Safety Evaluations of Innovative Intersection Designs for Pedestrians and Bicyclists

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FOREWORD

The research documented in this report was conducted as part of the Federal Highway Administration's (FHWA's) Evaluation of Low-Cost Safety Improvements Pooled Fund Study (ELCSI-PFS). FHWA established this Pooled Fund Study (PFS) in 2005 to conduct research on the effectiveness of safety improvements identified by the *National Cooperative Highway Research Program Report 500* guides as part of the implementation of the American Association of State Highway and Transportation Officials' *Strategic Highway Safety Plan*. ELCSI-PFS studies provide a crash modification factor and benefit–cost economic analysis for each targeted safety strategy identified as a priority by member States of the PFS.

The objective of this FHWA project was to investigate the operational and safety improvements of innovative intersection retrofitting designs that benefit pedestrians and bicyclists, while maintaining a reasonable service to motor vehicles. These designs are also called protected intersections, and that is the term used in this document. The project summarizes previous research efforts, develops three design types, identifies potential study sites (both before-after and comparison-existing pairs), and collects in-field operational behaviors of the users. This report details the method and results of this study.

This report may be of interest to transportation practitioners, those conducting transportation safety research, industry professionals, and those working to improve transportation safety.

Brian P. Cronin, P.E.
Director, Office of Safety and Operations
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The protected intersection is a type of innovative intersection design. Traffic professionals are exploring protected intersections to determine if they can successfully accommodate multimodal transportation by reducing conflicts between moving vehicles and vulnerable users (VU) or by lowering the impact force (reducing the vehicle speed and changing the collision angle in the event of a collision). For this Federal Highway Administration project, data were collected at 6 intersections both before and after the treatment was installed (for 12 site periods), at 14 intersections where the treatment was present (representing 14 site periods), and at 4 intersections where the treatment was not present (termed comparison sites and representing 4 site periods). Technicians recorded behaviors for 23,505 VU at these 30 site periods. Drivers yielded to bicyclists and pedestrians more at the treated sites compared to the untreated sites. For bicyclist crossings, 38 percent of the crossings for treated sites compared to 34 percent for untreated sites involved a vehicle yielding to the bicyclist. For pedestrian crossings, the comparison is 23 percent for treated sites compared to 16 percent for untreated sites. The protected intersection treatment is designed to slow turning vehicles and provide drivers additional opportunity to see the crossing VU. The addition of the treatment at three of the before-after sites with traffic control signals resulted in more frequent yielding by drivers to pedestrians (41 percent in the before period to 47 percent in the after period). Right-turn speeds are higher at a larger corner radius. Reducing the corner radius with the installation of the treatment resulted in a decrease in the speed of right-turning vehicles. Prediction equations were generated, and for a corner changed from a 60-ft radius to a 25-ft radius, a decrease in speed of about 2.6 mph is predicted. Including truck aprons can facilitate the turning of large vehicles while also encouraging smaller radius turns for right-turning vehicles.</td></tr>
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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1,000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2,000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2,000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	2.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

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LIST OF ABBREVIATIONS

ASL	advanced stop line
AUS	Austin
BER	Berkeley
CB	crossbike
CST	College Station
CW	crosswalk
ELCSI-PFS	Evaluation of Low-Cost Safety Improvements Pooled Fund Study
e-scooter	electronic scooter
FHWA	Federal Highway Administration
FRE	Fremont
MassDOT	Massachusetts Department of Transportation
MUTCD	Manual on Uniform Traffic Control Devices for Streets and Highways
NACTO	National Association of City Transportation Officials
NCHRP	National Cooperative Highway Research Program
NPA	Notice of Proposed Amendments
PFS	pooled fund study
PSL	posted speed limit
RBL	receiving bicycle lane
RPL	receiving parking lane
RVL1	receiving vehicle inside lane
RVL2	receiving vehicle middle lane
RVL3	receiving vehicle outside lane
SLC	Salt Lake City
SSP	Silver Spring
Veh	vehicle
VU	vulnerable users
WAS	Washington, DC

CHAPTER 1. INTRODUCTION

BACKGROUND

Many transportation agencies are increasing their emphasis on improving pedestrian and bicyclist safety and reducing the risk of a fatality or serious injury to these users. A wide variety of treatments and countermeasures have been conceived and implemented across the country in recent years. Some of them, such as the pedestrian hybrid beacon and median refuge islands, have had documented benefits so positive that they have been included in the Federal Highway Administration's (FHWA's) Proven Safety Countermeasures.[(1)] However, not all treatments are associated with such comprehensive results, and many have not had a thorough evaluation with respect to safety.

Recently, traffic professionals have conceived and implemented certain innovative intersection designs aimed at accommodating multimodal transportation, reducing conflicts between moving vehicles and vulnerable users (VU), and lowering the impact force (reducing vehicle speed and changing collision angle in the event of collision). In concept, these designs should improve conditions for pedestrians and bicyclists; however, studies that document the changes and potential benefits are not yet available. The goal of this FHWA project is to address this gap.

At intersections, roadway design elements have long sought to minimize delay to motorized traffic. However, to minimize exposure and improve safety for VU, a paradigm shift in roadway design is required, where features emphasize slower speeds and improved visibility between the motorist and VU. Traffic professionals are developing a variety of potential innovative intersection treatments that accomplish this paradigm shift, and have recently installed those treatments or planned for their installation. The number of intersections with existing or planned installations of these features presents an opportunity to investigate the benefits and tradeoffs of these designs. Assessments of these treatments should consider the specific intersection's geometric configuration, the approach cross section (e.g., number of lanes, presence and width of median, presence of onstreet parking, bicyclist lane width, presence of bicyclist lane buffer), changes in user demand, and interaction among pedestrians, bicyclists, and motor vehicles at intersecting points.

The evolving pedestrian- and bicyclist-centered infrastructure improvements have typically originated in urban centers seeking to encourage nonmotorized transportation to reduce congestion and emissions as well as encourage active lifestyles for citizens. These designs can be characterized by the level of exposure for the VU, such as the following categories used in the FHWA bikeway selection guide:[(2)]

- High exposure level: Conventional bicycle lanes and shared lanes.
- High-to-medium exposure level: Separated bicycle lanes with mixing zones.
- Medium-to-low exposure level: Separated bicycle lanes through roundabouts.
- Low exposure level: Protected intersections.

Even where progress toward improving safety for VU along a corridor has occurred, the benefits of those treatments along the corridor may not be fully realized when discontinued at intersections. Therefore, traffic professionals are developing, installing, and refining treatments to continue the benefits through the intersection. As an example, traffic professionals are modifying corner islands and turning paths to force vehicles further into an intersection before making a turning maneuver. This treatment has recently been incorporated into an FHWA university course module for intersection design.(3)

Several names are used for these types of intersections, including the term innovative intersections. In the broad category of innovative intersections are designs and concepts being used and discussed in other documents. For example, the National Association of City Transportation Officials (NACTO) is using the terms protected intersection and dedicated intersections.(4) In some international literature, these intersections are referred to as Dutch intersections or Dutch-style junctions. In all cases, the design attempts to establish and enhance physical separation between pedestrians, bicyclists, and motorists through the intersection. This report uses the term protected intersection.

PROJECT OBJECTIVE

The objective of this FHWA project was to investigate the operational and safety improvements of innovative intersection retrofitting designs that benefit pedestrians and bicyclists while maintaining a reasonable level of service to motor vehicles.

STUDY APPROACH

The approach used in this study included the following steps:

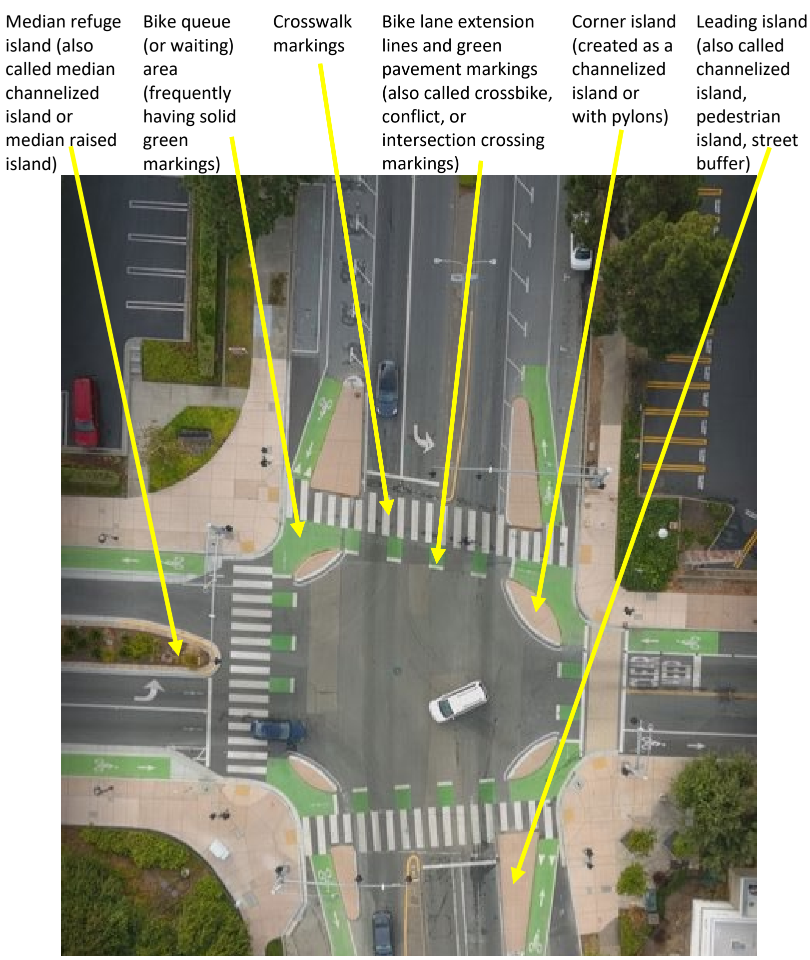
- Conduct a synthesis of the innovative intersection retrofitting designs that benefit pedestrians and bicyclists while maintaining a reasonable level of service to motor vehicles.
- Select two to three designs for formal evaluations and develop design templates for these designs.
- Identify State and local agencies that are planning to install such designs and conduct in-field before-after data collection.
- Identify existing and comparison sites—when sufficient before-after sites are not available due to timing of this study—and gather in-field operational behaviors of the users.
- Develop a half-day training course for the evaluated designs, and conduct an instructor-led pilot training for a class of 25 or more participants from Federal, State, and local agencies.

CHAPTER 2. LITERATURE

TERMS

Several terms are used to describe treatments added at intersections that benefit pedestrians and bicyclists while also maintaining a level of service to motor vehicles. FHWA used the term innovative intersections to cover several novel intersection designs, including the designs studied in this project. NACTO uses the terms protected intersection or dedicated intersection, while others use the term Dutch intersection or Dutch-style junction. This report uses the term protected intersection.

Figure 1 summarizes some of the terms used for features associated with the protected intersections studied in this project. The following sections use terms commonly found in the literature or terms identified by the research team.



Source: FHWA.

Figure 1. Photo. Terms associated with the features of a protected intersection.

OVERVIEW OF THE PROTECTED INTERSECTION CONCEPT

Protected intersections include features to separate bicyclists from motor vehicle traffic for a portion of the intersection, using physical elements (e.g., raised curbs, bollards, pylons). Because of the newness of this design concept, only a few studies in the literature have focused on the design. More studies are available that focus on features being incorporated into the protected intersection. In this literature review chapter, the term used to describe the intersection or feature will be the term provided by the authors; however, this report will also provide alternative terms.

In 2020, Lyons et al. documented a before-after case study of a protected intersection in Salt Lake City, UT.[(5)] They collected data in 2015 (before) and 2016 and 2018 (two after periods). The intersection was completed in late 2015 and represented one of the first examples of a protected intersection design in North America. They found that active transportation usage increased, with most of the growth attributed to electronic scooter (e-scooter) users. The authors identified nonoptimal behaviors, such as disobeying a signal or crossing outside of the crosswalk, and found a minimal change in the rates of nonoptimal behaviors by pedestrians and a decreased rate for bicyclists. E-scooter users, however, demonstrated nonoptimal behaviors at very high rates compared with other active transportation modes.

KEY REFERENCE DOCUMENTS

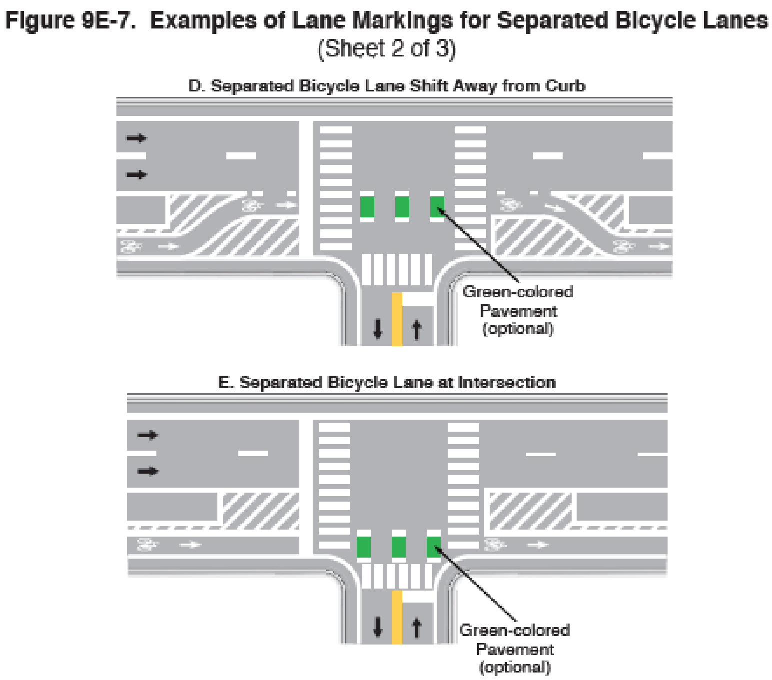
The *Manual on Uniform Traffic Control Devices for Streets and Highways* (MUTCD) is the key reference document for signing and markings for bicyclist treatments.[(6)] The current edition of the MUTCD is the 11th edition. A comprehensive update to the 11th edition of the MUTCD is ongoing at the time of the writing of this report. The Notice of Proposed Amendments (NPA) was released on December 14, 2020, and public comments were allowed. In developing the NPA, FHWA considered the results of official experiments, official interpretations, interim approvals, and other research. The NPA closed public comment in the *Federal Register* on May 14, 2021, after receiving more than 17,000 entries comprising over 35,000 individual comments.[(7)] The update to the MUTCD may contain several changes for bicycle facilities, including green colored pavement to add conspicuity to bicycle-only facilities.

In an FHWA memorandum released on January 5, 2017, the following information was provided regarding bicycle lane extension markings through intersections:

> Extensions of bicycle lanes are compliant with the MUTCD and can be marked as would be an extension of any other lane. The provisions of [MUTCD] Section 3B.08 - Extensions Through Intersections or Interchanges - apply to bicycle lanes. Among other guidance, Section 3B.08 states that "Where highway design or reduced visibility conditions make it desirable to provide control or to guide vehicles through an intersection or interchange... dotted line extension markings consisting of 2-ft line segments and 2- to 6-ft gaps should be used to extend longitudinal line markings through an intersection or interchange area." It should be noted that chevron markings are not permitted to be used in bicycle lanes or bicycle lane extensions, nor are shared-lane markings. Bicycle lane extensions through intersections can include standard bicycle lane arrows, bicycle symbols, or pavement word markings. Additionally, green-colored

pavement can be used to enhance conspicuity if the installing jurisdiction has received approval under Interim Approval 14.[8]

The proposed revision to the MUTCD includes several anticipated changes to bicyclist signing and markings.[9] One of the changes includes examples of lane markings for separated bicycle lanes. Figure 2 is one example. The markings in the intersection are labeled as “green-colored pavement (optional)” in figure 2 and are known as bicycle lane extension lines and green pavement markings. They are also called crossbike, conflict, or intersection crossing markings.



Source: FHWA.

Figure 2. Illustration. Proposed revision to MUTCD.[9]

Several other key pieces of literature in the United States discuss protected intersections, including on the public side the NACTO document entitled *Don’t Give Up at the Intersection,* the Massachusetts Department of Transportation (MassDOT) document *Separated Bike Lane Planning & Design Guide,* and the *Seattle Right-Of-Way Improvement Manual* section on Bike Intersection Design.[4,10,11] One of the major contributions from the private side is the document *Lessons Learned: Evolution of the Protected Intersection.*[12,13] Collectively, these documents identify 11 features of protected intersections, overlapping on several.

NACTO discusses two intersection design types: protected intersections and dedicated intersections. Their document, *Don’t Give Up at the Intersection,* provides illustrations of these two intersection forms.[4]

Key features of a protected intersection are illustrated in figure 1 and are described in the following section.

SPECIFIC FEATURES

The following sections discuss features of the protected intersection.

Corner Island

The corner island (sometimes referred to as a corner refuge island) is a raised area that separates the bicycle lane from the motor vehicle lane and is the defining feature of the innovative (protected) intersection concept, without which the other elements could not be used.[4,6] For example, the pedestrian islands, bikeway setback, and bicycle queuing area are only possible due to the presence of the corner island. If necessary, the corner island can be coupled with a corner apron to accommodate off-tracking by larger vehicles.[12,14]

Bicycle Queue Area

Bicyclists queue adjacent to the corner island and pedestrian refuge island, closer to the intersection. A forward stop bar is located near the curb to indicate to bicyclists where to wait to cross the intersection.[12] The design reduces bicyclists' crossing distance and creates a physical leading interval for bicyclists and pedestrians.[15]

Bicycle Yield Line for Pedestrians Crossing Bicycle Lane

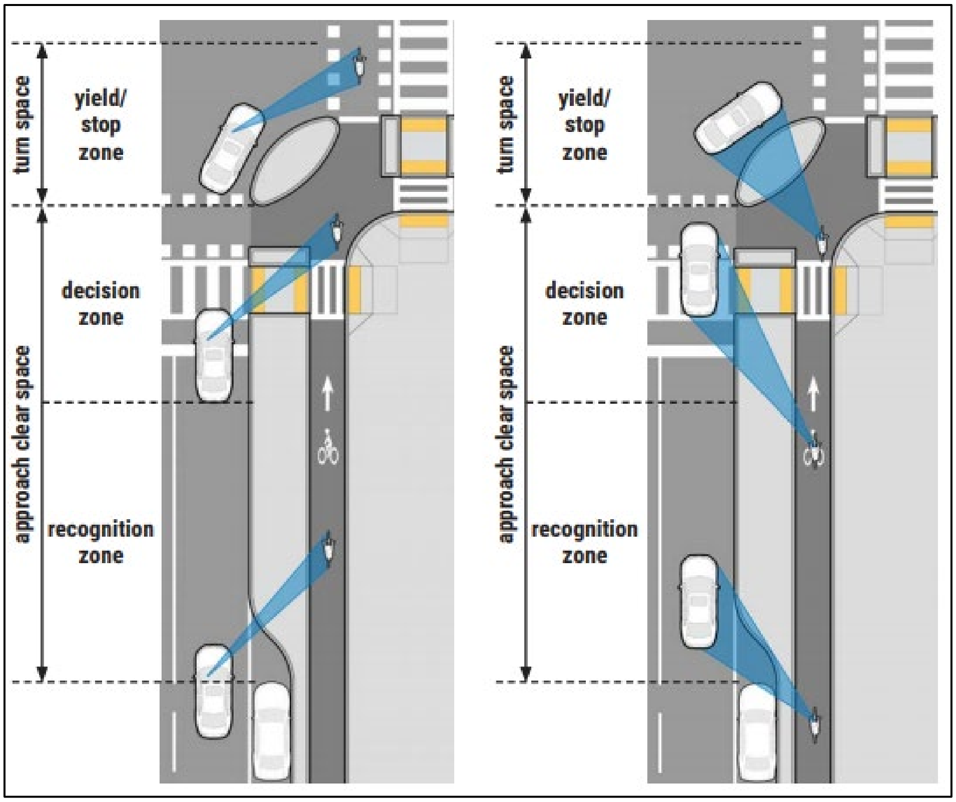
The intersection design calls for separate facilities for pedestrians, bicyclists, and motorized traffic. Consequently, conflict points for the nonmotorized traffic modes exist. NACTO indicates that bicycle yield markings are optional, depending on local policy.[4] MassDOT echoes this guidance, stating on page 71 of the *Separated Bike Lane Planning & Design Guide* that, "Yield lines in the bicycle lane in advance of the pedestrian crosswalk are typically used to emphasize pedestrian priority."[10]

Leading Island (Also Called Channelized Island, Pedestrian Island, and Street Buffer)

The distance from the edge of the bicycle lane to the edge of the motor vehicle traveled way defined by the corner island creates a buffer. The area where the pedestrian crosswalk intersects this buffer area provides space for pedestrians (sometimes called a pedestrian island or leading island). This space shortens the pedestrian crossing distance.[4,10,13]

No Stopping or No Standing Zone

MassDOT refers to space where there should not be any parking or drop-off zones because stopped vehicles would block the sight lines between motorists in the travel lane and bicyclists in the bicycle lane as a "decision zone." This space is part of a larger segment of the roadway called the "approach clear space." Prohibiting traffic from stopping in the area near the intersection (generally about 20 to 30 ft) is relatively common; however, MassDOT notes that the distance should reflect the multimodal nature of the intersection when the design is used.[10] By keeping this area free of parked vehicles, the bicyclists and motorists are provided with time to see one another and make modifications to their speed or yielding behavior that is necessary to facilitate both road users safely navigating the intersection.



Public domain illustration courtesy of MassDOT, 2015.

Figure 3. Illustration. MassDOT graphic on right-turning motorist and through bicyclist yielding behavior in the approach clear space.[(10)]

Bicycle Lane Extension Lines and Green Pavement Markings (Also Known as Crossbike, Conflict, or Intersection Crossing Markings)

The bicycle lane extension lines and green pavement markings serve the purpose of delineating bicycle space through the area of the intersection used by motor vehicles. These markings have also been referred to as crossbike markings in NACTO's *Don't Give Up at the Intersection*.[(4)] According to the NACTO *Urban Bikeway Design Guide*, the bicycle lanes should typically use solid white lines except in areas of conflict with motor vehicles, where dashed lines are used.[(16)] These markings can be supplemented with solid color in the conflict area, dashed color in the conflict area, or solid color outside of the conflict area.

Bikeway Setback

The bikeway setback is used to make it easier for drivers to see bicyclists and pedestrians.[(4)] The use of an approach taper has been identified in the existing literature, though not explicitly identified as a key feature in several documents.[(12)] NACTO describes the feature as a variation to the design.[(4)] Effectively, this treatment creates a bend-out and bend-in as the bicycle lanes approach and depart the intersection and was observed by the research team during a review of existing sites. This bend-out, bend-in technique, which is discussed as a general treatment in the Bend-Out Bend-In section, creates an alignment change as bicyclists approach the intersection. This alignment change can be used to separate a bicycle lane from motor vehicle traffic at the intersection, which facilitates the use of the intersection concept, particularly the bikeway setback, on bicycle lanes that are not separated at the corridor level. Another potential beneficial application of this technique is to create a speed calming effect, reducing bicyclist speed in areas of potential conflict with pedestrians.

Motorist Waiting Zone/Motorist Yield Zone

In this intersection design, the corner island causes the bicycle lane extension lines (also known as crossbike) and crosswalk locations to be offset from parallel vehicle traffic. This area of the intersection immediately adjacent to the corner island where right-turning motorists must wait for crossing bicyclists and pedestrians is called the motorist waiting zone.(4,10) MassDOT's *Separated Bike Lane Planning & Design Guide* points to literature that indicates a setback of 6 to 16 ft can have crash reduction benefits.(10)

Pedestrian Curb Ramp

The ultimate goal of the protected intersection design is to prioritize the safety and mobility of nonmotorized users. To this end, MassDOT indicates that ramps and detectable warning surfaces that are compliant with the Americans with Disabilities Act of 1990 should be used when transitioning from the sidewalk elevation to the roadway elevation.(10)

Signal Operations

Traffic signal operations are specifically called out by Gilpin et al. as one of the critical elements of protected intersection design.(12) The report by Gilpin et al. also emphasizes three principals of signalization previously outlined in NACTO's *Urban Street Design Guide*: short cycle lengths, a minimal number of phases, and bicycle-compatible signal progression.(17)

Alternative for Intersection with Geometric Constraints

NACTO discusses a design called a dedicated intersection that can be used when geometric constraints prevent a bicycle lane at an intersection from being set back as much as for the protected intersection design.(4) Like the NACTO protected intersection design, the crux of the dedicated intersection is the reduction of vehicle turning speeds. An overview of a dedicated intersection is shown in NACTO's *Don't Give Up at the Intersection*.(4)

Corner Wedge and Speed Bump

A corner wedge rather than a corner island is applied at a smaller scale in the dedicated intersection as opposed to the protected intersection. The use of a modular speed bump extends the curb further into the intersection, preventing high-speed turns and increasing driver yielding.(4)

Crosswalk Separator

The crosswalk separator is placed to discourage motorists from trying to cut through the pedestrian and bicyclist space created by the corner wedge.(4) Its functionality is similar to the pedestrian island (also called a leading island in figure 1) used in the protected intersection.

Centerline Hardening

Modular curbs are used with or without post-mounted delineators. Similar to the corner wedge, this design element is intended to force vehicles further into the intersection before beginning their turn so they make their turn at a lower speed.[(4)]

Bicycle lane Line Extensions (Also Known as Crossbike)

The pavement markings through the intersection are similar in concept to those of the protected intersection. The most notable difference is that bicyclists queue before crossing the pedestrian crosswalk rather than after crossing it.[(4)]

Buffer or Curb

The buffer or curb is similar in purpose to the pedestrian island (also called a leading island in figure 1) in the protected intersection. This design feature allows pedestrians to prepare to cross the intersection near the curb and separates bicyclists from motor vehicle traffic on the approach.[(4)]

RELEVANT FEATURES

A significant amount of literature, including FHWA's *Separated Bike Lane Planning and Design Guide*, presents designs and principles that can be used as standalone treatments at intersections, or in concert with a suite of other treatments at protected intersections.[(18)] An overview of the application and effectiveness of these treatments as standalone treatments is provided in the following section.

Mixing Zone and Fully Split-Phase Signals

Mixing zones and split-phase signals represent two distinct treatments. This section compares and contrasts the two designs. A mixing zone is formed when a dedicated bicycle lane stops (typically 110 ft from the crosswalk), forcing bicyclists and right-turning vehicles to share the same lane.[(18)] A fully split-phase signal requires dedicated space and signal time for motor vehicles and for bicycles.[(19)] Dedicated signals have been shown to be preferred to a number of other treatments.[(16)]

On the pedestrian side, Zhang et al. found that at exclusive phasing intersections, pedestrians crossing on the walk signal experienced lower interaction severity compared to those crossing at sites with concurrent phasing.[(20)] Additionally, pedestrians crossing concurrently when dedicated crossing time was available experienced higher interaction severity.[(20)] Intersections with concurrent phasing have fewer total pedestrian crashes than those with exclusive phasing (but the crashes that do occur tend to be more severe.)[(20)] The authors of the study felt that exclusive pedestrian signal time was only beneficial when pedestrians actually wait for the walk signal, and they recommended that dedicated pedestrian phasing be used only where compliance was high.

A paper by Sundstrom, Quinn, and Weld investigated the safety performance of mixing zones relative to fully split-phase signal treatments on protected bicycle lanes in New York, NY.(19) The results of that analysis indicated that shorter mixing zones are more effective than fully split-phase signal treatments at high-turn-volume locations, that mixing zones are equally effective at reducing bicycle crashes as fully split-phase signal treatments at low-turn-volume intersections, and that shorter mixing zones are more effective than longer mixing zones across all intersections.(19)

Monsere et al. examined the use of mixing zones on protected bicycle lanes.(21) The research team found a clear benefit to the restricted entry of vehicles into the turning lane based on 87-percent compliance of motorists and 91-percent compliance of bicyclists. Furthermore, the researchers found that mixing zones with yield markings had 93-percent turning vehicle compliance but only 63 percent of bicyclists correctly used the mixing zone when a car was present, indicating that bicyclists may benefit from a through bicycle lane or hatching.(21) Finally, Monsere et al. found that 1 percent to 18 percent of turning vehicles at mixing zones turn from the wrong lane.(21)

Research in Japan by Rahimi, Kojima, and Kubota examined five intersection safety treatments for safety and comfort: mixed traffic with left-turning motorist, left-turn in the intersection for motorist, bicycle signal, advanced stop lines (ASLs), and bicycle boxes.(22) Using a closed-course study, the researchers found that mixed traffic with left-turning motorists (i.e., a mixing zone) was the safest in terms of conflicts and in terms of the number of bicyclists entering the intersection from the blind spot of a motorist, while bicycle signals are the most comfortable design for bicyclists.

