Complete Streets—Safety Analysis

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FOREWORD

The Federal Highway Administration (FHWA) launched a Complete Streets initiative to prioritize safety, comfort, and connectivity for all road users including pedestrians, bicyclists, motorists, and transit riders across a broad spectrum of ages and abilities. Moving to a Complete Streets design model aims to reverse the trend of increasing fatalities and serious injuries on the Nation’s roadways to reach the goal of zero deaths. According to the report to Congress titled *Moving to a Complete Streets Design Model: A Report to Congress on Opportunities and Challenges*, supporting rigorous safety assessment has emerged as one of five overarching areas of opportunity for FHWA as it moves ahead in its Complete Streets efforts.

This study was conducted to 1) identify pedestrian and bicyclist safety treatments that agencies implemented in combination on Complete Streets projects, 2) determine which treatments have quality Crash Modification Factors (CMFs) for crash types and severities, and 3) characterize and assess existing methods for combining multiple CMFs. The study approach leveraged FHWA and National Cooperative Highway Research Program (NCHRP) projects that are developing CMFs for the *Highway Safety Manual* (HSM) (AASHTO 2010) and other Data-Driven Safety Analysis (DDSA) resources. This report may be of interest to transportation safety practitioners and Complete Streets stakeholders interested in understanding the potential safety improvements from prospective Complete Streets implementations.

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Research and Development

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16. Abstract The ability to fully quantify the expected safety benefits of Complete Streets transformations using crash-based, data-driven safety analysis (DDSA) methods such as those in the *Highway Safety Manual* (AASHTO 2010) is limited. The lack of crash modification factors (CMFs) for many Complete Streets treatments is a primary reason for this limitation. When CMFs for individual treatments exist, methods to combine the individual CMFs to estimate the expected safety benefits of treatment combinations on a Complete Streets project are at relatively early stages of testing. This report provides practitioners and other stakeholders with a resource that identifies and describes current capabilities, best practices, and future data and analysis needs for quantifying the safety-performance effects of multiple safety treatments that agencies implement simultaneously during the conversion of typical streets to Complete Streets. The recommendations include future research needs for DDSA and future directions related to the potential use of other performance metrics that could provide additional insights into Complete Streets benefits, including broader public health benefits. The report includes three appendices that detail Complete Streets treatments, methods to develop CMFs for treatment combinations, and five case studies that illustrate the analysis methods and inform the content of the primer in chapter 4.		
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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

AASHTO	American Association of State Highway and Transportation Officials
AADT	annual average daily traffic
ACPA	American Concrete Pavement Association
ADA	Americans with Disabilities Act
BRT	Bus Rapid Transit
CMF	crash modification factor
DALY	Disability-Adjusted Life Years
DDSA	Data-Driven Safety Analysis
EB	Empirical Bayes
FHWA	Federal Highway Administration
FI	Fatal and injury crashes
FTA	Federal Transit Administration
HSIP	Highway Safety Improvement Program
HSM	Highway Safety Manual
ITS	Intelligent Transportation System
KABCO	scale used to represent injury severity in crash reporting K = fatal A = suspected serious injury B = suspected minor injury C = possible injury O = no apparent injury
LPI	leading pedestrian interval
mph	miles per hour
MPO	Metropolitan Planning Organization
MUTCD	Manual on Uniform Traffic Control Devices
MV	multiple vehicle
NACTO	National Association of City Transportation Officials
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
PHB	pedestrian hybrid beacon
QALY	Quality-Adjusted Life Years
RRFB	rectangular rapid-flashing beacon
SPF	safety-performance function
SSA	Safe System Approach
SSI	Safe System for Intersections
SV	single vehicle
TSP	transit signal priority
TWLTL	two-way left-turn lane
USDOT	United States Department of Transportation
veh	vehicle(s)

CHAPTER 1. INTRODUCTION

OVERVIEW

The National Highway Traffic Safety Administration (NHTSA) estimated that the United States experienced 42,939 traffic fatalities in 2021 and 42,795 traffic fatalities in 2022 (USDOT 2023). Not since 2007 have annual U.S. traffic fatalities exceeded 40,000. Each year, pedestrian and bicyclist fatalities comprise about 19 percent of all traffic fatalities, approximately 6,000 pedestrian deaths and 850 bicyclist deaths annually (USDOT 2023). Safer streets are needed for all. Complete Streets is an approach to policymaking, planning, design, and operations that will help save lives (FHWA n.d.a).

In January 2022, the United States Department of Transportation (USDOT) announced the creation of the National Roadway Safety Strategy (NRSS), a collaborative effort to significantly reduce U.S. traffic fatalities and serious injuries (USDOT 2022). Notably, the strategy includes USDOT adoption of the Safe System Approach (SSA) to guide policies and actions based on five SSA elements: Safer People, Safer Roads, Safer Vehicles, Safer Speeds, and Post-Crash Care (FHWA 2020a).

The Federal Highway Administration (FHWA) is a leader in advancing knowledge and implementation of the SSA and has framed six SSA principles[1]. Central to the SSA is the belief that death and serious injury are unacceptable. In its SSA outreach materials, FHWA states a goal of zero traffic fatalities and serious injuries, and SSA as the approach to reach that goal. The SSA represents a foundational shift, showing how transportation agencies can take proactive actions to eliminate crash-related deaths and serious injuries.

Some Safe System principles are already evident in various U.S. road safety management policies and practices, including Complete Streets. Smart Growth America highlights that more than 1,600 Complete Streets policies have been passed in the U.S., including those adopted by 35 State governments, the Commonwealth of Puerto Rico, and Washington, DC (Smart Growth America 2023). The Infrastructure Investment and Jobs Act requires that States and metropolitan planning organizations (MPOs) use 2.5 percent of their planning and research funds for Complete Streets activities that will increase safe and accessible transportation options (U.S. Congress 2021). Complete Streets is FHWA’s default approach to non-access-controlled roadways, and FHWA is leading efforts to overcome challenges and capitalize on opportunities to grow the implementation of Complete Streets. FHWA has identified Complete Streets scenarios to include arterials where traffic speed and volume have historically taken priority over pedestrian, bicycle, and transit safety needs.

One set of challenges and opportunities in advancing Complete Streets is based on a need to improve methods for quantifying the safety-performance effects of multiple safety treatments that agencies implement together on Complete Streets projects. More specifically, FHWA’s *Moving to a Complete Streets Design Model: A Report to Congress on Opportunities and Challenges* (FHWA 2022a) highlights that the ability to fully quantify the impacts and benefits

[1]FHWA–Safe System Approach Flyer

of pedestrian and bicyclist safety treatments on safety performance for those users is limited because the availability of crash modification factors (CMFs) for pedestrians and bicyclists is also limited. In addition, for treatments where CMFs do exist, methods to combine multiple CMFs to estimate the safety benefits of treatment combinations on a Complete Streets project are still at relatively early stages of testing. Interest in Complete Streets is growing rapidly, but these safety-analysis gaps can sometimes limit the ability of planners, engineers, and decisionmakers to clearly see the multimodal safety benefits of a Complete Streets project. Identifying and addressing these gaps would help support broader implementation of Complete Streets projects, including more widespread applications beyond local roads. A Complete Streets safety-analysis needs assessment that characterizes current capabilities and identifies needs is a useful step toward achieving this vision.

OBJECTIVE

The objective of this report is to provide practitioners and other Complete Streets stakeholders with a resource that identifies and describes current capabilities, best practices, and future data and analysis needs for quantifying the safety-performance effects of multiple safety treatments that agencies implement simultaneously during the conversion of typical streets to Complete Streets. This report will focus on treatments expected to improve the safety of pedestrians and bicyclists; however, these same treatments may also affect the safety of other road users. The report describes methods and results of the following activities:

- Identify pedestrian and bicyclist safety treatments that agencies implement together on Complete Streets projects.
- Determine which of these treatments currently have quality CMFs for different crash types and severities.
- Characterize, assess, and evaluate methods for combining multiple CMFs.
- Develop marketing and outreach materials to share the findings with Complete Streets stakeholders.

The research approach leveraged FHWA and National Cooperative Highway Research Program (NCHRP) projects that are developing CMFs for the *Highway Safety Manual* (HSM) and other data-driven safety analysis (DDSA) resources (AASHTO 2010). The approach also incorporated additional literature reviews to identify other potential analysis options for pedestrian and bicyclist safety treatments and to discover future opportunities to incorporate health-related metrics into Complete Streets safety performance analysis.

This report should contribute toward multiple goals in the Report to Congress but will most notably be relevant to “study[ing] multi-variable CMFs to support context-sensitive safety analysis” and issuing “new guidance on safety analysis and performance” to “support rigorous safety assessment during project development and design to help prioritize safety outcomes across all project types” (FHWA 2022a).

CHAPTER 2. TREATMENT COMBINATIONS

This chapter characterizes combinations of pedestrian and bicyclist safety treatments that agencies implement together on Complete Streets projects. The project team first drew on its previous Complete Streets policy and project experiences to identify a geographically diverse sample of candidate Complete Streets projects. The projects were from both urban and rural areas and primarily on arterials with speed limits of 55 miles per hour (mph) or less. In addition, FHWA shared a sample of candidate projects from another ongoing task order focused on characterizing construction costs for Complete Streets projects.[2] Using both project documentation and satellite imagery (Google® Earth® 2011; Google Maps® 2021d), the project team collected the following information for each project:

- Area type.
- Functional classification (of mainline facility that is focus of the Complete Streets project).
- Basic number of through lanes.
- Median presence (e.g., divided road, undivided road, two-way left-turn lane (TWLTL)).
- Number of segments (between intersections) within project limits.
- Number of signalized intersections.
- Number of unsignalized intersections.
- Project description.
- Safety treatments that are part of the project.
- Whether the project is planned or already constructed.
- If constructed, construction year.
- Geographic coordinates.
- Route number and beginning/ending mileposts.

This approach resulted in data for 85 projects. Table 1, table 2, and table 3 show the number of projects by area type and functional classification. The projects span urbanized, urban, and rural areas and primarily focus on arterials per the project's scope. However, the project's FHWA advisory panel noted that some coverage of other functional classifications could be informative. The project team therefore kept coverage of collector and local roads as shown in table 2.

[2]FHWA shared this list with the project team. It is not publicly available.

Table 1. Projects by area type.

Area Type	Number of Projects	Percent of Projects
Rural	7	8.2
Urban	23	27.1
Urbanized	55	64.7
Total	**85**	**100.0**

Note: Rural = places with resident population < 5,000; Urban = places with resident population ≥ 5,000 and < 50,000; Urbanized = places with resident population ≥ 50,000.

Table 2. Projects by functional classification.

Functional Classification	Number of Projects	Percent of Projects
Arterial	60	70.6
Collector	15	17.6
Local	7	8.2
Not Available	1	1.2
Various	2	2.4
Total	**85**	**100.0**

Table 3. Projects by area type and functional classification.

Area Type	Functional Classification	Number of Projects	Percent of Projects with Area Type	Percent of Total Projects
Rural	Arterial	4	57.1	4.7
	Collector	3	42.9	3.5
Urban	Arterial	19	82.6	22.4
	Collector	1	4.3	1.2
	Local	2	8.7	2.4
	Various	1	4.3	1.2
Urbanized	Arterial	37	67.3	43.5
	Collector	11	20.0	12.9
	Local	5	9.1	5.9
	Not Available	1	1.8	1.2
	Various	1	1.8	1.2
Total		**85**	**N/A**	**100.0**

Based on the project documentation and satellite imagery, the project team identified 80 potential safety treatments across the 85 Complete Streets projects. Appendix A lists these 80 treatments, characterizes the number of safety studies and resulting CMFs that exist for each treatment, and provides a treatment definition with example pictures.

Table 4 summarizes the six most common treatments and the other treatments most often used in combination with the six most common ones. To the right of each treatment is the number of projects that implemented the treatment. For example, "Add separated bike lane" was a treatment on 24 of the 85 projects. Of those 24 projects that included a separated bike lane, six also included "improved lighting." The following paragraphs, figures, and tables provide additional characterizations of common treatment combinations representing the team's effort to consolidate the treatment list.

Table 4. Common treatment combinations from initial list of 80 treatments and frequency of occurrence in project sample (shown in parentheses) (Source: FHWA).

Treatment		Commonly Combined With:
	**Add bike lane (27)**	**Add Americans with Disabilities Act (ADA) ramps and/or entrances (13)**
		Add landscaping/streetscaping/hardscaping (11)*
		Improve lighting (10)*
		Add curb extension/bulb-out (9)*
		Add bicycle and pedestrian path/trail (7)*
	**Add separated bike lane (24)**	**Improve lighting (6)***
		Add bike signal (5)
		Add bicycle and pedestrian path/trail (4)*
		Add landscaping/streetscaping/hardscaping (4)
	**Add bicycle and pedestrian path/trail (24)**	**Add bike lane (7)***
		Add landscaping/streetscaping/hardscaping (6)*
		Add bike signal (5)
		Add separated bike lane (4)*
		Improve lighting (4)*
		Add ADA ramps and/or entrances (4)
		Add roundabout or hybrid roundabout (4)
	**Add landscaping/ streetscaping/ hardscaping (23)**	**Improve lighting (17)***
		Add ADA ramps and/or entrances (11)
		Add bike lane (11)*
		Add curb extension/bulb-out (10)*
		Add or enhance sidewalk (9)
		Add bicycle and pedestrian path/trail (6)*
	**Improve lighting (23)**	**Add landscaping/streetscaping/hardscaping (17)***
		Add curb extension/bulb-out (13)*
		Add ADA ramps and/or entrances (11)
		Add bike lane (10)*
		Add or enhance sidewalk (9)
		Add separated bike lane (6)*
		Add bicycle and pedestrian path/trail (4)*

Treatment		Commonly Combined With:
	**Add curb extensions (20)**	**Improve lighting (13)***
		Add landscaping/ streetscaping/hardscaping (10)*
		Add bike lane (9)*
		Add ADA ramps and/or entrances (8)
		Reduce number of lanes (6)
		Add outdoor seating (chairs, benches) or other furniture/objects (trash cans, etc.) (6)

All graphics in this table are source: FHWA.
Note: * indicates that the treatment combination is duplicated (in another order) elsewhere in the table.

Based on an assessment of the 80 treatments and initial treatment combination results, the project team concluded that grouping similar treatments that were given different names in their respective project's documentation could be beneficial. For example, the project team combined the individual treatments of "Add Pedestrian Hybrid Beacon (PHB)," "Add pedestrian signal," and "Add Rectangular Rapid-Flashing Beacon (RRFB)" under the treatment label "Add pedestrian-actuated signal or beacon." As another example, the project team combined the individual treatments "Perform a Road Diet" and "Reduce number of lanes" into one treatment called "Perform a Road Diet."

The project team also removed treatments related less to safety performance and more to user comfort, aesthetics, and ADA compliance (FHWA 2018a). While these types of treatments are central to a Complete Streets approach, quantitative, crash-based safety performance evaluations of them may not be possible or practical. Examples include "add ADA ramps and/or entrances," "add landscaping/ streetscaping/hardscaping," and "add outdoor furniture for seating." By temporarily removing these treatments, the team could focus on treatments for which the safety performance link seems clear and therefore for which safety evaluations have possibly already occurred or could occur soon.

Treatment screening and consolidation yielded the following 35 treatments. Note that the sub-bullets indicate individual treatments from the full list of 80 treatments that were combined to create this consolidated list.

Bicycle/Pedestrian:

- Add separated bike lane.
- Add or enhance pedestrian and bicyclist signal operation.
  - Add or enhance pedestrian and bicyclist signal operation.
  - Add or enhance bike detection and/or leading intervals for bikes.
  - Add bike signal.
  - Add leading pedestrian interval.
  - Add pedestrian pushbuttons and/or countdown timer.
- Add bike lane.
- Add bike box.

- Add shared-lane marking (sharrow).
- Add green colored pavement.
- Add curb extension/bulb-out.
    - Add curb extension/bulb-out.
    - Add larger bike and pedestrian sidewalk waiting areas.
- Add or enhance sidewalk.
    - Add or enhance sidewalk.
    - Increase sidewalk width.
- Add or enhance crosswalk (including high-visibility).
- Add or enhance midblock crossing.
- Add pedestrian refuge island.
- Add pedestrian-actuated signal or beacon.
- Add Danish offset to refuge island (Redmon 2011).
- Add raised crosswalk.
- Add bicyclist and pedestrian path/trail.
- Add or enhance bicyclist and pedestrian path/trail crossing.
- Add grade-separated pedestrian facility (tunnel, underpass, bridge).

Transit:

- Add bus island or floating bus stop.
- Add Bus Rapid Transit (BRT)/bus-only lanes/transit signal priority.
- Add bus boarding platform.
    - Add bus boarding platform.
    - Add bus pad.

Traffic: Add or enhance traffic signal operation.

- Add traffic signal.
- Upgrade traffic signal.

Roadway configuration and elements:

- Change parking configuration.
- Remove on-street parking.
- Add or enhance lighting.
- Perform a Road Diet.
    - Perform a Road Diet.
    - Reduce number of lanes.
- Decrease roadway or lane width.
- Add median.
- Add raised intersection.
- Improve signing and marking.
- Add roundabout.

- Increase shoulder width.
- Improve pavement condition.
- Add curb and gutter.
- Reduce speed limit.
- Add raised traffic separators.

The data in table 5 summarize the number of projects with different numbers of treatments (following screening and consolidation). Of the 85 projects, more than 60 percent implemented 4 or more safety treatments.

Table 5. Projects by total number of treatments.

Total Number of Treatments	Number of Projects	Percent of Projects
1	9	10.6
2	11	12.9
3	13	15.3
4	15	17.6
5	13	15.3
6	12	14.1
7	1	1.2
8	2	2.4
9	6	7.1
10	1	1.2
11	1	1.2
15	1	1.2
Total	**85**	**100.0**

The information in table 6 summarizes the six most common treatments from the revised list of 35 treatments and the other treatments most often used in combination with the 6 most common treatments. As with table 4, each treatment is next to the number of projects that included that treatment.

The project team also explored the most common combinations of two, three, and four treatments across the sample of 85 projects. This information is summarized in table 7, table 8, and table 9. The tables list the treatments and the number of projects that implemented the specific treatment combination. Table 8 and table 9 also include the frequencies of the intermediate combinations.

Table 6. Common treatment combinations from revised list of 35 treatments and frequency of occurrence in project sample (shown in parentheses) (Source: FHWA).

Treatment:		Commonly combined with:
	Add or enhance sidewalk (29)	**Add or enhance crosswalk (including high-visibility) (15)***
		Add or enhance lighting (15)*
		Improve signing and marking (10)
		Add bike lane (9)*
		Change parking configuration (9)
	Add bike lane (26)	**Add or enhance lighting (10)***
		Add or enhance sidewalk (9)*
		Add curb extension/bulb-out (8)
		Perform a Road Diet (7)
		Add or enhance pedestrian and bicyclist signal operation (7)
		Add or enhance crosswalk (including high-visibility) (7)
		Add bicyclist and pedestrian path/trail (7)*
	Add or enhance lighting (25)	**Add or enhance sidewalk (15)***
		Add curb extension/bulb-out (14)
		Add bike lane (10)*
		Perform a Road Diet (8)
		Add or enhance crosswalk (including high-visibility) (8)
		Add or enhance traffic signal operation (8)
		Improve signing and marking (8)
	Add separated bike lane (24)	**Add or enhance pedestrian and bicyclist signal operation (6)**
		Add or enhance lighting (6)
		Add or enhance sidewalk (5)
		Add bicyclist and pedestrian path/trail (5)
		Add bike lane (3)
		Add curb extension/bulb-out (3)
		Add pedestrian refuge island (3)
		Perform a Road Diet (3)
	Add bicyclist and pedestrian path/ trail (24)	**Add or enhance sidewalk (8)**
		Add bike lane (7)*
		Add or enhance crosswalk (including high-visibility) (7)
		Add pedestrian-actuated signal or beacon (7)
		Improve signing and marking (7)

Treatment:		Commonly combined with:
	**Add or enhance crosswalk (24)**	**Add or enhance sidewalk (15)***
		Improve signing and marking (12)
		Add pedestrian-actuated signal or beacon (11)
		Add curb extension/bulb-out (10)
		Add or enhance mid-block crossing (9)

All graphics in this table are source: FHWA.
Note: * indicates that the treatment combination is duplicated (in another order) elsewhere in the table.

Table 7. Common combinations of two treatments.

Treatment 1 + Treatment 2		No. of Projects
Add or enhance sidewalk	Add or enhance crosswalk (including high-visibility)	15
Add or enhance sidewalk	Add or enhance lighting	15
Add or enhance lighting	Add curb extension/bulb-out	14
Add or enhance crosswalk (including high-visibility)	Improve signing and marking	12
Add or enhance crosswalk (including high-visibility)	Add pedestrian-actuated signal or beacon	11
Add or enhance sidewalk	Add curb extension/bulb-out	11
Add bike lane	Add or enhance lighting	10
Add or enhance crosswalk (including high-visibility)	Add curb extension/bulb-out	10
Add or enhance sidewalk	Improve signing and marking	10
Add or enhance crosswalk (including high-visibility)	Add or enhance mid-block crossing	9
Add or enhance sidewalk	Add bike lane	9
Add or enhance sidewalk	Change parking configuration	9
Add bike lane	Add curb extension/bulb-out	8
Add or enhance lighting	Add or enhance crosswalk (including high-visibility)	8
Add or enhance lighting	Add or enhance traffic signal operation	8
Add or enhance lighting	Perform a Road Diet	8
Add or enhance lighting	Improve signing and marking	8
Add or enhance sidewalk	Add bicyclist and pedestrian path/trail	8
Add or enhance sidewalk	Add curb and gutter	8
Add bicyclist and pedestrian path/trail	Add pedestrian-actuated signal or beacon	7
Add bicyclist and pedestrian path/trail	Improve signing and marking	7
Add bike lane	Add or enhance crosswalk (including high-visibility)	7
Add bike lane	Add bicyclist and pedestrian path/trail	7
Add bike lane	Perform a Road Diet	7
Add or enhance crosswalk (including high-visibility)	Add bicyclist and pedestrian path/trail	7
Add or enhance crosswalk (including high-visibility)	Change parking configuration	7
Add or enhance crosswalk (including high-visibility)	Add curb and gutter	7
Add or enhance lighting	Change parking configuration	7
Add or enhance sidewalk	Add or enhance traffic signal operation	7

Treatment 1 + Treatment 2		No. of Projects
Add bike lane	Add or enhance pedestrian and bicyclist signal operation	6
Add bike lane	Add pedestrian refuge island	6
Add bike lane	Add pedestrian-actuated signal or beacon	6
Add bike lane	Add or enhance traffic signal operation	6
Add or enhance crosswalk (including high-visibility)	Add pedestrian refuge island	6
Add or enhance lighting	Add separated bike lane	6
Add or enhance lighting	Add bicyclist and pedestrian path/trail	6
Add or enhance sidewalk	Perform a Road Diet	6
Add separated bike lane	Add or enhance pedestrian and bicyclist signal operation	6

Table 8. Common combinations of three treatments.

