatality)	--	--	1.60 (0.1)	Meta-analysis	--	--	(Elvik and Vaa 2004)
Increase Cycle Length	Pedestrian (All)	- 50 %	- 4 %	0.5	Before-after with comparison group	244 intersections	New York City	(Chen et al. 2012)
Increase Cycle Length	Multi-Vehicle (All)	- 45 %	- 37 %	--	Before-after with comparison group	244 intersections	New York City	(Chen et al. 2012)

Increase Cycle Length	Pedestrian (All)	- 50 %	- 29 %	**0.49 (0.10)**	Before-after with comparison group and regression	244 intersections	New York City	(Chen et al. 2013)
Increase Cycle Length	All (All)	- 44 %	- 44%	0.98 (0.11)	Before-after with comparison group and regression	244 intersections	New York City	(Chen et al. 2013)
Increase Cycle Length	Bicyclist (All)	- 29 %	- 41 %	--	Before-after with comparison group and regression	244 intersections	New York City	(Chen et al. 2013)
Increase Cycle Length	Multi-Vehicle (All)	- 45 %	- 47 %	1.05 (0.11)	Before-after with comparison group and regression	244 intersections	New York City	(Chen et al. 2013)
Increase Cycle Length	All (Injury & Fatality)	- 45 %	- 42 %	0.89 (0.11)	Before-after with comparison group and regression	244 intersections	New York City	(Chen et al. 2013)
Narrow roadway from four lanes to three lanes	All (All)	--	--	0.71 (0.02)	Before-after with empirical bayes	Segments	--	(Harkey et al. 2008; FHWA, n.d.-d)
Road diet (urban)	Pedestrian (All)	- 19 %	--	0.81 (0.01)	Before-after with empirical bayes	30 segments	Iowa	(Pawlovich et al. 2006)
Road diet (suburban); signal removal	Pedestrian (All)	- 24 %	--	0.53 (0.02)	Before-after with empirical bayes	199 intersections	Philadelphia	(Persaud et al. 1997)
Road diet	Pedestrian (All)	+3 %	- 18 %	1.05 (0.16)	Before-after with comparison group and regression	324 intersections	New York City	(Chen et al. 2013)

Road diet	Pedestrian (All)	- 53 %	- 4 %	0.59 (0.27)	Before-after with comparison group and regression	460 segments	New York City	(Chen et al. 2013)
Road diet	All (All)	- 2 %	- 16 %	**0.87 (0.05)**	Before-after with comparison group and regression	324 intersections	New York City	(Chen et al. 2013)
Road diet	All (All)	- 56 %	+ 25 %	**0.33 (0.07)**	Before-after with comparison group and regression	460 segments	New York City	(Chen et al. 2013)
Road diet	Bicyclist (All)	+ 6 %	- 25 %	1.21 (0.30)	Before-after with comparison group and regression	324 intersections	New York City	(Chen et al. 2013)
Road diet	Bicyclist (All)	- 100 %	- 18 %	--	Before-after with comparison group and regression	460 segments	New York City	(Chen et al. 2013)
Road diet	Multi-Vehicle (All)	- 5 %	- 16 %	**0.81 (0.10)**	Before-after with comparison group and regression	324 intersections	New York City	(Chen et al. 2013)
Road diet	Multi-Vehicle (All)	- 52 %	+ 34 %	**0.33 (0.07)**	Before-after with comparison group and regression	460 segments	New York City	(Chen et al. 2013)
Road diet	All (Injury & Fatality)	- 13 %	- 21 %	**0.83 (0.06)**	Before-after with comparison group and regression	324 intersections	New York City	(Chen et al. 2013)
Road diet	All (Injury & Fatality)	- 65 %	+ 21 %	**0.30 (0.09)**	Before-after with comparison group and regression	460 segments	New York City	(Chen et al. 2013)
Prohibit parking near intersections	Pedestrian (All)	--	--	0.7	Survey of states	--	--	(Gan et al. 2005; FHWA 2018c)