Bicycle Box and ASL

The aforementioned study by Rahimi, Kojima, and Kubota examined additional intersection treatments beyond the signal and mixing zone that were previously discussed.(22) Two of those treatments include the ASL and the bicycle box. A bicycle box is a designated area at the head of a traffic lane providing a safe, visible area for bicyclists ahead of queuing traffic.(16) An ASL positions the stop bar for motor vehicles further from the intersection than the stop bar for bicyclists, thus allowing the bicyclist to be positioned in view of the motorist and get a head start on crossing the street.(22)

Ohlms and Kweon found that bicycle boxes installed on two legs of an intersection in Charlottesville, VA, had proper use rates of 46 and 24 percent and improper use rates of 40 and 10 percent.(23) A Portland, OR, study by Dill, Monsere, and McNeil found that 73 percent of stopping vehicles did not encroach on the box.(24) Additionally, the researchers found decreased encroachment of the pedestrian crosswalk by motorists and bicyclists, mixed results on motorist encroachment into the bicycle lane, and decreased conflicts observed as the volume of turning motorists and bicyclists increased. Both drivers and bicyclists perceived the treatment as making an intersection safer.

In a United Kingdom-based report, Wall, Davies, and Crabtree found that moving the motor vehicle stop line back did not impact intersection capacity or require signal retiming and was perceived favorably by survey respondents.(25) Moreover, the study found that bicyclist behavior at study locations (which the researchers noted had low bicyclist volume) did not impact intersection capacity. The study termed the design sites as ASLs, but since bicyclists queuing was allowed directly in front of the motor vehicles, the design seems to be more of a bicycle box.(25)

Additional research in the United Kingdom by Allen, Bygrave, and Harper looked at ASLs in the London metro area.(26) Again, the study uses ASL to describe what appears to be a bicycle box, potentially pointing to the evolving nature of treatment terminology. The researchers found that only 1 percent of bicyclists were involved in conflicts, and only 0.1 percent were involved in serious conflicts. Proper behavior of bicyclists and motorists was not always observed. For example, bicyclists were obstructed 1 percent to 10 percent of the time.(26) On the bicyclist side, bicyclists waited in the correct spot 38 percent of the time. The study examined the effect of the placement of feeder lanes to allow bicyclists to reach the ASL (bicycle box). Curbside feeder lanes were used 87 percent of the time, while bicyclists were observed riding curbside 77 percent of the time when no feeder lane was present, and feeder lane use dipped to 52 percent when the lane was centrally located.(26) The study team observed that bicyclists positioned themselves in front of motor vehicle traffic 78 percent of the time at treatment sites, versus 54 percent of the time at control sites.(26) One adverse effect of the treatment was that 17 percent of bicyclists violated red lights at ASL sites versus 13 percent at non-ASL sites. Another London study, this one by Atkins Services, found that relatively few bicyclists used the bicycle boxes in the intended manner, with about only 25 percent waiting in the bicycle box during the red signal and the rest crossing the intersection during the red phase.(27)

A bicycle box in Eugene, OR, on a one-way street with a left-side feeder lane was studied by Hunter.(28) After passing through the intersection, bicyclists could move to either a left-side or a right-side bicycle lane on the far side. The installation of the bicycle box reduced the proportion of bicyclists who would cross the intersection on the left side and then weave through traffic to get to the right lane from 53 to 35 percent.

Two-Stage Crossing

The two-stage crossing provides bicyclists the opportunity to make left turns at multilane intersections from a right-side bicycle lane by locating a queue box in front of far-side crossing traffic.(16) However, evidence in the literature suggests that the design may be confusing or inconvenient for bicyclists. Ohlms and Kweon studied the use of the design in Charlottesville, VA, and found that the design was improperly used 57–100 percent of the time and associated with a 290-percent increase in prohibited left turns.(23)

Pedestrian Refuge Island

The technique of using multiple stages to provide a crossing can also be applied to pedestrians' through movements on boulevards where median islands provide a pedestrian refuge. A study by Kang in New York, NY, found pedestrian refuge islands to be effective at reducing the rate of postproject pedestrian collisions.(29) A Chinese study by Cao, Ni, and Li found that the perception of safety by pedestrians is increased with the presence of a refuge island and that the perception increased as the width of the refuge island increased. However, this perceived safety may influence pedestrians to violate a traffic signal to complete the first part of the crossing.(30)

Hummer et al. found that a two-stage Barnes Dance is an effective pedestrian crossing design for high-volume superstreet intersections.(31) Furth and Wang indicated that more than two stages can be used if enough pedestrian refuge islands are present.(32)

Despite the advantages, challenges exist due to climatic issues. For example, Li and Fernie conducted an observational study in Toronto, Canada, and found that mean walking speed increases as temperature decreases in winter and pedestrians are more likely to walk against flashing or steady Don't Walk signals in uncomfortable weather.(33) Consequently, pedestrian compliance at two-stage crossing signals dropped from 13 to 3 percent when the weather was cold and snowing.

Signing and Pavement Markings

Signing and pavement markings play an important role in conveying the proper way for all road users to navigate an intersection. Many aspects of signs and markings have been studied for pedestrian and bicyclist considerations at intersections.

Boudart et al. examined MUTCD sign 9C-7 (which is intended to tell bicyclists where to wait to be detected for a green signal) and found that text explaining the sign was shown to improve comprehension through intercept surveys and video observations, while blue light feedback telling bicyclists that they have been detected had a nonsignificant reduction of red light running.(34) Warner et al. found that through intersection markings improved visual search and crash avoidance.(14) Interestingly, despite the common association of green pavement markings with bicycle facilities, the researchers found that a single or double dotted white bicycle line with bicycle stencil should be considered because those markings were more effective than green markings.(14)

The NACTO *Urban Bikeway Design Guide* provides guidance on several aspects of pavement markings on bicycle facilities.(16) The guide states that crossing striping shall be 6 inches wide, dotted lines should be 2 ft long with 2- to 6-ft spacing, white, skid resistant, and retroreflective. The NACTO guide also suggests other markings, such as shark teeth for crossing driveways and alleyways, colored pavement to increase visibility in conflict areas or entire intersections, and square markings as an alternative to a dotted line.(16)

Iasmin, Kojima, and Kubota indicated that color and brick pavements have been shown to be associated with a decreased likelihood of small-gap acceptance by drivers, as well as decreased incidence of high-severity conflicts (where driver action is taken at the last minute to avoid a collision) when drivers are turning (right- or left-hook collisions).(35)

Corner Radius and Right-Turn Speed

A recent FHWA study explored the relationship between observed right-turn vehicle speeds and roadway geometrics, especially corner radius, at signalized intersections.(36) The selection of a large radius for a corner permits higher turning vehicle speeds in free-flow situations. While the potential increased vehicle speed through the right-turn lane is more efficient for the driver, trade-offs exist for this design. Increased vehicle speeds create more challenges for pedestrians attempting to cross the roadway. The analysis included a total of 31 sites with a range of radii varying between 15 and 70 ft. Other geometric variables considered included the type of right-turn lane, the number of right-turn lanes, the length of the right-turn lane, the distance to the nearest upstream and downstream driveways, the number of lanes on the receiving leg, and the speed limit. No bicycle or parking lanes were present on the approach or the receiving leg for any of the sites. All sites were at a signalized intersection. The right-turn speed measurement methodology involved collecting video footage at signalized intersection approaches and post-processing the footage to extract speed measurements, along with headway between the turning vehicle and the preceding vehicle. This study allowed the inclusion of variables that described conditions present when the subject vehicle was turning right, including the signal indication (steady circular green indication or steady circular yellow indication), type of turning vehicle (car or truck), and characteristics of the vehicle immediately preceding the turning vehicle (straight or turning right). The conditions during the specific right turn (e.g., headway, signal indication) are more influential than the site characteristics, except for corner radius.

The analysis found convincing evidence that right-turn speeds are a function of corner radius, with the range of increases in turning speed for corner radii between 15 and 70 ft being about 4 mph. The larger the radius, the higher the turning speeds. The FHWA study generated a model that can be used to predict turning speeds. The model is available in the FHWA report.(36) It includes the following variables: corner radius (range of 15 to 70 ft), headway to preceding vehicle, signal indication (yellow or green), vehicle type (truck or passenger car), and preceding vehicle movement (straight or turning). For example, assuming the preceding vehicle goes straight through the intersection with a 6-s headway to a passenger car that is turning right on a yellow indication, the range of median turning speed is 13.1 mph for a 15-ft corner radius to 16.8 mph for a 70-ft corner radius. The range of 85th percentile speed with these assumptions is 16.0 mph to 20.4 mph for corner radii of 15 to 70 ft.

Granitto in 2016 summarized the protected (innovative) treatment as having a design that prioritizes comfortable pedestrian and bicycle movement instead of fast car turning.(37) Summala et al. found that drivers' visual scanning strategies when turning right are based on identifying vehicles coming from the left.(38) They compared their findings to the typical designs used at protected (innovative) intersection and noted that the corner islands create a bicycle queue area and place the bicyclists further forward in a more obvious position to drivers, while pedestrian islands provide some of the benefits of curb extensions. Bicyclists are not forced to merge into mixed traffic, have a dedicated path through the intersection, and have the right-of-way over the right-turn vehicles. Modifications to the design for large vehicles include mountable truck aprons with a separate corner radius.(38) In 2021, Deliali, Christofa, and Knodler reported on a simulator study that examined right-turn driver performance with various bicycle infrastructure treatments.(39) They found a correlation between the presence of the protected (innovative) intersection elements and a higher rate of right glances at the intersection before the right turn.

Several driving simulators have been used to study protected intersections in general and corner islands specifically. Christofa et al. used a driving simulator to determine that forcing drivers further into the intersection causes slow turning by motor vehicles.(40) Warner et al. used a simulator to illustrate that smaller curb radii (10 ft versus 30 ft) positively influence crash avoidance and decrease potential crash severity by affecting motorist behavior through a decrease in mean vehicle speed and reduction in speed variation.(14) The study also found that the addition of green pavement markings was not shown to be consistently effective at positively influencing driver behavior, while the presence of a bicyclist was associated with slower motorist speeds at protected intersections. Gilpin et al. recommend designing corners such that passenger car turning speeds are between 5 and 10 mph, using a corner radius of 20 ft (or larger depending on design vehicle) augmented with an apron that renders the effective radius to be 10–20 ft.[12]

Bend-Out and Bend-In

The bend-out design moves the bicycle lane away from adjacent traffic at the intersection using a pedestrian refuge island, a key component of the protected intersection concept.[4] Figure 4 illustrates the shifting of the bicycle lane. The design can also be used in reverse to move bicyclists closer to motor vehicles at an intersection where such positioning provides added conspicuity for the bicyclists or where geometric constraints exist.

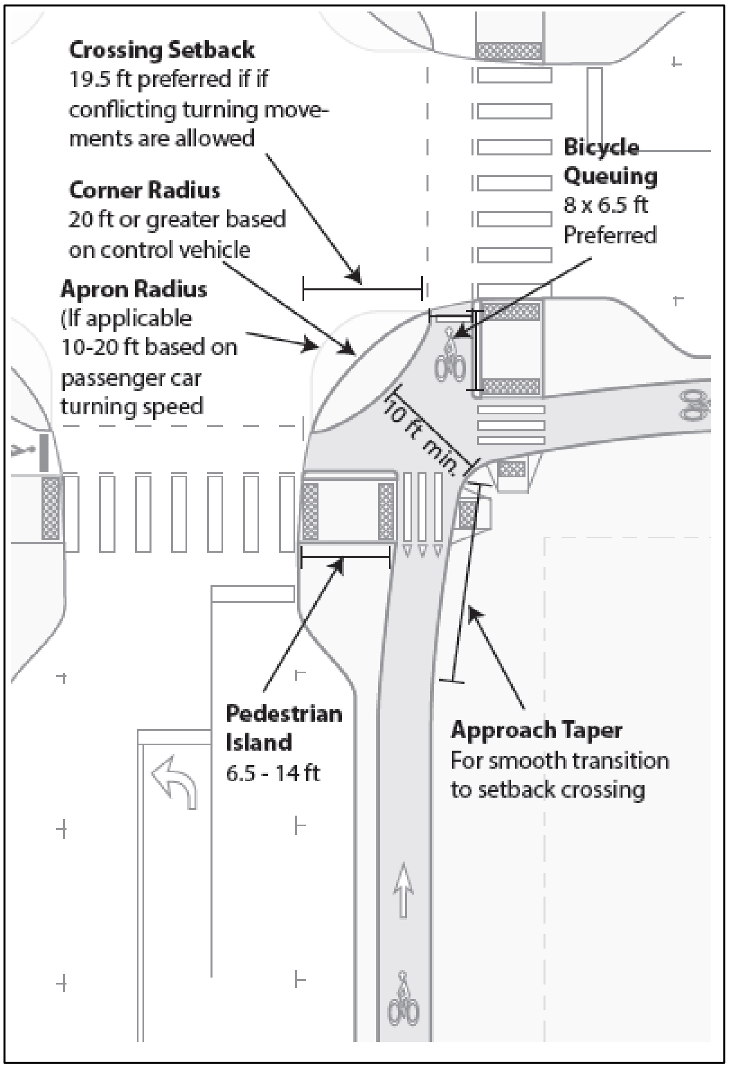


Figure 4. Illustration. Basic geometric elements and key dimensions of a protected intersection.[12]

Crosswalk Design

One modification to crosswalks at intersections to facilitate pedestrian safety is raising the crosswalk, effectively creating a speed hump. A case study by Candappa et al. found zebra markings on speed humps at a modified roundabout resulted in a speed reduction from 32.7 km/h to 30.7 km/h 30 m before the intersection and 17.6 km/h to 14.7 km/h 5 m from the intersection on weekdays (20.6 km/h to 17.9 km/h on weekends).[(41)] Mohammadipour et al. found that the vehicle speed change from the approach to the crosswalk is larger on wider streets, and that the raised crosswalk is more effective when the difference between the road grade and crosswalk ramp grade is 4 percent or greater.[(42)] Further study of raised crosswalks by Pratelli, Pratali, and Rossi found that the device was more effective at reducing speed as height increases, as well as when used in series rather than in isolation. They noted that the raised crosswalks are used in Italy at intersections and along corridors similar to speed humps.[(43)] Additionally, Gitelman et al. found them to be associated with positive road-user behavior, particularly for motorists, when used on segments in conjunction with preceding speed humps.[(44)]

Another unique crosswalk design is to set back the crosswalks in a manner similar to the setback of bikeways, or have a bend-out and bend-in treatment. This design results in crosswalks that are positioned approximately 20 ft back from the curb.[(45)] This positioning provides more space for vehicles that are turning and can reduce pedestrian conflicts with off-tracking vehicles and vehicles turning left against traffic. One downside of the design is that the path is less direct for pedestrians, so there may be a need for landscaping or a railing to guide pedestrians, and increased clearance time for vehicles needs to be provided.

Curb Extensions

Conventional curb extensions are a recommended feature where there is onstreet parking, but the term defines a category of treatments including midblock pinch points, gateways to minor streets, chicanes (curb-based lateral alignment changes), and bus bulbs.[(17)] The category is also sometimes referred to as bulb-out or nubs.[(46)] Fitzpatrick et al. stated that nubs permit buses to stop in a traffic lane without weaving around parked cars and provides additional waiting area for patrons.[(46)] Johnson conducted a case study and found that fewer vehicles pass a waiting pedestrian at uncontrolled intersections when curb extensions are present.[(47)] A study by Kang in New York, NY, found curb extensions to be effective at reducing the rate of pedestrian collisions after collision rates were adjusted for vehicle traffic volume.[(29)] These extensions can impact drainage at a given location. Consequently, they can be designed as edge islands with a 1- to 2-ft gap where drainage would be adversely impacted.[(17)]

Shared Space and Pedestrian Plazas

As municipalities continue to emphasize nonmotorized road users, several ideas are emerging and gaining traction among traffic professionals. For example, rather than use pavement markings to dictate which road users should operate in specific areas, shared space intersections are designed with little to no lane markings and signing guidance to create traffic calming through ambiguity in mode assignment.[(48)] Another example of a novel idea is the pedestrian plaza, where areas formerly used by motor vehicles for travel and parking are converted into pedestrian space.[(49)] Kang conducted a study of such facilities in New York, NY, and found pedestrian plazas to be effective at reducing the rate of pedestrian collisions after collision rates were adjusted for vehicle traffic.[29]

Bicycle Lane Designs

Several unique iterations of the bicycle lane have been developed at intersections to facilitate safe and efficient movement. *Through bicycle lanes* shift the bicycle lane between through and right-turning traffic at the intersection (as opposed to curbside). This treatment is also referred to as keyway and pocket (between the through and vehicle turn lane). NACTO noted that the presence of through bicycle lanes is associated with correct lane use rates of 87 percent for turning vehicles and 91 percent for bicyclists when turning vehicles have limited entry into the turning lane.[16]

Combined bicycle lanes and turn lanes are similar to the through bicycle lanes but use less space. Right-turning vehicles and bicyclists queue and operate in the same space.[16]

In *wide curb lanes* the lane nearest the curb is wider than a standard lane and provides space for motor vehicles and bicycles to share the lane.[50] Hunter et al found that differences in signal compliance were less than 1 percent between bicycle lanes and wide curb lanes, while compliance at stop signs was much lower (80.6 percent of bicyclists obeyed stop signs at intersections with bicycle lanes versus 55.2 percent at wide curb lanes).[50]

Intersection Characteristics for Cars That May Help Pedestrians

Channelized right turn lanes are an intersection feature that uses a channelizing island to separate right-turning vehicles from through vehicles. Al-Kaisy and Roefaro examined why this device was used and the perceptions of its effectiveness through a survey.[51] The researchers found that the device is primarily installed (and traffic control type determined) based on national and State guidelines and engineering judgment; the device is used to improve operations at locations with high right-turn volume. Additionally, mixed responses to surveys indicated that various survey respondents felt that they both improve and decrease pedestrian and motorist safety but are generally thought to improve both when used at signals.[51]

The continuous flow intersection, or more appropriately the displaced left turn intersection, is primarily designed for improving the safety and efficiency of motor vehicle travel. However, various documents have highlighted the ways it can be modified to improve pedestrian friendliness. For example, Bai and Li recommend that pedestrian refuge islands and signal optimization can provide superior service for pedestrians and vehicles, while a unique X-crossing design helps pedestrians at the expense of motorists.[52] Bonneson, Pratt, and Songchitruska documented the disadvantages of this design when pedestrians are present, noting a 20- to 40-percent increase in delay for vehicles at locations with low pedestrian volumes and a 40- to 80-percent delay for intersections with high pedestrian volumes.[53]

KEY TAKEAWAYS

The protected intersection is a combination of a suite of treatments, many of which have been examined as standalone safety features in the existing literature. However, the amount of literature dedicated to examining how these features function as a cohesive intersection design is limited. Additionally, although the protected (and dedicated) intersection is defined by the treatments used to reduce the curb radius, the effect of the islands and the bicycle lane taper on the approach as a chicane-like traffic calming feature for bicyclists has not been thoroughly examined.

The publication *Lessons Learned: Evolution of the Protected Intersection* recommends dimensions for various aspects of the protected intersection, including those shown in figure 4.(12)

CHAPTER 3. IDENTIFY CANDIDATE SITES

An initial effort in the project was to identify candidate treatments and study sites.

CREATING INITIAL REQUESTS FOR INFORMATION

With the relative newness of the protected intersection design in mind, the research team used several approaches to identify potential study sites, including:

- Announcing the FHWA study at professional meetings and requesting leads on locations.
- Using research team members' and FHWA staff's knowledge.
- Making calls to those regions with extensive bicycle networks.
- Searching the internet for news articles that talked about the installation of bicycle treatments. Those leads were followed with emails or phone calls to the identified potential sites.

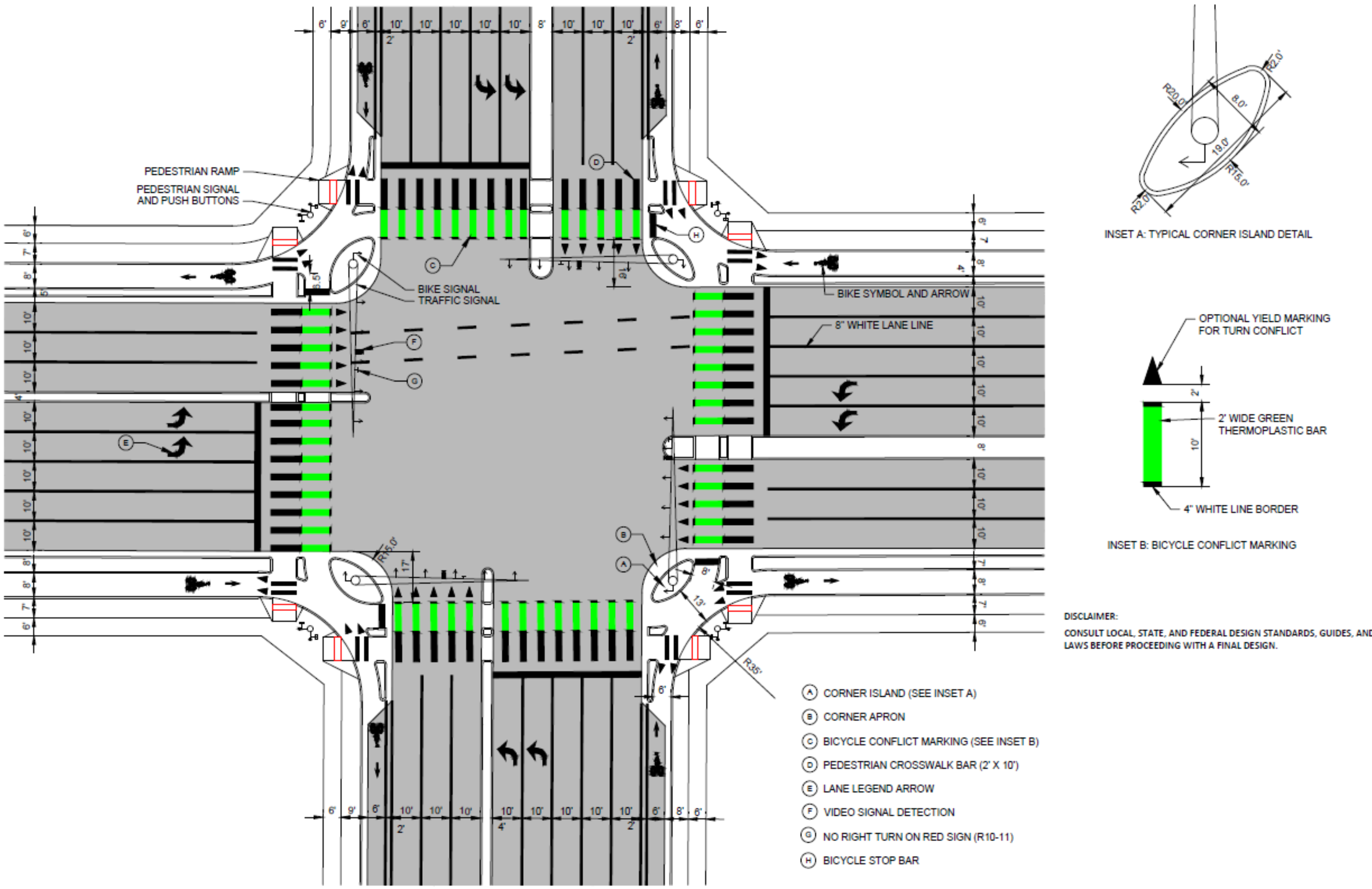
IDENTIFYING POTENTIAL STUDY SITES

With the goal of conducting 15 before-after evaluations, a key component to choosing sites was to identify the study site before the treatment had been installed so that before data could be collected. The study was also bound by a fixed end date, so the installation of the treatment had to occur in sufficient time to permit adequate time to collect the after data, to conduct the analysis, and to complete the required study documentation before the end date of the contract. With these restrictions, a limited number of study sites were identified where both before data and after data could be collected in the contract limits. The remaining sites were either sites with existing treatments or sites that could serve as a comparison to nearby sites with existing treatments.

CREATING THREE TYPICAL DESIGNS

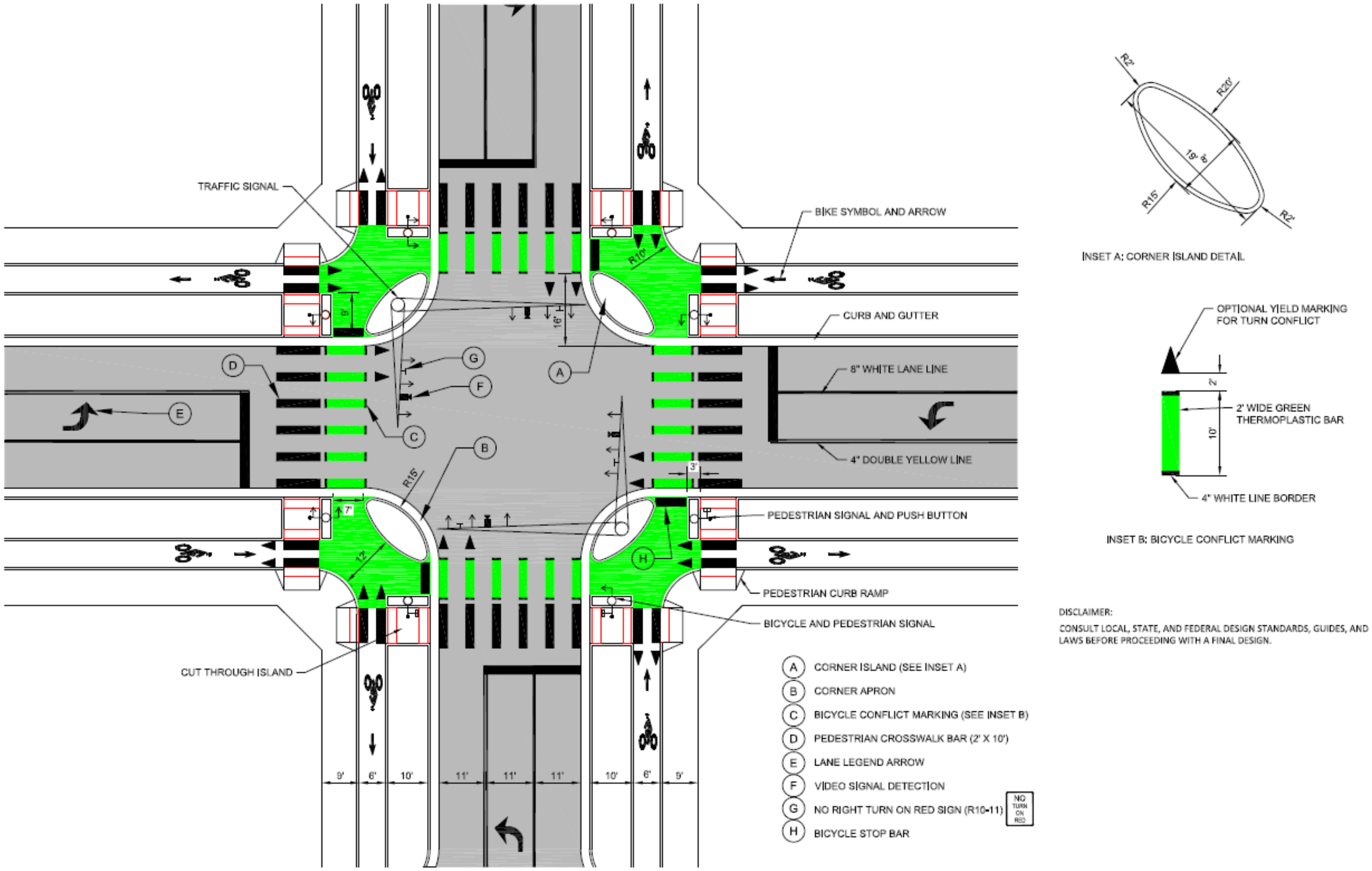
Combining the findings from the literature with information provided by those installing relevant treatments resulted in the creation of three typical designs. Protected intersection designs provide dedicated paths through the intersection for pedestrians and bicyclists. The bikeway is set back from the parallel motor vehicle traffic, which makes bicyclists more visible to turning drivers than in a conventional intersection. Corner islands are a key feature of the design. They create a bicycle queue area after the crosswalk and provide a place for bicyclists to wait. The three scenarios developed in this study using protected intersection design concepts are provided in the following figures:

- Figure 5, large intersection.
- Figure 6, small intersection.
- Figure 7, quick build.