Treatment 1 + Treatment 2 (# Projects (Combination of 2))		+ Treatment 3 (# Projects (Combination of 3))
Add or enhance sidewalk	Add or enhance lighting (15)	Add curb extension/bulb-out (9)
Add or enhance sidewalk	Add or enhance crosswalk (including high-visibility) (15)	Add or enhance lighting (8)
Add or enhance sidewalk	Add or enhance crosswalk (including high-visibility) (15)	Improve signing and marking (8)
Add or enhance crosswalk (including high-visibility)	Add pedestrian-actuated signal or beacon (11)	Add or enhance mid-block crossing (8)
Add or enhance sidewalk	Add or enhance crosswalk (including high-visibility) (15)	Change parking configuration (7)
Add or enhance sidewalk	Add or enhance crosswalk (including high-visibility) (15)	Add curb extension/bulb-out (7)
Add or enhance sidewalk	Improve signing and marking (10)	Add curb and gutter (7)
Add or enhance lighting	Add curb extension/bulb-out (14)	Perform a Road Diet (7)
Add or enhance crosswalk (including high-visibility)	Improve signing and marking (12)	Add or enhance mid-block crossing (7)
Add or enhance crosswalk (including high-visibility)	Improve signing and marking (12)	Add pedestrian-actuated signal or beacon (7)

Treatment 1 + Treatment 2 (# Projects (Combination of 2))		+ Treatment 3 (# Projects (Combination of 3))
Add or enhance sidewalk	Add or enhance crosswalk (including high-visibility) (15)	Add bicyclist and pedestrian path/trail (6)
Add or enhance sidewalk	Add or enhance crosswalk (including high-visibility) (15)	Add curb and gutter (6)
Add or enhance sidewalk	Add or enhance lighting (15)	Improve signing and marking (6)
Add or enhance sidewalk	Add or enhance lighting (15)	Add bike lane (6)
Add or enhance sidewalk	Add curb extension/bulb-out (11)	Change parking configuration (6)
Add bike lane	Add or enhance lighting (10)	Add curb extension/bulb-out (6)
Add or enhance lighting	Add curb extension/bulb-out (14)	Add or enhance crosswalk (including high-visibility) (6)
Add or enhance lighting	Add curb extension/bulb-out (14)	Change parking configuration (6)
Add or enhance crosswalk (including high-visibility)	Improve signing and marking (12)	Add curb and gutter (6)
Add or enhance crosswalk (including high-visibility)	Add pedestrian-actuated signal or beacon (11)	Add curb extension/bulb-out (6)
Add or enhance sidewalk	Add bicyclist and pedestrian path/trail (8)	Improve signing and marking (6)
Add or enhance sidewalk	Add or enhance lighting (15)	Add or enhance traffic signal operation (5)
Add or enhance sidewalk	Add or enhance lighting (15)	Change parking configuration (5)
Add or enhance sidewalk	Add or enhance lighting (15)	Add curb and gutter (5)
Add or enhance sidewalk	Add curb extension/bulb-out (11)	Improve signing and marking (5)
Add bike lane	Add or enhance lighting (10)	Add or enhance traffic signal operation (5)
Add bike lane	Add or enhance lighting (10)	Perform a Road Diet (5)
Add bike lane	Add curb extension/bulb-out (8)	Perform a Road Diet (5)
Add or enhance lighting	Add or enhance traffic signal operation (8)	Add curb extension/bulb-out (5)
Add or enhance lighting	Improve signing and marking (8)	Add curb extension/bulb-out (5)
Add or enhance lighting	Improve signing and marking (8)	Add curb and gutter (5)
Add or enhance crosswalk (including high-visibility)	Improve signing and marking (12)	Add curb extension/bulb-out (5)
Add or enhance crosswalk (including high-visibility)	Improve signing and marking (12)	Add bicyclist and pedestrian path/trail (5)

Treatment 1 + Treatment 2 (# Projects (Combination of 2))		+ Treatment 3 (# Projects (Combination of 3))
Add or enhance crosswalk (including high-visibility)	Add curb extension/bulb-out (10)	Add or enhance mid-block crossing (5)
Add or enhance crosswalk (including high-visibility)	Add curb extension/bulb-out (10)	Change parking configuration (5)
Add or enhance crosswalk (including high-visibility)	Add curb extension/bulb-out (10)	Add curb and gutter (5)
Add bicyclist and pedestrian path/trail	Add or enhance crosswalk (including high-visibility) (7)	Improve signing and marking (5)

Table 9. Common combinations of four treatments.

Treatment 1 + Treatment 2 (# Projects (Combination of 2))		+ Treatment 3 (# Projects (Combination of 3))	+ Treatment 4 (# Projects (Combination of 4))
Add or enhance crosswalk (including high-visibility)	Add pedestrian-actuated signal or beacon (11)	Add or enhance mid-block crossing (8)	Improve signing and marking (6)
Add or enhance crosswalk (including high-visibility)	Improve signing and marking (12)	Add or enhance mid-block crossing (7)	Add pedestrian-actuated signal or beacon (6)
Add or enhance crosswalk (including high-visibility)	Improve signing and marking (12)	Add pedestrian-actuated signal or beacon (7)	Add or enhance mid-block crossing (6)
Add or enhance crosswalk (including high-visibility)	Improve signing and marking (12)	Add curb and gutter (6)	Add or enhance sidewalk (6)
Add or enhance lighting	Add curb extension/bulb-out (14)	Add or enhance crosswalk (including high-visibility) (6)	Add or enhance sidewalk (6)
Add or enhance sidewalk	Add or enhance crosswalk (including high-visibility) (15)	Add or enhance lighting (8)	Add curb extension/bulb-out (6)
Add or enhance sidewalk	Add or enhance crosswalk (including high-visibility) (15)	Improve signing and marking (8)	Add curb and gutter (6)

Treatment 1 + Treatment 2 (# Projects (Combination of 2))		+ Treatment 3 (# Projects (Combination of 3))	+ Treatment 4 (# Projects (Combination of 4))
Add or enhance sidewalk	Add or enhance crosswalk (including high-visibility) (15)	Add curb extension/bulb-out (7)	Add or enhance lighting (6)
Add or enhance sidewalk	Add or enhance crosswalk (including high-visibility) (15)	Add curb and gutter (6)	Improve signing and marking (6)
Add or enhance sidewalk	Add or enhance lighting (15)	Add curb extension/bulb-out (9)	Add or enhance crosswalk (including high-visibility) (6)
Add or enhance sidewalk	Improve signing and marking (10)	Add curb and gutter (7)	Add or enhance crosswalk (including high-visibility) (6)
Add bicyclist and pedestrian path/trail	Add or enhance crosswalk (including high-visibility) (7)	Improve signing and marking (5)	Add or enhance sidewalk (5)
Add bike lane	Add curb extension/bulb-out (8)	Perform a Road Diet (5)	Add or enhance lighting (5)
Add bike lane	Add or enhance lighting (10)	Add curb extension/bulb-out (6)	Perform a Road Diet (5)
Add bike lane	Add or enhance lighting (10)	Perform a Road Diet (5)	Add curb extension/bulb-out (5)
Add or enhance crosswalk (including high-visibility)	Add curb extension/bulb-out (10)	Change parking configuration (5)	Add or enhance sidewalk (5)
Add or enhance crosswalk (including high-visibility)	Improve signing and marking (12)	Add bicyclist and pedestrian path/trail (5)	Add or enhance sidewalk (5)
Add or enhance lighting	Add curb extension/bulb-out (14)	Perform a Road Diet (7)	Add bike lane (5)
Add or enhance lighting	Add curb extension/bulb-out (14)	Change parking configuration (6)	Add or enhance sidewalk (5)
Add or enhance lighting	Improve signing and marking (8)	Add curb and gutter (5)	Add or enhance sidewalk (5)

Treatment 1 + Treatment 2 (# Projects (Combination of 2))		+ Treatment 3 (# Projects (Combination of 3))	+ Treatment 4 (# Projects (Combination of 4))
Add or enhance sidewalk	Add bicyclist and pedestrian path/trail (8)	Improve signing and marking (6)	Add or enhance crosswalk (including high-visibility) (5)
Add or enhance sidewalk	Add curb extension/bulb-out (11)	Change parking configuration (6)	Add or enhance crosswalk (including high-visibility) (5)
Add or enhance sidewalk	Add curb extension/bulb-out (11)	Change parking configuration (6)	Add or enhance lighting (5)
Add or enhance sidewalk	Add or enhance crosswalk (including high-visibility) (15)	Improve signing and marking (8)	Add bicyclist and pedestrian path/trail (5)
Add or enhance sidewalk	Add or enhance crosswalk (including high-visibility) (15)	Change parking configuration (7)	Add curb extension/bulb-out (5)
Add or enhance sidewalk	Add or enhance crosswalk (including high-visibility) (15)	Add curb extension/bulb-out (7)	Change parking configuration (5)
Add or enhance sidewalk	Add or enhance crosswalk (including high-visibility) (15)	Add bicyclist and pedestrian path/trail (6)	Improve signing and marking (5)
Add or enhance sidewalk	Add or enhance lighting (15)	Add curb extension/bulb-out (10)	Change parking configuration (5)
Add or enhance sidewalk	Add or enhance lighting (15)	Improve signing and marking (6)	Add curb and gutter (5)
Add or enhance sidewalk	Add or enhance lighting (15)	Change parking configuration (5)	Add curb extension/bulb-out (5)
Add or enhance sidewalk	Add or enhance lighting (15)	Add curb and gutter (5)	Improve signing and marking (5)
Add or enhance sidewalk	Improve signing and marking (10)	Add curb and gutter (7)	Add or enhance lighting (5)

The project team also examined the treatments by treatment category as shown in table 10 and table 11. The tables display different breakdowns of the treatment categories and treatment category combinations by area type. Approximately 50 percent of the projects implemented treatment combinations spanning pedestrian/bicyclist and roadway configuration. An additional 20 percent included treatment combinations spanning pedestrian/bicyclist and roadway configuration and additional transit or traffic treatments. For this sample of 85 projects, the pedestrian/bicyclist plus roadway configuration plus traffic treatment combinations were more common to rural and urban locations. All the pedestrian/bicyclist plus roadway configuration plus transit treatment combinations occurred in urbanized areas.

Table 10. Common treatment usage by category.

Treatment Category	Number of Projects	Percent of Projects
Pedestrian/Bicyclist	20	23.5
Transit	1	1.2
Pedestrian/Bicyclist & Transit	2	2.4
Pedestrian/Bicyclist & Traffic	2	2.4
Pedestrian/Bicyclist & Roadway Configuration	43	50.6
Pedestrian/Bicyclist & Transit & Roadway Configuration	5	5.9
Pedestrian/Bicyclist & Traffic & Roadway Configuration	11	12.9
Pedestrian/Bicyclist & Transit & Traffic & Roadway Configuration	1	1.2
Total	**85**	**100.0**

Table 11. Common treatment usage by category and area type.

Area Type	Treatment Category	Number of Projects	Percent of Projects with Area Type	Percent of Total Projects
Rural	Pedestrian/Bicyclist & Roadway Configuration	5	71.4	5.9
	Pedestrian/Bicyclist & Traffic & Roadway Configuration	2	28.6	2.4
Urban	Pedestrian/Bicyclist	3	13.0	3.5
	Pedestrian/Bicyclist & Roadway Configuration	17	73.9	20.0
	Pedestrian/Bicyclist & Traffic & Roadway Configuration	3	13.0	3.5
Urbanized	Pedestrian/Bicyclist	17	30.9	20.0
	Transit	1	1.8	1.2
	Pedestrian/Bicyclist & Transit	2	3.6	2.4
	Pedestrian/Bicyclist & Traffic	2	3.6	2.4
	Pedestrian/Bicyclist & Roadway Configuration	21	38.2	24.7

Area Type	Treatment Category	Number of Projects	Percent of Projects with Area Type	Percent of Total Projects
	Pedestrian/Bicyclist & Transit & Roadway Configuration	5	9.1	5.9
	Pedestrian/Bicyclist & Traffic & Roadway Configuration	6	10.9	7.1
	Pedestrian/Bicyclist & Transit & Traffic & Roadway Configuration	1	1.8	1.2
Total		**85**	**N/A**	**100.0**

Validation of Treatment Combination Findings

The methods and results in the previous section represented an empirical approach to arriving at common treatments and treatment combinations on Complete Streets projects, based on a sample of 85 projects. The empirical approach proved effective for determining common treatment combinations for characterizing safety-analysis capabilities and needs during future tasks of this project. However, the team concluded that a more diagnostic approach for arriving at common treatments and treatment combinations might be beneficial, if the approach considers the following:

- Common crash types leading to fatalities and serious injuries on arterials with speed limits of 55 mph or less.

- Treatment combinations applicable to different area types, facility types, and project types (e.g., resurfacing, restoration, rehabilitation (3R); reconstruction).

In addition to the project team's subject matter expertise, two recent references significantly informed this diagnostic approach:

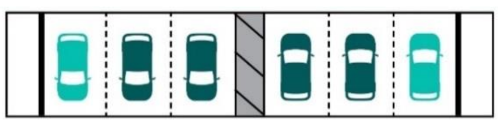
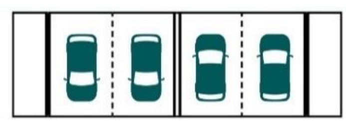
- FHWA's *Complete Streets Transformations: Six Scenarios to Transform Arterials using a Complete Streets Implementation Strategy* (2022).

- The "Scenario" appendix of the 2022 Atlanta Regional Commission Regional Safety Strategy (Atlanta Regional Commission 2022).

Figure 1 summarizes the results of the diagnostic approach.

In general, the diagnostic approach results validated the empirical approach, with common treatments across both. The diagnostic approach did, however, identify several additional treatments that were not part of the most common treatment combinations in table 6, including the following:

- Decrease roadway or lane width.[*]
- Remove shoulder.[#]
- Convert flush median to raised median.[#]
- Add bus island/floating bus stop or add bus boarding platform.[*]

<table>
<tr><td colspan="2">
</td></tr>
<tr><td></td><td></td></tr>
<tr><th>Urban four- or six-lane divided arterial (flush median)</th><th>Rural four-lane undivided arterial</th></tr>
<tr><td>This scenario assumes that vehicular volumes are high enough that the number of lanes will remain the same. A Complete Streets transformation might involve various combinations of the following treatments:</td><td>This scenario assumes vehicular volumes are at a level where a Road Diet is feasible. A Complete Streets transformation might involve various combinations of the following treatments:</td></tr>
<tr><td>Reduce lane widths
Remove shoulder
Add bike facility (per bikeway selection process)
Convert flushed median to raised
Add and/or enhance midblock pedestrian crossings
Install Pedestrian Hybrid Beacon (PHB)</td><td>Reduce number of lanes
Add TWLTL
Retain on-street parking
Add bike facility (per bikeway selection process)
Add and/or enhance midblock pedestrian crossings
Install PHB or Rectangular Rapid-Flashing Beacon (RRFB)</td></tr>
</table>

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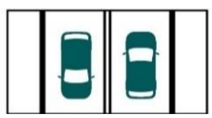
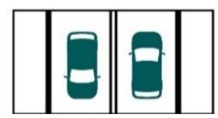
*Included in the original list of 80 treatments and the revised list of 35 treatments from the treatment screening and consolidation but not included in the most common treatment combinations.

#Not included in the original list of 80 treatments but added to CMF search based on diagnostic approach results.

○ Enhance visibility (signing, markings, lighting) ○ Provide pedestrian refuge (in median) with Danish offset (Redmon 2011) • Add and/or enhance bus stop structure/visibility • Install bus island/floating bus stop or bus pad • Enhance intersection crossings ○ Provide leading pedestrian interval ○ Provide pedestrian refuge ○ Enhance visibility (signing, markings, lighting)	○ Enhance visibility (signing, markings, lighting) ○ Provide pedestrian refuge (in median) • Add and/or enhance bus stop structure/visibility ○ Install bus pad • Enhance intersection crossings ○ Provide leading pedestrian interval ○ Provide pedestrian refuge ○ Install curb extensions ○ Enhance visibility (signing, markings, lighting)
	
Urban two-lane road	**Rural two-lane road**
A Complete Streets transformation might involve various combinations of the following treatments:	A Complete Streets transformation might involve various combinations of the following treatments:
• Narrow lanes • Reconfigure parking (angle to parallel or angle to back-in angle) • Add bike facility (per bikeway selection process) • Add and/or enhance midblock pedestrian crossings • Install PHB or RRFB • Enhance intersection crossings • Install curb extensions • Enhance visibility (signing, markings, lighting)	• Add and/or enhance midblock pedestrian crossings • Install PHB or RRFB • Enhance intersection crossings • Enhance visibility (signing, markings, lighting)
Additional treatments that apply to all scenarios: Add/enhance sidewalks; Add/enhance shared-use path; Provide landscape buffer	

Source: FHWA.

Figure 1. Graphic. Results of diagnostic approach to treatment combinations.

CHAPTER 3. CMF CAPABILITIES AND NEEDS

This chapter provides an assessment of current CMFs for quantifying the safety performance effects of the common Complete Streets treatments identified in chapter 2. The project team compiled available CMFs for the initial list of 80 treatments from the FHWA CMF Clearinghouse (FHWA 2023a). The team attempted to balance comprehensively cataloging all available CMFs and presenting the most relevant information by including at least one CMF from each study that dealt with a given treatment. The clearinghouse sometimes reported many CMFs for a single study (sometimes upward of 50) that applied only to very specific combinations of crash type, crash severity, area type, facility type, and/or other factors. In these cases, the project team cataloged the most relevant CMFs in the spreadsheet and left a note that the study also resulted in numerous other CMFs for these specific combinations of crash characteristics. The project team collected a total of 718 CMFs across the 80 treatments. Table 12 describes the availability of CMFs for the 15 treatments identified in table 6, plus the four additional treatments from the diagnostic review concluding chapter 2. Note that table 12 summarizes the CMF availability for the consolidated list of treatments as described in chapter 2. Some of the rows of table 12 account for multiple treatments from the initial list of 80 treatments. Appendix A provides a summary of CMF availability (including number of studies, number of CMFs, CMF star rating, and crash types and severities of available CMFs) for the 80 individual treatments.

Table 12. Summary of CMF availability for treatments that are part of common treatment combinations on Complete Streets.

Treatment Name	Number of Studies	Number of CMFs	Average CMF Star Rating (Min-Max Star Range)	Average CMF (Min-Max CMF Range)	Available Crash-Type CMFs				Most Severe Crash Severity CMF Available
					All	Vehicle/ pedestrian	Vehicle/ bicycle	Other*	
Add bike lane	6	8	2.1 (1-4)	0.68 (0.19-1.49)	X	–	X	–	KABC
Add bicyclist and pedestrian path/trail	2	2	2.0 (2)	0.79 (0.75-0.83)	–	–	X	–	KABCO
Add curb extension/bulb-out	None	–	–	–	–	–	–	–	–
Add or enhance crosswalk (including high-visibility)	3	4	2.8 (2-4)	0.60 (0.35-0.81)	X	X	–	X	KABCO
Add or enhance lighting	13	32	3.2 (2-4)	0.69 (0.00-1.39)	X	X	X	X	K
Add or enhance midblock crossing	1	1	4.0 (4)	0.82 (0.82)	–	X	–	–	KABCO
Add or enhance pedestrian and bicyclist signal operation	12	48	3.2 (1-5)	0.85 (0.30-1.10)	X	X	–	X	K
Add or enhance sidewalk	4	8	2.8 (2-3)	1.79 (0.41-3.09)	X	–	X	–	KA
Add or enhance traffic signal operation	25	89	3.1 (1-5)	0.87 (0.23-2.43)	X	X	–	X	K
Add pedestrian-actuated signal or beacon	6	22	3.6 (1-5)	0.66 (0.27-1.18)	X	X	–	X	KABC
Add pedestrian refuge island	1	1	3.0 (3)	0.54 (0.54-0.54)	–	X	–	–	KABCO
Add separated bike lane	3	7	2.3 (2-3)	0.82 (0.27-1.75)	–	X	X	–	ABC

Treatment Name	Number of Studies	Number of CMFs	Average CMF Star Rating (Min-Max Star Range)	Average CMF (Min-Max CMF Range)	Available Crash-Type CMFs				Most Severe Crash Severity CMF Available
					All	Vehicle/ pedestrian	Vehicle/ bicycle	Other*	
Change parking configuration	3	10	1.4 (1-3)	0.77 (0.35-2.11)	X	–	–	X	KABC
Improve signing and marking	6	20	2.9 (1-4)	0.73 (0.54-0.92)	X	–	–	X	KABC
Perform a Road Diet	8	27	2.6 (1-5)	0.69 (0.36-1.05)	X	–	–	X	KABC
Decrease roadway or lane width	8	56	2.8 (1-4)	1.16 (0.44-3.38)	X	–	X	X	KABC
Remove shoulder	6	15	2.8 (2-3)	1.20 (1.10-1.50)	X	–	–	X	KA
Convert flush median to raised median	None	–	–	–	–	–	–	–	–
Add bus island/floating bus stop or add bus boarding platform	None	–	–	–	–	–	–	–	–

* Other crash types include angle, head-on, left-turn, right-turn, sideswipe, rear-end fixed object, run off road, single-vehicle, nighttime, twilight, parking related, and other crash types as defined in the CMF Clearinghouse.
X = CMF available for crash type; – = CMF not available.