Decrease curb radius	Pedestrian (All)	--	--	see Table A2.	Regression	--	Virginia	(Federal Highway Administration et al. 2022)
Increase median width	All (All)	--	--	see Table A2.	Regression cross-section	6420 segments	Florida	(Park and Abdel-Aty 2016)
Increase median width	Bicyclist (All)	--	--	see Table A2.	Regression cross-section	6420 segments	Florida	(Park and Abdel-Aty 2016)
Presence of a Median	Bicyclist (All)	--	--	0.97	Regression cross-section	5607 site-years	Montreal, Canada	(Miranda-Moreno et al. 2011; FHWA, n.d.-d)
Install raised median	Pedestrian (All)	--	--	0.75	Survey of states	--	Kentucky, Montana	(Gan et al. 2005)
From two-way turn lane to Median	Pedestrian (All)	- 15 %	--	--	Naïve before-after	10 segments	Florida	(Alluri et al. 2016)
From two-way turn lane to Median	All (All)	- 28.5 %	--	--	Naïve before-after	10 segments	Florida	(Alluri et al. 2016)
From two-way turn lane to Median	Pedestrian (All)	- 28.9 %	--	0.711 (0.14)	Naïve before-after	18 segments	Florida	(Alluri et al. 2012; FHWA, n.d.-d)
From two-way turn lane to Median	Bicyclist (All)	- 4.5 %	--	0.955 (0.19)	Naïve before-after	18 segments	Florida	(Alluri et al. 2012; FHWA, n.d.-d)

From two-way turn lane to Median	All (All)	- 30.3 %	--	**0.697 (0.02)**	Naïve before-after	18 segments	Florida	(Alluri et al. 2012; FHWA, n.d.-d)
Pedestrian refuges	Pedestrian (All)	--	--	0.82 ($0.15^{!}$)	Meta-analysis	--	--	(Elvik and Vaa 2004)
Pedestrian refuges	Multi-Vehicle (All)	--	--	0.91 ($0.12^{!}$)	Meta-analysis	--	--	(Elvik and Vaa 2004)
Pedestrian refuges	All (All)	--	--	0.87 ($0.10^{!}$)	Meta-analysis	--	--	(Elvik and Vaa 2004)
Raised bicycle crossing for trails	Bicyclist (Injury & Fatality)	--	--	1.09^{+}	Meta analysis	--	--	(FHWA, n.d.-d; Elvik and Vaa 2004)
Raised pedestrian crossing	Pedestrian (Injury & Fatality)	--	--	0.55	Meta analysis	--	--	(FHWA, n.d.-d; Elvik and Vaa 2004)
Raised pedestrian crossing	All (Injury & Fatality)	--	--	0.55	Meta analysis	--	--	(FHWA, n.d.-d; Elvik and Vaa 2004)
Raised pedestrian crossing	Pedestrian (Injury & Fatality)	--	--	0.51	Meta analysis	--	--	(Elvik and Vaa 2004)
Raised pedestrian crossing	Multi-Vehicle (Injury & Fatality)	--	--	0.67	Meta analysis	--	--	(Elvik and Vaa 2004)
Raised pedestrian crossing	All (Injury & Fatality)	--	--	0.61	Meta analysis	--	--	(Elvik and Vaa 2004)
Raised pedestrian crossing	All (All)	--	--	0.7 (0.67)	Unpublished	--	--	(Bahar et al. 2007; 2008)