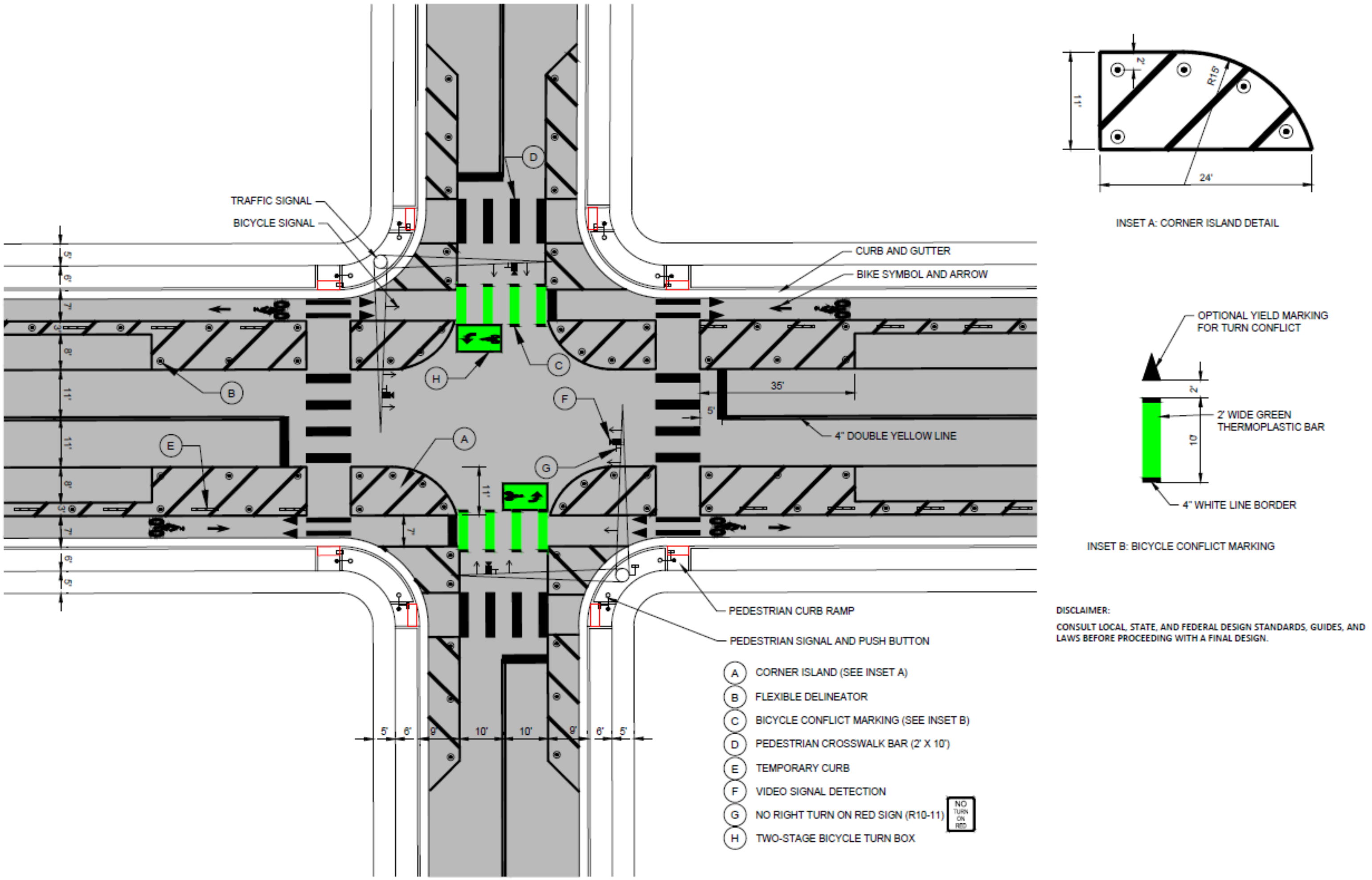
Source: FHWA.

Figure 5. Illustration. Large intersection with medians and bicycle lanes on all approaches.



Source: FHWA.

Figure 6. Illustration. Small intersection with bicycle lanes on all approaches.



Source: FHWA.

Figure 7. Illustration. Small intersection with bicycle lanes on major approaches only.

SITE SELECTION

All of the identified sites where the implementation of protected intersection features was planned and where construction would be completed by the fall of 2021 were initially selected for study. These sites included two sites in Fremont (FRE), CA; one site in Silver Spring (SSP), MD; three sites in Washington (WAS), DC; and four sites in Austin (AUS), TX. Unfortunately, the start date for the construction at the four sites in Austin, TX, was shifted to the point where those sites were no longer viable for study.

Since less than 15 sites were planned for changes in the period, the research team was instructed to identify sites with existing treatments along with nearby comparison sites. These sites were in Berkeley (BER), CA; Fremont, CA; College Station (CST), TX; and Salt Lake City (SLC), UT. The sites with existing treatments were assigned to one of the three typical design categories. Sites were removed from consideration or were given a lower priority if a two-way bicycle lane was present, if the vehicle speed limit was low, or if a corner island was not present for all corners. The sites for study were selected during a panel meeting of the research team and FHWA. Table 1 lists the sites included in this project and involved 6 before-after sites (for 12 site periods), 4 comparison sites (i.e., untreated intersections), and 12 existing (or treated) intersections. In most cases, the intersection traffic control was a signal with only 4 of the 24 intersections having all-way stop control. All but one of the intersections had four legs.

Table 1. Study sites selected for the project.

Site–Period	Condition	Type	Legs	Control
CA–BER–01–Exi	Existing	Traditional	4	Signal
CA–FRE–02–Exi	Existing	Large	4	Signal
CA–FRE–03–Exi	Existing	Large	4	Signal
CA–FRE–04–Exi	Existing	Large	4	Signal
CA–FRE–05–Com	Compare	Large	4	Signal
CA–FRE–05–Exi	Existing	Large	4	Signal
CA–FRE–06–Exi	Existing	Quick build	4	Signal
CA–FRE–07–Com	Compare	Large	4	Signal
CA–FRE–07–Exi	Existing	Quick build	3	Signal
CA–FRE–09–Exi	Existing	Large	4	Signal
CA–FRE–11–Bef or Aft	Before-after	Large	4	Signal
CA–FRE–12–Bef or Aft	Before-after	Large	4	Signal
DC–WAS–01–Bef or Aft	Before-after	Quick build	4	All-way stop
DC–WAS–02–Bef or Aft	Before-after	Quick build	4	All-way stop
DC–WAS–03–Bef or Aft	Before-after	Quick build	4	Signal
MD–SSP–01–Exi	Existing	Traditional	4	Signal
MD–SSP–02–Bef or Aft	Before-after	Traditional	4	Signal
TX–AUS–16–Com	Compare	Large	4	Signal
TX–AUS–16–Exi	Existing	Large	4	Signal
TX–CST–01–Exi	Existing	Traditional	4	All-way stop
UT–SLC–01–Com	Compare	Large	4	Signal
UT–SLC–01–Exi	Existing	Traditional	4	Signal
UT–SLC–03–Exi	Existing	Quick build	4	All-way stop

Bef = before; Aft = after; Exi = existing; Com = compare.

Table 2 provides the posted speed limit (PSL) by approach for each study site. When the PSL sign could not be identified, the value that was assumed based on State or city code is provided. The school speed limit value is also provided when present on the approach. All of the Washington, DC, sites, one Maryland site, and two California sites had PSLs of 25 mph on all approaches. Two of the Utah sites and one of the Texas sites had between 20 and 25 or 30 mph PSLs. Seven of the 24 sites had approaches with PSLs of 40 or 45 mph.

Table 2. PSL by approach for each study site.

Site	PSL-NB (mph)	PSL-SB (mph)	PSL-EB (mph)	PSL-WB (mph)
CA–BER–01	25	25	25	25
CA–FRE–01	25	30 (25 school)	35 (25 school)	35
CA–FRE–02	30	30	35	35
CA–FRE–03	25	25	35	35
CA–FRE–04	25 (assumed)	25 (assumed)	25	25
CA–FRE–05	35	35	30	30
CA–FRE–05	35	35	35	30
CA–FRE–06	35	Leg not present	40	45
CA–FRE–07	35	Driveway	40	45
CA–FRE–07	40	40	Ramp	45
CA–FRE–09	25 (assumed)	25	40	40
CA–FRE–11	35	40	35	35
CA–FRE–12	35	40	35	35
DC–WAS–01	25 (assumed)	25	25 (assumed)	25 (assumed)
DC–WAS–02	25 (assumed)	25	25 (assumed)	25 (assumed)
DC–WAS–03	25 (assumed)	25 (assumed)	25	25 (assumed)
MD–SSP–01	25	30	25	30
MD–SSP–02	25 (assumed)	25 (assumed)	25	25 (assumed)
TX–AUS–16	35	35	35 (20 school)	35 (20 school)
TX–AUS–16	40 (25 school)	40 (25 school)	40	35
TX–CST–01	25	Driveway	30	20
UT–SLC–01	25	25 (assumed)	20	20
UT–SLC–01	25	25	20	20
UT–SLC–03	30	25	25	25

NB = northbound; SB = southbound; EB = eastbound; WB = westbound.

CHAPTER 4. DATA COLLECTION

OVERVIEW OF DATA COLLECTION

A total of 24 unique site periods were studied with before-after data available for six of the 24 intersections. Table 3 provides the data collection dates for each site period.

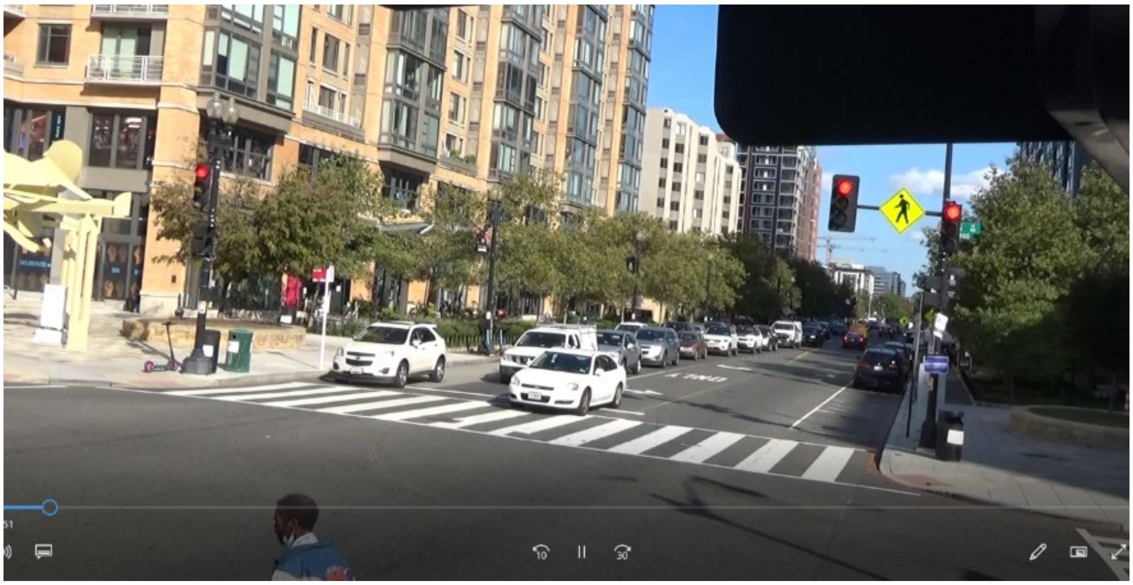
Table 3. Dates data collected at each study site.

Site–Period	Intersection	Data Collection Date
CA–BER–01–Exi	Alameda Drive and Hopkins Avenue	8/31/21
CA–FRE–01–Exi	Walnut Avenue and Gallaudet Drive	9/1/21
CA–FRE–02–Exi	Walnut Avenue and Guardino Drive	8/30/21
CA–FRE–03–Exi	Walnut Avenue and Civic Center Drive	8/23/21
CA–FRE–04–Exi	Civic Center Drive and Bart Way	8/27/21
CA–FRE–05–Com	Walnut Avenue and Fremont Boulevard	8/24/21
CA–FRE–05–Exi	Walnut Avenue and Paseo Padre Parkway	8/25/21
CA–FRE–06–Exi	Cushing Parkway and Northport Loop W	8/18/21
CA–FRE–07–Com	Cushing Parkway and Fremont Boulevard	8/19/21
CA–FRE–07–Exi	Cushing Parkway and Northport Loop E	8/17/21
CA–FRE–09–Exi	Grimmer Boulevard and Wisdom Road	11/21/21
CA–FRE–11–Aft	Fremont Boulevard and Mowry Avenue	11/22/21
CA–FRE–11–Bef	Fremont Boulevard and Mowry Avenue	12/15/20
CA–FRE–12–Aft	Fremont Boulevard and Stevenson Boulevard	11/20/21
CA–FRE–12–Bef	Fremont Boulevard and Stevenson Boulevard	12/15/20
DC–WAS–01–Aft	1st Street SE/Potomac Avenue and L Street	10/13/21
DC–WAS–01–Bef	1st Street SE/Potomac Avenue and L Street	10/13/20
DC–WAS–02–Aft	1st Street SE/Potomac Avenue and K Street	10/13/21
DC–WAS–02–Bef	1st Street SE/Potomac Avenue and K Street	10/14/20
DC–WAS–03–Aft	K Street NE/NW and 5th Street	10/12/21
DC–WAS–03–Bef	K Street NE/NW and 5th Street	10/15/20
MD–SSP–01–Exi	Spring Street and 2nd Avenue	12/10/20
MD–SSP–02–Aft	Fenton Street and Cameron Street	6/7/22
MD–SSP–02–Bef	Fenton Street and Cameron Street	12/10/20
TX–AUS–16–Com	Escarpment Boulevard and Davis Street	6/21/21
TX–AUS–16–Exi	Escarpment Boulevard and La Crosse Avenue	6/21/21
TX–CST–01–Exi	Bizzell Street and Ross Street	1/26/22
UT–SLC–01–Com	Temple Street and Broadway Avenue	11/18/21
UT–SLC–01–Exi	Broadway Avenue (also known as 300 South) and 200 West	11/17/21
UT–SLC–03–Exi	700 South and 300 East	11/19/21

SE = southeast; NE = northeast; NW = northwest.

Video from Cameras Installed for Study

For the Washington, DC, sites, the research team installed four video cameras on street light poles on either October 12 or October 13, 2020, to capture the before-modification condition. The installations occurred from October 20 to 22, 2021, for the after condition. Each camera covered one crosswalk at the intersection. Figure 8 shows the video from one of the cameras. Because one camera was needed for each approach, the number of hours of video data for Washington, DC, was much larger than for the sites with drone video data.



Source: FHWA.

Figure 8. Photo. Example of video view for one of the cameras at DC–WAS–03–Aft.

Video from Rooftop Camera

For the College Station, TX, site, a camera used to monitor traffic conditions on campus was used to collect the video data. The video for MD–SSP–02 used a mix of video taken by a drone and video recorded from the top story of a parking garage. Figure 9 provides an example of the video view from the rooftop camera.

Source: FHWA.

Figure 9. Photo. Example of view for rooftop camera at MD–SSP–02–Aft.

Video from Drone

For the remaining study site, video data were collected using a drone-mounted video camera. The drone-enabled camera permitted the collection of all crosswalk data in one view. Figure 10 shows an example.

Source: FHWA.

Figure 10. Photo. Example of view from the drone camera of CA–FRE–11–Aft.

Sample Camera Views for Each Site

The following figures show the views from the video or a Google® Earth™ view when the angle of the video is such that an overview of the intersection is not presented:(54)

- Figure 11 provides a view from the video of CA–BER–01–Exi.
- Figure 12 provides a view from the video of CA–FRE–01–Exi.
- Figure 13 provides a view from the video of CA–FRE–02–Exi.
- Figure 14 provides a view from the video of CA–FRE–03–Exi.
- Figure 15 provides a view from the video of CA–FRE–04–Exi.
- Figure 16 provides a view from the video of CA–FRE–05–Com.
- Figure 17 provides a view from the video of CA–FRE–05–Exi.
- Figure 18 provides a view from the video of CA–FRE–06–Exi.
- Figure 19 provides a view from the video of CA–FRE–07–Com.
- Figure 20 provides a view from the video of CA–FRE–07–Exi.
- Figure 21 provides a view from the video of CA–FRE–09–Exi.
- Figure 22 provides a view from the video of CA–FRE–11–Bef.
- Figure 23 provides a view from the video of CA–FRE–11–Aft.
- Figure 24 provides a view from the video of CA–FRE–12–Bef.
- Figure 25 provides a view from the video of CA–FRE–12–Aft.
- Figure 26 provides a view from the video of DC–WAS–01–Bef.
- Figure 27 provides a view from the video of DC–WAS–01–Aft.
- Figure 28 provides a view from the video of DC–WAS–02–Bef.
- Figure 29 provides a view from the video of DC–WAS–02–Aft.
- Figure 30 provides a view from the video of DC–WAS–03–Bef.
- Figure 31 provides a view from the video of DC–WAS–03–Aft.
- Figure 32 provides a Google Earth aerial view of DC–WAS–03–Bef.
- Figure 33 provides a Google Earth aerial view of DC–WAS–03–Aft.
- Figure 34 provides a view from the video of MD–SSP–01–Exi.
- Figure 35 provides a view from the video of MD–SSP–02–Bef.
- Figure 36 provides a view from the video of MD–SSP–02–Aft.
- Figure 37 provides a view from the video of TX–AUS–16–Com.
- Figure 38 provides a view from the video of TX–AUS–16–Exi.
- Figure 39 provides a Google Earth aerial view of TX–CST–01–Exi.
- Figure 40 provides a view from the video of TX–CST–01–Exi.
- Figure 41 provides a view from the video of UT–SLC–01–Exi.
- Figure 42 provides a view from the video of UT–SLC–01–Com.
- Figure 43 provides a view from the video of UT–SLC–03–Exi.

Source: FHWA.

Figure 11. Photo. View from the video of CA–BER–01–Exi.

Source: FHWA.

Figure 12. Photo. View from the video of CA–FRE–01–Exi.

Source: FHWA.

Figure 13. Photo. View from the video of CA–FRE–02–Exi.

Source: FHWA.

Figure 14. Photo. View from the video of CA–FRE–03–Exi.

Source: FHWA.

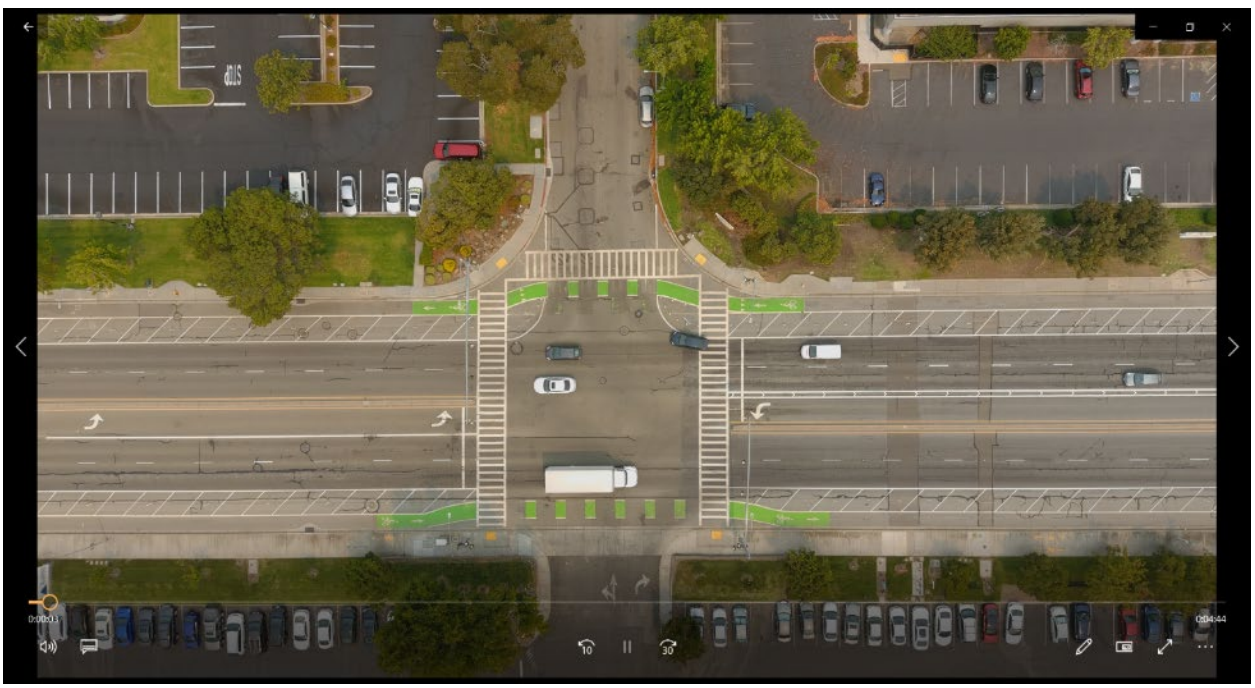
Figure 15. Photo. View from the video of CA–FRE–04–Exi.

Source: FHWA.

Figure 16. Photo. View from the video of CA–FRE–05–Com.

Source: FHWA.

Figure 17. Photo. View from the video of CA–FRE–05–Exi.

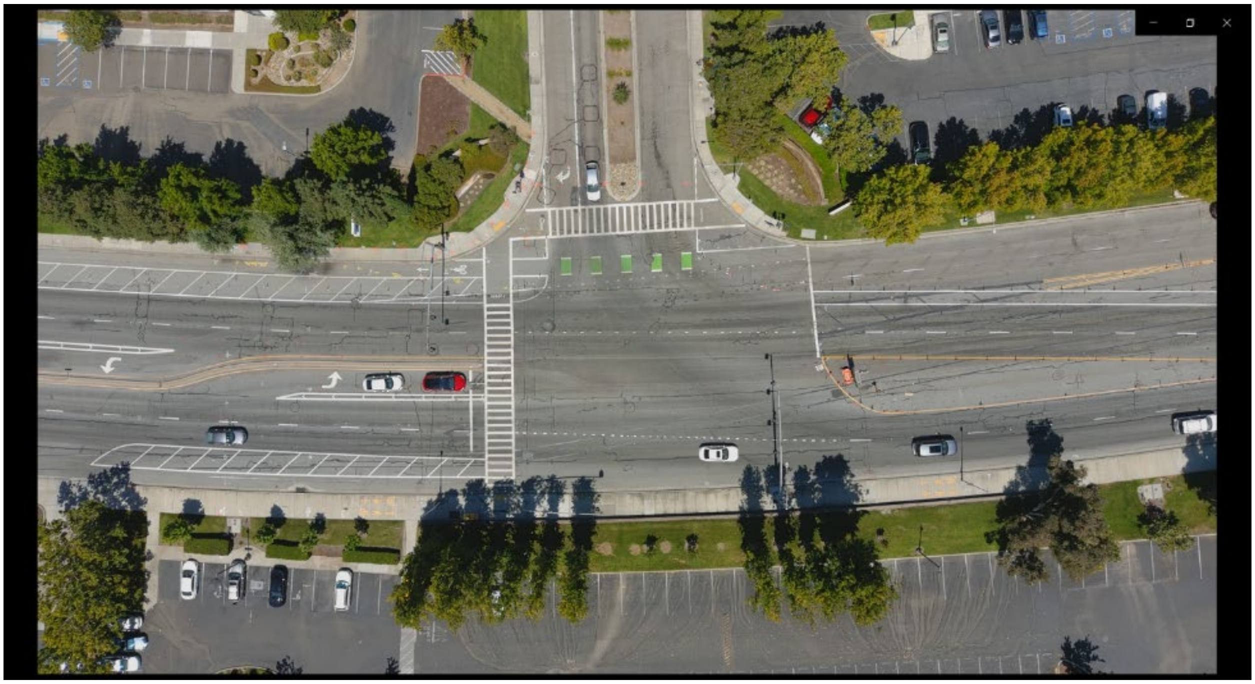


Source: FHWA.

Figure 18. Photo. View from the video of CA–FRE–06–Exi.

Source: FHWA.

Figure 19. Photo. View from the video of CA–FRE–07–Com.



Source: FHWA.

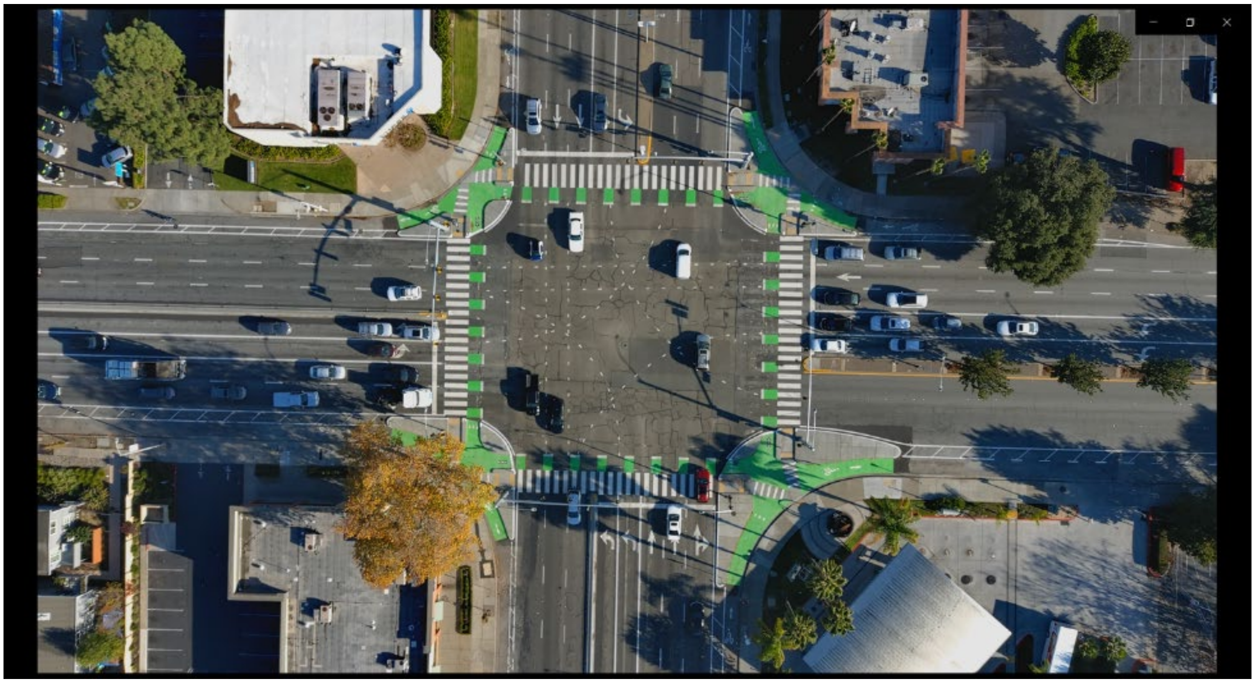
Figure 20. Photo. View from the video of CA–FRE–07–Exi.

Source: FHWA.

Figure 21. Photo. View from the video of CA–FRE–09–Exi.