After multiple decades of CMF-related research, significant CMF needs remain with respect to quantifying the safety performance effects of Complete Streets treatments for all users. Table 12 shows that some common treatments have no CMFs at all. Of the 15 treatments that have CMFs, the maximum CMF rating for 7 of the treatments is lower than 4 stars. Treatments expected to improve both pedestrian and bicyclist safety performance do not always have CMFs for both respective crash types. Finally, only three treatments have CMFs specific enough to focus on fatal and suspected serious injury (KA) crashes, which are the primary focus of the SSA. Without CMFs specific to KA crashes, analysts should assume that the effect on KA crashes is the same as the effect on KABC crashes. This assumption likely masks specific effects on the most serious crash types.

These CMF needs exist not for a lack of research but because of inherent challenges in developing CMFs for pedestrian and bicyclist safety treatments. Pedestrian and bicycle safety performance remain one of the most significant gaps in crash-based DDSA methods and tools. These gaps exist for multiple reasons, including the lack of pedestrian and bicyclist volume (i.e., exposure) information over the period of time that crash data are collected and the inability of more aggregate crash-based evaluations to capture nuanced effects on pedestrian and bicyclist safety performance, such as those related to the numbers of lanes that must be crossed, presence/type of refuge, and vehicle through and turning speeds.

In addition to individual CMF needs, methods to combine multiple CMFs are in relatively early stages of use. Some documentation of these methods recommends not using the methods for any more than three CMFs at a time (Carter et al. 2022). Fifty-two (61 percent) of the 85 Complete Streets projects that the team reviewed implemented four or more treatments.

This project leveraged the existing CMFs and the accuracy of combining multiple CMFs as part of a Complete Streets analysis. However, the conclusions and recommendations of this report document other potential analysis directions.

CHAPTER 4. COMPLETE STREETS SAFETY ANALYSIS PRIMER

INTRODUCTION

This chapter contains a primer on DDSA of Complete Streets projects using CMFs. The chapter is organized into the following sections:

1. Purpose of Primer
2. Predictive Analysis
    a. Step 1: Estimate Safety Performance of Future No-Build Condition
    b. Step 2: Determine CMF for Complete Streets Project
    c. Step 3: Estimate Safety Performance of Complete Streets Project
3. Safety Effectiveness Evaluations
    a. Step 1: Estimate Safety Performance in After Period WITHOUT Complete Streets Project
    b. Step 2: Compare Safety Performance in After Period WITH and WITHOUT Complete Streets Project
4. Data Needs and Preparation
    a. Crash Data
    b. Roadway Data
    c. Exposure Data
    d. Segmentation
5. Common Challenges and Limitations
6. Resources
7. Glossary
8. Appendix: Annual Average Daily Traffic (AADT) Coefficients by Facility Type and Crash Severity

The content of this primer was informed by an effort to conduct DDSA using CMFs on five Complete Streets case studies. Exploring approaches for identifying an appropriate CMF to represent the safety effects of different treatment combinations that occur on a Complete Streets project was a particular focus of the case studies. Appendix B summarizes methods to identify an appropriate CMF to represent the safety effects of different treatment combinations when each individual treatment has a CMF. Appendix C documents the data collection and analysis results for the five case studies.

PURPOSE OF PRIMER

The primer summarizes how to estimate the combined safety effect of multiple treatments for Complete Streets projects. The primer focuses on the following two applications:

1. **Predictive analysis**: The primer addresses the pre-construction application, allowing analysts to estimate the expected safety performance of a proposed Complete Streets project in comparison to an alternative condition (e.g., the no-build).

2. **Safety effectiveness evaluation**: The primer addresses the post-construction application, allowing analysts to estimate the safety effectiveness of a completed Complete Streets project (e.g., the build).

Following the discussion of analysis methods for the two applications, the primer describes the data needs and preparation, common challenges and limitations in existing data and methods, and future research needs. There are two target audiences for the guide: practitioners and researchers. Practitioners can use this primer to estimate the safety benefits of a proposed or completed Complete Streets alternative. Researchers can use this primer to evaluate the safety effectiveness of constructed Complete Streets projects or to identify and address the challenges related to the current data and methods.

PREDICTIVE ANALYSIS

This section applies to Complete Streets projects that are not yet constructed (i.e., still in planning and project development phases). Analysts can use the methods in this section to estimate the expected safety performance of a proposed Complete Streets project with multiple safety treatments.

Predictive analysis includes the following steps, which are described in more detail.

1. Estimate safety performance of future no-build condition.
2. Determine CMF for Complete Streets project.
3. Estimate the safety performance of the Complete Streets project.

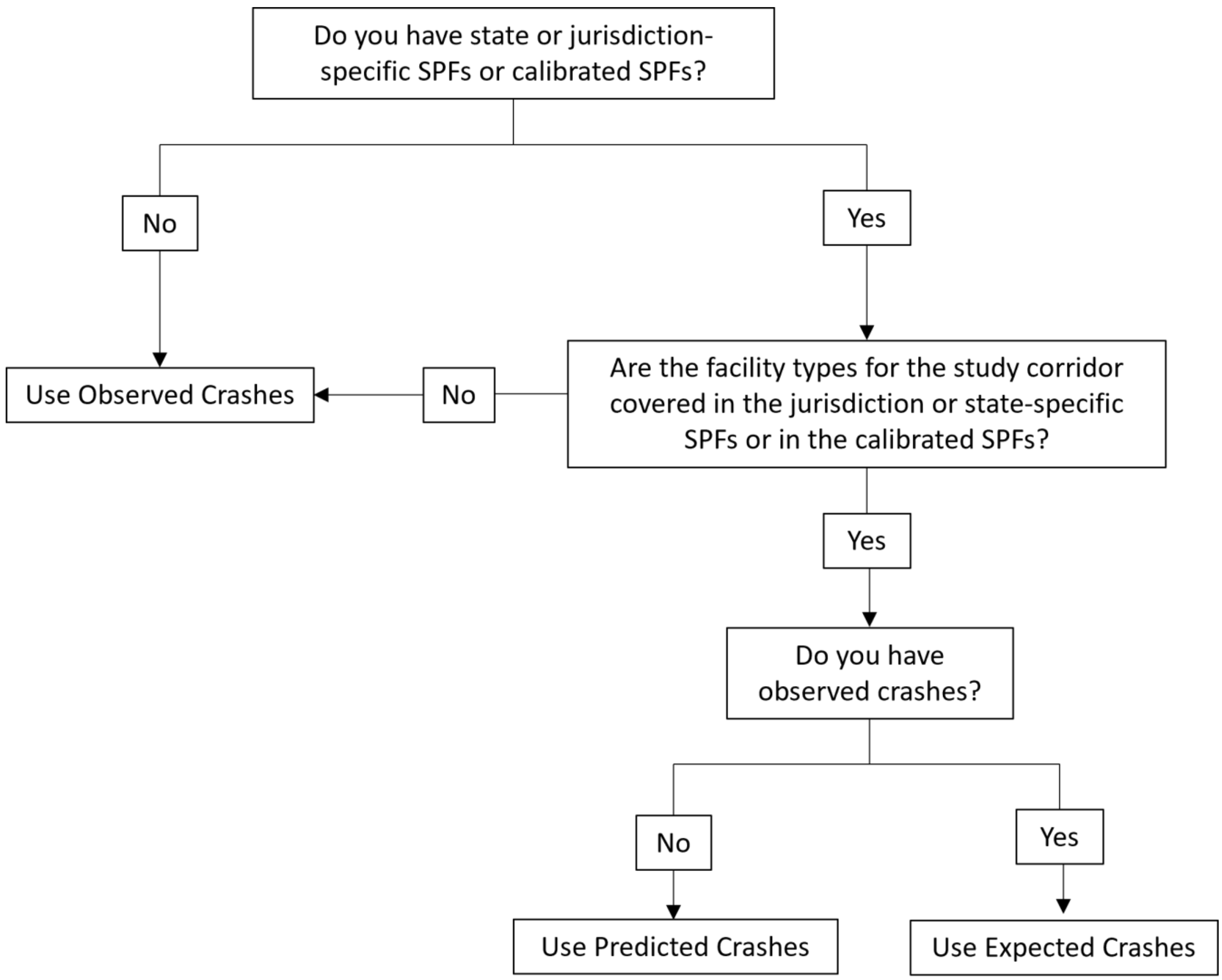
Step 1: Estimate Safety Performance of Future No-Build Condition

> ***Note**: Complete Streets projects may generate changes in traffic volume, which contribute to changes in safety. This method incorporates the safety benefit (or disbenefit) associated with changes in traffic volume that are attributable to the Complete Streets project.*

Several options for methods to estimate the future safety performance of the no-build condition exist, including using various combinations of observed, predicted, and expected number of crashes. The methods vary in terms of reliability and are presented as follows in priority order (decreasing reliability). Figure 2 presents a process for analysts to select a method based on the availability and reliability of historical crash data and calibrated or jurisdiction-specific SPFs for the study area, facility type, and site type of interest. Atkinson et al. (2016) notes that analysts should use calibrated or jurisdiction-specific SPFs to make crash predictions. The estimated safety performance for the future no-build scenario should also reflect changes in expected traffic volume if the Complete Streets project is not constructed. Analysts can use traffic forecasting methods (e.g., straight line growth, traffic growth rates, or a regional traffic model) to estimate this change in volume.

1. **Expected crashes**: Analysts should use the Empirical Bayes (EB) method to estimate the expected crashes when both reliable crash history and State- or jurisdiction-specific SPFs or calibrated SPFs are available for the existing facility type(s) and site type(s) along the study corridor.

2. **Predicted crashes**: Analysts should use an appropriate SPF to predict crashes when State- or jurisdiction-specific SPFs or calibrated SPFs are available for the facility type(s) and site type(s) along the study corridor, but observed crashes are not available or are not reliable.
3. **Observed crashes**: Analysts should use observed crashes when no State- or jurisdiction-specific SPFs or calibrated SPFs are available for the facility type(s) and site type(s) along the study corridor.



Source: FHWA.

Figure 2. Graphic. Process for selecting a method to estimate safety performance of future no-build conditions.

Method 1: Expected Crashes

The EB method is a weighted average of observed and predicted crashes, resulting in an estimate of expected crashes. This method is preferred for estimating the safety performance of the future no-build conditions. The EB method incorporates observed crash history and predicted crashes, adjusts for changes in traffic volume over time, and can account for fluctuations in crashes over time (regression to the mean). To apply this method, analysts need reliable crash history; a suitable, calibrated SPF; traffic volume data for the same period as the crash history; and projected traffic volume data under the future no-build scenario for the period of interest (typically the design year).

Analysts estimate the expected crashes for the current conditions using the crash history, traffic volumes associated with the crash history, and applicable SPF(s). They can then project that estimate into the future (e.g., design year), accounting for changes in traffic volume that would be expected *without* the Complete Streets project. This is shown in figure 3, where the ratio of future predicted crashes to current predicted crashes is used to project the current expected crashes into the future.

$$Estimated\ Crashes_{future\ ,WITHOUT} = Expected\ Crashes_{current\ ,WITHOUT} * \left(\frac{Predicted\ Crashes_{future\ ,WITHOUT}}{Predicted\ Crashes_{current\ ,WITHOUT}}\right)$$

Figure 3. Equation. Estimating crashes in future no-build using Method 1.

Where:

> Estimated $\text{Crashes}_{\text{future,WITHOUT}}$ = estimated crashes in future without the Complete Streets project (i.e., future no-build).
>
> Expected $\text{Crashes}_{\text{current,WITHOUT}}$ = expected crashes in current period.
>
> Predicted $\text{Crashes}_{\text{future,WITHOUT}}$ = predicted crashes in future period without the Complete Streets project (i.e., future no-build). Note this prediction should use the traffic volume for the future no-build scenario. In this case, the analyst should use traffic forecasting methods (e.g., straight line growth, traffic growth rates, or a regional traffic model) to estimate the future traffic volume that would be expected if the Complete Streets project is not constructed.
>
> Predicted $\text{Crashes}_{\text{current,WITHOUT}}$ = predicted crashes in current period.

Method 2: Predicted Crashes

If a suitable, calibrated SPF is available but reliable crash data are not available, then the preferred method for estimating future safety performance is to use predicted crashes as shown in figure 4. One obvious limitation of this method is that it does not account for historical crashes at the location of interest; however, this method does help to account for fluctuations in crashes over time because it is based on the safety performance of many similar locations.

$$Estimated\ Crashes_{future\ ,WITHOUT} = Predicted\ Crashes_{future\ ,WITHOUT}$$

Figure 4. Equation. Estimating crashes in future no-build using Method 2.

Where:

Estimated $\text{Crashes}_{\text{future,WITHOUT}}$ = estimated crashes in future without the Complete Streets project (i.e., future no-build).

Predicted $\text{Crashes}_{\text{future,WITHOUT}}$ = predicted crashes in future period without the Complete Streets project (i.e., future no-build). Note this prediction should use the traffic volume for the future no-build scenario. In this case, the analyst should use traffic forecasting methods (e.g., straight line growth, traffic growth rates, or a regional traffic model) to estimate the future traffic volume that would be expected if the Complete Streets project is not constructed.

Method 3: Observed Crashes with Traffic Volume Adjustment

If a suitable, calibrated SPF is not available but reliable crash and traffic volume data are available, then the preferred method for estimating future safety performance is to use observed crashes with adjustments for traffic volume. Analysts can use observed crash history to estimate the safety performance of current conditions and then adjust for future projected traffic volumes to estimate the estimated number of crashes for the future no-build condition, as shown in figure 5 (example for segments) and figure 6 (example for intersections). Analysts can include several years of crash history to improve the estimate of current safety performance. The HSM recommends using at least 2 yr of crash data (AASHTO 2010). When practical, using at least 5 yr of data will improve the reliability of the estimated average crash frequency. However, analysts should be aware that using more years of crash data can introduce confounding factors when other changes that occurred during the extended historical time period impact the number of crashes. One limitation of this method is that it does not account for fluctuations in crashes over time (i.e., it is susceptible to regression-to-the-mean bias).

The example segment and intersection equations in figure 5 and figure 6 are based on a majority of the AADT relationships in the first edition of the HSM (AASHTO 2010). As methods evolve, the AADT relationships may take on different forms. The same general approach in figure 5 and figure 6 would still hold, but the ratio of future to current AADT and the associated parameters would reflect the new AADT form.

In addition, most models in the HSM's first edition do not currently account for pedestrian and bicyclist volumes (AASHTO 2010). However, future predictive methods could incorporate pedestrian or bicycle volumes by using a similar approach. The parameters associated with pedestrian and bicyclist volumes could possibly take on very different values than the parameters for AADT. Some research has shown pedestrian and bicyclist crash probability may decrease as pedestrian and bicyclist volumes increase, a "safety in numbers" effect (Hamilton et al. 2021). Additional research in this area is needed.

For a segment:

$$Estimated\ Crashes_{future\ ,WITHOUT} = Observed\ Crashes_{current\ ,WITHOUT} * \left(\frac{AADT^{a}_{future\ ,WITHOUT}}{AADT^{a}_{current\ ,WITHOUT}}\right)$$

Figure 5. Equation. Estimating segment crashes in future no-build using Method 3.

For an intersection:

$$Estimated\ Crashes_{future\ ,WITHOUT} = Observed\ Crashes_{current\ ,WITHOUT} * \left(\frac{Major\ AADT^{b}_{future\ ,WITHOUT} * Minor\ AADT^{c}_{future\ ,WITHOUT}}{Major\ AADT^{b}_{current\ ,WITHOUT} * Minor\ AADT^{c}_{current\ ,WITHOUT}}\right)$$

Figure 6. Equation. Estimating intersection crashes in future no-build using Method 3.

Where:

Estimated $\text{Crashes}_{\text{future,WITHOUT}}$ = estimated crashes in future period without the Complete Streets project (i.e., future no-build).

Observed $\text{Crashes}_{\text{current,WITHOUT}}$ = observed crashes in current period.

$\text{AADT}_{\text{future,WITHOUT}}$ = traffic volume for segment in future period. Note this prediction should use the traffic volume for the future no-build scenario. In this case, the analyst should use traffic forecasting methods (e.g., straight line growth, traffic growth rates, or a regional traffic model) to estimate the expected future traffic volume if the Complete Streets project is not constructed.

$\text{AADT}_{\text{current,WITHOUT}}$ = traffic volume for segment in current period.

Major $\text{AADT}_{\text{future,WITHOUT}}$ = major road traffic volume for intersection in future period. Note this prediction should use the traffic volume for the future no-build scenario. In this case, the analyst should use traffic forecasting methods (e.g., straight line growth, traffic growth rates, or a regional traffic model) to estimate the expected future traffic volume if the Complete Streets project is not constructed.

Major $\text{AADT}_{\text{current,WITHOUT}}$ = major road traffic volume for intersection in current period without the Complete Streets project.

Minor $\text{AADT}_{\text{future,WITHOUT}}$ = minor-road traffic volume for intersection in future period without the Complete Streets project. Note this prediction should use the traffic volume for the future no-build scenario. In this case, the analyst should use traffic forecasting methods (e.g., straight line growth, traffic growth rates, or a regional traffic model) to estimate the expected future traffic volume if the Complete Streets project is not constructed.

Minor $\text{AADT}_{\text{current,WITHOUT}}$ = minor-road traffic volume for intersection in current period without treatment.

a,b,c = SPF AADT parameters. Note that analysts can obtain these coefficients from the HSM or other State- or jurisdiction-specific SPFs. In the absence of coefficients, the analyst could assume a coefficient of 1.0 for all parameters. The appendix section of this primer provides AADT parameters by facility type from the HSM, which can be applied in figure 5 and figure 6.

Step 2: Determine CMF for Complete Streets Project

Identifying an appropriate CMF to represent the combined treatment that would occur as a result of the Complete Streets project includes the following steps:

1. Identify CMFs for each treatment.
2. Select or estimate CMF for combined treatment effect.

> ***Note**: This method assumes the CMF reflects the net benefit of the Complete Streets project, including changes in safety associated with changes in traffic volume that are attributable to the Complete Streets project. The validity of this assumption depends on the methods used to develop the CMF and may be determined by reviewing the underlying research report.*

Step 2a. Identify CMFs for Each Treatment

Analysts should identify applicable CMFs for each treatment that comprises the Complete Streets project. Some CMFs apply to a single treatment, while others apply to multiple treatments (e.g., combined effect of both lane narrowing and adding a bike lane). Multiple resources are available to search for CMFs, including:

- State-specific CMF lists.
- CMF Clearinghouse (FHWA 2023a).[3]

CMFs should be applicable to the condition of the treatment location (e.g., same before condition, area type, functional classification, number of lanes). Additionally, all CMFs for a Complete Streets project should be applicable to the same crash type and severity levels. For example, if some CMFs are applicable to specific severity levels (e.g., fatal and injury crashes) while others apply to specific crash types (e.g., right angle or pedestrian crashes), then the analyst should convert all CMFs to total crash CMFs using crash severity and/or crash-type distributions, before moving on to Step 2b.

Chapter 2 of this report summarizes an effort to determine common combinations of safety treatments implemented on Complete Streets projects. Chapter 3 provides a summary of available CMFs as well as CMF needs for the treatments in chapter 2. Appendix C demonstrates the selection and application of CMFs for five case studies.

Step 2b. Select/Estimate CMF for Combined Treatment

In some cases, CMFs are available for combined treatments (e.g., install a raised median with a marked crosswalk); however, in many cases, individual CMFs exist for some or all components of the Complete Streets project but not for the combined treatment. Here, the analyst will often need to select or estimate a CMF to represent the combined treatment effect. Appendix B provides a summary of the multiple methods available to estimate the effect of the combined treatment. This primer focuses on the dominant effect and dominant common residuals methods. Carter et al. (2022) and Massachusetts Department of Transportation (MassDOT) (2021) suggest these two methods may be the most appropriate in contexts where overlap exists in crash types

[3]Note: the CMF Clearinghouse includes the CMFs from Part D of the HSM 1st Edition.

targeted by the countermeasures. These methods also performed consistently better than other methods based on an empirical analysis of the Complete Streets case study results in this report (see Appendix C).

Dominant effect: The dominant effect method applies the most effective CMF in the analysis. This method assumes overlap among the effects of the various treatments (e.g., both treatments target the same crash types or underlying safety issues). However, the dominant effect method may underestimate crash reductions if the other treatments improve safety beyond the most effective treatment. It may also overestimate crash reductions if some treatments result in an increase in crashes.

$$CMF_t = CMF_1$$

Figure 7. Equation. Dominant effect method for estimating CMF for combined treatment.

Dominant common residuals: The dominant common residuals method raises the product of the CMFs to the power of the CMF with the greatest crash reduction, shown in figure 8 (Carter et al. 2022). This method also assumes some overlap among the effects of the various treatments but gives credit for the benefits (or disbenefits) of each additional treatment. Note that using this method is not appropriate if the most safety effective treatment is greater than 1.0. In this case, the effect of the CMFs would be intensified.

$$CMF_t = (CMF_1 * CMF_2 * \cdots * CMF_n)^{CMF_1}$$

Figure 8. Equation. Dominant common residuals method for estimating CMF for combined treatment.

Where:

CMF_t = CMF for combined treatment effect.

CMF_1 = CMF for most effective treatment.

CMF_2 = CMF for second effective treatment.

CMF_n = CMF for n^{th} most effective treatment. While the method can apply to more than three countermeasures, the case studies in the appendix tested the method with no more than three CMFs on a given segment or intersection.

Step 3: Estimate Safety Performance of Complete Streets Project

Finally, analysts can apply the CMF for the combined treatment (results from step 2) to the estimated safety performance of the future no-build scenario (results from step 1) as shown in figure 9. This produces an estimate of the safety performance with the Complete Streets project.

***Note**: This method assumes the CMF includes the safety effect from changes in traffic volume that could result from the implementation of a treatment.*

$$Estimated\ Crashes_{future\ ,WITH} = CMF_t * Estimated\ Crashes_{future\ ,WITHOUT}$$

Figure 9. Equation. Estimating safety performance of Complete Streets project.