Raised bicyclist crossing	Bicyclist (All)	--	--	**0.49 (0.11)**	Regression cross-section	852 site-years	Netherlands	(Schepers et al. 2011)
Colored bicycle lanes	Bicyclist (All)	- 44 %	- 4 %*	0.61	Before-after with comparison group	38 approaches	New Zealand and Australia	(Turner et al. 2011)
Install intersection lighting	Pedestrian (All)	--	--	0.3	Regression cross-section	--	The Netherlands	(Wanvik 2009)
Install intersection lighting	Bicyclist (All)	--	--	0.4	Regression cross-section	--	The Netherlands	(Park and Abdel-Aty 2016)
Install intersection lighting	Pedestrian (Fatality)	--	--	0.19 (0.28)	Meta-analysis	--	--	(FHWA, n.d.-d; Elvik and Vaa 2004)
Install intersection lighting	Pedestrian (Injury)	--	--	0.41 (0.20)	Meta-analysis	--	--	(FHWA, n.d.-d; Elvik and Vaa 2004)
Install intersection lighting	Pedestrian, nighttime (Fatality)	--	--	0.22 (0.87)	Meta-analysis	--	--	(FHWA, n.d.-d; Elvik and Vaa 2004)
Install intersection lighting	Pedestrian, nighttime (Injury)	--	--	0.58 (0.18)	Meta-analysis	--	--	(FHWA, n.d.-d; Elvik and Vaa 2004)
Install intersection lighting	All (Fatality)	--	--	0.23 (0.28)	Meta-analysis	--	--	(FHWA, n.d.-d; Elvik and Vaa 2004)
Install intersection lighting	All (Injury)	--	--	0.50 (0.21)	Meta-analysis	--	--	(FHWA, n.d.-d; Elvik and Vaa 2004)
Install intersection lighting	All, nighttime (Injury)	--	--	**0.62 (0.13)**	Meta-analysis	--	--	(FHWA, n.d.-d; Elvik and Vaa 2004)

Install intersection lighting	Pedestrian (All)	--	--	0.56	Regression cross-section	330 site-years	--	(Ye et al. 2008; FHWA, n.d.-d)

Note: bold indicates a statistically significant CMF at the 5% level. "--" indicates that there was no data provided in the study.
[+]some studied intersections were unsignalized

Table A.2. CMFs for increasing corner radius on pedestrian crashes, based on a baseline 10 ft corner radius (Federal Highway Administration et al. 2022).

Corner Radius (ft)	CMF	CMF Standard Error Range
10	1.00	--
20	1.18	1.03 - 1.35
30	1.30	1.05 - 1.61
40	1.39	1.06 - 1.83
50	1.47	1.07 - 2.01
60	1.53	1.08 - 2.18
70	1.59	1.08 - 2.33

Table A.3. CMFs for increasing median width on bicyclist crashes, based on a baseline 10 ft median width (Park and Abdel-Aty 2016).

Median Width (ft)	CMF for All Crashes (Std. Error)	CMF for Bicyclist Crashes (Std. Error)
10	1.000 (--)	1.000 (--)
20	0.953 (0.015)	0.867 (0.025)
30	0.908 (0.029)	0.751 (0.032)
40	0.866 (0.042)	0.651 (0.045)
50	0.825 (0.053)	0.564 (0.056)

Appendix B. Signal Timing Equations

The following equations were used to calculate the cycle length and phase times. Yellow and all red times are derived from Herman's equations and the equations recommended by ITE. Webster's equation is used to optimize cycle length.

Yellow times

$$y = t + \frac{1.47\ S_{85}}{2a + 64.4\ (.01\ G)}$$

All red times

$$ar = \frac{w + L}{1.47\ S_{15}}$$

Cycle length

$$C_0 = \frac{1.5\ (\sum_{i=1}^{n} y_i + \sum_{i=1}^{n} ar_i) + 5}{1 - \sum_{i=1}^{n} b_i}$$

Green times

$$G_i = \left(C - \sum_{i=1}^{n} y_i\right) \frac{N_i}{\sum_{i=1}^{n} N_i}$$

Minimum cycle length for pedestrian crossing

$$C_{ped} = \left(5 + {}^{w_1}\!/_{r}\right) + \left(5 + {}^{w_2}\!/_{r}\right)$$

where:

t is the perception reaction time, assumed to be 1 second in this case

S_{85} is the 85th percentile approach speed in mph, estimated as mean speed + 5 mph

S_{15} is the 15th percentile approach speed in mph, estimated as mean speed - 5 mph

a is the deceleration rate in ft/s^2, assumed to be 10 in this case

G is the approach grade as a percent, assumed to be 0 in this case

w is the distance from the departure stop line to the far side of the farthest conflicting lane, in feet. 80 ft for the major and minor streets for our 2 lane each direction with no turn lane geometry.