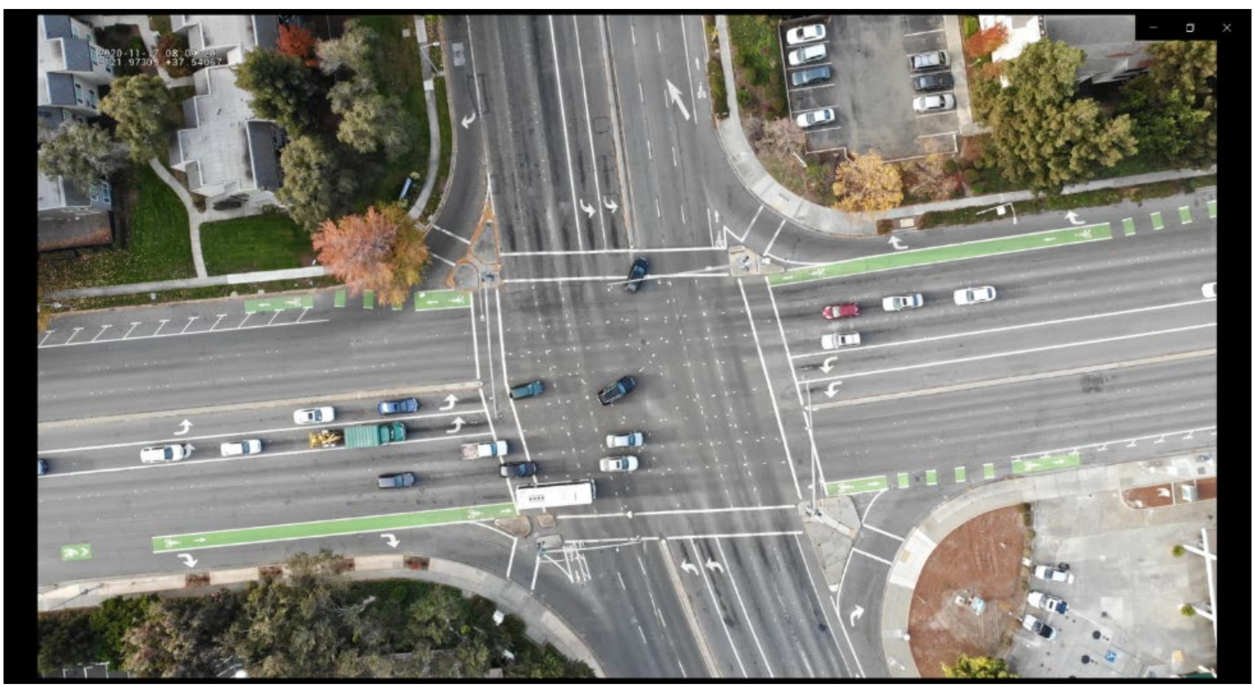
Source: FHWA.

Figure 22. Photo. View from the video of CA–FRE–11–Bef.



Source: FHWA.

Figure 23. Photo. View from the video of CA–FRE–11–Aft.

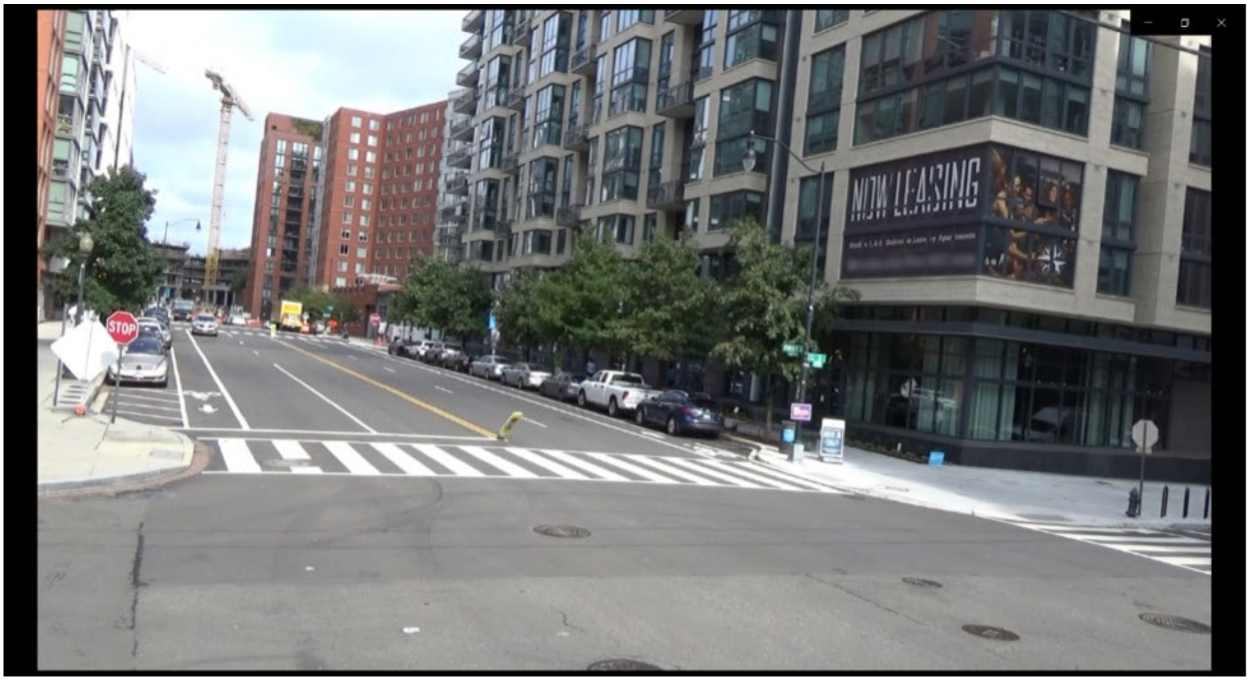


Source: FHWA.

Figure 24. Photo. View from the video of CA–FRE–12–Bef.

Source: FHWA.

Figure 25. Photo. View from the video of CA–FRE–12–Aft.

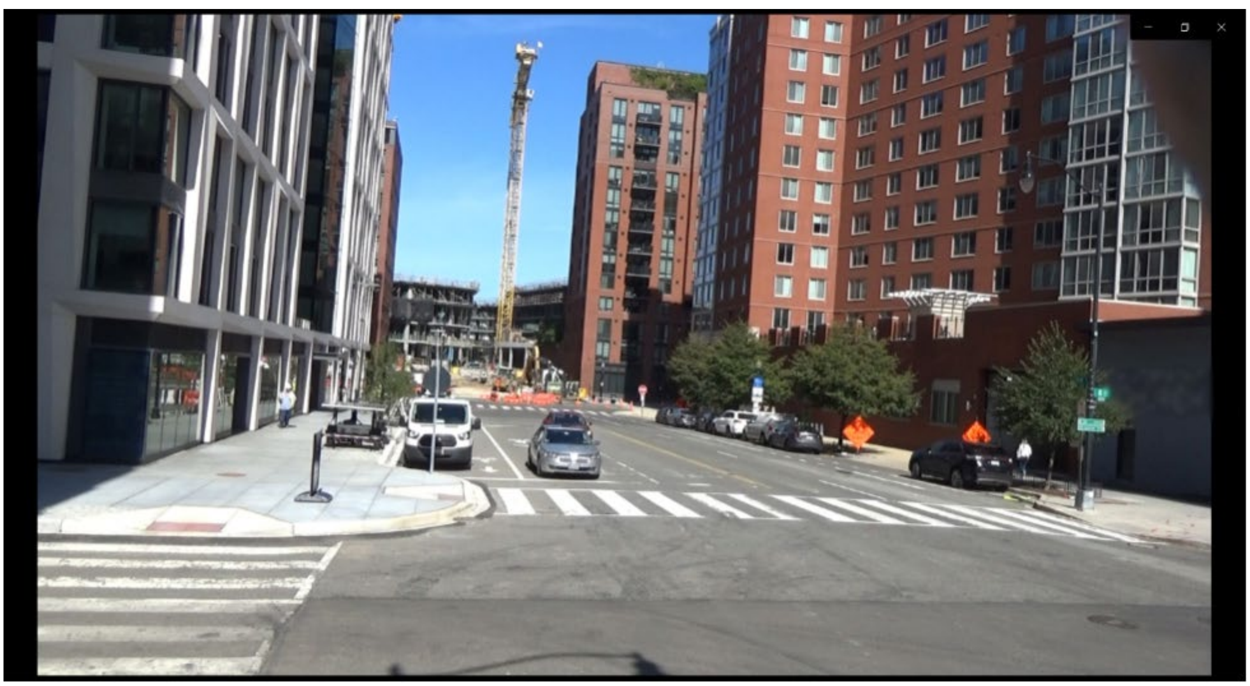


Source: FHWA.

Figure 26. Photo. View from the video of DC–WAS–01–Bef, northbound.

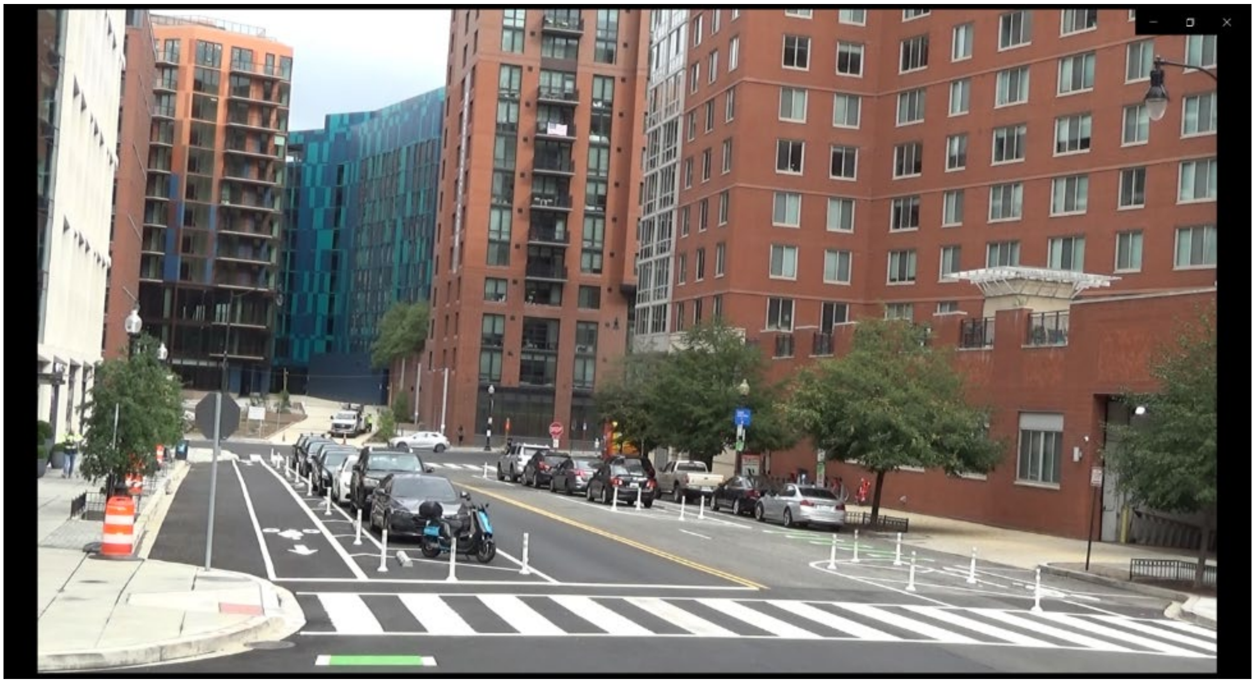
Source: FHWA.

Figure 27. Photo. View from the video of DC–WAS–01–Aft, northbound.



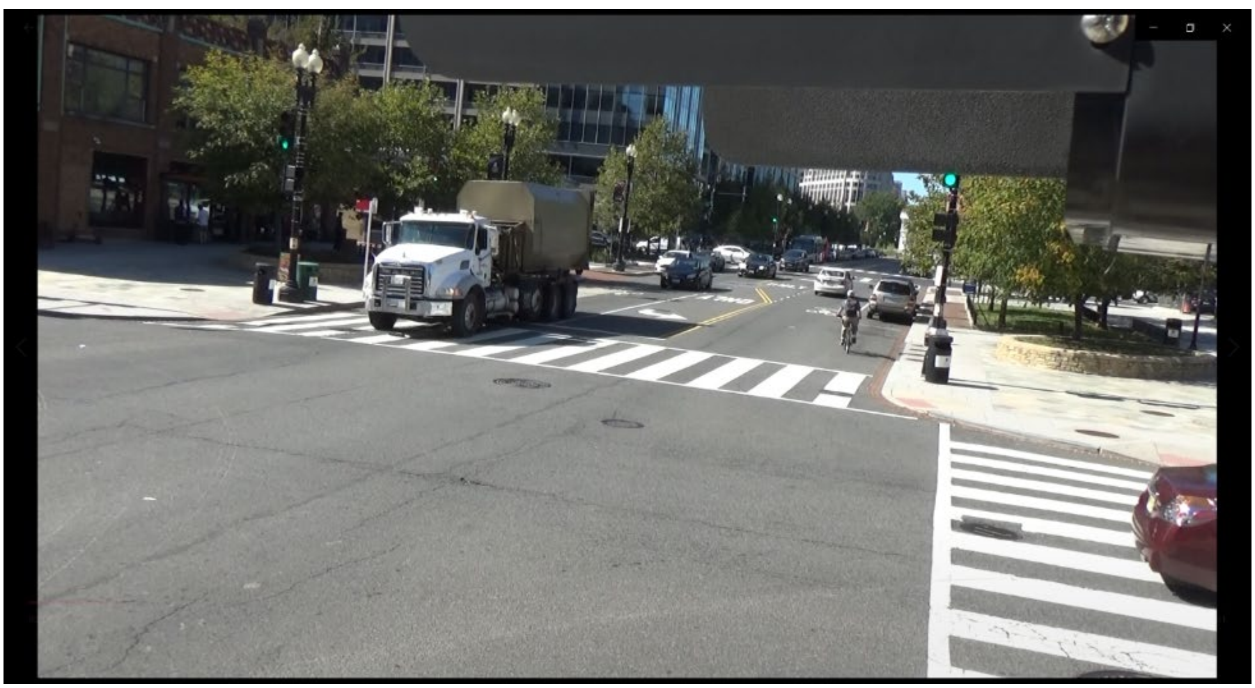
Source: FHWA.

Figure 28. Photo. View from the video of DC–WAS–02–Bef, northbound.



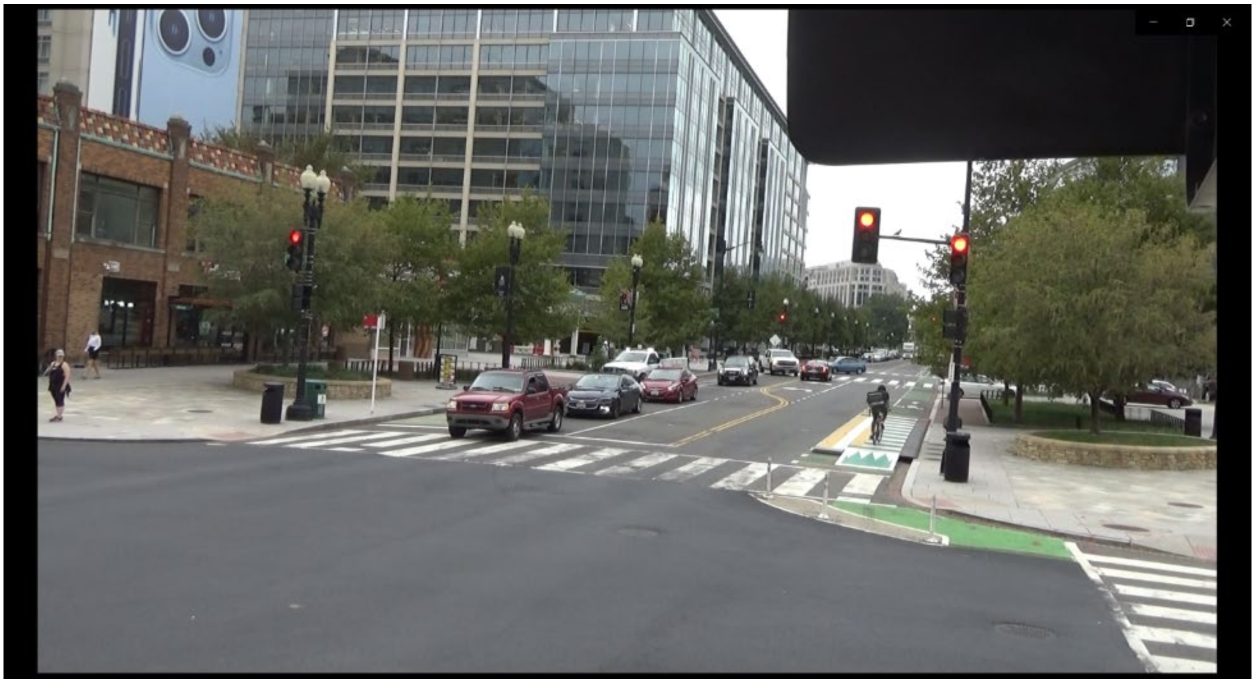
Source: FHWA.

Figure 29. Photo. View from the video of DC–WAS–02–Aft, northbound.



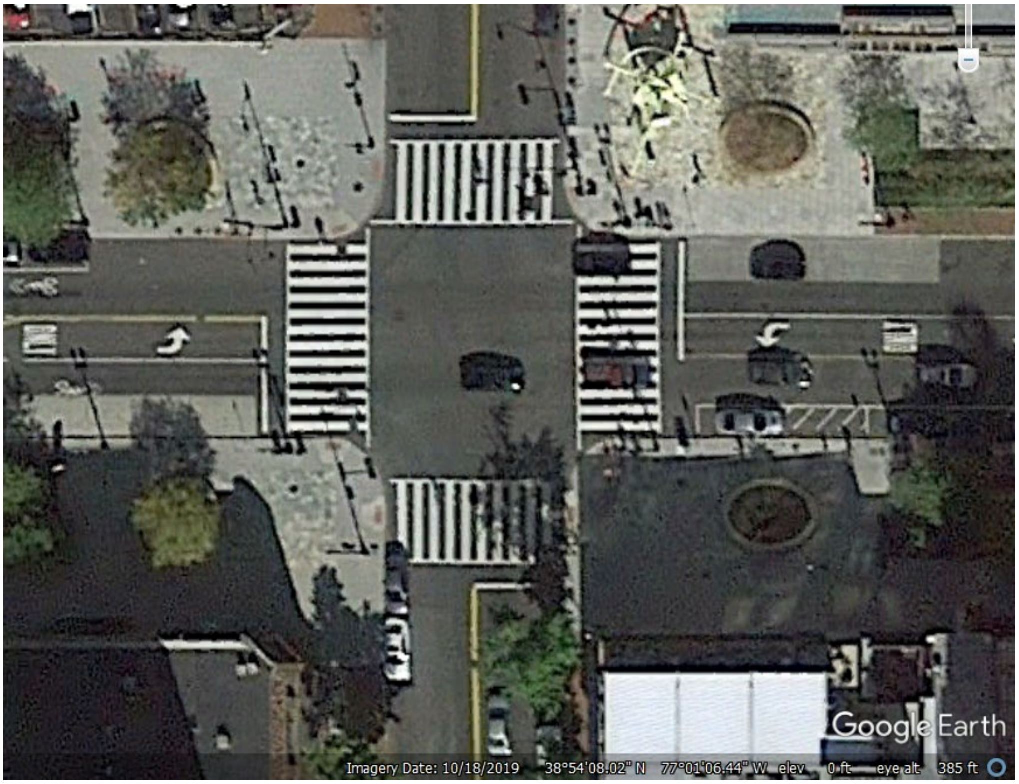
Source: FHWA.

Figure 30. Photo. View from the video of DC–WAS–03–Bef, westbound.



Source: FHWA.

Figure 31. Photo. View from the video of DC–WAS–03–Aft, westbound.



Original map: © 2019 Google® Earth™.[54]
Note: Google Earth photo date is October 2019.

Figure 32. Photo. DC–WAS–03–Bef.

Original map: © 2022 Google® Earth™.[54]
Note: Google Earth photo date is July 2022.

Figure 33. Photo. DC–WAS–03–Aft.

Source: FHWA.

Figure 34. Photo. View from the video of MD–SSP–01–Exi.

Source: FHWA.

Figure 35. Photo. View from the video of MD–SSP–02–Bef.

Source: FHWA.

Figure 36. Photo. View from the video of MD–SSP–02–Aft.

Source: FHWA.

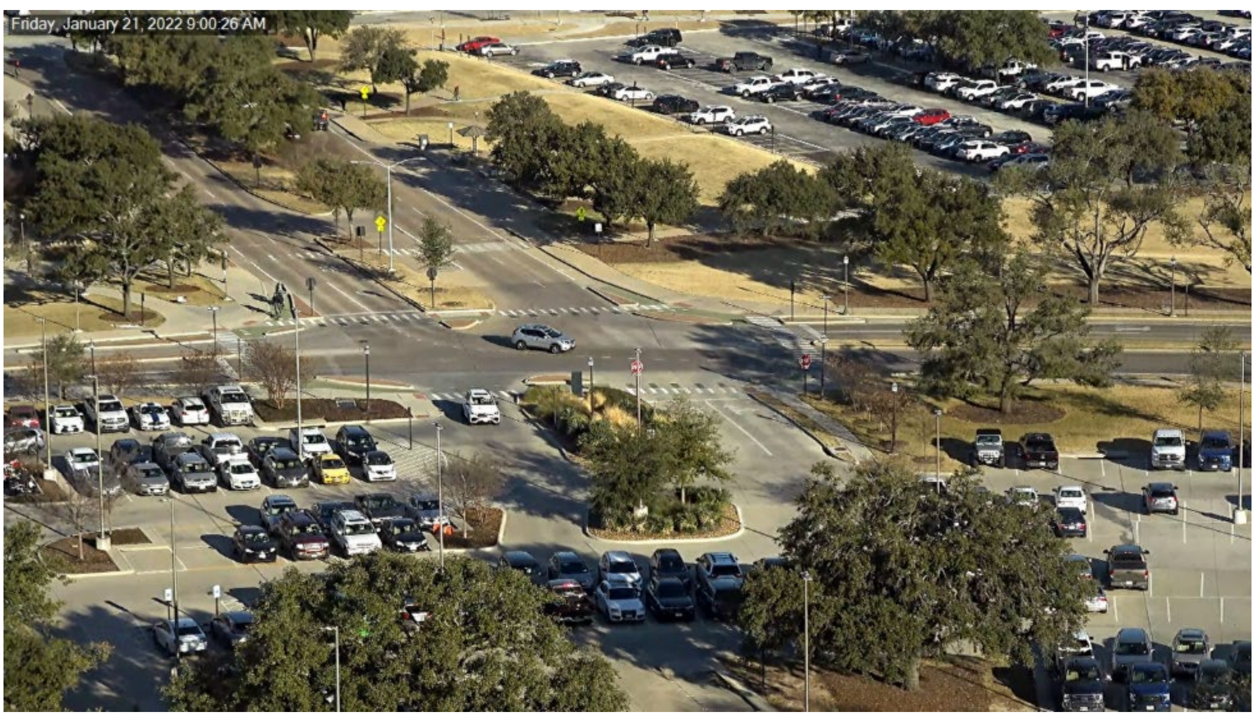
Figure 37. Photo. View from the video of TX–AUS–16–Com.

Source: FHWA.

Figure 38. Photo. View from the video of TX–AUS–16–Exi.

Original map: © 2022 Google® Earth™.(54)
Note: Google Earth photo date is March 2022.

Figure 39. Photo. TX–CST–01–Exi.

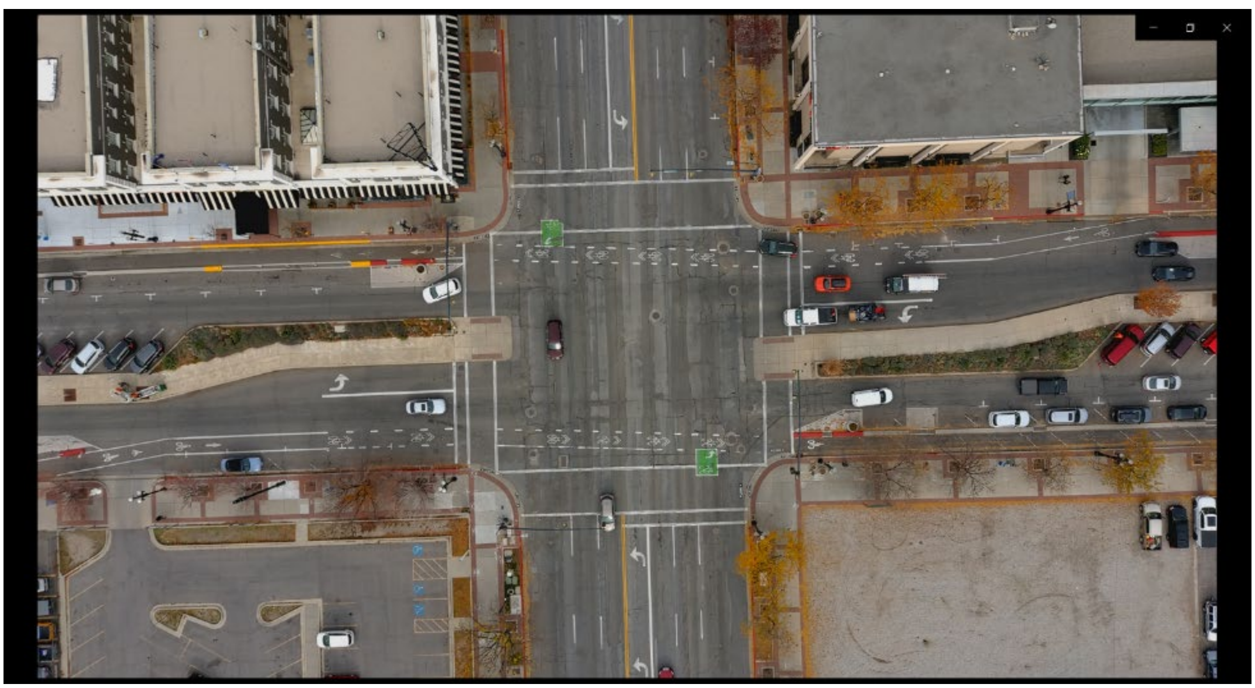


Source: FHWA.

Figure 40. Photo. View from the video of TX–CST–01–Exi.

Source: FHWA.

Figure 41. Photo. View from the video of UT–SLC–01–Exi.



Source: FHWA.

Figure 42. Photo. View from the video of UT–SLC–01–Com.

Source: FHWA.

Figure 43. Photo. View from the video of UT–SLC–03–Exi.

OVERVIEW OF DATA REDUCTION

Based on the review of the literature along with the engineering judgment of the research team and FHWA panel, the measures listed in table 4 were to be obtained from the videos.

Considering the measures shown in table 4, the research team developed a protocol for the data reduction. The technicians would watch each video and obtain the data listed in table 5 for each VU. Over 149 h of video (about 5 h per site period) were reduced.

Additional data reduction efforts used video analytics software to obtain details on right-turning speed and vehicle path for selected site periods. Details on those efforts are included in chapter 5.

Table 4. User behavior measures collected at the study sites.

Measure	Measuring	Before-After Analysis	Comparison Analysis
Throughput (for bicyclists)	Number of bicyclists on the approach	Did number of bicyclists increase from the before period to the after period?	Number of bicyclists per hour
Driver yielding behaviors	Driver yielding to crossing bicyclist or pedestrian	Change in percentage of driver yielding	Descriptive statistics
Bicyclist yielding behaviors	Bicyclist yielding to pedestrian	Change in percentage of bicyclist yielding	Descriptive statistics
Conflicts	Conflicts between users	Descriptive statistics	Descriptive statistics
Typical pedestrians and bicyclists travel path	Number of users along specified travel path	Descriptive statistics	Descriptive statistics
Where are pedestrians and bicyclists waiting?	Number of users waiting in specified locations	Descriptive statistics	Descriptive statistics

Table 5. Data collected from the video.