Where:

Estimated $\text{Crashes}_{\text{future,WITH}}$ = estimated future crashes with the Complete Streets project.

CMF_t = CMF for combined treatment effect.

Estimated $\text{Crashes}_{\text{future,WITHOUT}}$ = estimated future crashes without the Complete Streets project (i.e., future no-build).

By comparing the estimated safety performance with and without the Complete Streets project, analysts can express the expected benefit of the Complete Streets project in terms of the change in the number of crashes (figure 10) or the percent change in crashes (figure 11).

$$Change\ in\ crash\ frequency = Estimated\ Crashes_{future\ ,WITHOUT} - Estimated\ Crashes_{future\ ,WITH}$$

Figure 10. Equation. Expected benefit of Complete Streets project in change in number of crashes.

$$Percent\ change\ in\ crash\ frequency = \left(1 - \frac{Estimated\ Crashes_{future,WITH}}{Estimated\ Crashes_{future,WITHOUT}}\right) * 100\%$$

Figure 11. Equation. Expected benefit of Complete Streets project in percent change in number of crashes.

SAFETY EFFECTIVENESS EVALUATIONS

This section applies to Complete Streets projects that are constructed and open to traffic. Analysts can use the methods in this section to determine the success of Complete Streets projects (e.g., determining if the project improved safety performance). Further, safety effectiveness evaluations can help to estimate CMFs for treatment combinations for use in future predictive analysis (refer to the Common Challenges and Limitations section for further discussion of lack of CMFs for predictive analysis).

> ***Note**: Safety effectiveness evaluations should account for the full benefit of the Complete Streets project, including any changes in traffic volume that resulted from the implementation of the project.*

Safety effectiveness evaluations include the following two steps, which are described in more detail below.

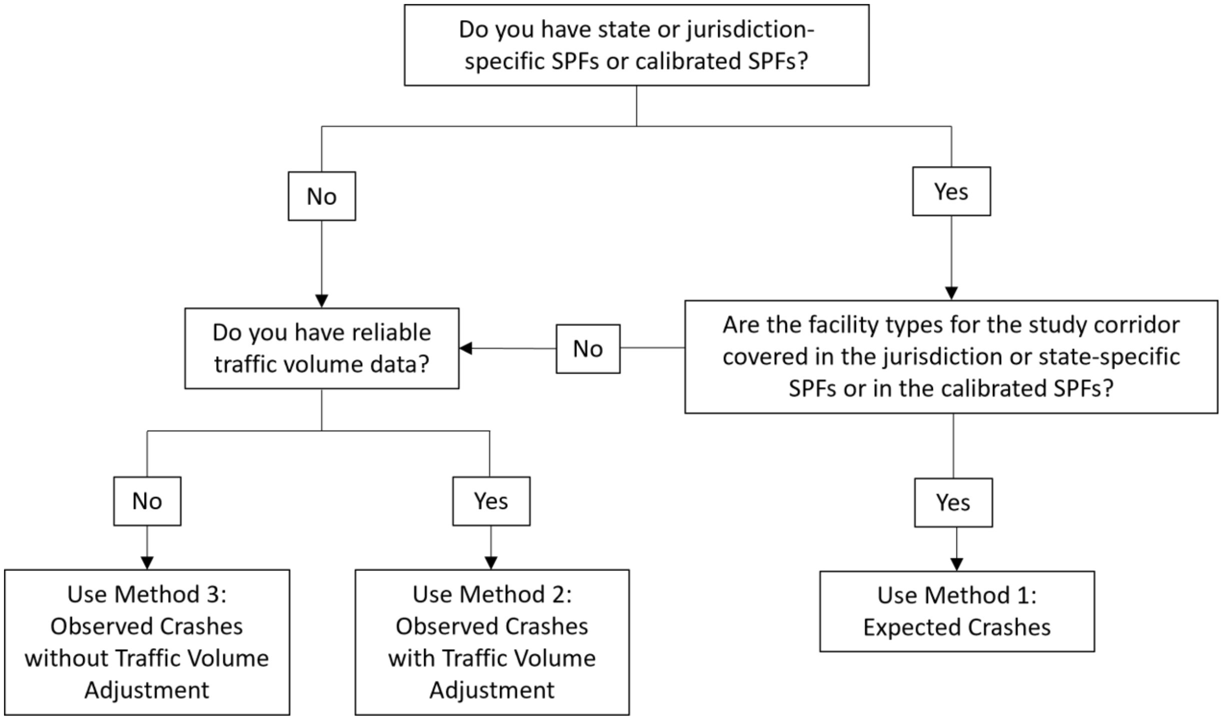
1. **Estimate the safety performance in the after period WITHOUT the Complete Streets project** (i.e., future no-build scenario). This provides an estimate of what the safety performance would have been if the Complete Streets project were not constructed. Note that this step also occurs when performing a predictive analysis.
2. **Compare the safety performance in the after period WITH and WITHOUT the Complete Streets project**. This provides an estimate of the safety performance with the Complete Streets project constructed. Analysts can then compare the safety performance with and without the Complete Streets project to calculate the project's safety effect.

Refer to FHWA's *Highway Safety Improvement Program (HSIP) Evaluation Guide* (Gross 2017) and *A Guide to Developing Quality CMFs* (Gross et al. 2010) for further details on computing project benefits and CMFs.

Step 1: Estimate Safety Performance in After Period WITHOUT the Complete Streets Project

> ***Note**: When feasible, the estimate of future safety performance without treatment should reflect the traffic volume that would be expected under the no-build condition (i.e., if the Complete Streets project was not constructed).*

The first step to evaluating the safety performance of a constructed Complete Streets project is to estimate "what would have been"—the safety performance of the study area in the after period if the Complete Streets project not been constructed. Several methods to estimate the future safety performance for the no-build condition exist, including the use of some combination of observed, predicted, and expected crashes. The following methods vary in terms of reliability and are presented in priority order (decreasing reliability). Figure 12 presents a process for analysts to select a method for step 1 based on the availability and reliability of calibrated SPFs for the study area, facility type, and site type of interest, based on the availability of traffic volume data.



Source: FHWA.

Figure 12. Graphic. Process for selecting a method for step 1 to estimate safety performance in the after period without the Complete Streets project.

Method 1: Expected Crashes

The EB before-after method is preferred for safety effectiveness evaluations because it incorporates observed crash history and predicted crashes, adjusts for changes in traffic volume over time, and can account for fluctuations in crashes over time (regression to the mean). The EB method is a weighted average of observed and predicted crashes, resulting in an estimate of expected crashes. To apply this method, analysts need reliable crash data for the before and after period, a suitable, calibrated SPF, and traffic volume data.

Analysts compute the expected crashes for the before period and then project that estimate into the after period, accounting for expected changes in traffic volume under the no-build condition. Figure 13 shows the ratio of predicted crashes in the after period without the Complete Streets alternative to predicted crashes in the before period without the Complete Streets alternative, which is used to project the expected crashes before treatment into the future no-build condition.

$$Estimated\ Crashes_{After,WITHOUT} = Expected\ Crashes_{Before,WITHOUT} * \left(\frac{Predicted\ Crashes_{after,WITHOUT}}{Predicted\ Crashes_{before,WITHOUT}}\right)$$

Figure 13. Equation. Estimating crashes in future no-build for safety evaluation using Method 1.

Where:

Estimated $\text{Crashes}_{\text{After,WITHOUT}}$ = estimated crashes in the after period without the Complete Streets project (i.e., future no-build).

Expected $\text{Crashes}_{\text{Before,WITHOUT}}$ = expected crashes in the before period without the Complete Streets project.

Predicted $\text{Crashes}_{\text{After,WITHOUT}}$ = predicted crashes in the after period without treatment. Note this prediction should use the expected traffic volume in the after period without treatment (i.e., future no-build). In this case, the analyst should use traffic forecasting methods (e.g., straight line growth, traffic growth rates, or a regional traffic model) to estimate the expected traffic volume in the after period if the Complete Streets project was not constructed.

Predicted $\text{Crashes}_{\text{Before,WITHOUT}}$ = predicted crashes in the before period without treatment.

Method 2: Observed Crashes with Traffic Volume Adjustment

If a suitable, calibrated SPF is not available, then the next preferred method is to use observed crashes and adjust for changes in traffic volume. In these situations, analysts can use observed crash history from the before period, adjusting for changes in traffic volume, to estimate the average crash frequency in the after period under no-build conditions, as shown in figure 14 (example for segments) and figure 15 (example for intersections). Analysts can include several years of crash history to improve the estimate of current safety performance. The HSM recommends at least 2 yr of crash data (AASHTO 2010). When practical, using at least 5 yr of data will improve the reliability of the estimated average crash frequency. However, analysts should be aware that using more years of crash data can introduce confounding factors when other changes that occurred during the extended historical time period impact the number of crashes. One limitation of this method is that it does not account for fluctuations in crashes over time (i.e., it is susceptible to regression-to-the-mean bias). The example segment and intersection equations in figure 14 and figure 15 are based on a majority of the AADT relationships in the first edition of the HSM (AASHTO 2010). The Predictive Analysis section of this primer describes how these concepts of traffic volume and crash data can apply to different AADT relationships and to pedestrian and bicyclist volumes.

For a segment:

$$Estimated\ Crashes_{After\ ,WITHOUT} = Observed\ Crashes_{Before\ ,WITHOUT} * \left(\frac{AADT^{a}_{after\ ,WITHOUT}}{AADT^{a}_{before\ ,WITHOUT}}\right)$$

Figure 14. Equation. Estimating segment crashes in future no-build for safety evaluation using Method 2.

For an intersection:

$$Estimated\ Crashes_{After\ ,WITHOUT} = Observed\ Crashes_{Before\ ,WITHOUT} * \left(\frac{Major\ AADT^{b}_{after\ ,WITHOUT} * Minor\ AADT^{c}_{after\ ,WITHOUT}}{Major\ AADT^{b}_{before\ ,WITHOUT} * Minor\ AADT^{c}_{befor\ e,WITHOUT}}\right)$$

Figure 15. Equation. Estimating intersection crashes in future no-build for safety evaluation using Method 2.

Where:

Estimated $\text{Crashes}_{\text{After,WITHOUT}}$ = estimated crashes in the after period without the Complete Streets project (i.e., future no-build).

Observed $\text{Crashes}_{\text{Before,WITHOUT}}$ = observed crashes in the before period without the Complete Streets project.

$\text{AADT}_{\text{After,WITHOUT}}$ = traffic volume for the segment in the after period. Note this prediction should use the expected traffic volume in the after period without treatment (i.e., future no-build). In this case, the analyst should use traffic forecasting methods (e.g., straight line growth, traffic growth rates, or a regional traffic model) to estimate the expected traffic volume in the after period if the Complete Streets project was not constructed.

$\text{AADT}_{\text{Before,WITHOUT}}$ = traffic volume for segment in the before period without the Complete Streets project.

Major $\text{AADT}_{\text{After,WITHOUT}}$ = major road traffic volume for intersection in the after period. Note this prediction should use the expected traffic volume in the after period without treatment (i.e., future no-build). In this case, the analyst should use traffic forecasting methods (e.g., straight line growth, traffic growth rates, or a regional traffic model) to estimate the expected traffic volume in the after period if the Complete Streets project was not constructed.

Major $\text{AADT}_{\text{Before,WITHOUT}}$ = major road traffic volume for intersection in the before period without the Complete Streets project.

Minor $\text{AADT}_{\text{After,WITHOUT}}$ = minor-road traffic volume for intersection in the after period. Note this prediction should use the expected traffic volume in the after period without treatment (i.e., future no-build). In this case, the analyst should use traffic forecasting methods (e.g., straight line growth, traffic growth rates, or a regional traffic model) to estimate the expected traffic volume in the after period if the Complete Streets project was not constructed.

Minor $AADT_{Before,WITHOUT}$ = minor-road traffic volume for intersection in the before period without the Complete Streets project.

a,b,c = SPF AADT parameters. Note analysts can obtain these coefficients from the HSM or other State- or jurisdiction-specific SPFs. In the absence of coefficients, the analyst could assume a coefficient of 1.0 for all parameters. The appendix section of this primer provides AADT parameters by facility type from the HSM (AASHTO 2010), which can be applied in figure 14 and figure 15.

Method 3: Observed Crashes without Volume Adjustment

If a suitable SPF and reliable traffic volume data are not available, then the final method for estimating safety performance in the after period is to simply use the average observed crashes in the before period, as shown in figure 16. One obvious limitation of this method is that it does not account for changes in traffic volume over time. Another limitation is that effects due to changes other than the Complete Streets project cannot be separated from effects of the Complete Streets project.

$$Estimated\ Crashes_{After,WITHOUT} = Observed\ Crashes_{Before,WITHOUT}$$

Figure 16. Equation. Estimating crashes in future no-build for safety evaluation using Method 3.

Where:

Estimated $Crashes_{After,WITHOUT}$ = estimated crashes in the after period without the Complete Streets project (i.e., future no-build).

Observed $Crashes_{Before,WITHOUT}$ = observed crashes in the before period without the Complete Streets project.

Step 2: Compare Safety Performance in After Period WITH and WITHOUT the Complete Streets Project

The second step is to compare the expected safety performance without the Complete Streets project to the actual safety performance with the Complete Streets project in the after period. Two primary measures for expressing the results exist, as follows:

Change in crash frequency: calculated as the difference between the estimated crashes in the after period WITH and WITHOUT the Complete Streets project (figure 17).

Percent change in crash frequency: calculated as the ratio of the estimated crashes in the after period WITH and WITHOUT the Complete Streets project, typically expressed as a percent (figure 18).

$$Change\ in\ crash\ frequency = Estimate\ Crashes_{After,WITHOUT} - Observed\ Crashes_{After,WITH}$$

Figure 17. Equation. Actual benefit of Complete Streets project in change in number of crashes.

Where:

> Observed $\text{Crashes}_{\text{After,WITH}}$ = observed crashes in the after period with the Complete Streets project.

$$Percent\ change\ in\ crash\ frequency = \left(1 - \frac{Observed\ Crashes_{After,WITH}}{Estimated\ Crashes_{After,WITHOUT}}\right) * 100$$

Figure 18. Equation. Actual benefit of Complete Streets project in percent change in number of crashes.

DATA NEEDS AND PREPARATION

Data needs for predictive analysis and safety effectiveness evaluations include crash, roadway, and exposure data. The following sections discuss specific variables to collect for each data category and any differences in specific data needs for the predictive analysis and safety effectiveness evaluation.

Crash Data

Both predictive analysis and safety effectiveness evaluation can use observed crash data along the study corridor for the study period of interest. Predictive analysis can include historical crash data if available and reliable. Safety effectiveness evaluations rely on observed crash data before and after construction to assess the change in safety performance.

For predictive analysis, the study period may include one or more years of historical data. Having at least 2 yr of crash data is desirable (AASHTO 2010). For safety effectiveness evaluations, the study period typically includes data from 3–5 yr before and after construction; however, analysts may determine that more years are needed to increase sample size. While additional years can help to increase the sample size, adding years can also introduce confounding factors if there are other major changes that influence safety during the extended time period. For safety effectiveness evaluations, using the same number of years in the before and after periods is ideal; however, this is not required and may not be possible if limited years are available in the after period. In these cases, the analyst can apply an adjustment to one period to make it comparable to the other period.

Analysts might need to geolocate crashes to specific segments and intersections within the study area (see Segmentation for further discussion of how to define segments and intersections). Predictive analysis methods typically apply to segments and intersections separately, so the analyst will likely need to geolocate crashes to each specific segment and intersection along the study corridor. For safety effectiveness evaluations, analysts could assign crashes to the corridor as a whole or to individual segments and intersections depending on the scope of the analysis. As such, assigning crashes to individual segments and intersections for safety effectiveness evaluations may not be necessary.

Crash data typically include the following variables, at a minimum:

- Date and location
- Crash type and severity
- Number of vehicles involved (SV or MV)
- Bicycle-involved
- Pedestrian-involved

Depending on the scope of the analysis, other variables of interest may include the conditions at the time of the crash (e.g., roadway, weather, and light conditions).

Analysts can collect crash data from a variety of sources, including State or local transportation agencies, departments of motor vehicles, public health offices, or law enforcement agencies.

Roadway Data

Roadway data include geometric and traffic control features for both segments and intersections. Table 13 displays common roadway and intersection variables needed for analysis. If using SPFs, analysts should refer to the source of the SPFs or predictive method for specific variables.

Table 13. Roadway and intersection data commonly needed for analysis.

Roadway Data	Intersection Data
• Functional classification • Area type (e.g., rural, urban) • Number of lanes • Lane width • Median type • Shoulder presence and width • Sidewalk presence • Bike lane presence	• Number of intersection legs (e.g., 3-leg, 4-leg) • Traffic control type (e.g., signalized, minor-road stop control) • Presence of turn lanes • Presence of crosswalks

Analysts can obtain roadway data from a variety of sources, including field data collection, aerial images, and roadway inventories. Starting with existing roadway inventory data and supplementing as needed with aerial imagery, street level imagery, or site visits may be the most efficient method. Roadway data should be collected for all segments and intersections along the entire study corridor, reflecting changes in cross-section and other variables that can influence safety (see Segmentation for more details).

Exposure Data

Both predictive analysis and safety effectiveness evaluation use data such as vehicle, pedestrian, and bicycle volumes along the corridor of interest and at the intersecting roads to account for exposure (and changes in exposure) during the study period. Vehicle volumes are typically expressed as AADT. Pedestrian and bicycle volumes may be expressed as hourly, daily, or annual volumes depending on the form of the SPF.

For predictive analysis, the exposure data may include past years, current year, and future design year. For safety effectiveness evaluation, the study period typically includes 3 to 5 yr before and after construction (see Crash Data for further discussion of sample size).

Analysts can obtain traffic volume data from a variety of different sources, including State and local transportation agencies and field data collection. When feasible, traffic volume data should be obtained for each year in the study period. When this is not feasible, the HSM (AASHTO 2010) offers the following guidance on what values to use:

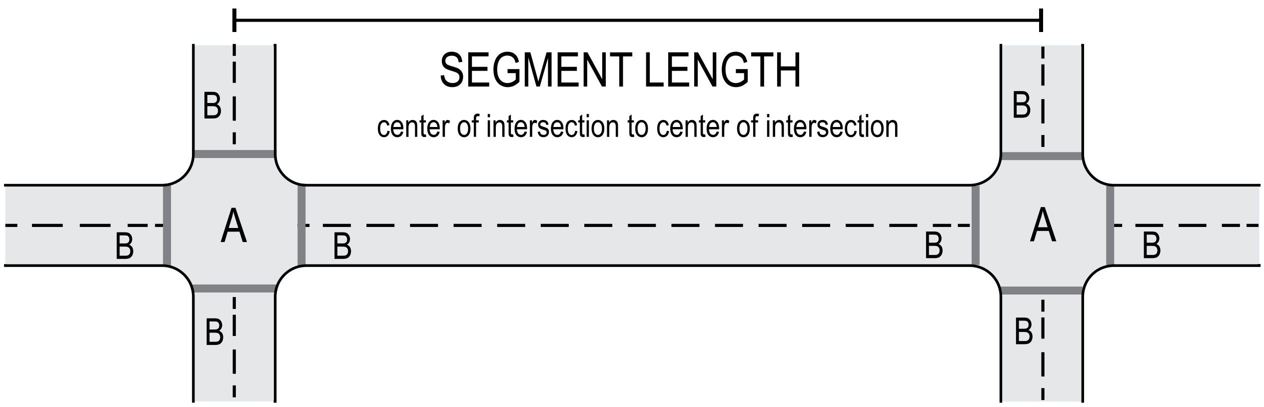
- If only a single year of traffic volume data is available during the study period, that value should be used for all years in the study period.
- If traffic volumes are available for two or more years, volumes for the remaining years should be interpolated.
- The traffic volume for the earliest year available should be used for all prior years. Similarly, the traffic volume for the latest year available should be applied to all later years.

Segmentation

The segmentation process divides a study corridor into homogenous segments and intersections. According to the HSM (AASHTO 2010), analysts should segment a corridor based on roadway and traffic characteristics, including geometric features (e.g., number of lanes, median type), traffic volume, and traffic control features. As figure 19 shows, a new segment begins at each intersection or when a change in the geometric or traffic characteristics occurs. Segments are measured from center of intersection to center of intersection, assuming the segment characteristics remain consistent along the entire length. If the geometric or traffic operational elements change, then a new segment is created, and the segment length is measured as the length of the homogeneous segment. Segmentation is necessary because predictive methods apply to specific facility types and site types (e.g., urban stop-controlled intersections vs. urban four-lane undivided arterials). Further, analysts need to assign crashes to either a segment or intersection as follows:

1. **Region A**: All crashes that occur in region A are coded as intersection crashes and assigned to the respective intersection.
2. **Region B**: Crashes that occur in region B may be coded as segment- or intersection-related. Crashes that occur within the functional area of the intersection and

are related to the presence of the intersection should be coded as “intersection-related” and assigned to the respective intersection. All other crashes (i.e., those occurring between intersections and not related to the intersections) should be coded as “segment-related” and assigned to the respective segment.



Source: FHWA

Figure 19. Graphic. HSM segmentation (AASHTO 2010).

The case studies in Appendix C of this report provide details on how each case study was disaggregated into a series of segments and intersections for analysis.

COMMON CHALLENGES AND LIMITATIONS

Due to limitations in current safety-analysis methods and data availability, analysts may face challenges when analyzing the safety performance of a Complete Streets project. The limitations and challenges discussed in the following sections generally apply to both predictive analysis and safety effectiveness evaluations, unless otherwise noted. When faced with these limitations, analysts may need to make assumptions to use the predictive analysis or safety effectiveness evaluation methods as presented in this primer.

Challenge 1: Lack of SPFs

One common challenge is the lack of a reliable SPF for the facility and site type(s) that are part of the Complete Streets project. Reliable SPFs include State- or jurisdiction-specific SPFs or calibrated SPFs from the HSM (AASHTO 2010) or other jurisdictions. If reliable SPFs are not available for the facility and site type(s) of interest, the analyst should not use predicted or expected crashes as measures of performance. Instead, the analyst should rely on historical crash data, which is prone to issues such as fluctuations over time.