L is the length of a standard vehicle, assumed to be 19 feet

n is the number of phases

N_i is the critical lane flow for phase i

b_i is the ratio of critical lane flow to saturation flow for phase i, where saturation flow is assumed to be 1900 vph. Left-turning traffic is weighted by a factor of 2, 2.8, or 6 depending on opposing volumes while right-turning traffic is weighted by a factor of 1.4. straight-through traffic is assumed to be split 50/50 in each lane at the moment.

Appendix C. TxDOT Value of Research Template

Project #	25-018 0-7209		
Project Name:	Develop Guidance for Sustaibable Traffic Signal Operation Strategies to Support All Intersection Users		
Agency:	Center for Tran. Research	Project Budget	$ 194,160
t Duration (Yrs)	1.0	Exp. Value (per Yr)	$ 46,500
Expected Value Duration (Yrs)	10	ed Discount Rate	3%

Economic Value

Total Savings:	$ 270,840	Net Present Value (NPV):	$ 385,101
Payback Period (Yrs):	4.175485	Cost Benefit Ratio (CBR, $1 : $___):	$ 2

Years	Expected Value
0	$0
1	$46,500
2	$46,500
3	$46,500
4	$46,500
5	$46,500
6	$46,500
7	$46,500
8	$46,500
9	$46,500
10	$46,500

Notes:

Amounts on Value of Research are estimates.

Project cost should be expensed at a rate of no more than the expected value per year.

This electronic form contains formulas that may be corrupted when adding or deleting rows, by variables within the spreadsheet, or by conversion of the spreadsheet. The university is responsible for the accuracy of the Value of Research submitted.

Years	Expected Value	Expected Value	Expected Value	NPV
0	$0	$0	$0.00	$0.00
1	$46,500	$46,500	$0.05	$0.04
2	$46,500	$93,000	$0.09	$0.09
3	$46,500	$139,500	$0.14	$0.13
4	$46,500	$186,000	$0.19	$0.17
5	$46,500	$232,500	$0.23	$0.21
6	$46,500	$279,000	$0.28	$0.24
7	$46,500	$325,500	$0.33	$0.28
8	$46,500	$372,000	$0.37	$0.32
9	$46,500	$418,500	$0.42	$0.35
10	$46,500	$465,000	$0.47	$0.39

	Project #	0-7209				
	Project Name:	Develop Guidance for Sustainable Traffic Signal Operation Strategies to Support All				
	Agency:					
	Variable Amounts					
Economic Benefit Area	#1	#2	#3	#4	#5*	Totals
Expedited Project Delivery	Time TxDOT saves	Time Users save				$ -
Materials and Pavements	1/3 of base matterial per mile					$ -
Intelligent Transportation Systems	Decrease call volume to HERO/911	Traffic flow will increase by 50%				$ -
Safety	Save lives, reduce number of injuries		$ 21,372,000.00			$ 21,372,000.00
					Total	$ 21,372,000.00

Project Statement	This project's findings have the potential to significantly impact the way TxDOT approaches traffic signal operations within Complete Street proj
Title	Develop Guidance for Sustainable Traffic Signal Operation Strategies to support All Intersection Users

Selecte	Benefit Area	Qualitative	Economic	Both	TxDOT	State	Both	Definition in context to the Project Stateme
x	Level of Knowledge	X			X			
	Management and Policy	X			X			
X	Quality of Life	X			X			
	Customer Satisfaction	X			X			
x	Environmental Sustainability	X				X		
x	System Reliability		X		X			
	Increased Service Life		X		X			
	Improved Productivity and Work Efficiency		X		X			
	Expedited Project Delivery		X		X			
	Reduced Administrative Costs		X		X			
x	Traffic and Congestion Reduction		X			X		
	Reduced User Cost		X			X		
	Reduced Construction, Operations, and Maintenance Cost		X			X		
	Materials and Pavements		X			X		
	Infrastructure Condition		X				X	
	Freight movement and Economic Vitality		X				X	
X	Intelligent Transportation Systems		X				X	
x	Engineering Design Improvement			X			X	
X	Safety			X			X	