Heading	Description of Data
Site	Full site name.
Period	What is the period type: Existing, Comparison, Before, or After?
File Name	Video file name.
VU-TimeStamp	Time VU appeared in video.
VU-CWLeg	What leg was the VU crossing: North, South, East, or West?
VU Type	What is the VU type: Pedestrian, Bicyclist, or Other (expand this list if skateboard or e-scooters are common for the intersection)?
VU-FromWhere	Where was the VU when entering the field of view: Sidewalk, BikeLane, Street, CornerRefugeIsland, or Other?
VU-WaitArea	Where did the VU wait: Sidewalk, Pedestrian Ramp, etc. (expand list as needed for site characteristics)?
VU-MoveType	What was the VU movement: Through, Left, or Right?
VU-ToWhere	Where did the VU go at end of crossing: Sidewalk, BikeLane, Street, or CornerRefugeIsland?
VU-StayInCWorCB	Did the VU stay within the marked crosswalk or crossbike markings? Yes, Most, or No (use "Most" when the VU was not on the markings for a portion of the crossing)?
VehBikeEnterCW-VUCrossing	Did a vehicle or bicyclist enter the crossing during the VU crossing: No, Yes (Vehicle), or Yes (Bike)?
ConflictVehMan	If a vehicle or bicyclist enters the crossing during the VU crossing, what is the type of maneuver for entering vehicle or bicycle: Through, Left, or Right?
WhoYield	If a vehicle or bicyclist enters the crossing during the VU crossing, who yielded: Pedestrian, Bicyclist, Veh, Both, Neither (e.g., the vehicle entered the crossing after the pedestrian has cleared the area), or Ped Should (use when the VU was crossing during the steady upraised hand phase)?
Conflict	Was there a conflict: Yes or No? (A conflict could be present if a user reacted to another user, e.g., a pedestrian stepped back because of an approaching bicyclist or vehicle. If yes, describe briefly in comment column.)
Comment	Add comments that you want to bring to the attention of the rest of the team.

CW = crosswalk; CB = crossbike; Veh = vehicle.

CHAPTER 5. OBSERVATIONS

VULNERABLE USERS

The research team collected data at a total of 30 site periods. The number of VU observed at each site is shown in table 6. More than 20,600 pedestrians and 2,454 bicyclists were observed. In addition, data for 332 scooters and 79 skateboards were gathered. The remaining 38 VU observed were grouped into the other category and included pedestrians on roller skates, in a wheelchair, or on an e-scooter. The other category also included a lawn mower and mopeds. Because the number of minutes reduced per site varied, table 7 provides the number of VU per hour observed at the site period. A few sites had a very high number of pedestrians, with more than 300 per hour. The site with the highest number of bicycles per hour (TX–CST–01) was on a college campus.

Table 6. Number of VU observed at each site.

Site–Period	Pedestrians	Bicycles	Scooters	Skateboards	Other	Total
CA–BER–01–Exi	257	119	0	0	0	376
CA–FRE–01–Exi	60	49	2	0	0	111
CA–FRE–02–Exi	140	28	1	0	0	169
CA–FRE–03–Exi	171	40	2	4	0	217
CA–FRE–04–Exi	147	8	0	0	0	155
CA–FRE–05–Com	106	55	1	0	0	162
CA–FRE–05–Exi	183	82	3	0	0	268
CA–FRE–06–Exi	85	24	0	0	0	109
CA–FRE–07–Com	54	16	0	0	0	70
CA–FRE–07–Exi	38	8	0	0	0	46
CA–FRE–09–Exi	9	24	1	1	0	35
CA–FRE–11–Bef	385	91	2	5	0	483
CA–FRE–11–Aft	183	74	0	10	0	267
CA–FRE–12–Bef	72	85	0	0	0	157
CA–FRE–12–Aft	75	45	7	2	0	129
DC–WAS–01–Bef	1,594	145	35	7	2	1,783
DC–WAS–01–Aft	1,982	68	27	2	4	2,083
DC–WAS–02–Bef	1,450	108	20	2	0	1,580
DC–WAS–02–Aft	2,062	119	33	0	6	2,220
DC–WAS–03–Bef	3,029	275	61	6	4	3,375
DC–WAS–03–Aft	2,914	257	94	4	17	3,286
MD–SSP–01–Exi	222	32	2	0	0	256
MD–SSP–02–Bef	1,806	27	0	0	0	1,833
MD–SSP–02–Aft	1,273	20	2	0	0	1,295
TX–AUS–16–Com	184	52	0	0	1	237
TX–AUS–16–Exi	106	140	0	0	0	246
TX–CST–01–Exi	1,209	307	29	28	0	1,573
UT–SLC–01–Com	332	59	4	1	4	400
UT–SLC–01–Exi	358	54	5	6	0	423
UT–SLC–03–Exi	116	43	1	1	0	161
Total	*20,602*	*2,454*	*332*	*79*	*38*	*23,505*

Table 7. Number of VU per hour observed at each site.

Site–Period	Reduced (h)	Pedestrians (per h)	Bicycles (per h)	Scooters (per h)	Skateboards (per h)	Other (per h)
CA–BER–01–Exi	4.2	61.4	28.4	0.0	0.0	0.0
CA–FRE–01–Exi	4.2	14.3	11.7	0.5	0.0	0.0
CA–FRE–02–Exi	4.7	30.0	6.0	0.2	0.0	0.0
CA–FRE–03–Exi	4.0	43.0	10.1	0.5	1.0	0.0
CA–FRE–04–Exi	5.3	27.9	1.5	0.0	0.0	0.0
CA–FRE–05–Com	4.0	26.2	13.6	0.2	0.0	0.0
CA–FRE–05–Exi	4.0	45.2	20.3	0.7	0.0	0.0
CA–FRE–06–Exi	4.0	21.0	5.9	0.0	0.0	0.0
CA–FRE–07–Com	4.4	12.2	3.6	0.0	0.0	0.0
CA–FRE–07–Exi	4.0	9.4	2.0	0.0	0.0	0.0
CA–FRE–09–Exi	4.0	2.2	6.0	0.2	0.2	0.0
CA–FRE–11–Bef	7.1	53.9	12.7	0.3	0.7	0.0
CA–FRE–11–Aft	4.2	43.9	17.7	0.0	2.4	0.0
CA–FRE–12–Bef	5.3	13.7	16.1	0.0	0.0	0.0
CA–FRE–12–Aft	4.1	18.1	10.9	1.7	0.5	0.0
DC–WAS–01–Bef	6.8	236.0	21.5	5.2	1.0	0.3
DC–WAS–01–Aft	6.9	288.4	9.9	3.9	0.3	0.6
DC–WAS–02–Bef	6.8	214.7	16.0	3.0	0.3	0.0
DC–WAS–02–Aft	7.6	271.4	15.7	4.3	0.0	0.8
DC–WAS–03–Bef	6.4	475.3	43.2	9.6	0.9	0.6
DC–WAS–03–Aft	6.2	467.4	41.2	15.1	0.6	2.7
MD–SSP–01–Exi	4.7	47.7	6.9	0.4	0.0	0.0
MD–SSP–02–Bef	5.3	340.1	5.1	0.0	0.0	0.0
MD–SSP–02–Aft	4.1	313.5	4.9	0.5	0.0	0.0
TX–AUS–16–Com	4.5	40.7	11.5	0.0	0.0	0.2
TX–AUS–16–Exi	6.4	16.6	22.0	0.0	0.0	0.0
TX–CST–01–Exi	4.0	302.3	76.8	7.3	7.0	0.0
UT–SLC–01–Com	4.0	82.9	14.7	1.0	0.2	1.0
UT–SLC–01–Exi	4.4	81.1	12.2	1.1	1.4	0.0
UT–SLC–03–Exi	3.5	32.8	12.2	0.3	0.3	0.0

Table 8 shows the change in VU rates for the sites where before and after data are available. In addition to improving safety, convenience, and comfort for VU, it may be that, over time, the installation of the protected intersection treatments will encourage greater use and higher volumes of VU. Overall, pedestrians per hour between the two periods was similar. There was a slight decrease in the number of bicyclists and a slight increase in the number of scooters between the two periods. For the two California sites, one experienced an increase in bicycle usage, while the other experienced a decrease in bicyclists per hour. The lack of a sizable increase in use may be influenced by only having a few months between the end of construction and the collection of after data. Also, the data represent an hourly basis, and daily, weekly, or annual use may possibly be higher. The attractiveness of the treatment may not yet be realized by the VU in the area.

Table 8. Comparison of pedestrians, bicyclists, and scooters per hour for before-after sites.

VU	Site	Before (VU/h)	After (VU/h)	Change (VU/h)	VU Increase (percent)
Pedestrian	CA–FRE–11	53.9	43.9	−10.0	−19
Pedestrian	CA–FRE–12	13.7	18.1	4.5	33
Pedestrian	DC–WAS–01	236.0	288.4	52.5	22
Pedestrian	DC–WAS–02	214.7	271.4	56.7	26
Pedestrian	DC–WAS–03	475.3	467.4	−7.9	−2
Pedestrian	MD–SSP–02	340.1	313.5	−26.6	−8
Pedestrian	*All before-after sites*	*222.3*	*233.8*	*11.5*	*5*
Bicycle	CA–FRE–11	12.7	17.7	5.0	39
Bicycle	CA–FRE–12	16.1	10.9	−5.2	−32
Bicycle	DC–WAS–01	21.5	9.9	−11.6	−54
Bicycle	DC–WAS–02	16.0	15.7	−0.3	−2
Bicycle	DC–WAS–03	43.2	41.2	−1.9	−4
Bicycle	MD–SSP–02	5.1	4.9	−0.2	−3
Bicycle	*All before-after sites*	*19.1*	*16.7*	*−2.4*	*−12*
Scooters	CA–FRE–11	0.3	0.0	−0.3	−100
Scooters	CA–FRE–12	0.0	1.7	1.7	NC
Scooters	DC–WAS–01	5.2	3.9	−1.3	−24
Scooters	DC–WAS–02	3.0	4.3	1.4	47
Scooters	DC–WAS–03	9.6	15.1	5.5	58
Scooters	MD–SSP–02	0.0	0.5	0.5	NC
Scooters	*All before-after sites*	*3.0*	*4.3*	*1.3*	*42*

NC = not calculated as the before rate was 0.0 VU/h.

YIELDING BEHAVIORS AND POTENTIAL CONFLICTS

Overall, for this database, most of the VU did not have a vehicle enter their space during their crossing. As shown in table 9, 81 percent of the bicyclists and 67 percent of the pedestrians did not have a vehicle enter the crosswalk or crossbike marked area during their crossing. For all site periods, pedestrians were more likely to interact with a vehicle (33 percent of the pedestrian crossings involved a vehicle) compared to bicyclists (19 percent of the bicyclist crossings).

Table 9. Number of potential conflicts between VU and other traffic.

VU Type	Period Type	VU Crossings without Vehicle or Bicyclist Entering (count)	VU Crossings without Vehicle or Bicyclist Entering (percent)	VU Crossings with Vehicle or Bicyclist Entering (count)	VU Crossings with Vehicle or Bicyclist Entering (percent)	Total
Bicyclist	Compare	150	82	32	18	182
Bicyclist	Before	585	80	146	20	731
Bicyclist	After	768	80	190	20	958
Bicyclist	Existing	483	83	100	17	583
Bicyclist	*Subtotal*	*1,986*	*81*	*468*	*19*	*2,454*
Pedestrian	Compare	439	65	237	35	676
Pedestrian	Before	5,855	70	2,481	30	8,336
Pedestrian	After	1,649	53	1,452	47	3,101
Pedestrian	Existing	5,949	70	2,540	30	8,489
Pedestrian	*Subtotal*	*13,892*	*67*	*6,710*	*33*	*20,602*
Both bicyclists and pedestrians	*Grand total*	*15,878*	*69*	*7178*	*31*	*23,056*

Table 10 provides the distribution of who yielded during the interaction between the VU and the vehicle or bicyclist that entered the crossing when the VU was crossing. In most cases the vehicle yielded to the pedestrian or bicyclist or neither yielded (situation occurred when the vehicle entered the crossing after the VU had departed that space). Another interpretation could be that the vehicle yielded to the pedestrian or bicyclist, in that the driver slowed or timed their passage to avoid the pedestrian or bicyclist. The technicians were instructed to use “Veh” for the “who yielded” field when the driver of the vehicle obviously yielded to the VU.

Table 10. Number of interactions between the VU and a vehicle or bicyclist that enters the crossing, arranged by treatment presence and who yielded during the interaction.

VU Type	Who Yielded	Treated (count)	Treated (percent)	Untreated (count)	Untreated (percent)	Total (count)	Total (percent)
Bicyclist	Bicyclist	34	12	7	4	41	9
Bicyclist	Both	15	5	29	16	44	9
Bicyclist	Neither	132	46	82	46	214	46
Bicyclist	Veh	109	38	60	34	169	36
Bicyclist	*Subtotal*	*290*	*100*	*178*	*100*	*468*	*100*
Pedestrian	Both	286	7	339	12	625	9
Pedestrian	Neither	2,420	61	1,760	65	4,180	62
Pedestrian	Pedestrian should	238	6	131	5	369	5
Pedestrian	Pedestrian	125	3	55	2	180	3
Pedestrian	Veh	923	23	433	16	1,356	20
Pedestrian	*Subtotal*	*3,992*	*100*	*2,718*	*100*	*6,710*	*100*

The distribution was compared between the intersections with a protected intersection treatment (i.e., after condition and existing sites) and those intersections without (i.e., the before condition or the comparison sites). For treated sites, more vehicles yielded to bicyclists (38 percent for treated sites compared to 34 percent for untreated sites) and yielded to pedestrians (23 percent for treated sites compared to 16 percent for untreated sites).

The treatment is designed to slow turning vehicles and provide drivers additional opportunity to see the crossing VU. The addition of the treatment should result in more frequent yielding by drivers. For the before-after sites in Fremont, CA, and Silver Spring, MD, a greater percentage of the interactions did result in the vehicle yielding to the pedestrian. As shown in table 11, the percentage of vehicles that yielded to the crossing pedestrian increased for each of the signalized intersections (46 to 59 percent for CA–FRE–11, 48 to 57 percent for CA–FRE–12, and 37 to 42 percent for MD–SSP–02). The number of pedestrians at the Silver Spring, MD, site was much higher and included several inappropriate crossings made outside of the crosswalk or during the steady upraised hand (do not walk) interval, resulting in situations where the pedestrian should have yielded. Overall, for these three signalized intersection sites, 41 percent of the pedestrian crossings in the before period involved the vehicle yielding, while an increase to 47 percent of the crossings in the after period involved the vehicle yielding to the pedestrian.

Table 11. Who yields to a pedestrian at before-after sites in California or Maryland.

Value	Who Yields	CA–FRE–11		CA–FRE–12		MD–SSP–02		All Three Sites	
		Before	After	Before	After	Before	After	Before	After
Count	Both	2	0	0	0	0	1	2	1
Count	Neither	128	48	21	24	150	66	299	138
Count	Pedestrian should	8	6	2	1	98	161	45	15
Count	Pedestrian	6	0	0	1	39	14	108	168
Count	Veh	124	79	21	35	168	172	313	286
Percent	Both	1	0	0	0	0	0	0	0
Percent	Neither	48	36	48	39	33	16	39	23
Percent	Pedestrian should	3	5	5	2	22	39	6	2
Percent	Pedestrian	2	0	0	2	9	3	14	28
Percent	Veh	46	59	48	57	37	42	41	47
Count	*Total*	*268*	*133*	*44*	*61*	*455*	*414*	*767*	*608*

Table 12 shows the distribution of who yielded to the pedestrian at the Washington, DC, sites. These sites have lower speeds and heavy pedestrian and bicyclist activity. The DC–WAS–01 and –02 sites are all-way stop control; therefore, with vehicles legally required to come to a complete stop before proceeding, logically there are fewer situations where a vehicle or a pedestrian would need to yield. In almost all cases, the technicians coded the interactions as having neither or both users yielding. An example of a scenario when neither yield is when a right-turning vehicle enters the crosswalk after the pedestrian has cleared the area. DC–WAS–03 has a traffic control signal with only one observation where the pedestrian or vehicle obviously yielded to the other.

Table 12. Who yields to pedestrian at before-after sites in Washington, DC.

Value	Who Yields	DC–WAS–01 All-Way Stop		DC–WAS–02 All-Way Stop		DC–WAS–03 Signal		All Three DC Sites	
		Before	After	Before	After	Before	After	Before	After
Count	Both	88	107	57	47	190	116	335	270
Count	Neither	301	619	253	427	822	610	1,376	1,656
Count	Pedestrian	2	5	1	0	0	0	3	5
Count	Veh	0	1	0	0	0	0	0	1
Percent	Both	23	15	18	10	19	16	20	14
Percent	Neither	77	85	81	90	81	84	80	86
Percent	Pedestrian	1	1	0	0	0	0	0	0
Percent	Veh	0	0	0	0	0	0	0	0
Count	*Total*	*391*	*732*	*311*	*474*	*1,012*	*726*	*1,714*	*1,932*

TYPICAL TRAVEL PATHS—BICYCLISTS

The typical travel paths for bicyclists were identified at each site. These typical paths could start (or end) on the bicycle lane, the road (i.e., the portion of the street that was not the bicycle lane), or the sidewalk.

Bicyclists Travel Paths for Before-After Sites

For the six before-after sites, most of the sites saw increased use of the bicycle lane-to-bicycle lane path from the before period to the after period, along with a decrease in the sidewalk-to-sidewalk path. See table 13 for specific numbers. The comparison included 1,314 bicyclists. In the before period, only 13 percent of the observed bicyclists were riding from the bicycle lane to the bicycle lane. In the after period for these six sites, the percentage of bicyclists riding from bicycle lane to bicycle lane increased to 52 percent. The percentage of the bicyclists moving from the sidewalk to the sidewalk decreased in the after period (from 21 percent of all bicyclists to only 12 percent in the after period).

Table 13. Bicycle paths at six before-after sites.

Value	VU From Where	VU To Where	Before	After
Count	Bicycle lane	Bicycle lane	95	303
Count	Bicycle lane	Road	28	24
Count	Bicycle lane	Sidewalk	11	47
Count	Road	Bicycle lane	79	17
Count	Road	Road	219	36
Count	Road	Sidewalk	51	15
Count	Sidewalk	Bicycle lane	35	61
Count	Sidewalk	Road	58	11
Count	Sidewalk	Sidewalk	155	69
Percent	Bicycle lane	Bicycle lane	13	52
Percent	Bicycle lane	Road	4	4
Percent	Bicycle lane	Sidewalk	2	8
Percent	Road	Bicycle lane	11	3
Percent	Road	Road	30	6
Percent	Road	Sidewalk	7	3
Percent	Sidewalk	Bicycle lane	5	10
Percent	Sidewalk	Road	8	2
Percent	Sidewalk	Sidewalk	21	12
Count	*All*	*All*	*731*	*583*

Increased use of the crossbike or crosswalk markings is another way to identify the ways that bicyclists are using the space at the intersection. As shown in table 14, the use of the crossbike and crosswalk space increased at CA–FRE–11 (from 51 to 93 percent) and CA–FRE–12 (from 18 to 84 percent). For the other two before-after signalized intersections (DC–WAS–03 and MD–SSP–02), bicyclists frequently either did not use the crossbike space or only used it for part of the crossing (coded as “most” for the question “did bicyclist stay within the crossbike or crosswalk area?”). For the two all-way stop controlled sites in Washington, DC (DC–WAS–01 and –02), the percentage of bicyclists who did not use the space available for bicyclists went from 74 or 81 percent no to only 18 or 13 percent no. In other words, bicyclists at the all-way stop-controlled intersections would more frequently use the crossbike marked area in the after condition.

Table 14. Bicyclists use of crossbike or crosswalk markings at before-after sites (Did bicyclists stay within the crossbike or crosswalk area?).

Site	Period Type	Yes (count)	No (count)	Most (count)	Yes (percent)	No (percent)	Most (percent)	Total (count)
CA–FRE–11	Before	46	23	22	51	25	24	91
CA–FRE–11	After	69	1	4	93	1	5	74
CA–FRE–12	Before	15	38	32	18	45	38	85
CA–FRE–12	After	38	1	6	84	2	13	45
DC–WAS–01	Before	10	107	28	7	74	19	145
DC–WAS–01	After	24	12	32	35	18	47	68
DC–WAS–02	Before	12	88	8	11	81	7	108
DC–WAS–02	After	96	15	8	81	13	7	119
DC–WAS–03	Before	133	94	48	48	34	17	275
DC–WAS–03	After	69	95	93	27	37	36	257
MD–SSP–02	Before	9	11	7	33	41	26	27
MD–SSP–02	After	4	9	7	20	45	35	20
Grand total	*Both*	*525*	*494*	*295*	*40*	*38*	*22*	*1,314*

The addition of the protected intersection treatment could encourage left-turning bicyclists to take advantage of the additional coverage provided by the corner islands. The number of left-turning bicyclists observed was small; therefore, conclusions on whether there were changes in paths cannot be made. For many of the before-after sites, several left-turning bicyclists were observed to start from the sidewalk even after the installation of the treatment. See table 15 for specific numbers.

Table 15. Bicyclists starting position at before-after sites, subdivided by the type of intersection control.

Value	From Where	All-Way Stop Before	All-Way Stop After	Signal Before	Signal After	Grand Total
Count	Bicycle lane	3	5	8	8	24
Count	Road	7	10	17	11	45
Count	Sidewalk	15	14	20	19	68
Percent	Bicycle lane	12	17	18	21	18
Percent	Road	28	34	38	29	33
Percent	Sidewalk	60	48	44	50	50
Count	*All*	*25*	*29*	*45*	*38*	*137*

Bicyclists' Travel Paths for Existing and Comparison Sites

Table 16 provides the distribution of the paths used by bicyclists at the existing and comparison sites, showing that bicyclists most often went from the bicycle lane to the bicycle lane, with a sizable number going from sidewalk to sidewalk (14 percent at existing sites and 19 percent at comparison sites).

Table 16. Bicyclists starting and ending positions at existing and comparison sites.

Value	From Where	To Where	Existing	Compare	Both
Count	Bicycle lane	Bicycle lane	506	102	608
Count	Bicycle lane	Road	30	5	35
Count	Bicycle lane	Sidewalk	76	11	87
Count	Road	Bicycle lane	55	8	63
Count	Road	Road	42	4	46
Count	Road	Sidewalk	17	1	18
Count	Sidewalk	Bicycle lane	81	15	96
Count	Sidewalk	Road	19	1	20
Count	Sidewalk	Sidewalk	132	35	167
Percent	Bicycle lane	Bicycle lane	53	56	53
Percent	Bicycle lane	Road	3	3	3
Percent	Bicycle lane	Sidewalk	8	6	8
Percent	Road	Bicycle lane	6	4	6
Percent	Road	Road	4	2	4
Percent	Road	Sidewalk	2	1	2
Percent	Sidewalk	Bicycle lane	8	8	8
Percent	Sidewalk	Road	2	1	2
Percent	Sidewalk	Sidewalk	14	19	15
Count	*All*	*All*	*958*	*182*	*1,140*

Bicyclists' Travel Paths by Movement Type

The sites were regrouped to reflect whether the data represented whether the intersection was treated (existing or after sites) or untreated (comparison or before sites). As shown in table 17, more bicyclists started their path from the bicycle lane when the intersection was treated (64 percent) compared to untreated (28 percent). Table 18 provides the distribution by movement type. A greater proportion of each movement type started from the bicycle lane for the treated sites, with larger proportions being present for the right turns and through movements.

Table 17. Start of bicyclist path for treated and untreated sites.

Value	From	Untreated	Treated	Grand Total
Count	Bicycle lane	252	986	1,235
Count	Road	362	182	545
Count	Sidewalk	299	373	674
Percent	Bicycle lane	28	64	50
Percent	Road	40	12	22
Percent	Sidewalk	33	24	27
Count	*All*	*913*	*1,541*	*2,454*

Table 18. Start of bicyclist path by movement type for treated and untreated sites.

Value	From	Left Untreated	Left Treated	Right Untreated	Right Treated	Through Untreated	Through Treated
Count	Bicycle lane	16	77	8	15	228	891
Count	Road	30	58	7	3	325	122
Count	Sidewalk	40	58	7	7	252	310
Percent	Bicycle lane	19	40	36	60	28	67
Percent	Road	35	30	32	12	40	9
Percent	Sidewalk	47	30	32	28	31	23
Count	*All*	*86*	*193*	*22*	*25*	*805*	*1,323*

BICYCLISTS BEHAVIORS WITH REGARD TO CORNER ISLANDS

A greater proportion of the bicyclist's path through an intersection is separated from motorized vehicles with the presence of corner islands. At some sites, following the intended path results in longer travel time through the intersection, including having to slow to accommodate the bend-out and bend-in bicycle path that can be generated by the location of the corner island. Each bicyclist's path with respect to the corner island was reviewed to determine if the bicyclists followed the intended path or if they bypassed the corner islands by moving into the travel lane. If the bicyclist was traveling in the opposite direction compared to the direction the bicyclists should be going in the neighboring bicycle lane, the bicyclist was coded as "Opp." The remaining bicyclists were coded as either "To Left" or "To Right" with respect to the corner island. The path was coded as "To Left" when the bicyclist went to the left and bypassed the corner island. The path was coded as "To Right" when the bicyclist followed the marked crossbike area and went to the right of the corner island.

With regard to sites with raised islands (table 19), most of the bicyclists (66 percent) did follow the marked path and went to the right of the corner islands. Sites where more than 40 percent of the bicyclists bypassed the corner island and went to the left included CA–FRE–09, MD–SSP–01, and MD–SSP–02. The bicyclists appeared to be seeking the shortest path for many of these cases. A high percentage of the bicyclists at these sites (22 percent overall) were traveling the opposite direction with respect to the bicycle lanes. In many cases, these bicyclists came from or were going to the sidewalk, perhaps to access a nearby development, and used the crosswalk for part of their crossing.

Table 19. Bicyclist paths with respect to the corner island for sites with raised islands or a mix of raised islands and pylons.

Site	Period	To Left (count)	To Right (count)	Opp (count)	To Left (percent)	To Right (percent)	Opp (percent)	Total (count)
CA–BER–01	Existing	31	81	7	26	68	6	119
CA–FRE–01	Existing	4	41	4	8	84	8	49
CA–FRE–02	Existing	2	25	1	7	89	4	28
CA–FRE–03	Existing	1	32	7	3	80	18	40
CA–FRE–04	Existing	0	5	3	0	63	38	8
CA–FRE–05	Existing	0	75	7	0	91	9	82
CA–FRE–09	Existing	10	13	1	42	54	4	24
CA–FRE–11	After	1	47	26	1	64	35	74
CA–FRE–12	After	3	30	12	7	67	27	45
MD–SSP–01	Existing	14	17	1	44	53	3	32
MD–SSP–02	After	11	4	5	55	20	25	20
TX–AUS–16	Existing	8	89	43	6	64	31	140
TX–CST–01	Existing	26	187	94	8	61	31	307
UT–SLC–01	Existing	7	33	14	13	61	26	54
All	*All*	*118*	*679*	*225*	*12*	*66*	*22*	*1,022*

To Left = bicyclist rode to left of corner island; To Right = bicyclist rode to right of corner island; Opp = bicyclist rode in the opposite direction as compared to the neighboring one-way bicycle lane.

Table 20 provides the bicyclist paths for those sites where the corner island was created using pylons. Again, most of the bicyclists (58 percent) followed the marked path and went to the right of the corner island. A sizable number (17 percent) traveled in the opposite direction with respect to the bicycle lane or rode through the pylons (19 percent).

Table 20. Bicyclist paths with respect to the corner island for sites with pylons.

Site	Period	Thru (count)	To Left (count)	To Right (count)	Opp (count)	Thru (%)	To Left (%)	To Right (%)	Opp (%)	Total (count)
CA–FRE–06	Existing	1	0	23	0	4	0	96	0	24
CA–FRE–07	Existing	2	0	6	0	25	0	75	0	8
DC–WAS–01	After	1	6	37	24	1	9	54	35	68
DC–WAS–02	After	5	9	91	14	4	8	76	12	119
DC–WAS–03	After	78	15	114	50	30	6	44	19	257
UT–SLC–03	Existing	10	1	30	2	23	2	70	5	43
All	*Both*	*97*	*31*	*301*	*90*	*19*	*6*	*58*	*17*	*519*

Thru = bicyclist rode through the pylons; To Left = bicyclist rode to left of corner island; To Right = bicyclist rode to right of corner island; Opp = bicyclist rode in the opposite direction as compared to the neighboring one-way bicycle lane.