For a Complete Streets project comprising multiple segments and intersections, an agency may find they have State- or jurisdiction-specific SPFs for some segment and intersection types but not for others. In this case, analysts can use a combination of methods (e.g., expected crashes for some segments/intersections, observed crashes for others) to estimate the number of crashes in the after period without the Complete Streets project (i.e., future no-build). If multiple Complete Streets alternatives are being assessed, analysts should use the same method for each alternative.

In other words, the key is to use a consistent method for a given segment/intersection, but the same method does not have to be applied across all segments/intersections.

Challenge 2: Lack of traffic volume data

Traffic volume data may not be available for all years and on all segments and intersecting cross-street legs. As was discussed in the Exposure Data section, the HSM offers guidance for estimating missing years of traffic data, such as through interpolation or using the first or last year of available data (AASHTO 2010). Cross-street data at intersections may be more difficult to obtain, especially if the data are for non-State roads. Analysts may need to make volume assumptions for those roads. In rare cases, analysts may need to exclude these cross-streets from the analysis (e.g., when no traffic data is available, and the analyst cannot determine a reasonable value).

Challenge 3: Lack of pedestrian or bicycle volume data

Having pedestrian and bicycle data is beneficial when analyzing the safety performance of Complete Streets projects, especially when estimating the specific impacts on those users. However, a related challenge is the availability of pedestrian and bicycle volume data. These data are typically difficult to obtain or simply not available. If pedestrian or bicycle volume data are not available, analysts may still be able to analyze the safety impacts of Complete Streets projects but will not be able to account for changes in pedestrian and bicyclist exposure over time.

Challenge 4: Attributing crash or volume changes to Complete Streets projects

As discussed previously in the Predictive Analysis and Safety Effectiveness Evaluation sections, the analyst can incorporate adjustments to reflect changes in traffic volume over time. However, determining the volume changes that *would have occurred* without the Complete Streets project may be difficult. The variations in the predictive analysis and safety effectiveness evaluation methods attempt to account for volume changes, but analysts may need to make assumptions when attributing volume changes to the Complete Streets project.

Challenge 5: Volume and safety changes to surrounding network

An unintended consequence of a Complete Streets project may be changes to the surrounding networks in terms of traffic volume or crashes. For example, if a Complete Streets project reduces traffic volumes along the project corridor, some of that volume may have switched travel routes (i.e., increased traffic volumes elsewhere) or may have switched to other modes (e.g., transit, walking, or biking). To understand the full effects of a Complete Streets project, analysts may need to expand the study area to include the surrounding network and be able to estimate changes in demand.

Challenge 6: Lack of CMFs for Complete Streets treatments

This challenge is specific to predictive analysis; safety effectiveness evaluations can help to create more CMFs for treatment combinations for use in future predictive analysis. Typically, Complete Streets projects consist of a combination of multiple treatments. Predictive analysis methods use CMFs to estimate the effects of those treatments. If applicable CMFs are not available for one or more treatments, then the analyst may not be able to estimate the potential benefits of those treatments. However, options may exist for estimating a CMF for use in the analysis. One option is to develop a CMF from similar past completed projects (i.e., perform a safety effectiveness evaluation). Another option may be to use CMFs for similar treatments that apply to different site conditions. For example, a CMF may be available for a similar facility type, area type, or AADT range. Analysts should exercise caution in these cases to determine whether it is appropriate to make assumptions and include the proxy CMF or to exclude the CMF (and associated treatment) from the analysis. Upcoming guidance in the Second Edition of the HSM is expected to include information on estimating countermeasure effects without having applicable, high-quality CMFs.

RESOURCES

- American Association of State Highway and Transportation Officials (AASHTO). 2010. *Highway Safety Manual*.
- Appendices B and C of Complete Streets – Safety Analysis Report.
- Carter, D., B. Persaud, R. Srinivasan, F. Gross, S. Himes, T. Le, B. Persaud, C. Lyon, and J. Bonneson. 2022. *Guidelines for the Development and Application of Crash Modification Factors*. NCHRP Report 991.
- Federal Highway Administration. 2023. Crash Modification Factors Clearinghouse. https://www.cmfclearinghouse.org/.
- Massachusetts Department of Transportation (MassDOT). 2021. *MassDOT Safety: Alternatives Analysis Guide*. https://www.mass.gov/doc/massdot-safety-alternatives-analysis-guide/download.
- “Safety Data and Analysis: Selecting a Method to Analyze Multiple CMFs”: https://www.youtube.com/watch?v=OPvAjUpT6Dg
- “Safety Data and Analysis: Applying a Method to Analyze Multiple CMFs”: https://www.youtube.com/watch?v=48M7TBKTCM0

GLOSSARY

After period: Time after construction or implementation of the countermeasure.

Before period: Time before construction or implementation of the countermeasure.

Crash modification factor: A multiplicative factor that indicates the expected change in crashes associated with a countermeasure.

Empirical Bayes (EB): Method used to estimate the expected crashes as a weighted average of observed crashes and predicted crashes.

Expected crashes: An estimate of the long-term average crash frequency in a given period based on the EB methodology (weighted average of observed and predicted crashes).

Observed crashes: Reported crashes in a given period.

Predicted crashes: Estimated crashes using State- or jurisdiction-specific SPFs or calibrated SPFs.

Regression to the mean: When periods with relatively high crash frequencies are followed by periods with relatively low crash frequencies (and vice versa) due to the variability of crashes and not the project in question.

Safety-performance function: An equation used to predict the average number of crashes per year at a location as a function of exposure and, in some cases, roadway or intersection characteristics.

Segmentation: Process of creating homogeneous roadway segments and intersections for analysis purposes.

AADT COEFFICIENTS BY FACILITY TYPE AND CRASH SEVERITY

Table 14 provides the AADT parameters by facility type and crash severity from Part C of the HSM (AASHTO 2010). When coefficients are provided for SV and MV crashes, the analyst should analyze these two crash groups separately and then combine the results

Table 14. AADT Coefficients from HSM by facility type and crash severity.

Facility Type	Total			Fatal and Injury			Property Damage Only		
	AADT (a)	$AADT_{maj}$ (b)	$AADT_{min}$ (c)	AADT (a)	$AADT_{maj}$ (b)	$AADT_{min}$ (c)	AADT (a)	$AADT_{maj}$ (b)	$AADT_{min}$ (c)
Rural 2-lane undivided	1.000	–	–	–	–	–	–	–	–
Rural 2-lane, 3-leg stop control	–	0.790	0.490	–	–	–	–	–	–
Rural 2-lane, 4-leg stop control	–	0.600	0.610	–	–	–	–	–	–
Rural 2-lane, 4-leg signalized	–	0.600	0.200	–	–	–	–	–	–
Rural 4-lane undivided	1.176	–	–	1.094	–	–	–	–	–
Rural 4-lane divided	1.049	-	-	0.958	–	–	–	–	–
Rural 4-lane, 3-leg stop control	–	1.204	0.236	–	1.107	0.236	–	–	–
Rural 4-lane, 4-leg stop control	–	0.848	0.448	–	0.888	0.525	–	–	–
Rural 4-lane, 4-leg signalized	–	0.722	0.337	–	0.638	0.232	–	–	–
Urban 2-lane undivided MV	1.680	–	–	1.660	–	–	1.690	–	–
Urban 3-lane TWLTL MV	1.410	–	–	1.690	–	–	1.330	–	–

Facility Type	Total			Fatal and Injury			Property Damage Only		
	AADT (a)	$AADT_{maj}$ (b)	$AADT_{min}$ (c)	AADT (a)	$AADT_{maj}$ (b)	$AADT_{min}$ (c)	AADT (a)	$AADT_{maj}$ (b)	$AADT_{min}$ (c)
Urban 4-lane undivided MV	1.330	–	–	1.250	–	–	1.380	–	–
Urban 4-lane divided MV	1.360	–	–	1.280	–	–	1.380	–	–
Urban 5-lane TWLTL MV	1.170	–	–	1.120	–	–	1.170	–	–
Urban 2-lane undivided SV	0.560	–	–	0.230	–	–	0.640	–	–
Urban 3-lane TWLTL SV	0.540	–	–	0.470	–	–	0.560	–	–
Urban 4-lane undivided SV	0.810	–	–	0.610	–	–	0.840	–	–
Urban 4-lane divided SV	0.470	–	–	0.660	–	–	0.450	–	–
Urban 5-lane TWLTL SV	0.540	–	–	0.350	–	–	0.610	–	–
Urban 3-leg stop control MV	–	1.110	0.410	–	1.160	0.300	–	1.200	0.510
Urban 4-leg stop control MV	–	0.820	0.250	–	0.930	0.280	–	0.770	0.230
Urban 3-leg signalized MV	–	1.110	0.260	–	1.020	0.170	–	1.140	0.300
Urban 4-leg signalized MV	–	1.070	0.230	–	1.180	0.220	–	1.020	0.240
Urban 3-leg stop control SV	–	0.160	0.510	–	–	–	–	0.250	0.550
Urban 4-leg stop control SV	–	0.330	0.120	–	–	–	–	0.360	0.250
Urban 3-leg signalized SV	–	0.420	0.400	–	0.270	0.510	–	0.450	0.330

Facility Type	Total			Fatal and Injury			Property Damage Only		
	AADT (a)	$AADT_{maj}$ (b)	$AADT_{min}$ (c)	AADT (a)	$AADT_{maj}$ (b)	$AADT_{min}$ (c)	AADT (a)	$AADT_{maj}$ (b)	$AADT_{min}$ (c)
Urban 4-leg signalized SV	–	0.680	0.270	–	0.430	0.290	–	0.780	0.250
Parclo type A2/B2 signalized terminal	–	–	–	–	0.325	0.212	–	0.592	0.516
Diamond 3-leg exit and Parclo Type A4 signalized terminal	–	–	–	–	0.379	0.394	–	0.797	0.384
Diamond 3-leg entrance and Parclo type B4 signalized terminal	–	–	–	–	0.265	0.905	–	0.741	0.845
Diamond 4-leg signalized terminal	–	–	–	–	1.191	0.131	–	0.879	0.545
Parclo type A2/B2 stop control terminal	–	–	–	–	0.260	0.947	–	0.773	0.878
Diamond 3-leg exit and Parclo Type A4 stop control terminal	–	–	–	–	0.582	0.899	–	0.595	0.937
Diamond 3-leg entrance and Parclo type B4 stop control terminal	–	–	–	–	0.709	0.730	–	0.885	0.350
Diamond 4-leg stop control terminal	–	–	–	–	1.008	0.177	–	0.845	0.476

Note: MV = multiple-vehicle; SV = single-vehicle; TWLTL = two-way left-turn lane; – = not applicable.

CHAPTER 5. CONCLUSIONS AND RECOMMENDATIONS

This report documents current practices, capabilities, and needs for quantifying the safety-performance effects of multiple safety treatments that agencies implement simultaneously during the conversion of typical streets to Complete Streets. This report's primary focus is arterials with speed limits of 55 mph or less in both urban and rural areas.

Based on a review of 85 Complete Streets projects from across the U.S. and an additional diagnostic analysis of common street transformations, the project team identified 37 commonly used Complete Streets treatments and classified them into four categories:

Bicycle/Pedestrian:

- Add separated bike lane.
- Add or enhance pedestrian and bicyclist signal operation.
- Add bike lane.
- Add bike box.
- Add shared-lane marking (sharrow).
- Add green colored pavement.
- Add curb extension/bulb-out.
- Add or enhance sidewalk.
- Add or enhance crosswalk (including high-visibility).
- Add or enhance midblock crossing.
- Add pedestrian refuge island.
- Add pedestrian-actuated signal or beacon.
- Add Danish offset to refuge island (Redmon 2011).
- Add raised crosswalk.
- Add bicyclist and pedestrian path/trail.
- Add or enhance bicyclist and pedestrian path/trail crossing.
- Add grade-separated pedestrian facility (tunnel, underpass, bridge).

Transit:

- Add bus island or floating bus stop.
- Add BRT/bus-only lanes/transit signal priority.
- Add bus boarding platform.

Traffic: Add or enhance traffic signal operation.

Roadway configuration and elements:

- Change parking configuration.
- Remove on-street parking.
- Add or enhance lighting.

- Perform a Road Diet.
- Decrease roadway or lane width.
- Add median.
- Add raised intersection.
- Improve signing and marking.
- Add roundabout.
- Increase shoulder width.
- Improve pavement condition.
- Add curb and gutter.
- Reduce speed limit.
- Add raised traffic separators.
- Remove shoulder.
- Convert flush median to raised median.

Chapter 2 summarized the most commonly used individual treatments on the 85 reviewed projects and the most common combinations of two treatments and three treatments. The 85 projects were not selected by way of a randomized study design, and therefore, broadly generalizable conclusions about national practices are not possible from this data. However, the information served as a starting point for assessing current capabilities with respect to estimating the safety effects of multiple treatments. The information can also be helpful to practitioners and researchers interested in common treatment combinations.

The project team identified 718 CMFs related to the Complete Streets treatments in chapter 2 using the FHWA CMF Clearinghouse (FHWA 2023a). Chapter 3 and Appendix A summarize CMF availability and quality. The availability of these CMFs support DDSA for Complete Streets safety analysis. In addition, work documented on NCHRP Report 991, *Guidelines for the Development and Application of Crash Modification Factors*, provided potential methods for identifying an appropriate CMF to represent the safety effects of different treatment combinations that occur on a Complete Streets project (Carter et al. 2022). Leveraging these efforts and applying practices from the HSM and other DDSA resources, the project team developed a primer on DDSA for Complete Streets projects. Content in the primer was also informed by five Complete Streets safety-analysis case studies in Appendix C. The primer focuses on two applications of DDSA:

1. **Predictive analysis**: This section addresses the pre-construction application, allowing analysts to estimate the expected safety performance of a proposed project in comparison to an alternative condition (e.g., the no-build).
2. **Safety effectiveness evaluation**: This section addresses the post-construction application, allowing analysts to estimate the safety effectiveness of a completed project.

The five case studies generally illustrated the closest agreement between predictive analysis and actual safety outcomes using either the dominant effect or dominant common residuals approaches for identifying an appropriate CMF to represent the safety effects of different treatment combinations. While both methods generally performed acceptably, the predictive analysis overestimated safety benefits in three of the five case studies. Therefore, the method providing the lowest predicted percent crash reduction was closest to the actual safety outcome. The analysis did not incorporate uncertainty in estimates arising from the randomness of crash counts and error in CMF estimates.

While the primer outlines DDSA principles and practices, and the case studies demonstrated successful applications, both activities highlighted key limitations in DDSA methods for Complete Streets. These limitations resulted in the case study applications relying on observed crashes instead of predicted or expected crashes. DDSA resources, along with the Complete Streets Safety Analysis primer developed for this project, characterize the use of observed crashes as less desirable than predicted or expected crashes. However, this approach is practical for agencies to implement at their early stages of DDSA applications. Some of the limitations of using observed crash counts can be overcome by using more years of crash data.

The following sections provide additional details on limitations and associated future research recommendations.

Lack of SPFs

One common challenge is the lack of reliable, calibrated SPFs for the facility and site type(s) that are part of the Complete Streets project. Example limitations encountered during the case study analysis included three-leg, all-way stop-controlled intersections; four-lane including center TWLTL; and rural arterials through small rural towns. For SPFs that exist, the stated base conditions do not capture some of the most commonly used Complete Streets characteristics. Therefore, knowing whether these treatments were already present at some of the locations used to develop SPFs is impossible. Continued funding of strategic research programs is needed to improve existing SPFs and fill SPF gaps. In particular, a new suite of urban and suburban crash prediction models is needed to more fully capture the multimodal safety effects of combinations of safety and operational strategies, operating speed, and geometric design characteristics.

Lack of traffic volume data

Traffic volume data may not be available for all years and on all segments and intersecting cross-street legs. As discussed in the Exposure Data section of the primer, the HSM offers guidance for estimating missing years of traffic data, such as through interpolation or using the first or last year of available data. Cross-street data at intersections may be more difficult to obtain, especially if they are for non-State roads. Analysts may need to make volume assumptions for those roads. In rare cases, excluding these cross-streets from the analysis (e.g., when no traffic data is available, and the analyst cannot determine a reasonable value) may be necessary. Continued research is ongoing related to the use of probe data to obtain daily volume estimates. Complete Streets safety analysis can benefit from this research, particularly for newer projects with available probe data.

Lack of pedestrian or bicycle volume data

Having pedestrian and bicycle data is key to fully analyzing and explaining the safety performance of Complete Streets projects, especially when estimating the specific impacts on these users. However, pedestrian and bicycle volume data is still rarely available. If pedestrian or bicycle volume data are not available, analysts may still be able to analyze the safety impacts of Complete Streets projects but will not be able to account for changes in pedestrian and bicyclist exposure over time and uncover potential benefits such as the “safety in numbers” effect (Jacobsen 2015). Until pedestrian and bicycle volume data is available on a more widespread bases, future research should continue to seek ways to estimate these volumes based on land-use characteristics, network characteristics, and road characteristics. An example of such an approach is documented in the Highway Safety Information System report, *An Exploration of Pedestrian Safety Through the Integration of HSIS and Emerging Data Sources: Case Study in Charlotte, NC* (Hamilton et al. 2021).

Improved methods for attributing crash or volume changes to Complete Streets projects

As discussed in the Predictive Analysis and Safety Effectiveness Evaluation sections of the chapter 4 primer, the safety analysis of Complete Streets transformations can incorporate adjustments to reflect changes in road-user volumes over time. However, determining the volume changes that *would have occurred* without the Complete Streets project and therefore the actual volume changes attributed to the project may be difficult. In addition, information is not readily available on whether the development of CMFs available in resources, such as the CMF Clearinghouse (FHWA 2023a), differentiated between volume changes caused by the treatment and volume changes that would have occurred without the treatments. Given these limitations, safety analysts may need to make assumptions when using traffic volume observations, traffic volume projections, and CMFs. Future work is needed to develop guidance for DDSA when projects, or individual treatments that are part of those projects, induce significant changes in road-user volumes.

Volume and safety changes to surrounding network

A Complete Streets project may also change the surrounding streets and network with respect to travel patterns. For example, if a Complete Streets project reduces traffic volumes along the project corridor, some of that volume may have switched travel routes (i.e., increased traffic volumes elsewhere) or may have switched to other modes (e.g., transit, walking, or biking). To understand the full effects of a Complete Streets project, analysts may need to expand the study area to include the surrounding network and be able to estimate changes in demand by mode. Future work is needed to develop guidance for DDSA when projects or treatments result in broader network changes in travel patterns.

Lack of CMFs for Complete Streets treatments

This challenge is specific to predictive analysis. Several CMF limitations were noted for commonly used treatments on Complete Streets projects. Some common treatments have no CMFs at all, and some have CMFs that are not high-quality. In addition, treatments expected to improve both pedestrian and bicyclist safety performance do not always have CMFs for both respective crash types. Finally, very few treatments have CMFs specific enough to focus on KA crashes, which are the primary focus of the SSA. Without CMFs specific to KA crashes, analysts need to assume that the effect on KA crashes is the same as the effect on KABC crashes. Such an assumption likely masks specific effects on the most serious crash types. Continued funding of strategic research programs is needed to improve existing CMFs and fill CMF gaps.

OTHER POTENTIAL SAFETY PERFORMANCE METRICS

After multiple decades of CMF-related research, significant CMF needs remain with respect to quantifying the safety-performance effects of Complete Streets treatments for all users.

These CMF needs exist because of inherent challenges in developing CMFs for multimodal safety treatments and not necessarily because of a lack of research. Pedestrian and bicycle safety performance remain one of the most significant gaps in crash-based DDSA methods and tools. These gaps exist for multiple reasons, including the lack of pedestrian and bicyclist volume (i.e., exposure) information over the period of time that crashes are collected and the inability of more aggregate crash-based evaluations to capture nuanced effects on pedestrian and bicyclist safety performance, such as those related to the numbers of lanes that must be crossed, presence/type of refuge, and vehicle through and turning speeds.

The following sections document other potential analysis directions for Complete Streets that could provide additional insights to Complete Streets benefits, including broader public health benefits.

SAFE SYSTEM-BASED METRICS

Safe System-based metrics could play an effective role in evaluating Complete Streets treatments by capturing more foundational outcomes that Complete Streets treatment combinations are trying to achieve, such as:

- Reducing exposure (capturing not only volumes but the length over which users interact).
- Increasing separation between users.
- Managing potential collision speeds and angles.
- Reducing complexity for all users, captured by metrics such as:
- Number of lanes carrying vehicle traffic.
- Speed of vehicle traffic (influencing gap acceptance complexity).
- Crossing distance.
- Number of lanes crossed without refuge.
- Presence of traffic control devices focused on movement separation and user awareness of other users.

Analysts might be able to collect these more fundamental performance outcomes on a representative sample of roads, combine them into one or more composite metrics, and then relate these performance outcomes and composite metrics to crash frequency (by crash type and severity).

Examples of composite Safe System-based metrics that capture these types of characteristics are contained in the FHWA Safe System for Intersections (SSI) method (Porter et al. 2021). The SSI method includes factors that account for exposure, severity, and movement complexity at intersection conflict points. The concepts, however, could also be applicable to midblock crossings and segments, including crossings and segments with parallel pedestrian and bicyclist facilities.

The SSI method has steps that estimate exposure, severity, and movement complexity individually. For example, the method includes steps to identify the following individually:

- Locations and types of conflict points.
- Level of vehicle-vehicle and vehicle-nonmotorized user exposure at each conflict point.
- Probability of fatal or serious injury for specific conflict point if there was a crash based on estimated vehicle speeds, users, and collision angles.
- Number of lanes carrying conflicting traffic.
- Speed of conflicting traffic.
- Number of lanes crossed without refuge.
- Traffic control type and ability to reduce movement complexity.

However, the final SSI method steps involve combining these different pieces into SSI scores for the individual conflict-point types and the overall location. The SSI score accounts for the different individual characteristics. Higher SSI scores are associated with more effective Safe System (or Complete Streets) concepts.

To evaluate Complete Streets treatments with this new approach, analysts could first determine how the treatments in combination affect more fundamental performance outcomes, combine the more fundamental performance outcome into a composite metric like the SSI score (in this case, it could be called the Complete Streets score), and then determine the relationship between the composite metric and the number of crashes (by different crash types and severities).

USE OF COMPREHENSIVE HEALTH AND SAFETY METRICS

As previously noted, the project team removed treatments more related to user comfort, aesthetics, and ADA compliance where quantitative safety performance evaluations may not be possible or practical. Examples of treatments include add ADA ramps and/or entrances, add landscaping/streetscaping/hardscaping, and add outdoor furniture for seating. Temporarily removing these treatments allows the next steps of this project to focus on treatments for which the safety-performance link seems clear and for which safety evaluations have possibly already occurred or could occur in the near future. However, these treatments also bring benefits, including higher levels of accessibility and attractiveness for all users. Analysts can capture these types of benefits, in addition to crash benefits, with more comprehensive health performance indicators of which reduced fatalities and injuries from crashes are one part. The following are two examples of these health performance indicators:

Disability-Adjusted Life Years (DALYs) Averted. This metric can describe the severity of a crash. A fatal crash loses more DALYs than a crash with a minor injury. The more DALYs averted, the larger the treatment benefit. In addition, analysts can estimate DALYs averted due to more users choosing more active transportation. If, for example, 1,000 people are riding their bikes per day, and on average, the health benefits of bicycling adds 1 yr to their lives, then this comprises 1,000 DALYs averted. Whereas, preventing one fatal crash might avert 20 DALYs and a nonfatal crash might avert 10 DALYs. Analysts can also use this rationale regarding DALYs averted due to reduced air pollution on a population level if fewer individual motor vehicles use the Complete

Streets segment. Rojas-Rueda et al. (2013) is an example of one such study that took this comprehensive health approach to a safety analysis.

Quality-Adjusted Life Years (QALYs) Gained. This indicator can be thought of as the reverse of a DALY. QALYs represent the number of years of good health gained by a particular decision or behavior and may have significant potential for Complete Streets. Some ways that QALYs are "gained" by Complete Streets treatments include:

- Increased physical activity leading to better physical health and longer life.
- Increased mental health from active transport, increased accessibility for those with disabilities, and accessibility to community resources (grocery stores, libraries, health facilities).

APPENDIX A. COMPLETE STREETS TREATMENTS

This appendix addresses the 80 Complete Streets treatments identified by the project team as described in chapter 2. The appendix lists these 80 treatments, characterizes the number of safety studies and resulting CMFs for each treatment, and provides a treatment definition with example pictures.

This appendix does not represent a comprehensive cataloging of every available CMF for all 80 treatments. The project team reviewed each study that produced CMFs for the 80 treatments and cataloged the most relevant CMF(s) from each study. Therefore, the CMF availability, quality, and values reported here are representative of what the project team judged as the most relevant CMFs from the available studies that addressed a given Complete Streets treatment. Treatments in the list below are linked to their respective sections in the appendix.

Add ADA Ramps and/or Entrances
Add Additional Lane
Add Bicyclist and Pedestrian Path/Trail
Increase Width of Bicyclist and Pedestrian Path/Trail
Add or Enhance Bicyclist and Pedestrian Path/Trail Crossing
Add Larger Bike and Pedestrian Sidewalk Waiting Area
Add Bike Box
Add or Enhance Bike Detection and/or Leading Interval for Bikes
Add Bike Parking
Add Bike Signal
Add Bus Boarding Platform
Add Bus Island or Floating Bus Stop
Add Bus Pad
Add Bus Rapid Transit (BRT)
Upgrade Bus/Transit Stop (Bus Shelter, Etc.)
Add Bus-Only Lane
Add Colored Crosswalk
Add or Enhance Crosswalk (Including High Visibility)
Add Curb and Gutter
Add Curb Extension Art
Add Curb Extension/Bulb-Out
Add Danish Offset
Add Dynamic Signing
Add Fencing for Trail
Add Flex Lane
Add Flush Street
Add Grade-Separated Pedestrian Facility (Tunnel, Underpass, Bridge)
Add Green Colored Pavement
Add or Improve Interchange
Improve ITS Communications
Add Landscaping/Streetscaping/ Hardscaping
Add Leading Pedestrian Interval (LPI)
Add Left Turn Lane
Add or Enhance Lighting
Add Median
Add or Enhance Midblock Crossing
Add Mountable Curb
Reduce Number of Lanes
Convert One-Way Road to Two-Way Road
Remove On-Street Parking
Add Outdoor Furniture or Seating Including Restaurants (Benches, Trash Cans, Etc.)
Change Parking Configuration
Improve Pavement Condition
Improve Pavement Marking
Add or Enhance Pedestrian and Bicyclist Signal Operation
Add Pedestrian Hybrid Beacon (PHB)
Add Pedestrian Pushbuttons and/or Countdown Timer
Add Pedestrian Refuge Island
Add Pedestrian Signal
Add Public Art
Add Quiet Zone Railroad Crossing
Add Raised Crosswalk
Add Raised Intersection
Add Raised Traffic Separators

Realign Intersection
Add Real-Time Bus Arrival Sign
Add Rectangular Rapid-Flashing Beacon (RRFB)
Perform a Road Diet
Decrease Roadway or Lane Width
Reverse Street Direction
Increase Roadway or Lane Width
Add Roundabout
Implement Safe Routes to School
Add Separated Bike Lane
Add Shared Lane Marking (Sharrow)
Increase Shoulder Width
Add or Enhance Sidewalk
Increase Sidewalk Width
Improve Signing
Reduce Speed Limit
Improve Stormwater/Drainage
Add Streetcar
Add Traffic Calming Devices
Add Traffic Signal
Upgrade Traffic Signal
Add Transit Signal Priority (TSP)
Add Tree Belts
Add Two-Way Left-Turn Lane
Upgrade or Relocate Utilities

ADD ADA RAMPS AND/OR ENTRANCES

The project team did not identify any studies that developed CMFs for adding ADA ramps and/or entrances. An ADA ramp creates access between the sidewalk and street and to building entrances, especially for people with mobility issues (FHWA 2018a). Curb ramps include a detectable warning surface, ramp, flare, landing, and approach that must meet specific size and grade requirements (FHWA 2018a). Figure 20 and figure 21 provide examples of ADA ramps and/or entrances.

Source: FHWA.

Figure 20. Photograph. Example of an intersection corner with ADA ramps (Gomez et al. 2015).

Source: FHWA.

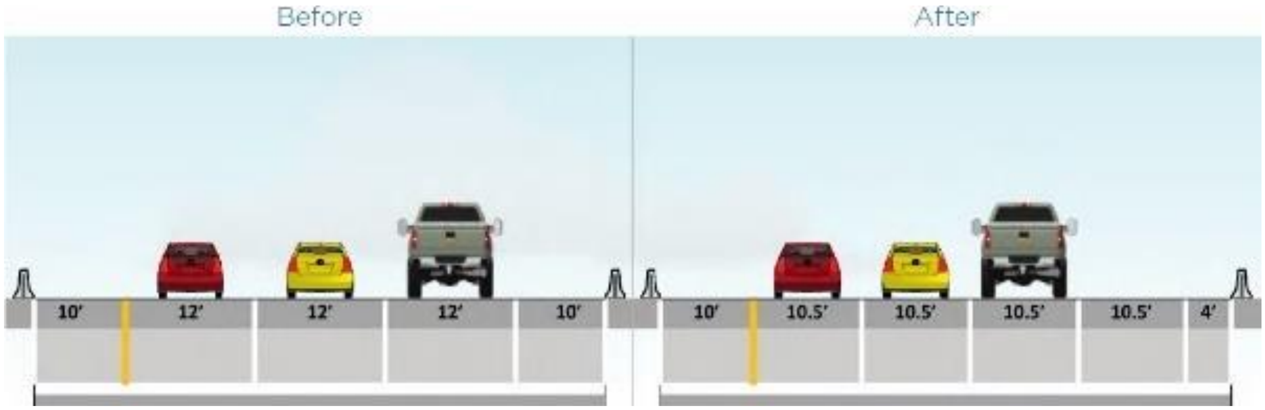
Figure 21. Photograph. Example of an intersection corner with ADA ramps (Gomez et al. 2015).

ADD ADDITIONAL LANE

The project team identified one study that developed CMFs for adding an additional lane (Dixon, Fitzpatrick, and Avelar 2016). CMF scores for adding an additional lane were the following:

- Number of studies: 1.
- Number of CMFs: 3.
- Average CMF value: 0.75.
- CMF value range: 0.74–0.76.
- Average CMF rating: 3.0.
- CMF rating range: 3.
- Available crash-type CMFs: all.
- Most severe crash severity CMF: KABC.

Adding an additional lane could occur by widening the entire roadway or by reallocating space within the existing roadway, including reducing the width of other lanes. Figure 22 provides an example of adding an additional lane.



Source: FHWA.

Figure 22. Graphic. Example of adding an additional lane (FHWA 2020b).

ADD BICYCLIST AND PEDESTRIAN PATH/TRAIL

The project team identified two studies that developed CMFs for adding a bicyclist and pedestrian path/trail (Alluri et al. 2017; Daniels, et al. 2009). CMF scores for adding a bicyclist and pedestrian path/trail were the following:

- Number of studies: 2.
- Number of CMFs: 2.
- Average CMF value: 0.79.
- CMF value range: 0.75–0.83.
- Average CMF rating: 2.0.
- CMF rating range: 2.
- Available crash-type CMFs: vehicle/bicycle.
- Most severe crash severity CMF: all.

Adding a bicyclist and pedestrian path/trail means bicycle facilities are physically separated from traffic and are intended for shared use by a variety of groups, including pedestrians, bicyclists, and joggers (Goodman et al. 2015). Figure 23 provides an example of a bicycle and pedestrian path/trail.

Source: FHWA.

Figure 23. Photograph. Example of a bicyclist and pedestrian path/trail (Goodman et al. 2015).

INCREASE WIDTH OF BICYCLIST AND PEDESTRIAN PATH/TRAIL

The project team did not identify any studies that developed CMFs for increasing the width of the bicyclist and pedestrian path/trail. AASHTO (1999) defines this treatment as increasing the width of a trail. Trails can be shared-use paths or unimproved recreational facilities. Figure 24 provides an example of a wide bicyclist and pedestrian path/trail.

Source: FHWA.

Figure 24. Photograph. Example of a wide bicyclist and pedestrian path/trail (FHWA 2006a).

ADD OR ENHANCE BICYCLIST AND PEDESTRIAN PATH/TRAIL CROSSING

The project team did not identify any studies that developed CMFs for adding or enhancing the bicyclist and pedestrian path/trail crossing. Trail crossings are locations where bicyclist and pedestrian paths or trails intersect with roadways. These crossings can be signalized or unsignalized. Figure 25 provides an example enhancement of a bicyclist and pedestrian path/trail crossing.

Source: FHWA.

Figure 25. Photograph. Example of enhancement of a bicyclist and pedestrian path/trail crossing (Blackburn, Patterson, and Gross 2021).

ADD LARGER BIKE AND PEDESTRIAN SIDEWALK WAITING AREA

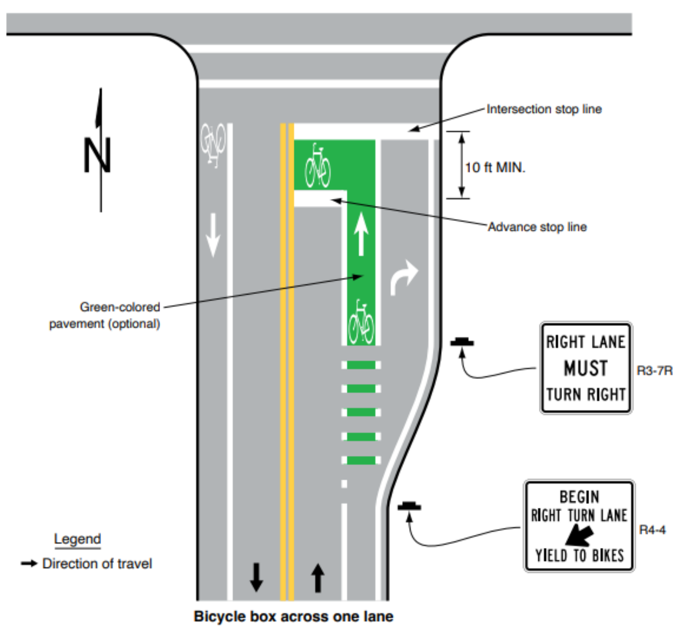
The project team did not identify any studies that developed CMFs for adding larger bike and pedestrian sidewalk waiting areas. The National Center for Safe Routes to School (n.d.) defines this treatment as larger waiting areas at crosswalks and “stand-back” lines painted to keep people further back from busy streets when waiting to cross. Figure 26 provides an example of a larger bike and pedestrian sidewalk waiting area.

Source: FHWA.

Figure 26. Photograph. Example of a larger bike and pedestrian sidewalk waiting area (Rodegerdts, Nevers, and Robinson, 2004).

ADD BIKE BOX

The project team did not identify any studies that developed CMFs for adding a bike box. Goodman et al. (2015) define this treatment as designated spaces at signalized intersections for bicyclists to queue in front of motor vehicles during red phases. Because they are placed between the stop line and the pedestrian crosswalk, bike boxes increase the visibility of queued bicyclists and provide bicyclists with the ability enter the intersection in front of motor vehicles when the signal turns green. Figure 27 provides an example of a bike box.



Source: FHWA.

Figure 27. Photograph. Example of a bike box (FHWA 2023b).

ADD OR ENHANCE BIKE DETECTION AND/OR LEADING INTERVAL FOR BIKES

The project team did not identify any studies that developed CMFs for adding or enhancing bike detection and/or leading intervals for bikes. Goodman et al. (2015) define this treatment as automatic detection by induction loops, radar, or video to send signals to the traffic signal controller based on the presence of a bicyclist at the intersection. Other detector feedback devices should be considered to provide information for bicyclists to receive a green light. Examples include the *To Request Green Wait On Symbol* sign (*Manual on Uniform Traffic Control Devices* [MUTCD] R10-22 2009), blue-light detector device, and others. These detector feedback devices are typically designed specifically for bikes. A leading bicycle interval uses a bicycle signal lens to provide 3–5 s of green time before the corresponding vehicle green indication. Figure 28 provides an example of bike detection.

Source: FHWA.

Figure 28. Photograph. Example of bike detection (Goodman et al. 2015).

ADD BIKE LANE

The project team identified six studies that developed CMFs for adding a bike lane (Abdel-Aty et al. 2014; Avelar et al. 2021; Jensen 2008; Nosal and Miranda-Moreno 2012; Rodegerdts, Nevers, and Robinson 2004; Turner et al. 2011). CMF scores for adding a bike lane were the following:

- Number of studies: 6.
- Number of CMFs: 8.
- Average CMF value: 0.68.
- CMF value range: 0.19–1.49.
- Average CMF rating: 2.1.
- CMF rating range: 1–4.
- Available crash-type CMFs: all.
- Most severe crash severity CMF: KABC.

Goodman et al. (2015) define this treatment as an on-road bicycle facility designated by striping, signing, and pavement markings. Figure 29 and figure 30 provide examples of bike lanes.

Source: FHWA.

Figure 29. Photograph. Example of a bike lane (Goodman et al. 2015).

Source: FHWA.

Figure 30. Photograph. Example of a bike lane (Schultheiss et al. 2019).

ADD BIKE PARKING

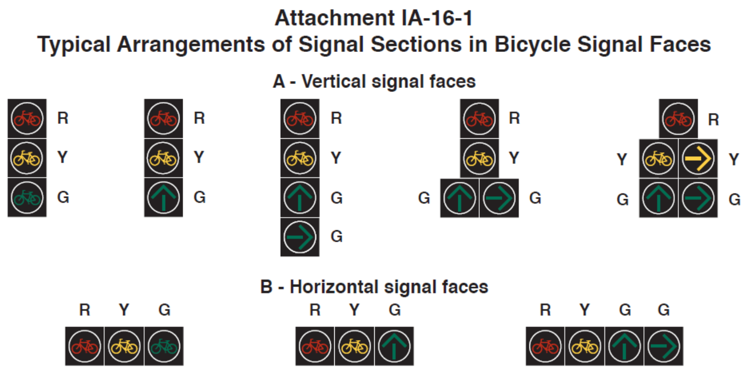
The project team did not identify any studies that developed CMFs for adding bike parking. FHWA (2006b) defines this treatment as a designated space to park bicycles, such as bicycle racks or bicycle lockers. This parking can be in public space or private development. Figure 31 provides an example of bike parking.

Source: FHWA.

Figure 31. Photograph. Example of bike parking (Goodman et al. 2015).

ADD BIKE SIGNAL

The project team did not identify any studies that developed CMFs for adding a bike signal. Goodman et al. (2015) noted bicycle signals may be used to separate bicycle through movements from vehicle right-turning movements for increased safety. Bicycle signalization can include bicycle signal head, signal timing for clearances, bicycle detection, and/or bicycle push buttons. Figure 32 provides an example of bike signals.



Source: FHWA.
R=red; Y= yellow; G = green.

Figure 32. Graphic. Example of bicycle signals (FHWA 2017).

ADD BUS BOARDING PLATFORM

The project team did not identify any studies that developed CMFs for adding a bus boarding platform. Colon (2019) noted bus boarding platforms allow for level boarding for buses. They can be characterized as raised curb extensions to allow more space for pedestrians boarding and alighting buses. Figure 33 provides an example of a bus boarding platform.

Figure 33. Photograph. Example of a bus boarding platform (Maus 2021).

ADD BUS ISLAND OR FLOATING BUS STOP

The project team did not identify any studies that developed CMFs for adding a bus island or floating bus stop. The National Association of City Transportation Officials (NACTO) (n.d.) notes that dedicated waiting and boarding areas for passengers streamline transit service and improve accessibility by enabling in-lane stops. Side boarding islands are separated from the sidewalk by a bike channel, eliminating conflicts between transit vehicles and bikes at stops. Figure 34 provides an example of a bus island or floating bus stop.

Source: FHWA.

Figure 34. Photograph. Example of a bus island or floating bus stop (FHWA n.d.b).

ADD BUS PAD

The project team did not identify any studies that developed CMFs for adding a bus pad. Nabors et al. (2008) defined this treatment as a landing pad that allows pedestrians to enter and exit the bus safely without entering the street. The pad must be connected to the adjacent sidewalk network. Figure 35 provides an example of a bus pad.

Source: FHWA.

Figure 35. Photograph. Example of a bus stop (Nabors et al. 2008).

ADD BRT

The project team did not identify any studies that developed CMFs for adding BRT. The Federal Transit Administration (FTA) (2015a) defines this treatment as a high-quality, bus-based transit system that delivers faster and more efficient service. BRT may include dedicated lanes, busways, transit signal priority, off-board fare collection, elevated platforms, and enhanced stations. Figure 36 provides an example of BRT.

Source: FHWA

Figure 36. Photograph. Example of BRT (FHWA 2015).

UPGRADE BUS/TRANSIT STOP (BUS, SHELTER, ETC.)

The project team did not identify any studies that developed CMFs for upgrading the bus/transit stop as part of their Complete Streets improvements. This treatment includes improvements to bus stops that increase safety and access for people walking, biking, and taking transit. Figure 37 provides an example of an upgraded bus/transit stop.

Source: FHWA

Figure 37. Photograph. Example of an upgraded bus/transit stop (Nabors et al. 2008).

ADD BUS-ONLY LANE

The project team did not identify any studies that developed CMFs for adding a bus-only lane. The FTA (2015b) defines this treatment as a traffic lane on a surface street reserved for the exclusive use of buses. Figure 38 provides an example of a bus-only lane.

Source: FHWA

Figure 38. Photograph. Example of a bus-only lane (FHWA 2020c).

ADD COLORED CROSSWALK

The project team did not identify any studies that developed CMFs for adding colored crosswalks. The American Concrete Pavement Association (ACPA) (2004) defines this treatment as applying color to the crosswalk area to enhance the appearance of the concrete surface and easily differentiate the crosswalk from other surfaces. Figure 39 provides an example of a colored crosswalk.

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Figure 39. Photograph. Example of a colored crosswalk.

ADD OR ENHANCE CROSSWALK (INCLUDING HIGH-VISIBILITY)

The project team identified three studies that developed CMFs for adding or enhancing crosswalks (L. Chen, C. Chen, and Ewing 2012; Feldman, Manzi, and Mitman 2010; Haleem and Abdel-Aty 2011). CMF scores for adding or enhancing the crosswalk (including high-visibility) were the following:

- Number of studies: 3.
- Number of CMFs: 4.
- Average CMF value: 0.60.
- CMF value range: 0.35–0.81.
- Average CMF rating: 2.8.
- CMF rating range: 2–4.
- Available crash-type CMFs: all, vehicle/pedestrian, angle, head-on, left-turn, rear end, rear to rear, right-turn, sideswipe.
- Most severe crash severity CMF: all.

Blackburn et al. (2018) and FHWA (2021a) define a crosswalk as a pedestrian crossing location marked by patterns that include zebra, ladder, or continental markings as described by the MUTCD (FHWA 2022e). High-visibility crosswalks use patterns (i.e., bar pairs, continental, ladder) that drivers and pedestrians can see from farther away compared to traditional transverse line crosswalks. Figure 40 provides an example of an enhanced crosswalk.

Source: FHWA.

Figure 40. Photograph. Example of an enhanced crosswalk (FHWA 2006b).

ADD CURB AND GUTTER

The project team identified two studies that developed CMFs for adding curb and gutter (Baek and Hummer 2008; Raihan et al. 2019). CMF scores for adding curb and gutter were the following:

- Number of studies: 2.
- Number of CMFs: 2.
- Average CMF value: 1.05.
- CMF value range: 0.89–1.21.
- Average CMF rating: 3.5.
- CMF rating range: 3–4.
- Available crash-type CMFs: all, vehicle/bicycle.
- Most severe crash severity CMF: all.

Brown et al. (2013) notes that a curb and gutter combination forms a triangular channel that can convey runoff equal to or less than the design flow without interruption of the traffic. Figure 41 provides an example of curb and gutter.

Source: FHWA.