WAITING LOCATIONS

The locations where pedestrians and bicyclists waited were identified. In most cases, the pedestrian or bicyclist did not have to wait before crossing, especially for the all-way stop intersections. For all-way stop intersections, 95 percent of the VU did not wait before entering the crossing. While the details of State laws vary, for all-way stops the general rule is first come first served; however, when pedestrians wish to cross the road, they take priority over vehicles. In Washington, DC: "When official traffic-control signals are not in place or not in operation, the driver of a vehicle shall stop and give the right-of-way to a pedestrian crossing the roadway within any marked crosswalk or unmarked crosswalk at an intersection."(55)

For the signalized intersections included in this evaluation, overall, 54 percent of the VU did not wait. Of those who waited, 44 percent waited on the ramp, 30 percent on the sidewalk, and 10 percent on the corner island.

The two intersections that converted the right-turn lane to the protected intersection treatment had similar trends (CA–FRE–11 and –12; see table 21 for specific numbers). Most of the pedestrians who waited on the channelizing island in the before condition were now waiting in the pedestrian ramp area in the after condition. These pedestrians did not have to weave through the moving right-turning motorized vehicles to reach the refuge area where they stood and waited before crossing the intersection. Bicyclists also shifted from waiting on the right-turn lane corner island to waiting either on the pedestrian ramp or the bicycle lane ramp.

Table 21. Waiting area for bicyclists in before and after periods for CA–FRE–11 and CA–FRE–12.

	CA–FRE–11		CA–FRE–12		CA–FRE–11		CA–FRE–12	
Wait Area	**Before (count)**	**After (count)**	**Before (count)**	**After (count)**	**Before (percent)**	**After (percent)**	**Before (percent)**	**After (percent)**
Bicycle lane	4	26	14	15	4	35	16	33
Bicycle waiting	0	0	0	1	0	0	0	2
Island	54	0	29	0	59	0	34	0
NA	17	21	30	16	19	28	35	36
Other	0	2	0	0	0	3	0	0
Pedestrian ramp	0	24	0	13	0	32	0	29
Road or CW or CB	15	1	11	0	16	1	13	0
Sidewalk	1	0	1	0	1	0	1	0
All	*91*	*74*	*85*	*45*	*100*	*100*	*100*	*100*

NA = not applicable.

Table 22. Waiting area for pedestrians in before and after periods for CA–FRE–11 and CA–FRE–12.

Wait Area	CA–FRE–11 Before (count)	CA–FRE–11 After (count)	CA–FRE–12 Before (count)	CA–FRE–12 After (count)	CA–FRE–11 Before (percent)	CA–FRE–11 After (percent)	CA–FRE–12 Before (percent)	CA–FRE–12 After (percent)
Bicycle lane	0	2	0	2	0	1	0	3
Bicycle waiting	0	4	0	0	0	2	0	0
Island	309	15	67	4	80	8	93	5
NA	65	26	1	6	17	14	1	8
Other	0	4	0	2	0	2	0	3
Ramp	1	129	0	61	0	70	0	81
Road or CW or CB	2	1	2	0	1	1	3	0
Sidewalk	8	2	2	0	2	1	3	0
All	*385*	*183*	*72*	*75*	*100*	*100*	*100*	*100*

MOTORISTS RIGHT-TURN BEHAVIORS

This section provides observations on motorists right-turn behaviors such as the speed used when turning right.

Speeds at Available Before-After Sites

The following sections contain details about the right-turn speed study.

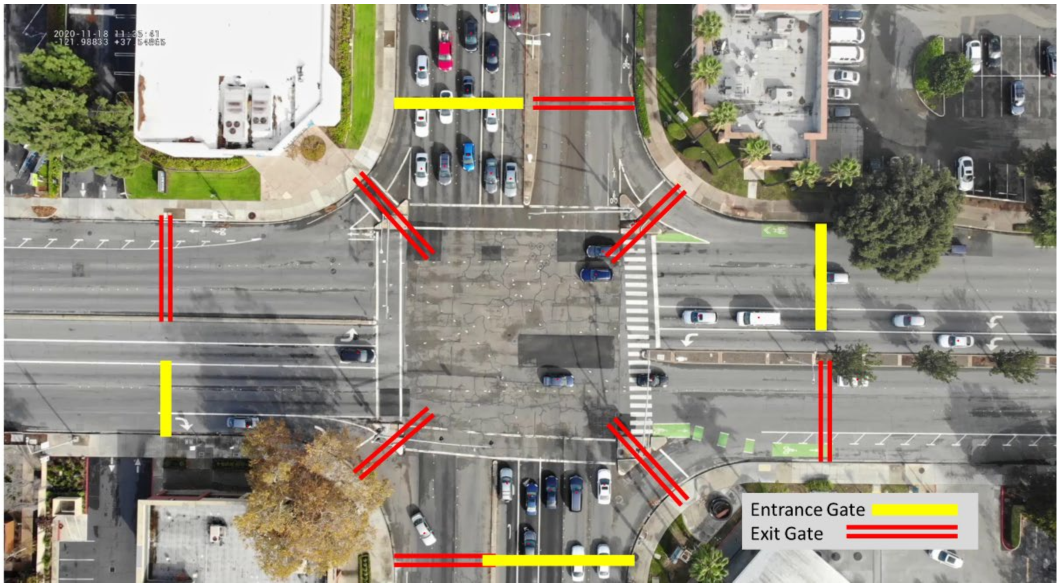
Study Site Characteristics

While video was used to collect user behaviors at all sites, the video cameras installed near the intersection, such as on mast arms, are not positioned so that right-turn speed could be measured. However, when drones were used, the speeds of right-turning vehicles could be gathered. Two California sites used drones and can provide data for before and after the installation of the treatment. Right-turn speed data, along with the associated vehicle type and headway, were reviewed for the two before-after sites where the free-flow, right-turn lane was replaced with protected intersection elements. The study team placed "gates" in the following locations for each intersection corner:

- On the approach to the turn.
- At the corner of the intersection.
- Where the turning movement was completed.

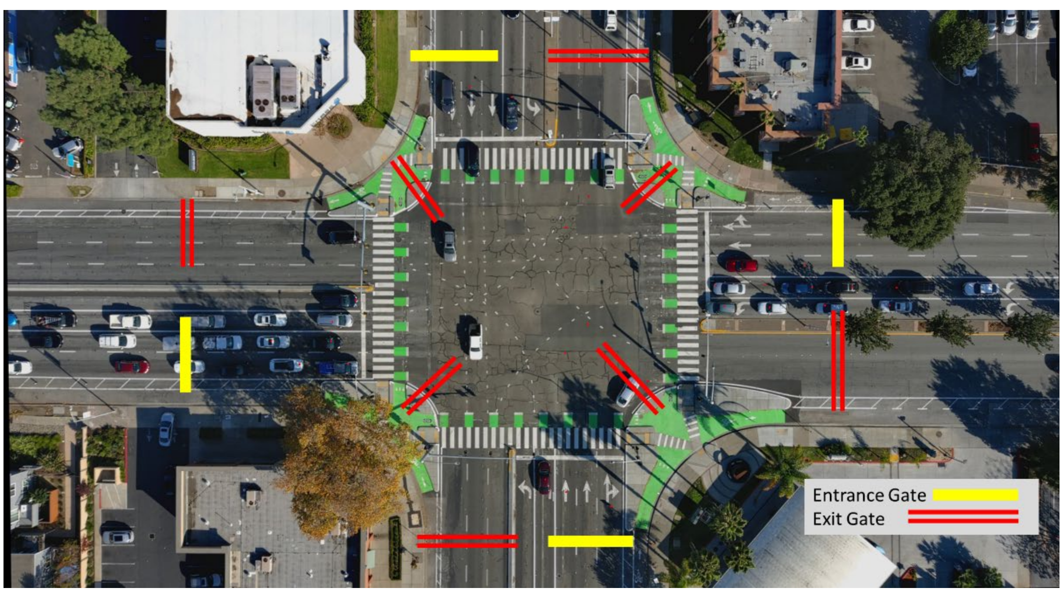
In instances where the starting or completion points were not captured in the video, the closest captured locations were selected. The study team attempted to place the gates in similar locations for the before and after periods.

Figure 44 and figure 45 show assigned gates for before and after periods for CA–FRE–11. Similarly, figure 46 and figure 47 show gates for before and after periods for CA–FRE–12. The orientation of the drone videos for before and after conditions were not similar, and the research team assigned gate names according to their geographic location rather than the location relative to the captured pictured frame.



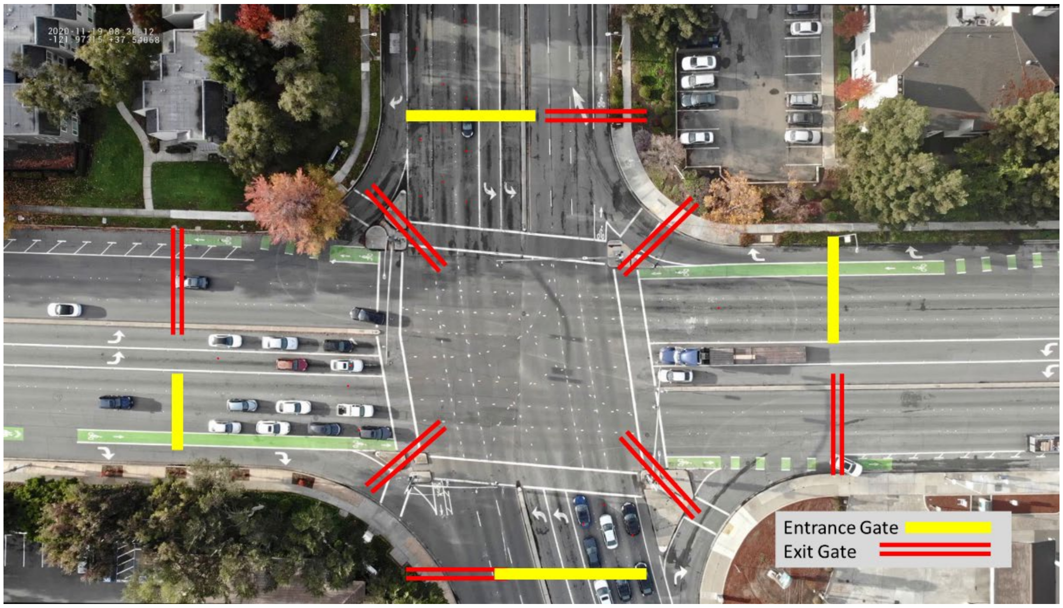
Source: FHWA.

Figure 44. Photo. CA–FRE–11 before-period gates.



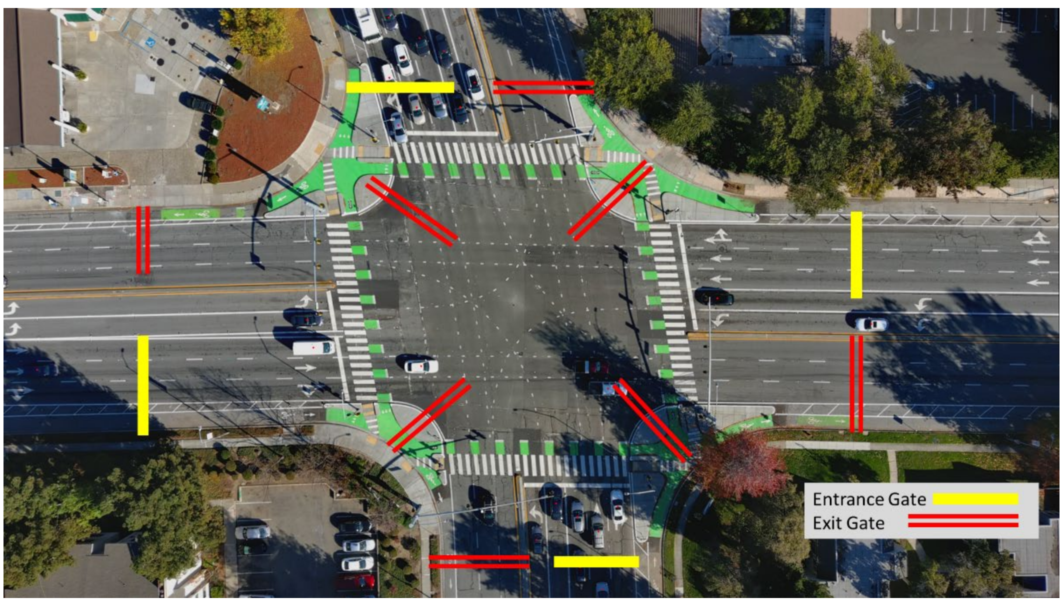
Source: FHWA.

Figure 45. Photo. CA–FRE–11 after-period gates.



Source: FHWA.

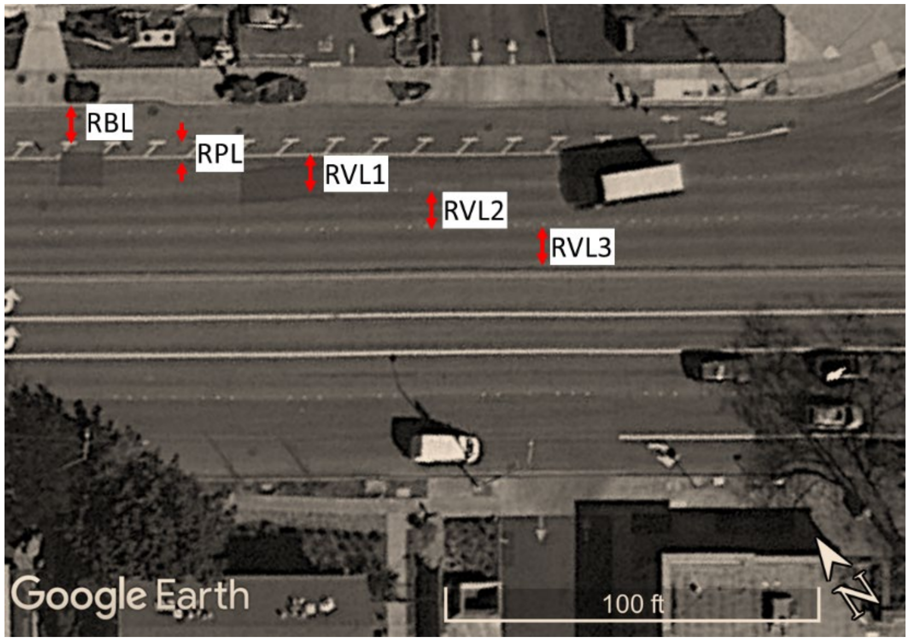
Figure 46. Photo. CA–FRE–12 before-period gates.



Source: FHWA.

Figure 47. Photo. CA–FRE–12 after-period gates.

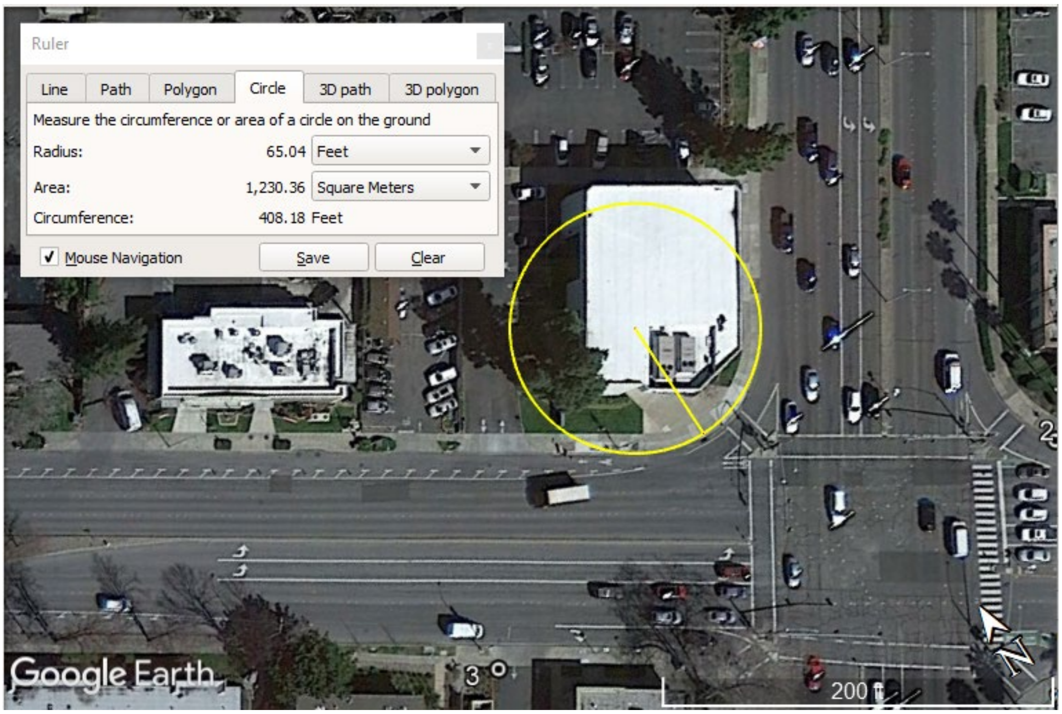
The resulting database from image processing (including vehicle type, vehicle speed, and headway at the three gates) was postprocessed to acquire the receiving lane for the turning vehicle. Vehicles turning into the farthest lane have a larger effective turning radius and can have a larger turning speed. Figure 48 illustrates the receiving lanes that were considered and included the bicycle lane (RBL), the parking lane (RPL), the inside vehicle lane (RVL1), the middle vehicle lane (RVL2), or the outside vehicle lane (RVL3).



Original map: © 2022 Google® Earth™[54], modified by FHWA (see Acknowledgments).

Figure 48. Photo. Receiving lane names.

The turning radii and turn angle were obtained using measuring tools in Google Earth. Because the current Google Earth aerial view only reflected the before condition, the research team added an image overlay using a frame of the captured video. The captured videos' viewing angles could be slightly different from the Google Earth Pro's viewing angle, but the error introduced by this difference was negligible. Figure 49 shows an example of measuring the turning radius and table 23 shows the radii and turn angle for the study corners.



Original map: © 2022 Google® Earth™(54), modified by FHWA (see Acknowledgements).

Figure 49. Photo. Measuring turning radius using Google Earth Pro.

Table 23. Turning radii for intersection corners.

Site	Period	East Leg Entry Radius (ft)	East Leg Entry Turn Angle (degree)	North Leg Entry Radius (ft)	North Leg Entry Turn Angle (degree)	South Leg Entry Radius (ft)	South Leg Entry Turn Angle (degree)	West Leg Entry Radius (ft)	West Leg Entry Turn Angle (degree)
CA–FRE–11	After	25	90	25	90	25	90	25	90
CA–FRE–11	Before	65	90	65	90	65	90	65	90
CA–FRE–12	After	30	105	22	75	25	90	25	90
CA–FRE–12	Before	120	119	60	69	65	90	60	90

Vehicle Speed Data

Speed and headway information were collected with a goal of having at least 30 right-turning vehicles at each intersection corner for each period (before and after). Table 24 shows the number of right-turn movements for each intersection corner. Upon review of the data, the research team decided to remove vehicles that were not identified as being a car from the evaluation due to small sample sizes for the other categories. Cars that turned into the bicycle lane (one car) or parking lane (seven cars) were also removed.

Table 24. Count of right-turning cars for study intersections.

Site	Site Leg	Before (count)	After (count)
CA–FRE–11	East leg entry	77	38
CA–FRE–11	North leg entry	48	38
CA–FRE–11	South leg entry	109	54
CA–FRE–11	West leg entry	108	66
CA–FRE–11	Subtotal for site	342	196
CA–FRE–12	East leg entry	101	61
CA–FRE–12	North leg entry	29	31
CA–FRE–12	South leg entry	97	114
CA–FRE–12	West leg entry	78	83
CA–FRE–12	Subtotal for site	305	289
Both sites	*Grand total*	*647*	*485*

Additional review of a sample of the data revealed that the signal indication for the right-turning vehicle was needed. Each right-turning vehicle was coded as having one of the following conditions:

- Green: The signal indication on the approach was green.
- Red: The signal indication on the approach was red.
- Red-no conflict: The signal indication on the approach was red; however, the movement with the green did not generate conflicting vehicles. For example, when the north and south approaches had green for the left-turn movements, right-turning vehicles on the east and west approach would have a red indication but no conflicting vehicles. In this scenario, the right-turning vehicles on the north and south approach would be coded as "Red" since they would conflict with the left-turning vehicles. The vehicle was also coded as "Red" if the right-turning speed was influenced by a U-turning vehicle.

Table 25 shows that, overall, the average right-turn speed during a green signal indication for cars turning into a travel lane went from 16.0 mph in the before period down to 13.3 mph in the after period. Another interesting trend shown in table 26 is that fewer right-turning vehicles turned during the red indications after the treatment was installed. For CA–FRE–11, the proportion that turned during the red indications went from 52 percent in the before condition to 16 percent in the after condition. For CA–FRE–12, the change was 58 percent to 29 percent.

Table 25. Average right-turn speed for before and after periods.

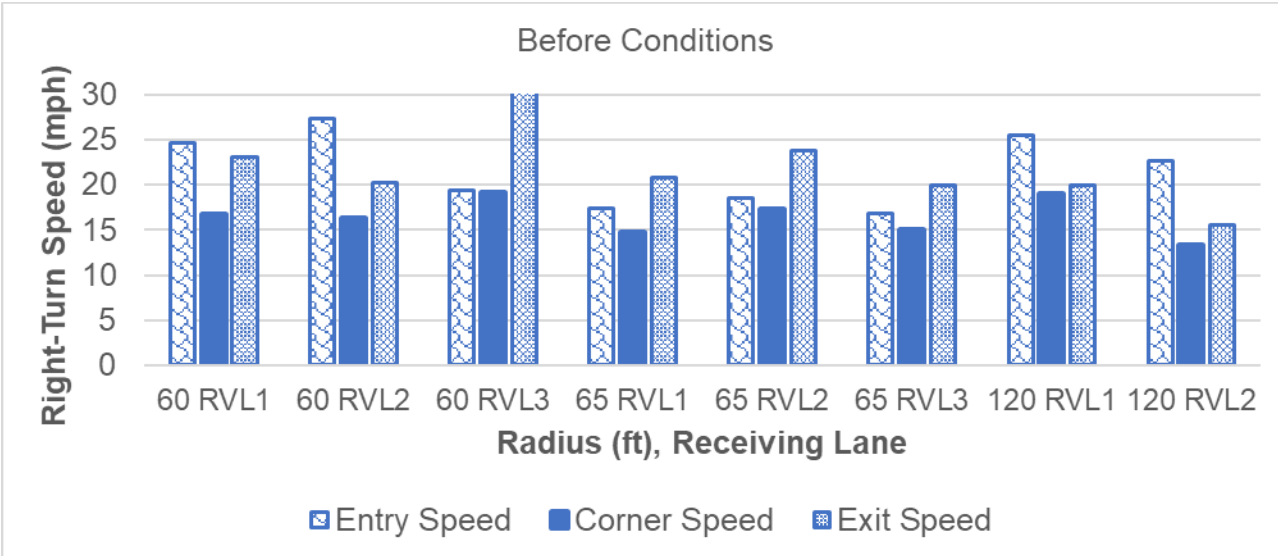
Signal Indication	Site	Before (count)	Before (average corner speed in mph)	After (count)	After (average corner speed in mph)	Count
Green	CA–FRE–11	162	14.8	164	13.2	326
Green	CA–FRE–12	126	17.6	205	13.5	331
Green	*Total or weighted average speed*	*288*	*16.0*	*369*	*13.4*	*657*
Red	CA–FRE–11	141	7.5	15	10.6	156
Red	CA–FRE–12	139	8.9	38	12.3	177
Red	*Total or weighted average speed*	*280*	*8.2*	*53*	*11.8*	*333*
Red-no conflict	CA–FRE–11	35	11.6	16	9.7	51
Red-no conflict	CA–FRE–12	37	10.7	46	12.3	83
Red-no conflict	*Total or weighted average speed*	*72*	*11.1*	*62*	*11.6*	*134*
All	*Total or weighted average speed*	*640*	*12.0*	*484*	*13.0*	*1,124*

Table 26. Distribution of right-turning vehicles by signal indication.

Signal Indication	CA–Fre–11–Before (count)	CA–FRE–11–Before (percent)	CA–FRE–11–After (count)	CA–FRE–11–After (percent)	CA–FRE–12–Before (count)	CA–FRE–12–Before (percent)	CA–FRE–12–After (count)	CA–FRE–12–After (percent)
Green	162	48	164	84	126	42	205	71
Red	141	42	15	8	139	46	38	13
Red-no conflict	35	10	16	8	37	12	46	16
Grand total	*338*	*100*	*195*	*100*	*302*	*100*	*289*	*100*

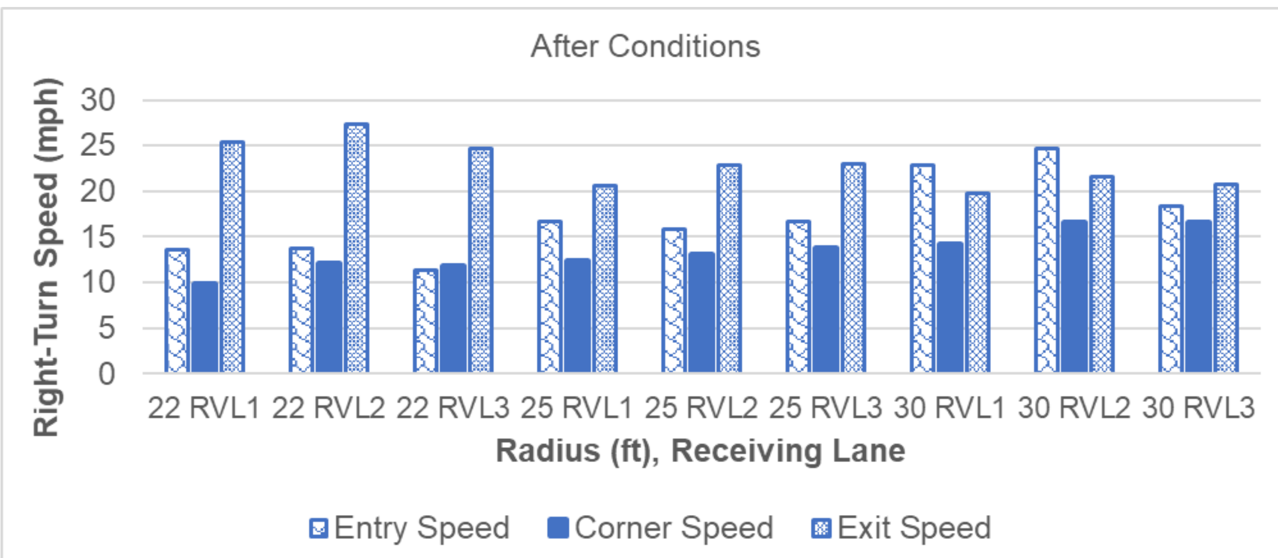
Right-Turn Speeds at Entry, Corner, and Exit

The study team collected speed values at the beginning (or entry), corner, and end (or exit) of the right turn. Figure 50 and figure 51 show the average speed of cars during a green signal indication at the entry, corner, and exit points of the turning movement for different turning radii and receiving lanes for the before and after periods, respectively. As illustrated in these plots and as expected, the corner speeds, as opposed to the entry or exit speeds, were the lowest speed, regardless of the receiving lane or turning radius.



Source: FHWA.

Figure 50. Graph. Entry, corner, and exit right-turn speeds for vehicles turning on a green signal indication, based on turning radius and receiving lane, for the before period.



Source: FHWA.

Figure 51. Graph. Entry, corner, and exit right-turn speeds for vehicles turning on a green signal indication, based on turning radius and receiving lane, for the after period.

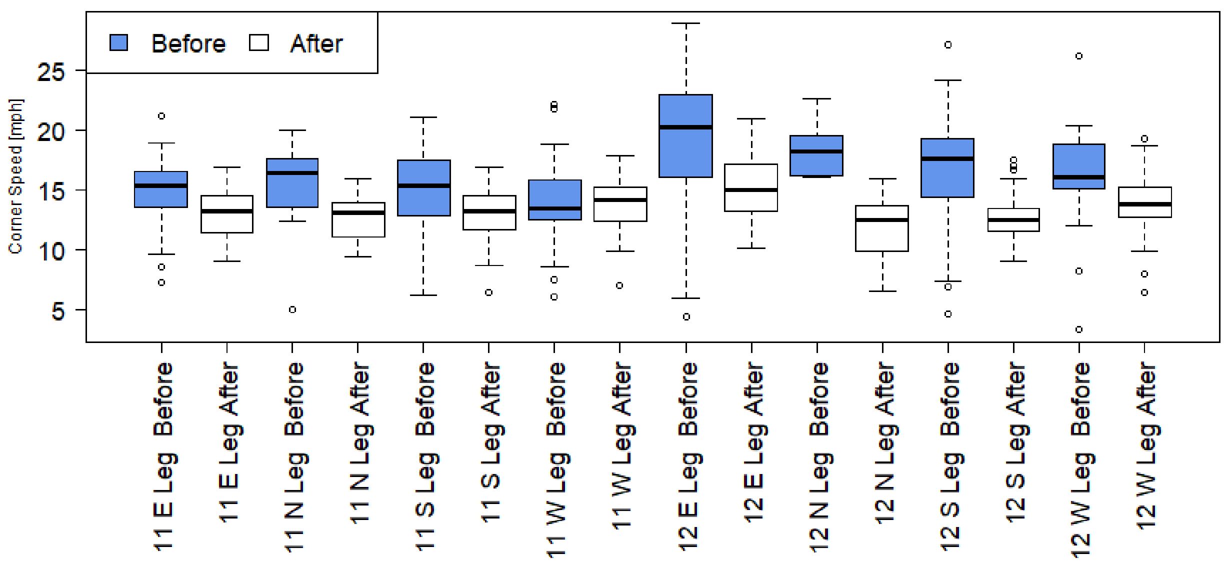
Comparison of Right-Turn Corner Speeds

When drivers turn into a lane other than the one nearest to the curb, they are increasing their effective radius. Therefore, the effective radius, or the receiving lane, needs to be considered. Table 27 shows that 89 percent of the right turns were into the nearest vehicle lane in the before period for CA–FRE–11 (free-flow, right-turn lane is present) when only 26 percent of the right turns turned into that lane in the after period. When multiple receiving lanes are available, the data for these two sites show that drivers are more likely to use a larger radius when making the right turn.

Table 27. Count (or percent) of cars by site, period, and receiving lane.

Receiving Lane	CA–FRE–11–Before (count)	CA–FRE–11–Before (percent)	CA–FRE–11–After (count)	CA–FRE–11–After (percent)	CA–FRE–12–Before (count)	CA–FRE–12–Before (percent)	CA–FRE–12–After (count)	CA–FRE–12–After (percent)
RVL1	149	89	44	26	103	80	23	11
RVL2	17	10	86	50	24	19	120	58
RVL3	1	1	42	24	2	2	63	31
Grand total	*167*	*100*	*172*	*100*	*129*	*100*	*206*	*100*

Figure 52 shows box plots of the measured speeds at each corner for both the before and after periods. This graph illustrates another potential characteristic of the protected intersection design. Not only did the average speed drop compared to the before conditions (with one exception in CA–FRE–11 west leg), the range of speed also dropped. The box plot represents the interquartile range of the data, in other words the data between the lower quartile and the upper quartile. The solid bar represents the median value. As shown in figure 52, the boxes for the after periods are smaller than the boxes for the before period (except CA–FRE–12 north leg), indicating that vehicles turn right not only more slowly, but also in a more uniform manner.



Source: FHWA.

Figure 52. Graph. Vehicle speeds at each intersection corner for study sites during before and after conditions.

Linear Regression of Right-Turn Corner Speeds

The research team conducted a regression analysis to determine how the corner speed was impacted by the vehicle headway, corner radius, and receiving lane. The study team added the period, receiving lane, turning radius, and corner headways as independent factors to the model. The model was done using only cars (no motorcycles or heavy vehicles) that had a green signal when they arrived at the intersection and turned into vehicle receiving lanes (vehicles that turned into parking lanes or bicycle lanes were eliminated). Table 28 shows the estimates, standard deviations, *t* values, and *p* values for the parameters in the simple linear regression model. Cars turning into RVL1 were the base for the model. This study clearly showed that while turning radius has a positive correlation with turning speed, the target lane choice also impacts right-turning speed.

Table 28. Linear regression parameters.

Parameter	Estimate	Standard Error	*t* Value	*p* Value
After	10.23	0.434771	23.529	<0.0001
Before	10.32	0.723572	14.269	<0.0001
RVL2	1.34	0.366833	3.643	0.0003
RVL3	1.69	0.480656	3.506	0.0005
Turning radius	0.07	0.009203	7.803	<0.0001
Corner headway	0.01	0.005019	2.703	0.0071

Residual standard error: 3.22 on 597 degrees of freedom; Multiple *R*-squared: 0.9544; Adjusted *R*-squared: 0.9539; *F*-statistic: 2081 on 6 and 597 degrees of freedom, *p* value: <0.0001.

The equation for right-turn speed is given in figure 53. The coefficient values for the equation in figure 53 are shown in table 28. Figure 54 shows the model functional form with the corresponding coefficient estimate values.

$$v_{RT} = \left(\beta_a I_A + \beta_b I_B + \beta_c I_{RVL2} + \beta_d I_{RVL3} + \beta_e \mathrm{R} + \beta_f \mathrm{CH}\right)$$

Figure 53. Equation. Median right-turn speed functional form.

Where:

v_{RT} = predicted median right-turn speed for vehicle of interest (mph).
β_i = calibration coefficients.
I_A = indicator for after period (1.0 for after period, 0.0 otherwise).
I_B = indicator for before period (1.0 for before period, 0.0 otherwise).
I_{RVL2} = indicator for vehicle turning into RVL2 (1.0, 0.0 otherwise).
I_{RVL3} = indicator for vehicle turning into RVL3 (1.0, 0.0 otherwise).
R = corner turning radius (ft).
CH = corner headway (s).

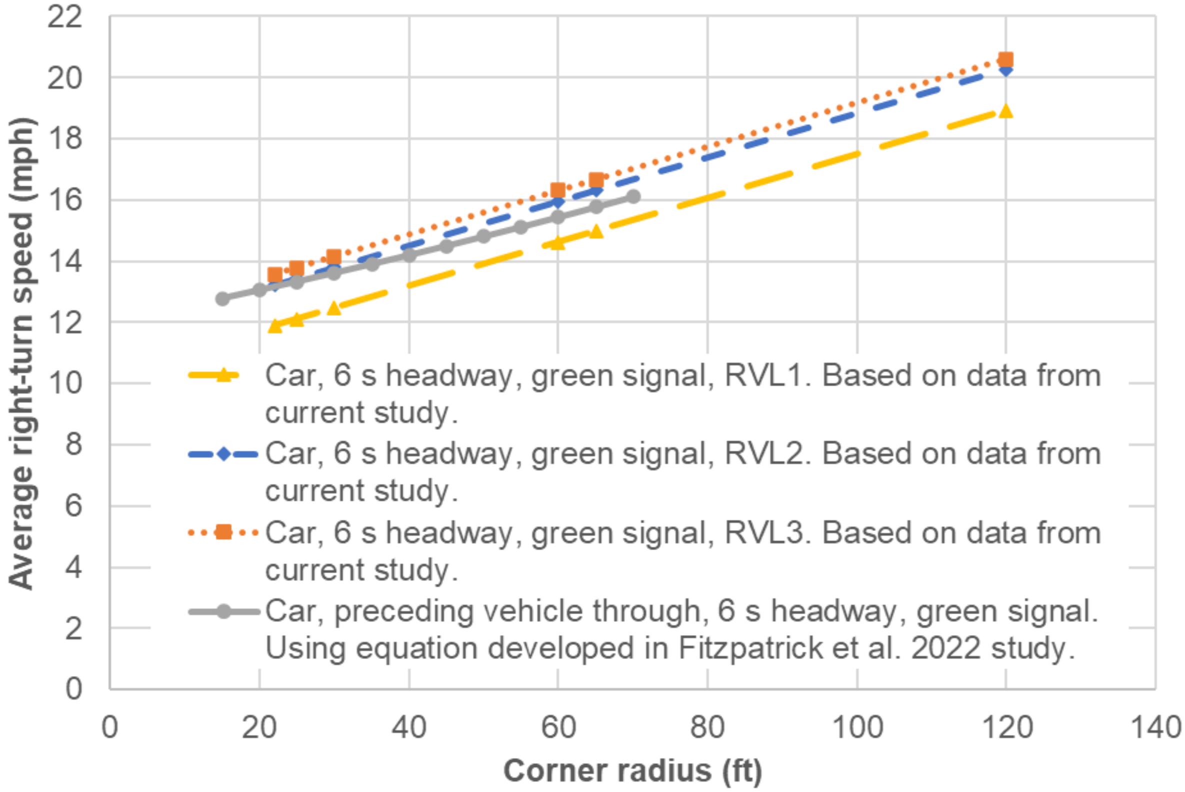
$$v_{RT} = (10.23 I_A + 10.32 I_B + 1.34 I_{RVL2} + 1.69 I_{RVL3} + 0.07\mathrm{R} + 0.01\mathrm{CH})$$

Figure 54. Equation. Median right-turn speed functional form with coefficients.

Fitzpatrick et al. previously studied right-turn speeds at 31 urban intersections in TX.[36] The path (i.e., the receiving lane) followed by the vehicle during the turn was used to calculate the vehicle speed and not included in the modeling efforts. Most of the vehicles turned into the nearest lane to the curb in that study. From those 31 Texas intersections, the variables that impact right-turn speeds included turning radii, vehicle type (car or trucks), signal indication at the time of arrival (yellow or green), whether the preceding vehicle was going straight or turning right, and vehicle headway.

Figure 55 compares the findings between this study and the Fitzpatrick et al. work.[36] The range of radii included in the Fitzpatrick et al. work was 15 to 70 ft, while the range of radii included in this evaluation was 22 to 120 ft. As shown in figure 55, the plot of the equation from both studies shows similar trends. The current study provided the opportunity to illustrate the difference in speeds between vehicles turning into different receiving lanes. The RVL2 and the RVL3 had significantly higher turning speed values.

This evaluation demonstrated that a protected intersection results in reduced turning speeds with the installation of smaller corner radii.



Source: FHWA.

Note: Lines with squares, diamonds, and triangles are for the current study. Lines with circles are for the Fitzpatrick et al. 2022 study.

Figure 55. Graph. Comparison of findings between this current study and the Fitzpatrick et al. 2022 study.[36]

Sites with Apron Markings or Pylons

A few of the sites included truck aprons, had pavement markings to simulate a truck apron, or included pylons, to assist in informing the motorist of the edge of the corner. The research team observed that some of the right-turning vehicles drove on the truck apron, which was not unexpected because the truck apron is provided in situations where the additional space is needed. Additional review was conducted for those sites with an apron or pylons. Table 29 summarizes the corner characteristics for the sites included in this review. For the MD–SSP–01–Exi site, all right-turning vehicles were visually reviewed to determine whether the vehicle drove on the apron. The type of vehicle was also identified. For the other sites, the trajectories for a sample of the available videos, generally about 15 min, were reviewed to count the number of vehicles that drove in the marked area.

Table 29. Characteristics of sites with truck apron or pylons with drone video available.

Site–Period	Presence of Raised Truck Apron	Other Corner Characteristics	Presence of Pylons
CA–BER–01–Exi	No.	*Pavement markings and buttons create a flush truck apron on all four corners.*	No.
CA–FRE–06–Exi	No.	*Pavement markings create a flush truck apron.*	*Yes.*
CA–FRE–07–Exi	No.	*Pavement markings in NW corner create a small flush truck apron.*	*Yes, on NE and NW corners.*
MD–SSP–01–Exi	*Yes, raised apron present on all four corners.*	No additional comments.	No.
MD–SSP–02–Aft	*Yes, raised on SW corner.*	Yellow raised markings are included on NE and SE corner that create a flush truck apron. White markings are included on NW corner.	*Yes, on NE and SE corners.*
UT–SLC–03–Exi	No	No additional comments	*Yes.*

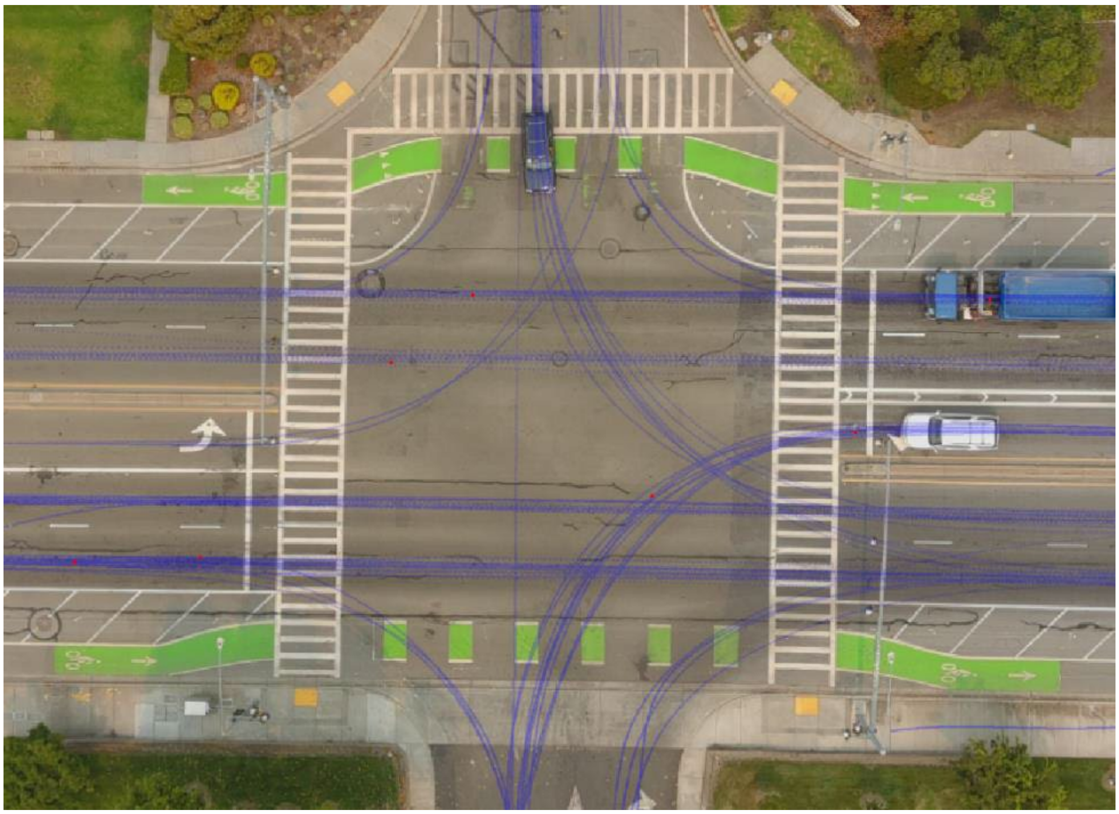
NW = northwest; NE = northeast; SW = southwest; SE = southeast.
Note: Shaded cells with *italic* type represent the cells of greatest interest for evaluation.

In most cases, only a few of the vehicles used the apron when turning. As shown in Table 30 none of the observed vehicles used the raised or flush aprons at CA–FRE–06–Exi, CA–FRE–07–Exi, or MD–SSP–02–Aft. A screen capture of the trajectories for these three sites are shown in figure 56, figure 57, and figure 58, respectively.

Table 30. Percentage of vehicles on the truck apron.

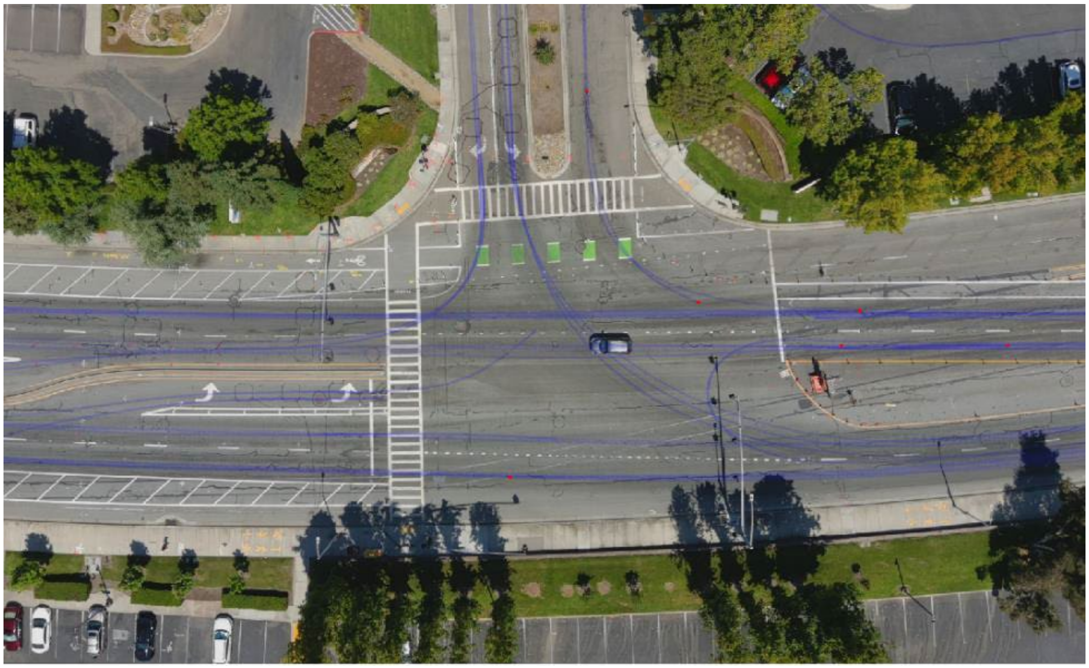
Site–Period	Corners Considered	Vehicles on Apron (No.)	Vehicles Outside Apron (No.)	Total Vehicles (No.)	Vehicles on Apron (percent)
CA–BER–01–Exi	All 4	18	19	37	4
CA–FRE–06–Exi	NE, NW	0	23	23	0
CA–FRE–07–Exi	NE, NW	0	15	15	0
MD–SSP–01–Exi	All 4	97	448	545	18
MD–SSP–02–Aft	All 4	0	11	11	0
UT–SLC–03–Exi	All 4	4	16	20	20

NE = northeast; NW = northwest.



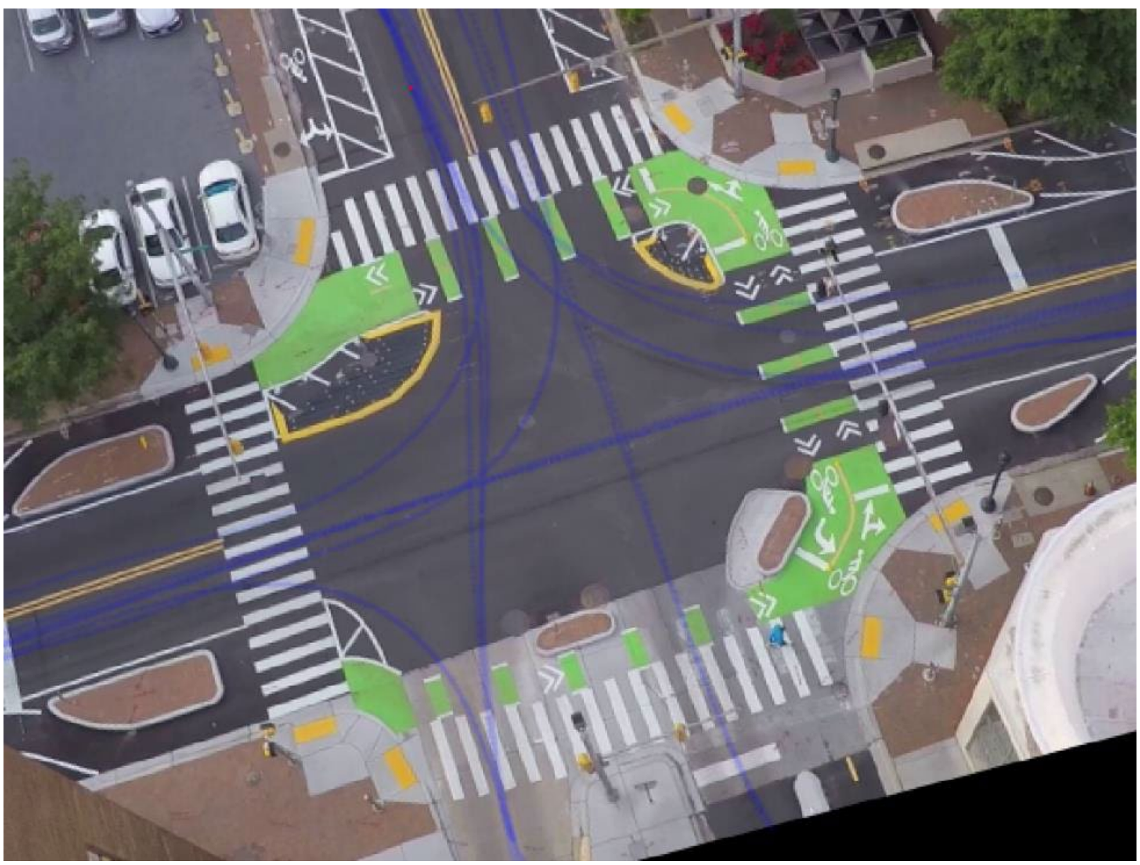
Source: FHWA.

Figure 56. Photo. Trajectories of all vehicles for a 4-min, 47-s interval at CA–FRE–06–Exi.



Source: FHWA.

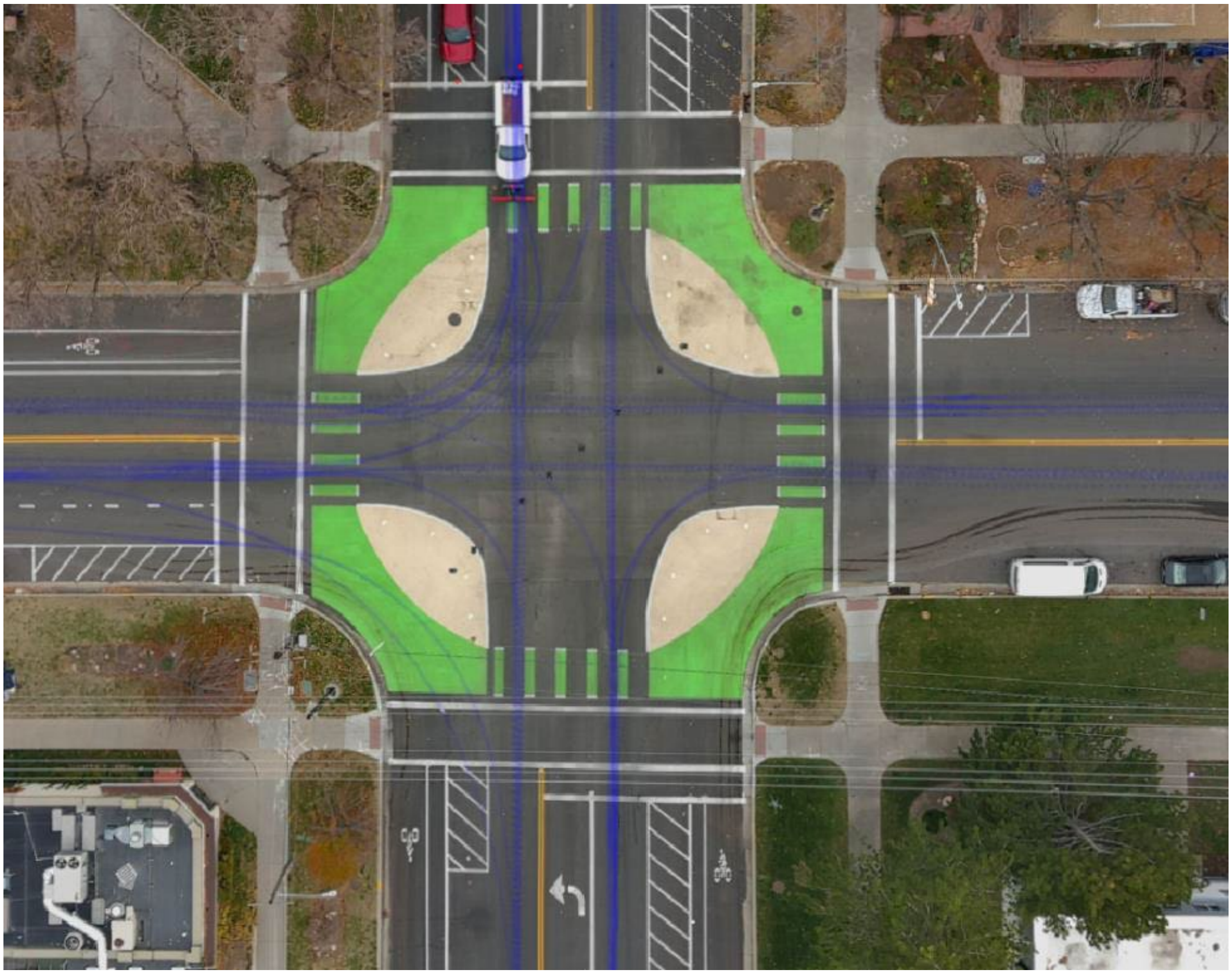
Figure 57. Photo. Trajectories of all vehicles for a 4-min, 47-s interval at CA–FRE–07–Exi.



Source: FHWA.

Figure 58. Photo. Trajectories of all vehicles for a 5-min, 01-s interval at MD–SSP–02–Aft.

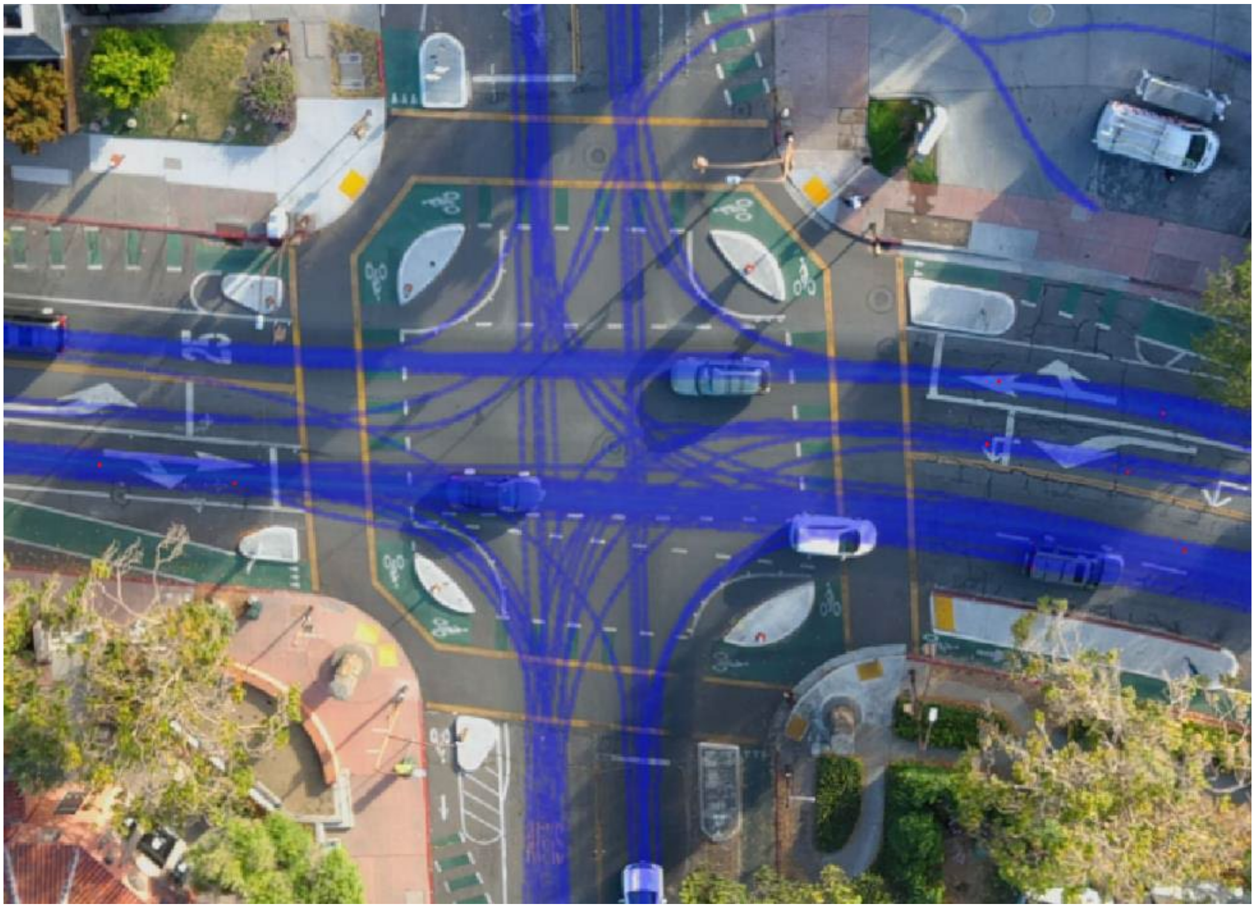
Several of the right-turning vehicles at UT–SLC–03–Exi drove on the area of the intersection marked with green markings (the area located behind the island). For the period reviewed, approximately 20 percent of the vehicles drove either on the area with green markings or on the area marked as an island (area looks tan in the example shown in figure 59).