Figure 41. Photograph. Example of curb and gutter (FHWA 2021b).

ADD CURB EXTENSION ART

The project team did not identify any studies that developed CMFs for adding curb extension art as part of their Complete Streets improvements. Move Culver City (2023) describes this treatment as asphalt art or community-inspired artwork located within curb extensions. Figure 42 provides an example of curb extension art.

Figure 42. Photograph. Example of curb extension art (Move Culver City 2023).

ADD CURB EXTENSION/BULB-OUT

The project team did not identify any studies that developed CMFs for adding curb extensions/bulb-outs. Bulb-outs extend the sidewalk or curb line into the parking lane, which reduces the effective street width (FHWA n.d.d). Figure 43 provides an example of a curb extension/bulb-out.

Source: FHWA.

Figure 43. Photograph. Example of a curb extension/bulb-out (FHWA 2013).

ADD DANISH OFFSET

The project team did not identify any studies that developed CMFs for adding a Danish offset. Redmon (2011) described this treatment as a median refuge configured to orient pedestrians toward oncoming traffic. Figure 44 provides an example of a Danish offset.

Source: FHWA.

Figure 44. Photograph. Example of a Danish offset (Nambisan et al. 2009).

ADD DYNAMIC SIGNING

The project team did not identify any studies that developed CMFs for adding dynamic signing. Pulsipher et al. (2020) describes this treatment as signs that change based on prevailing conditions. For example, “No Turn On Red” messages can be provided by a dynamic sign that changes when pedestrians are present, by time of day, by a call made by an emergency vehicle, and/or at rail or light-transit crossings. Figure 45 provides an example of dynamic signing.

Source: FHWA.

Figure 45. Photograph. Example of dynamic signing (FHWA 2013).

ADD FENCING FOR TRAIL

The project team identified one study that developed CMFs for adding fencing between the trail and the roadway (L. Chen et al. 2013). CMF scores for adding fencing between the trail and the roadway were the following:

- Number of studies: 1.
- Number of CMFs: 8.
- Average CMF value: 0.83.
- Maximum CMF value range: 0.52–1.18.
- Average CMF rating: 2.5.
- CMF rating range: 2–3.
- Available crash-type CMFs: all, Vehicle/pedestrian, MV.
- Most severe crash severity CMF: KABC.

Figure 46 provides an example of fencing along a trail.

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Figure 46. Photograph. Example of fencing between a trail and the roadway.

ADD FLEX LANE

The project team did not identify any studies that developed CMFs for adding a flex lane. REV Birmingham (2021) defines this treatment as a painted lane between the curb and the travel lanes. This lane creates a buffer from traffic for pedestrians on the sidewalk; adapts to business needs like curbside food pickup, valet stands, and more creative uses; gives bikes, scooters and other micromobility devices a well-defined space to travel in; and reduces the width of the travel lane. Figure 47 provides an example of a flex lane.

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Figure 47. Photograph. Example of a flex lane (REV Birmingham 2021).

ADD FLUSH STREET

The project team did not identify any studies that developed CMFs for adding a flush street as part of their Complete Streets improvements. A flush street is a design that puts the street and sidewalk at the same height (i.e., there are not vertical differences between them). Figure 48 provides an example of a flush street.

Figure 48. Photograph. Example of a flush street.

ADD GRADE-SEPARATED PEDESTRIAN FACILITY (TUNNEL, UNDERPASS, BRIDGE)

The project team did not identify any studies that developed CMFs for adding a grade-separated pedestrian facility (e.g., tunnel, underpass, or bridge). Pedestrian crossings use either tunnels, underpasses, bridges, or overpasses to avoid at-grade conflicts between pedestrians and motor vehicle traffic. Figure 49 provides an example of a grade-separated pedestrian facility.

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Figure 49. Photograph. Example of grade-separated pedestrian facility.

ADD GREEN COLORED PAVEMENT

The project team did not identify any studies that developed CMFs for adding green colored pavement. Green colored pavement can be used in marked bicycle lanes and in extensions of bicycle lanes through intersections and other traffic conflict areas (FHWA 2011a). Figure 50 provides an example of green colored pavement.

Source: FHWA.

Figure 50. Photograph. Example of green colored pavement (Schultheiss et al. 2019).

ADD OR IMPROVE INTERCHANGE

The project team did not identify any studies that developed CMFs for adding or improving interchanges. The team defined this treatment as adding new access points to controlled-access highways or improving existing access points on controlled-access highways. Figure 51 provides an example of an improved interchange.

Figure 51. Graphic. Example of an improved interchange (Rudick 2022).

IMPROVE INTELLIGENT TRANSPORTATION SYSTEM (ITS) COMMUNICATIONS

The project team did not identify any studies that developed CMFs for improved ITS communications. FHWA (2021c) noted that ITS technologies focus on innovations to advance transportation safety, mobility, and environmental sustainability. ITS technologies augment traditional infrastructure improvement approaches by integrating advanced communications technologies into vehicles and existing infrastructure to improve transportation operations, efficiency, and reliability. Figure 52 provides a representation of ITS communications.

Source: FHWA.

Figure 52. Graphic. Example of ITS communication (Smith 2017).

ADD LANDSCAPING/STREETSCAPING/HARDSCAPING

The project team identified one study that developed CMFs for adding landscaping, streetscaping, or hardscaping (Lin et al. 2013). CMF scores for adding landscaping/streetscaping/hardscaping were the following:

- Number of studies: 1.
- Number of CMFs: 3.
- Average CMF value: 1.92.
- CMF value range: 0.82–3.26.
- Average CMF rating: 2.0.
- CMF rating range: 2.
- Available crash type CMFs: all.
- Most severe crash severity CMF: KABC.

Smith, Reed, and Baker (2010) note that elements such as plants, trees, flowers, stones, and other features can help attract more people to stop and stroll through downtown areas. Figure 53 provides an example of landscaping/streetscaping/hardscaping.

Source: FHWA.

Figure 53. Photograph. Example of landscaping/streetscaping/hardscaping (Smith et al. 2010).

ADD LEADING PEDESTRIAN INTERVAL (LPI)

The project team identified one study that developed CMFs for adding LPI (Goughnour et al. 2018). CMF scores for adding LPI were the following:

- Number of studies: 1.
- Number of CMFs: 3.
- Average CMF value: 0.85.
- CMF value range: 0.81–0.90.
- Average CMF rating: 5.0.
- CMF rating range: 5.
- Available crash-type CMFs: all.
- Most severe crash severity CMF: KABC.

FHWA (2021d) noted LPI gives pedestrians the opportunity to enter the crosswalk at an intersection 3–7 seconds before vehicles are given a green indication. Figure 54 provides an example of an LPI.

Source: FHWA.

Figure 54. Photograph. Example of a pedestrian using an LPI (FHWA 2021d).

ADD LEFT-TURN LANE

The project team identified 15 studies that developed CMFs for adding a left-turn lane (Abdel-Aty et al. 2014; Al-Marafi, Somasundaraswaran, and Bullen 2010; El-Basyouny and Sayed 2011; Elvik and Vaa 2004; Haleem and Abdel-Aty 2011; Haleem, Abdel-Aty, and Mackie 2010; Harwood et al. 2002; Haque, Chin, and Huang 2010; Maze et al. 2010; Morena, Wainwright, and Ranck 2007; Preston and Schoenecker 1999; Rodegerdts, Nevers, and Robinson 2004; Srinivasan, Lan, and Carter 2014; Wang and Abdel-Aty 2007; Ye et al. 2009) . This treatment has CMFs that are included in the first edition of the HSM. CMF scores for adding a left-turn lane were the following:

- Number of studies: 15.
- Number of CMFs: 42.
- Average CMF value: 0.74.
- Maximum CMF value range: 0.15–1.4.
- Average CMF rating: 2.9.
- CMF rating range: 1–4.
- Available crash-type CMFs: all, left-turn, head-on, rear end, angle, sideswipe.

- Most severe crash severity CMF: KABC.

FHWA (2021e) describes this treatment as the physical separation between left-turning traffic that is slowing or stopped and adjacent through traffic at approaches to intersections by way of a left-turn lane. Left-turn lanes can be designed to provide for deceleration prior to a turn and for storage of vehicles that are stopped and waiting for the opportunity to complete a turn. Figure 55 provides an example of adding a left-turn lane.

Source: FHWA.

Figure 55. Photograph. Example of adding a left-turn lane (FHWA 2021e).

ADD OR ENHANCE LIGHTING

The project team identified 13 studies that developed CMFs for adding or enhancing lighting (Abdel-Aty et al. 2014; Bullough, Donnell, and Rea 2012; Donnell, Porter, and Shankar 2010; Elvik and Vaa 2004; Li et al. 2021; Q. Li et al. 2021; Sacchi and Tayebikhorami 2021; Torbic et al. 2015; Wang et al. 2017a, 2017b; Yang et al. 2019; Wanvik 2009; Ye et al. 2009). CMF scores for adding a left-turn lane were the following:

- Number of studies: 13.
- Number of CMFs: 32.
- Average CMF value: 0.69.
- CMF value range: 1.39.
- Average CMF rating: 3.2.
- CMF rating range: 2–4.
- Available crash-type CMFs: all, nighttime, vehicle/pedestrian, vehicle/bicycle, night-to-day crash ratio, angle, twilight, other.
- Most severe crash severity CMF: K.

The team defined this treatment as upgrades to lighting, which can include new light posts, additional lighting, light-emitting diode (LED) lights, and other improvements. Figure 56 provides an example of enhanced lighting at a pedestrian crossing.

Source: FHWA.

Figure 56. Photograph. Example of enhanced lighting (Redmon et al. 2021).

ADD MEDIAN

The project team identified 11 studies that developed CMFs for adding a median (Abdel-Aty et al. 2014; Alluri et al. 2012; Al-Marafi, Somasundaraswaran, and Bullen 2010; Elvik and Vaa 2004; Mauga and Kaseko 2010; Miranda-Moreno, Strauss, and Morency 2011; Schultz et al. 2011; Schultz, Braley, and Boschert 2008; Stokes et al. 2016; X. Li et al. 2021; Yanmaz-Tuzel and Ozbay 2010). CMF scores for adding a median were the following:

- Number of studies: 11.
- Number of CMFs: 44.
- Average CMF value: 0.72.
- CMF value range: 0.26–2.28.
- Average CMF rating: 2.8.
- CMF rating range: 2–4.
- Available crash-type CMFs: all, angle, head-on, vehicle/bicycle, driveway-related, rear end, left-turn, right-turn, sideswipe, vehicle/pedestrian, angle, fixed object, head-on, rear end, run off road, sideswipe, SV.
- Most severe crash severity CMF: KABC.

FHWA (2021f) defines this treatment as the area between opposing lanes of traffic, excluding turn lanes. Medians in urban and suburban areas can be defined by pavement markings, raised medians, or islands to separate motorized and nonmotorized road users. Figure 57 provides an example of a median.

Source: FHWA.

Figure 57. Photograph. Example of a median (FHWA 2021f).

ADD OR ENHANCE MIDBLOCK CROSSING

The project team identified one study that developed CMFs for adding or enhancing a midblock crossing (Kadeha et al. 2022). CMF scores for adding or enhancing a midblock crossing were the following:

- Number of studies: 1.
- Number of CMFs: 1.
- Average CMF value: 0.82.
- CMF value range: 0.82.
- Average CMF rating: 4.0.
- CMF rating range: 4.
- Available crash-type CMFs: vehicle/pedestrian.
- Most severe crash severity CMF: all.

FHWA (2006b) defines midblock crossings as nonintersection crossings for pedestrians. Figure 58 provides an example of an enhanced midblock crossing.

Source: FHWA.

Figure 58. Photograph. Example of an enhanced midblock crossing (FHWA 2021g).

ADD MOUNTABLE CURB

The project team did not identify any studies that developed CMFs for adding mountable curbs. Brewer and Bedsole (2015) defined this treatment as curbs that can be driven upon by vehicles without damage but which are not intended to be in the normal path of traffic. Figure 59 provides an example of a mountable curb.

Figure 59. Photograph. Example of a mountable curb (Chester County Planning Commission n.d.).

REDUCE NUMBER OF LANES

The project team identified one study that developed CMFs for reducing the number of lanes (Al-Marafi, Somasundaraswaran, and Bullen 2010). CMF scores for reducing the number of lanes were the following:

- Number of studies: 1.
- Number of CMFs: 1.
- Average CMF value: 0.88.
- Maximum CMF value range: 0.88.
- Average CMF rating: 3.0.
- CMF rating range: 3.
- Available crash-type CMFs: all.
- Most severe crash severity CMF: KABC.

This treatment comprises removing one or more travel lanes to reallocate space for other uses (e.g., for bike lanes, shoulder, etc.). See definition for “Perform a Road Diet” for additional information. Figure 60 provides an example of a road on which the number of lanes has been reduced.

Source: FHWA.

Figure 60. Photograph. Example of a road on which the number of lanes has been reduced (FHWA n.d.e).

CONVERT ONE-WAY ROAD TO TWO-WAY ROAD

The project team did not identify any studies that developed CMFs for converting a one-way road to a two-way road. The team defined this treatment as changing a one-way street to allow two-way traffic. Figure 61 provides an example of converting a one-way road to a two-way road.

Source: FHWA.

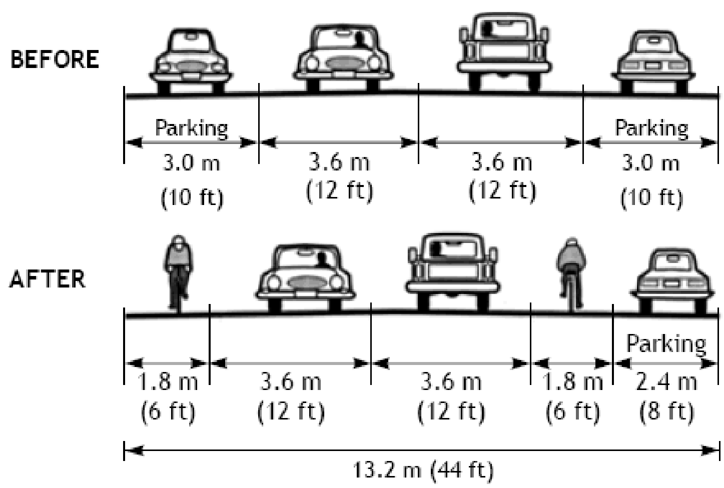
Figure 61. Photograph. Example of converting a one-way road to a two-way road (FHWA n.d.e).

REMOVE ON-STREET PARKING

The project team identified three studies that developed CMFs for removing on-street parking (AASHTO 2010; Bissell et al. 1982; Elvik and Vaa 2004). This treatment has CMFs that are included in the first edition of the HSM (AASHTO 2010). CMF scores for removing on-street parking were the following:

- Number of studies: 3.
- Number of CMFs: 8.
- Average CMF value: 0.78.
- CMF value range: 0.52–1.49.
- Average CMF rating: 2.0.
- CMF rating range: 1–3.
- Available crash-type CMFs: all.
- Most severe crash severity CMF: KABC.

The team defined this treatment as eliminating on-street parking and reallocating that space for other uses (e.g., bike lane, sidewalk). Figure 62 provides an example of removing on-street parking.



Source: FHWA.

Figure 62. Graphic. Example of removing on-street parking (FHWA 2006c).

ADD OUTDOOR FURNITURE OR SEATING INCLUDING RESTAURANTS (BENCHES, TRASH CANS, ETC.)

The project team did not identify any studies that developed CMFs for adding outdoor furniture or seating. FHWA (n.d.f) defines this treatment as outdoor design elements such as benches, trash cans, and water fountains. Figure 63 provides an example of outdoor furniture.

Source: FHWA.

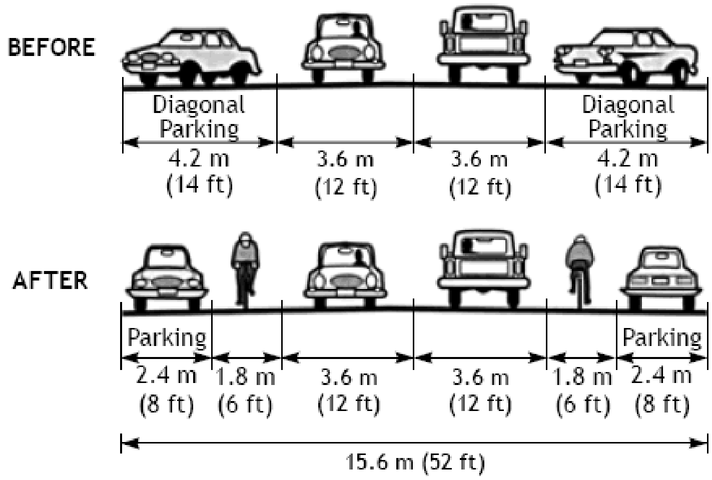
Figure 63. Photograph. Example of outdoor furniture (Carlson, Greenberg, and Kanninen 2011).

CHANGE PARKING CONFIGURATION

The project team identified three studies that developed CMFs for changing the parking configuration (Bissell et al. 1982; Box 2001; Elvik and Vaa 2004). CMF scores for improving pavement condition were the following:

- Number of studies: 3.
- Number of CMFs: 10.
- Average CMF value: 0.77.
- CMF value range: 0.35–2.11.
- Average CMF rating: 1.4.
- CMF rating range: 1–3.
- Available crash type CMFs: All, Parking related.
- Most severe crash severity CMF: KABC.

The team defined this treatment as various changes to vehicle parking, including parking lot improvements (additional space, striping, resurfacing upgraded lighting, security cameras), adding or removing on-street parking; and adding back-in diagonal parking. Figure 64 provides an example of changing the parking configuration.



Source: FHWA.

Figure 64. Graphic. Example of changing the parking configuration (FHWA 2006c).

IMPROVE PAVEMENT CONDITION

The project team identified six studies that developed CMFs for improving pavement condition (Abdel-Aty, Devarasetty, and Pande 2009; Choi et al. 2015; Hussein and Hassan 2018; Oh, Ragland, and Chan 2010; Park, Abdel-Aty, and Wang 2017; Zeng, Fontaine, and Smith 2014). CMF scores for improving pavement condition were the following:

- Number of studies: 6.
- Number of CMFs: 14.
- Average CMF value: 0.86.
- CMF value range: 0.50–1.07.
- Average CMF rating: 3.6.
- CMF rating range: 1–5.
- Available crash-type CMFs: all, rear end, wet road.
- Most severe crash severity CMF: KABC.

The team defines this treatment as improvements to asphalt or concrete, such as asphalt overlay, street reconstruction, driveway and roadway paving, and pavement repair/repaving. Figure 65 provides an example of pavement in good condition.

Source: FHWA.

Figure 65. Photograph. Example of pavement in good condition (FHWA 2015).

IMPROVE PAVEMENT MARKING

The project team identified five studies that developed CMFs for improving pavement markings (Carlson et al. 2015; Donnell, Karwa, and Sathyanarayanan 2009; Park et al. 2012; Potts et al. 2011; Smadi et al. 2008). CMF scores for improving pavement markings were the following:

- Number of studies: 5.
- Number of CMFs: 19.
- Average CMF value: 0.71.
- CMF value range: 0.54–0.85.
- Average CMF rating: 2.8.
- CMF rating range: 1–4.
- Available crash-type CMFs: all, nighttime, nighttime cross median, fixed object, frontal and opposing direction sideswipe, head-on, run off road, sideswipe, SV.
- Most severe crash severity CMF: KA.

The team defined this treatment as restriping and adding pavement markings. Figure 66 provides an example of improved pavement markings.

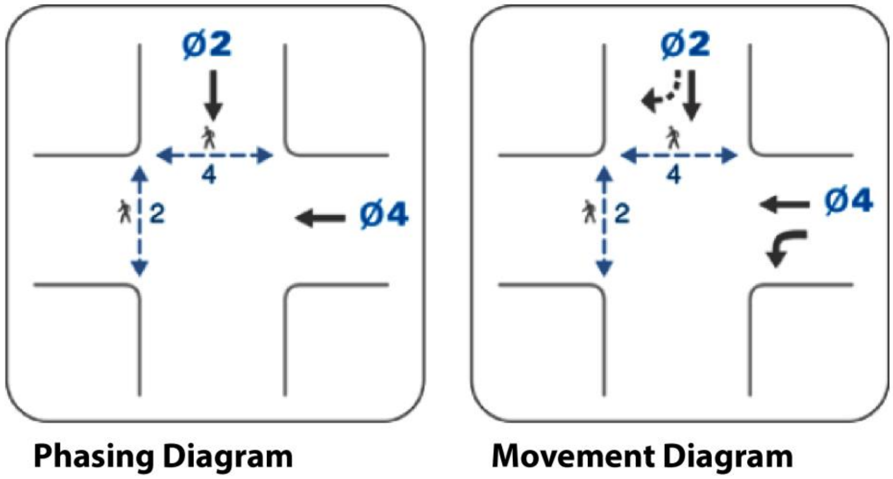
Figure 66. Photograph. Example of a street with improved centerline pavement markings.

ADD OR ENHANCE PEDESTRIAN AND BICYCLIST SIGNAL OPERATION

The project team identified two studies that developed CMFs for adding or enhancing pedestrian and bicyclist signal operation (L. Chen, C. Chen, and Ewing 2012; L. Chen et al. 2013). CMF scores for adding or enhancing pedestrian and bicyclist signal operation were the following:

- Number of studies: 2.
- Number of CMFs: 12.
- Average CMF value: 0.80.
- CMF value range: 0.49–1.1.
- Average CMF rating: 2.2.
- CMF rating range: 2–3.
- Available crash-type CMFs: all, vehicle/pedestrian, MV, angle, head-on, left-turn, rear end, rear to rear, right-turn, sideswipe.
- Most severe crash severity CMF: KABC.

Goodman et al. (2015) defines this treatment as signal phasing that accommodates bike and pedestrian signal phasing. Bike and pedestrian phases can either be exclusive movements or incorporated with vehicle movement phases. Figure 67 provides an example of pedestrian and bicyclist signal operation.



Source: FHWA.