Source: FHWA.

Figure 59. Photo. Trajectories of all vehicles for a 4-min, 47-s interval showing some vehicles driving inside the bottom left pylons (on the bicycle area) in UT–SLC–03–Exi study site.

About half of the right-turning vehicles (18 of 37 right-turning vehicles) at CA–BER–01–Exi drove on the flush truck apron. Examples are shown in figure 60.



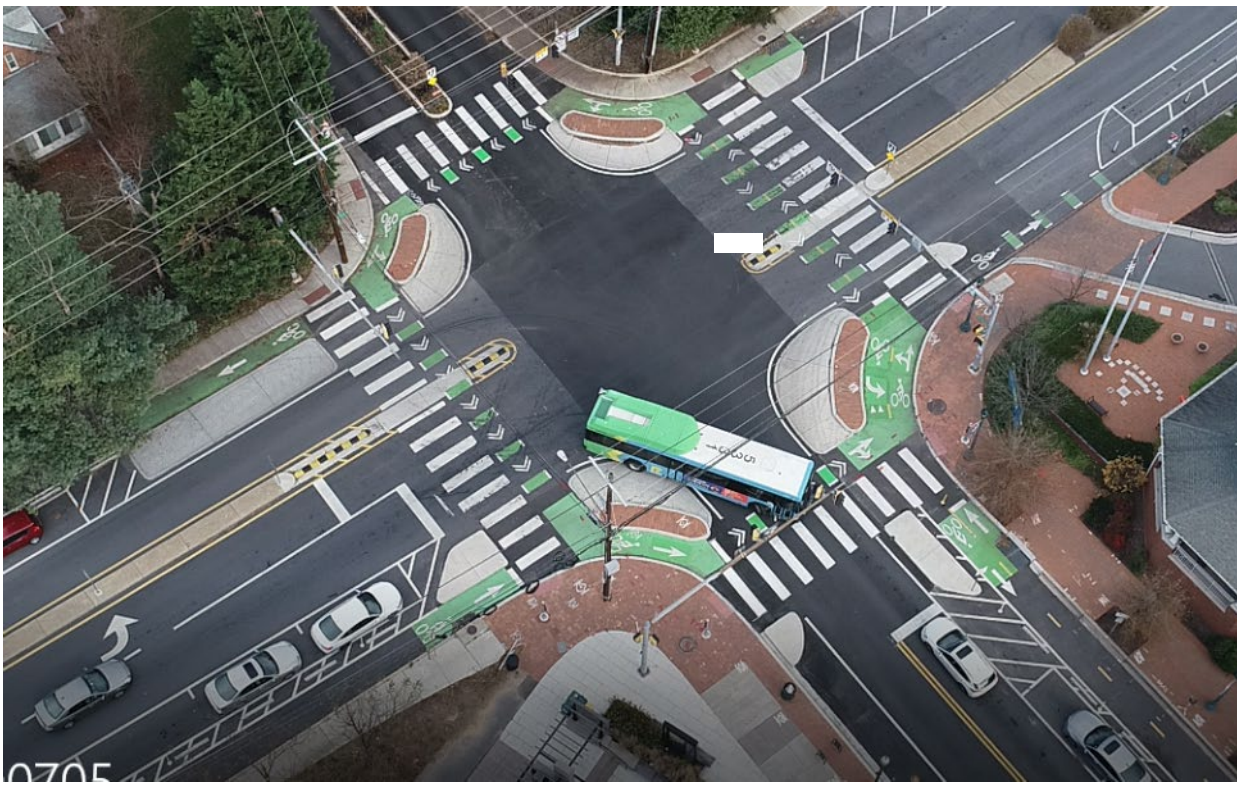
Source: FHWA.

Figure 60. Photo. Trajectories of all vehicles for a 4-min, 47-s interval showing some vehicles driving inside the raised pavement markers and solid white line for the truck apron at CA–BER–01–Exi.

The MD–SSP–01–Exi site has raised truck aprons, and, overall, about 18 percent of the turning vehicles use the truck apron. Several large vehicles were present at the intersection with about half of these larger vehicles using the truck apron. Table 31 provides the number or percentage of right-turning vehicles using the truck apron at MD–SSP–03–Exi by vehicle type. Figure 61 shows an example of a city bus using the truck apron space during the right turn. The intersection was designed to accommodate the needs of these larger turning vehicles, including placing the stop bar further upstream of the intersection so that the larger vehicles have space to complete their turn.

Table 31. Number or percentage of right-turning vehicles using the truck apron at MD–SSP–03–Exi.

Vehicle Type	Vehicles Not Using Apron (No.)	Vehicles Not Using Apron (percent)	Vehicles Using Apron (No.)	Vehicles Using Apron (percent)	Total Vehicles (No.)
Car, passenger	414	86	70	14	484
City bus	24	73	9	27	33
Concrete truck	1	25	3	75	4
Garbage truck	0	0	2	100	2
Large truck	0	0	2	100	2
Motorcycle	2	100	0	0	2
Two-axle truck	7	39	11	61	18
Grand total	*448*	*82*	*97*	*18*	*545*



Source: FHWA.

Figure 61. Photo. Example of a city bus turning right at the southwest corner at MD–SSP–01–Exi.

Motorists Turning on Bicycle Queue Area

A behavior of concern that was observed was motorized vehicles turning across the marked bicyclist queuing or waiting area. This behavior was observed at 4 intersections, with most of the observed behaviors (41 of 58) at a site with pylons rather than the sites with raised islands (table 32). All of these situations involved a vehicle turning right except in the site with pylons, where one of the occurrences involved a utility vehicle turning left.

Table 32. Number of vehicles observed on marked bicyclist waiting area.

Site–Period	Treatment	Car	Van or Utility Vehicle	Motorcycle	Grand Total
CA–BER–01–Exi	Raised island	3	0	0	3
CA–FRE–11–After	Raised island	9	0	2	11
TX–CST–01–Exi	Raised island	0	0	3	3
UT–SLC–03–Exi	Pylons	33	8	0	41
Grand total	*Either*	*46*	*8*	*5*	*58*

For the CA–FRE–11–Aft site, the previous right-turn lanes were converted into space for VU. The observed drivers may still be adjusting to the new lane usage. The three drivers at CA–BER–01–Exi moved into the space at low speeds, perhaps being confused as to where they needed to be to complete a right turn. All of the motor vehicles in the bicycle queue area at TX–CST–01–Exi were motorcycles.

The UT–SLC–03–Exi intersection has the onstreet parking lane next to the curb, with the bicycle lane between the onstreet parking lane and the travel lane (figure 62). Mixed messages may be present for drivers as to where they should be positioned during a right turn because drivers have to move through the bicycle lane to access the onstreet parking and because of the presence of no-parking markings. In addition, the width of the green marked area is wide enough for cars to enter. Figure 62 and figure 63 show an example of a white car entering and leaving, respectively, the marked bicyclist queue area.

Source: FHWA.

Figure 62. Photo. Right-turning car (white) entering the green marked bicycle queue area at UT–SLC–03–Exi.

Source: FHWA.

Figure 63. Photo. Right-turning car (white) leaving the green marked bicycle queue area at UT–SLC–03–Exi.

CHAPTER 6. CONCLUSIONS

SUMMARY

Traffic professionals are exploring innovative intersection designs to determine if they can successfully accommodate multimodal transportation by reducing conflicts between moving vehicles and VU or by lowering the impact force (reducing the vehicle speed and changing the collision angle in the event of a collision). The term protected intersection is used in this report. The objective of this FHWA project was to investigate the operational and safety improvements of innovative intersection retrofitting designs that benefit pedestrians and bicyclists while maintaining a reasonable service to motor vehicles. The project included summarizing previous research efforts, developing three design types, identifying potential study sites (both before-after and comparison-existing sets), and collecting in-field operational behaviors of the users.

With the goal of conducting 15 before-after evaluations, a key component was to identify the study sites before the treatment had been installed so that before data could be collected. The research study was also bound by a fixed end date, so the installation of the treatment had to occur in sufficient time to permit adequate time to collect the after data, to conduct the analysis, and to complete the required study documentation before the end date of the contract. With these restrictions, six study sites were identified where both before data and after data could be collected within the contract limits. These 6 sites represented 12 site periods, resulting in a need of 18 additional site periods. The remaining intersections to be selected either already had the treatment (14 intersections) or served as a comparison to nearby sites with existing treatments (4 intersections). For each site period, data were collected using video obtained either from installing cameras on a pole or on a rooftop at the site, or from drones. Because identifying VU with software to process the video was not sufficiently accurate, technicians watched the video and recorded user behaviors. Behaviors for 23,505 users were recorded for the 30 site periods.

KEY OBSERVATIONS

The key observations from this research effort included the following:

- Overall, pedestrians were more likely to interact with a vehicle (33 percent of the pedestrian crossings involved a vehicle) compared to bicyclists interacting with a vehicle (19 percent of bicyclist crossings).
- Drivers yielded to bicyclists and pedestrians more at the treated sites compared to the untreated sites. For bicyclist crossings, 38 percent of the crossings for treated sites compared to 34 percent for untreated sites involved a vehicle yielding to the bicyclist. For pedestrian crossings, the comparison is 23 percent for treated sites compared to 16 percent for untreated sites.

- The treatment is designed to slow turning vehicles and provide drivers additional opportunity to see the crossing VU. The addition of the treatment at three of the before-after sites with traffic control signals resulted in more frequent yielding by drivers to pedestrians (41 percent in the before period to 47 percent in the after period).

- For the six before-after sites, the percentage of bicyclists riding from the bicycle lane to the bicycle lane increased from 13 percent to 52 percent, while the percent riding from the sidewalk to the sidewalk decreased from 21 percent to 12 percent. More of the bicyclists were in the space designed for their use after the treatment was installed.

- Corner islands separate a greater proportion of the bicyclist's path through an intersection from motorized vehicles. At some sites, following the intended path results in longer travel time through the intersection, including slowing to accommodate the bend-out and bend-in bicycle path in that can be generated by the location of the corner island. With regard to sites with raised islands, most of the bicyclists (66 percent) did follow the marked path and went to the right of the corner islands. For those sites where the corner island was created using pylons, again, most of the bicyclists (58 percent) followed the marked path and went to the right of the corner island. However, a sizable number rode through the pylons (19 percent).

- Bicyclists may want to go in the opposite direction along a street and appear to be doing so at protected intersections by using the sidewalks or crosswalks rather than the bicycle lane or green marked waiting area.

- In some cases, bicyclists are leaving the bicycle lane and entering the sidewalk to use the pedestrian push button.

- The two intersections that converted the right-turn lane to the protected intersection treatment had similar trends. Most of the pedestrians who waited on the channelizing island in the before condition were now waiting in the pedestrian ramp area in the after condition. These pedestrians did not have to weave through the moving right-turning motorized vehicles to reach the refuge area where they waited before crossing the intersection.

- Right-turn speeds are higher at corners with a larger corner radius. The receiving lane for the right-turning vehicle also influences the right-turn speed, with drivers turning faster to the lane that is the furthest from the curb.

- The right-turn speeds were compared before and after the installation of the protected intersection treatment at two California sites. The results are as follows:
    - With the decrease in corner radius from the before to the after period with the installation of the protected intersection, the average right-turn speeds decreased. For example, a corner being changed from a 60-ft radius to a 25-ft radius is predicted to have about a 2.6 mph decrease in speed.
    - In addition, the range of turning speeds in the period after the treatment was installed was smaller compared to the before period for most of the corners. In other words, the addition of the protected intersection treatment is also associated with fewer drivers turning at high right-turn speeds.
    - The inclusion of truck aprons can facilitate the turning of large vehicles while also encouraging smaller radius turns for right-turning vehicles.

FUTURE RESEARCH NEEDS

This research study investigated users' behaviors while moving through a protected intersection. The following additional research could increase the profession's understanding of the value of these types of intersection forms:

- Document the benefits in having a network of protected intersections, especially with respect to increased demand.
- Examine the types of crashes associated with these types of intersections, including the development of a crash modification factor once a sufficient sample size is available (number of sites and number of years of after data).
- Explore the influence of signal phasing and timing on yielding behaviors and conflicts.
- Explore the use of bicycle signals with this type of treatment.
- Investigate the safety and operations of protected intersection elements with two-way bikeways.

ACKNOWLEDGMENTS

The original maps in figure 48 and figure 49 are the copyrighted property of Google® Earth™ and can be accessed from https://www.google.com/earth. Labels and arrows were added to figure 48. Lines showing the turning radius were added to figure 49.

REFERENCES

1. Federal Highway Administration. 2022. "Proven Safety Countermeasures" (web page). https://safety.fhwa.dot.gov/provencountermeasures/, last accessed June 28, 2022.

2. Schultheiss, B., D. Goodman, L. Blackburn, A. Wood, D. Reed, and M. Elbech. 2019. *Bikeway Selection Guide*. Report No. FHWA-SA-18-077. Washington, DC: Federal Highway Administration. https://safety.fhwa.dot.gov/ped_bike/tools_solve/docs/fhwasa18077.pdf, last accessed December 17, 2022.

3. Brookshire, K., L. Sandt, A. West, and M. Bryson. 2019. *FHWA Bicycle and Pedestrian Transportation University Course Module 10: Intersections*. Report No. FHWA-SA-19-034. Washington, D.C: Federal Highway Administration.

4. NACTO. 2019. *Don't Give Up at the Intersection: Designing All Ages and Abilities Bicycle Crossings*. New York, NY: National Association of City Transportation Officials.

5. Lyons, T. D. Choi, K. Park, and S. H. Ameli. 2020. "Safety and Nonoptimal Usage of a Protected Intersection for Bicycling and Walking: A Before-and-After Case Study in Salt Lake City, Utah." *Sustainability* 12, no. 21:9195.

6. FHWA. 2009. *Manual on Uniform Traffic Control Devices for Streets and Highways*. Washington, DC: Federal Highway Administration. http://mutcd.fhwa.dot.gov/pdfs/2009r1r2/pdf_index.htm, last accessed June 30, 2019.

7. FHWA. 2022. "Manual on Uniform Traffic-Control Devices for Streets and Highways MUTCD News Feed" (web page). https://mutcd.fhwa.dot.gov/mutcd_news.htm#dec_17_20, last accessed October 28, 2022.

8. Arnold, R. E. 2017. R.E. Arnold to Directors of Federal Lands Divisions, Division Administrators, memorandum, "MUTCD - Clarifications of Existing Standards and Guidance on new and Innovative Traffic Control Devices," January 5, 2017. https://mutcd.fhwa.dot.gov/resources/policy/tcdstatusmemo/tcd_status_memo.pdf, last accessed October 28, 2022.

9. Office of the Federal Register. 2020. "National Standards for Traffic Control Devices; the Manual on Uniform Traffic Control Devices for Streets and Highways; Revision." *Federal Register* 85, no. 240 (December 14, 2020): 80890-80979. https://www.federalregister.gov/documents/2020/12/14/2020-26789/national-standards-for-traffic-control-devices-the-manual-on-uniform-traffic-control-devices-for#h-41, last accessed October 28, 2022.

10. MassDOT. 2015. *Separated Bike Lane Planning & Design Guide 2015*. Boston, MA: Massachusetts Department of Transportation. https://www.mass.gov/lists/separated-bike-lane-planning-design-guide, last accessed December 17, 2022.

11. City of Seattle. 2017. "Seattle Right-of-Way Improvements Manual: Bike Intersection Design" (web page). https://streetsillustrated.seattle.gov/design-standards/bicycle/bike-intersection-design/#crossbicycle, last accessed October 28, 2022.

12. Gilpin, J., N. Falbo, M. Repsch, A. Zimmerman. 2015. *Lessons Learned: Evolution of the Protected Intersection*. Portland, OR: Alta Planning + Design. https://altago.com/wp-content/uploads/Evolution-of-the-Protected-Intersection_ALTA-2015.pdf, last accessed March 2, 2023.

13. Alta Planning + Design. 2015. "Resources for *Lessons Learned: Evolution of the Protected Intersection*" (web page). https://altago.com/resources/evolution-of-the-protected-intersection/, last accessed March 2, 2023.

14. Warner, J., D. S. Hurwitz, C. M. Monsere, and K. Fleskes. 2017. "A simulator-based analysis of engineering treatments for right-hook bicycle crashes at signalized intersections," *Accident Analysis & Prevention* 104: 46–57.

15. Gilpin, J. 2016. "Building Better Communities Through Complete Streets–The Protected Intersection." *ITE Journal* 86, no. 3: 40–43.

16. NACTO. 2011. *Urban Bikeway Design Guide*. New York, NY: National Association of City Transportation Officials.

17. NACTO. 2013. *Urban Street Design Guide*. New York, NY: National Association of City Transportation Officials.

18. FHWA. 2015. *Separated Bike Lane Planning and Design Guide*. Washington, DC: Federal Highway Administration. https://www.fhwa.dot.gov/environment/bicycle_pedestrian/publications/separated_bikelane_pdg/page00.cfm, last accessed December 17, 2022.

19. Sundstrom, C. A., S. M. Quinn, and R. Weld. 2019. "Bicyclist Crash Comparison of Mixing Zone and Fully Split Phase Signal Treatments at Intersections with Protected Bicycle Lanes in New York City." *Transportation Research Record: Journal of the Transportation Research Board* 2673, no. 12: 1–10.

20. Zhang, Y., S. A. Mamun, J. N. Ivan, N. Ravishanker, and K. Haque. 2015. "Safety effects of exclusive and concurrent signal phasing for pedestrian crossing." *Accident Analysis and Prevention* 82: 26–36.

21. Monsere, C. M., N. Foster, J. Dill, and N. McNeil. 2015. "User Behavior and Perceptions at Intersections with Tuning and Mixing Zones on Protected Bike Lanes." *Transportation Research Record: Journal of the Transportation Research Board* 2520, no. 1: 112–122.

22. Rahimi, A. R., A. Kojima, and H. Kubota. 2013. "Experimental Research on Bicycle Safety Measures at Signalized Intersections." *Journal of the Eastern Asia Society for Transportation Studies* 10: 1426–1445.

23. Ohlms, P. B. and Y.-J. Kweon. 2019. *Effectiveness of Innovative Pavement Markings in Facilitating Safe Bicycle Travel.* Report No. FHWA/VTRC 19-R17. Richmond, VA: Virginia Department of Transportation. https://www.virginiadot.org/vtrc/main/online_reports/pdf/19-r17.pdf, last accessed December 17, 2022.

24. Dill, J., C. M. Monsere, and N. McNeil. 2012. "Evaluation of bike boxes at signalized intersections." *Accident Analysis and Prevention* 44, no. 1: 126–134.

25. Wall, G. T., D. G. Davies, and M. Crabtree. 2003. *Capacity Implications of Advanced Stop Lines for bicyclists*. Crowthorne, UK: TRL Limited.

26. Allen, D., S. Bygrave, and H. Harper. 2005. *Behaviour at Cycle Advanced Stop Lines*. Report No. PPR240. Crowthorne, UK: Transport for London. https://nacto.org/wp-content/uploads/2010/08/Behaviour-at-cycle-advanced-stop-lines.pdf, last accessed December 17, 2022.

27. Atkins Services. 2005. *Advanced Stop Line Variations Research Study*. London, UK: Transport for London.

28. Hunter, W. W. 2000. "Evaluation of Innovative Bike-Box Application in Eugene, Oregon." *Transportation Research Record: Journal of the Transportation Research Board* 1705, no. 1: 99–106.

29. Kang, B. 2019. "Identifying street design elements associated with vehicle-to-pedestrian collision reduction at intersections in New York City." *Accident Analysis and Prevention* 122: 308–317.

30. Cao, Y., Y. Ni, and K. Li. 2017. "Effects of Refuge Island Settings on Pedestrian Safety Perception and Signal Violation at Signalized Intersections.," Presented at the 96th Annual Meeting of the Transportation Research Board, vol. 750, pp. 1-16. Washington, DC: Transportation Research Board.

31. Hummer, J. E., A. M. Holzem, N. M. Rouphail, C. M. Cunningham, S. W. O'Brien, B. J. Schroeder, K. Salamati, and R.S. Foyle. 2014. *Pedestrian and Bicycle Accommodations on Superstreets*. Report No. FHWA/NC/2012-13. Raleigh, NC: North Carolina Department of Transportation. https://connect.ncdot.gov/projects/research/RNAProjDocs/2012-13finalreport.pdf, last accessed December 17, 2022.

32. Furth, P. G., and Y. Wang. 2015. *Delay Estimation and Signal Timing Design Techniques for Multi-Stage Pedestrian Crossings and Two-Stage Bicycle Left Turns.* Presented at the 94th Annual Meeting of the Transportation Research Board, Washington, DC.

33. Li, Y., and G. Fernie. 2010. "Pedestrian behavior and safety on a two-stage crossing with a center refuge island and the effect of winter weather on pedestrian compliance rate." *Accident Analysis and Prevention* 42, no. 4: 1156–1163.

34. Boudart, J., N. Foster, P. Koonce, J. Maus, and L. Okimoto. 2017. “Improving Bicycle Detection Pavement Marking Symbols to Increase Comprehension at Traffic Signals.” *ITE Journal* 87, no. 3: 29–34.

35. Iasmin, H., A. Kojima, and H. Kubota. 2016. “Safety effectiveness of pavement design treatment at intersections: Left turning vehicles and pedestrians on crosswalks.” *IATSS Research* 40, no. 1: 47–55.

36. Fitzpatrick, K., R. Avelar, M. P. Pratt, S. Das, and D. Lord. 2022. *Crash Modification Factor for Corner Radius, Right-Turn Speed, and Prediction of Pedestrian Crashes at Signalized Intersections*. Report No. FHWA-HRT-21-105. Washington, DC: Federal Highway Administration.

37. Granitto, D. 2016. “Protected Intersections” (web page). https://www.concreteconstruction.net/projects/infrastructure/protected-intersections_o, last accessed December 17, 2022.

38. Summala, H., E. Pasanen, M. Räsänen, and J. Sievänen. 1996. “Bicycle Accidents and Drivers’ Visual Search at Left and Right Turns.” *Accident Analysis and Prevention* 28, no. 2: 147–153.

39. Deliali, K., E. Christofa, M. Knodler Jr. 2021. “The role of protected intersections in improving bicycle safety and driver right-turning behavior.” *Accident Analysis and Prevention* 159: 106295.

40. Christofa, E., M. Knodler Jr., A. Deliali, and N. Campbell. 2019. *Dissecting the Safety Benefits of Protected Intersection Design Features*. Amherst, MA: Safety Research Using Simulation University Transportation Center. http://safersim.nads-sc.uiowa.edu/final_reports/UM%202%20Y2__report.pdf, last accessed December 17, 2022.

41. Candappa, N., K. Stephan, N. Fotheringham, M. G. Lenné, and B. Corben. 2014. “Raised Crosswalks on Entrance to the Roundabout—A Case Study on Effectiveness of Treatment on Pedestrian Safety and Convenience.” *Traffic Injury Prevention* 15, no. 6: 631–629.

42. Mohammadipour, A. H., A. R. Archilla, C. S. Papacostas, and S. H. Alavi. 2011. *Pedestrian (RPC) Influence on Speed Reduction*. Washington, DC: Transportation Research Board.

43. Pratelli, A., R. Pratali, and M. Rossi. 2011. “Raised crosswalks efficacy on the lowering of vehicle speeds.” *WIT Transactions on The Built Environment: Urban Transport* 116: 541–552.

44. Gitelman, V., R. Carmel, F. Pesahov, and S. Chen. 2017. “Changes in road-user behaviors following the installation of raised pedestrian crosswalks combined with preceding speed humps, on urban arterials.” *Transportation Research Part F: Traffic Psychology and Behaviour* 46, B: 356–372.

45. Jacquemart, G. 2012. "Determining the Ideal Location for Pedestrian Crosswalks at Signalized Intersections." *ITE Journal* 82, no. 9: 44–47.

46. Fitzpatrick, K., K. Hall, D. Perkinson, L. Nowlin, and R. Koppa. 1996. *TCRP Report 19: Guidelines for the Location and Design of Bus Stops*. Washington, DC: Transportation Research Board.

47. Johnson, R. S. 2005. *Pedestrian Safety Impacts of Curb Extensions: A Case Study*. Report No. FHWA-0R-DF-06-01. Salem, OR: Oregon Department of Transportation. https://nacto.org/docs/usdg/pedestrian_safety_impacts_of_curb_extensions_randal.pdf, last accessed December 17, 2022.

48. Duncan, A. B. 2016. "Cyclist Path Choices Through Shared Space Intersections in England." Ph.D. dissertation. Portland State University.

49. Global Designing Cities Initiative. 2019. "*Case Study: Plaza Program; New York City, USA*" (web page). https://globaldesigningcities.org/publication/global-street-design-guide/streets/pedestrian-priority-spaces/pedestrian-plazas/case-study-plaza-program-new-york-city-usa/, last accessed November 26, 2019.

50. Hunter, W. W., J. R. Stewart, J. C. Stutts, H. H. Huang, and W. E. Pein. 1999. *A Comparative Analysis of Bicycle Lanes Versus Wide Curb Lanes: Final Report*. Report No. FHWA-RD-99-034. Washington, DC: Federal Highway Administration. https://www.fhwa.dot.gov/publications/research/safety/pedbike/99034/99034.pdf, last accessed December 17, 2022.

51. Al-Kaisy, A., and S. Roefaro. 2012. "Channelized Right-Turn Lanes At Signalized Intersections: The U.S. Experience." *Advances in Transportation Studies: An International Journal Section B* 26: 57–68.

52. Bai, Y., and Li, S. 2017. *Geometric and Signal Optimization for Pedestrian Crossing at Continuous Flow Intersection*. Presented at the 96th Annual Meeting of the Transportation Research Board. Washington, DC: Transportation Research Board.

53. Bonneson, J., M. Pratt, and P. Songchitruksa. 2012. *Development of Guidelines for Pedestrian Safety Treatments at Signalized Intersections*. Report No. FHWA/TX-11/0-6402-1. Austin, TX: Texas Department of Transportation.

54. Google®. 2022. Google® Earth™, Mountain View, CA, obtained from https://earth.google.com/web/, last accessed December 21, 2022.

55. DC Municipal Regulation. 2021. "Right-Of-Way: Intersections," 18 § 2208.11. https://casetext.com/regulation/district-of-columbia-administrative-code/title-18-vehicles-and-traffic/chapter-18-22-moving-violations/rule-18-2208-right-of-way-intersections#:~:text=A%20driver%20of%20any%20vehicle,safety%20island%2C%20whichever%20is%20nearest, last accessed November 9, 2022.

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