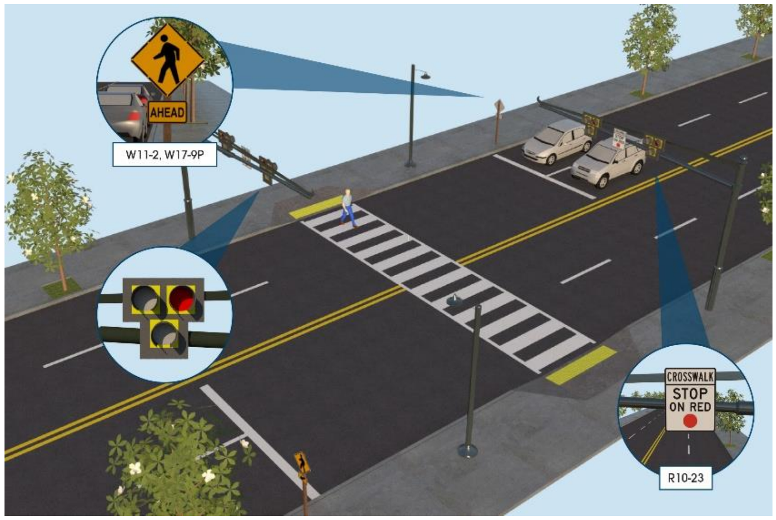
Figure 67. Graphic. Example of pedestrian and bicyclist signal operation (FHWA 2021g).

ADD PHB

The project team identified three studies that developed CMFs for adding a PHB (Fitzpatrick et al. 2019; Fitzpatrick and Park 2012; Zeeger et al. 2017). CMF scores for adding a PHB were the following:

- Number of studies: 3.
- Number of CMFs: 10.
- Average CMF value: 0.62.
- CMF value range: 0.31–0.87.
- Average CMF rating: 3.7.
- CMF rating range: 3–5.
- Available crash-type CMFs: all, vehicle/pedestrian, rear end, sideswipe.
- Most severe crash severity CMF: KABC.

A PHB is a traffic control device with a face that consists of two red lenses above a single yellow lens (Blackburn et al. 2018). Unlike a traffic signal, the PHB remains dark until a pedestrian activates it via pushbutton or other form of detection. Figure 68 is an example of a crosswalk with a PHB.



Source: FHWA.

Figure 68. Graphic. Example of a crosswalk with a PHB (Blackburn et al. 2018).

ADD PEDESTRIAN PUSHBUTTONS AND/OR COUNTDOWN TIMER

The project team identified seven studies that developed CMFs for adding a pedestrian pushbutton and/or countdown timer (Boateng et al. 2019; Camden et al. 2012; Kitali et al. 2017; Kwigizile et al. 2016; Markowitz et al. 2006; Srinivasan et al. 2022; Van Houten, LaPlante, and Gustafson 2012). CMF scores for adding a pedestrian pushbutton and/or countdown timer were the following:

- Number of studies: 7.
- Number of CMFs: 33.
- Average CMF value: 0.88.
- CMF value range: 0.30–1.04.
- Average CMF rating: 3.5.
- CMF rating range: 1–5.
- Available crash-type CMFs: all, vehicle/pedestrian, older driver, non-older driver, rear end, angle.
- Most severe crash severity CMF: K.

Pedestrian signal heads provide special types of traffic signal indications exclusively intended for controlling pedestrian traffic (FHWA 2022b, FHWA 2022c). These signal indications consist of the illuminated symbols of a walking person (symbolizing walk) and an upraised hand (symbolizing do not walk). Some pedestrian signals may require users to push a button to actuate the countdown timer. Push buttons are typically located adjacent to the crosswalk. Figure 69 provides an example of a pedestrian pushbutton and countdown timer.

Figure 69. Photograph. Example of a pedestrian pushbutton and countdown timer.

ADD PEDESTRIAN REFUGE ISLAND

The project team identified one study that developed a CMF for adding a pedestrian refuge island (Zeeger et al. 2002). CMF scores for adding a pedestrian refuge island were the following:

- Number of studies: 1.
- Number of CMFs: 1.
- Average CMF value: 0.54.
- CMF value range: 0.54.
- Average CMF rating: 3.0.
- CMF rating range: 3.
- Available crash-type CMFs: vehicle/pedestrian.
- Most severe crash severity CMF: all.

A pedestrian refuge island is a median or crossing island with a refuge area that is intended to help protect pedestrians who are crossing a road (FHWA 2021f, FHWA n.d.g). Figure 70 provides an example of an intersection with pedestrian refuge islands.

Source: FHWA.

Figure 70. Photograph. Example of an intersection with pedestrian refuge islands (FHWA 2006d).

ADD PEDESTRIAN SIGNAL

The project team identified one study that developed CMFs for adding pedestrian signals (Sacchi, Sayed, and Osama 2015). CMF scores for adding pedestrian signals were the following:

- Number of studies: 1.
- Number of CMFs: 3.
- Average CMF value: CMFunction.
- CMF value range: CMFunction.
- Average CMF rating: 4.0.CMF rating range: 4.
- Available crash-type CMFs: all.
- Most severe crash severity CMF: KABC.

A pedestrian signal is a dedicated traffic signal for pedestrian traffic that crosses vehicular traffic at a midblock location. Bicyclists frequently use these signals to cross the roadway. Figure 71 provides an example of a pedestrian signal.

Figure 71. Photograph. Example of a pedestrian signal (Applied Information 2019).

ADD PUBLIC ART

The project team did not identify any studies that developed CMFs for adding public art. This treatment includes art displayed publicly, such as sculptures or murals on buildings (Loh and Smith 2012). Art enhancements can help address boring concrete surfaces, unwelcoming public spaces, and disruption of existing neighborhoods when new roads and noise walls are installed. Art can enliven those paved surfaces and noise walls while creating public spaces that attract residents and visitors alike. Figure 72 provides an example of public art.

Source: FHWA.

Figure 72. Photograph. Example of public art (Loh and Smith 2012).

ADD QUIET-ZONE RAILROAD CROSSING

The project team did not identify any studies that developed CMFs for adding a quiet-zone railroad crossing. A quiet zone is a rail line section at least 0.5 mi long that contains one or more consecutive public highway-rail grade crossings at which locomotive horns are not routinely sounded when trains are approaching the crossings (Federal Railroad Administration 2013). Figure 73 provides an example of a quiet-zone railroad-crossing sign.

Source: Federal Railroad Administration.

Figure 73. Graphic. Example of quiet zone for railroad-crossing sign (Federal Rail Administration 2013).

ADD RAISED CROSSWALK

The project team identified one study that developed CMFs for adding a raised crosswalk (Elvik and Vaa 2004). CMF scores for adding a raised crosswalk were the following:

- Number of studies: 1.
- Number of CMFs: 3.
- Average CMF value: 0.63.
- CMF value range: 0.55–0.64.
- Average CMF rating: 3.0.
- CMF rating range: 3.
- Available crash-type CMFs: all, vehicle/pedestrian.
- Most severe crash severity CMF: ABC.

A raised crosswalk is a ramped speed table spanning the entire width of the roadway and often placed at midblock crossing locations (FHWA 2018b). The crosswalk is demarcated with paint and/or special paving materials. These crosswalks act as traffic-calming measures that allow the pedestrian to cross at grade with the sidewalk. Construction involves providing ramps on each intersection approach and elevating the entire intersection to the level of the sidewalk. Figure 74 is an example of a raised crosswalk.

Source: FHWA.

Figure 74. Photograph. Example of a raised crosswalk (FHWA n.d.c).

ADD RAISED INTERSECTION

The project team identified one study that developed CMFs for adding a raised intersection (Elvik and Vaa 2004). CMF scores for adding a raised crosswalk were the following:

- Number of studies: 1.
- Number of CMFs: 2.
- Average CMF value: 1.09.
- CMF value range: 1.05–1.13.
- Average CMF rating: 3.0.
- CMF rating range: 3.
- Available crash-type CMFs: all.
- Most severe crash severity CMF: ABC.

A raised intersection is a speed table spanning an entire intersection, elevating the intersection to the level of the sidewalk where the crosswalks on each intersection approach are also elevated (FHWA, n.d.h). Figure 75 is an example of a raised crosswalk at an intersection.

© Google Street View.

Figure 75. Photograph. Example of a raised intersection (FHWA n.d.c).

ADD RAISED TRAFFIC SEPARATORS

The project team did not identify any studies that developed CMFs for adding raised traffic separators. Raised traffic separators are physical dividers installed on the roadway to prohibit specific vehicular movements. For example, traffic separators could be added to the road to remove left-turn movements or to provide vertical separation for a bike lane. Figure 76 is an example of raised traffic separators.

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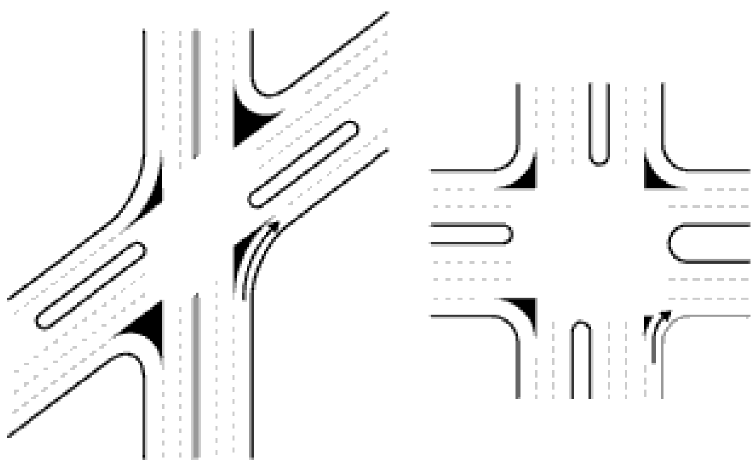
Figure 76. Photograph. Example of raised traffic separators.

REALIGN INTERSECTION

The project team identified one study that developed CMFs for realigning an intersection (Harwood et al. 2000). This treatment has CMFs that are included in the first edition of the HSM (AASHTO 2010).

- Number of studies: 1.
- Number of CMFs: 1.
- Average CMF value: CMFunction.
- CMF value range: CMFunction.
- Average CMF rating: not rated (HSM).
- CMF rating range: not rated (HSM).
- Available crash-type CMFs: all.
- Most severe crash severity CMF: all.

A skewed intersection occurs when roads intersect at angles 60 degrees or less (FHWA 2011b). Intersections may be redesigned and reconstructed to improve skew by having angles at or closer to 90 degrees. Figure 77 provides an example of a skewed intersection that may be in need of realignment.



Source: FHWA.

Figure 77. Photograph. Example of a skewed intersection (FHWA 1998).

ADD REAL-TIME BUS ARRIVAL SIGN

The project team did not identify any studies that developed CMFs for adding real-time bus arrival signs. These signs present real-time bus operations information to the public (Cham et al. 2006). Figure 78 provides an example of a real-time bus arrival sign.

Source: Federal Transit Administration.

Figure 78. Photograph. Example of a real-time bus arrival sign (Cham et al. 2006).

ADD RRFB

The project team identified three studies that developed CMFs for adding an RRFB (Goswamy, Abdel-Aty, and Mahmoud 2022; Monsere et al. 2017; Zegeer et al. 2017). CMF scores for adding an RRFB were the following:

- Number of studies: 1.
- Number of CMFs: 3.
- Average CMF value: 0.71.
- CMF value range: 0.27–1.18.
- Average CMF rating: 3.3.
- CMF rating range: 1–4.
- Available crash-type CMFs: all, vehicle/pedestrian, non-pedestrian, rear end.
- Most severe crash severity CMF: KABC.

RRFBs are pedestrian-actuated conspicuity enhancements used in combination with a pedestrian, school, or trail-crossing warning sign to improve safety at uncontrolled, marked crosswalks (Blackburn et al. 2018). The device includes two rectangular-shaped yellow indications, each with an LED-array-based light source, that flash with high frequency when activated. Figure 79 provides an example of an RRFB.

Source: FHWA.

Figure 79. Photograph. Example of an RRFB (FHWA 2018c).

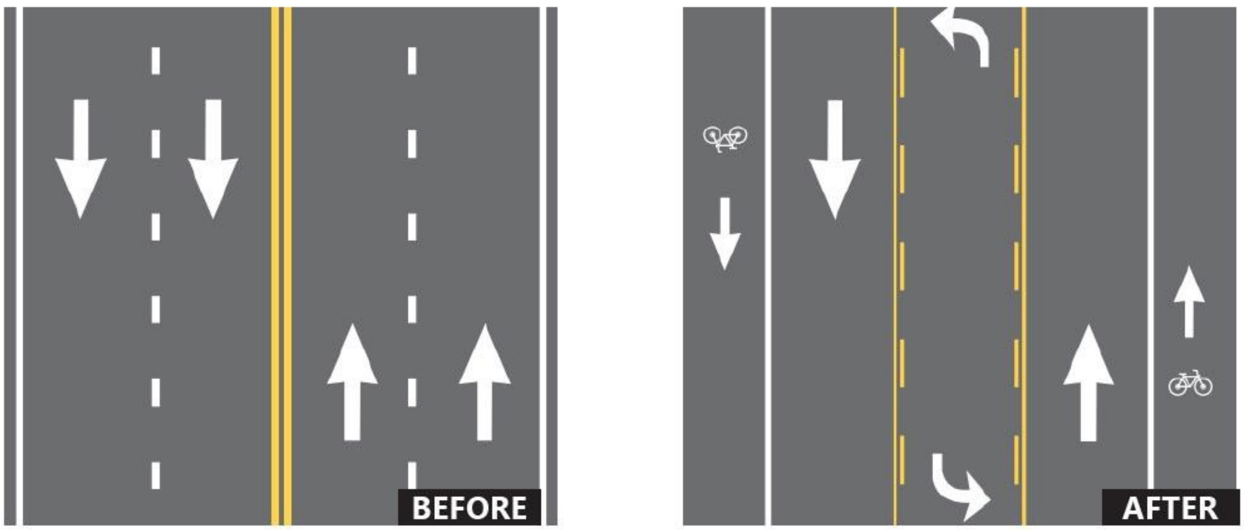
PERFORM A ROAD DIET

The project team identified eight studies that developed CMFs for performing a Road Diet (Abdel-Aty et al. 2014; Harkey et al. 2008b; Lim and Fontaine 2022; Lyles et al. 2012; Pawlovich et al. 2016; Persaud et al. 2010; Sun and Rahman 2019; Zhou et al. 2022). CMF scores for performing a Road Diet were the following:

- Number of studies: 8.
- Number of CMFs: 26.
- Average CMF value: 0.68.
- CMF value range: 0.36–1.05.

- Average CMF rating: 2.6.
- CMF rating range: 1–5.
- Available crash-type CMFs: All.
- Most severe crash severity CMF: KABC.

Blackburn et al. (2018) define this treatment as a roadway reconfiguration resulting in a reduction in the number of travel lanes. The space gained by eliminating lanes is typically reallocated for other uses and travel modes. Figure 80 provides an example of a Road Diet.



Source: FHWA.

Figure 80. Graphic. Example of a Road Diet (FHWA 2021i).

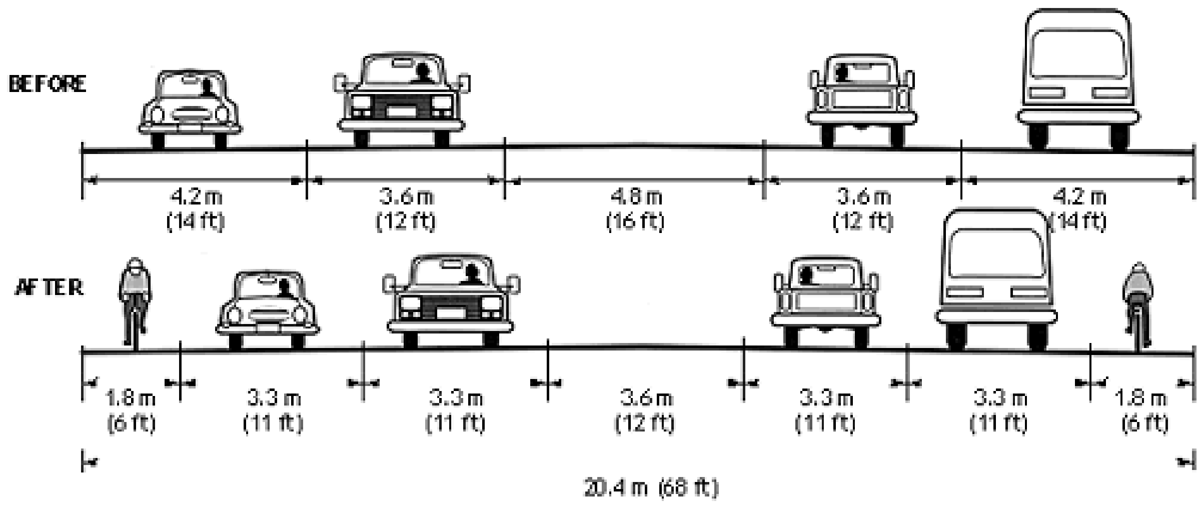
DECREASE ROADWAY OR LANE WIDTH

The project team identified eight studies that developed CMFs for decreasing the roadway or lane width (Abdel-Aty et al. 2014; Abdel-Rahim and Sonnen 2012; Bared et al. 2008; Hauer 2000; Lord and Bonneson 2007; Raihan et al. 2019; Wood, Gooch, and Donnel 2015; Wu, Sun, and Li 2019). This treatment has CMFs that are included in the first edition of the HSM. CMF scores for decreasing the roadway or lane width were the following:

- Number of studies: 8.
- Number of CMFs: 3.
- Minimum CMF value: 0.44.
- Average CMF value: 1.16.
- CMF value range: 0.44–3.40.
- Average CMF rating: 2.8.
- CMF rating range: 1–4.
- Available crash-type CMFs: all, vehicle/bicycle, angle, rear end, sideswipe, SV, MV, head-on, other.

- Most severe crash severity CMF: KABC.

This treatment involves reducing the lane width or roadway width and typically allocating that space to other elements, such as wider sidewalks, bike lanes, medians, or reconfigured parking. Figure 81 provides an example of decreasing roadway the roadway or lane width.

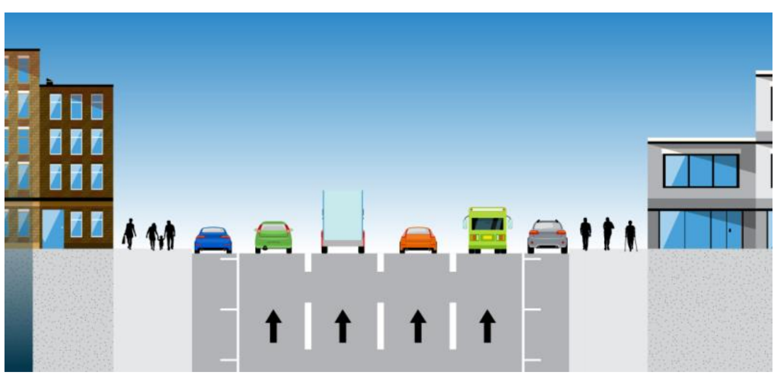


Source: FHWA.

Figure 81. Graphic. Example of decreasing roadway or lane width (FHWA 2006c).

REVERSE STREET DIRECTION

The project team did not identify any studies that developed CMFs for reversing the direction of a street. This treatment involves reversing the direction of a one-way street so that traffic flows in the opposite direction. Figure 82 shows an example of a one-way street configuration.



Source: FHWA.

Figure 82. Graphic. Example of one-way street configuration (FHWA 2022d).

INCREASE ROADWAY OR LANE WIDTH

The project team identified seven studies that developed CMFs for increasing the roadway or lane width (Acqua and Russo 2011; Alluri et al. 2017; Dixon, Fitzpatrick, and Avelar 2016; Hauer 2000;

Park and Abdel-Aty 2016; Wang et al. 2011; Yanmaz-Tuzel and Ozbay 2010). The CMFs were the following:

- Number of studies: 7.
- Number of CMFs: 22.
- Average CMF value: 0.75.
- CMF value range: 0.24–0.95.
- Average CMF rating: 2.8.
- CMF rating range: 2–4.
- Available crash-type CMFs: all, vehicle/bicycle, truck-related.
- Most severe crash severity CMF: KA.

Figure 83 shows an example of a roadway that was widened to provide space for bicycle lanes.

Figure 83. Photograph. Example of road where width was increased to add bike lanes.

ADD ROUNDABOUT

The project team identified 23 studies that developed CMFs for adding a roundabout (Abdel-Aty et al. 2014; Bagdade et al. 2011; Claros et al. 2022; Daniels, Nuyts, and Wets 2008; De Brabander and Vereeck 2007; De Pauw et al. 2014; Elvik 2017; Gbologah, Guin, and Rodgers 2019; Gross et al. 2013; Hu et al. 2014; Jensen 2017; Mamlouk and Souliman 2019; Persaud et al. 2001; Pulugurtha, Mishra, and Mathew 2021; Qin et al. 2013; Rodegerdts et al. 2007; Russo et al. 2014; Schoon and van Minnen 1994; Srinivasan et al. 2011; Sun et al. 2018; Uddin, Headrick, and Sullivan 2012; Zhang and Wang 2017; Zhao, Andrey, and Deadman 2018). CMF scores for adding a roundabout were the following:

- Number of studies: 23.
- Number of CMFs: 114.
- Average CMF value: 0.77.
- CMF value range: 0.004–6.01.
- Average CMF rating: 2.8.
- CMF rating range: 1–5.
- Available crash-type CMFs: all, vehicle/pedestrian, vehicle/bicycle.
- Most severe crash severity CMF: K.

A roundabout is an intersection with a circular configuration that safely and efficiently moves traffic (FHWA 2021j). Roundabouts feature channelized, curved approaches that reduce vehicle speed, provide entry/yield control that gives right-of-way to circulating traffic, and create counterclockwise flow around a central island to minimize conflict points. Figure 84 provides an example of a roundabout.

Source: FHWA.

Figure 84. Graphic. Example of a roundabout (FHWA 2021j).

IMPLEMENT SAFE ROUTES TO SCHOOL

The project team identified one study that developed CMFs for implementing Safe Routes to School (Guiterrez et al. 2008). CMF scores for implementing Safe Routes to School were the following:

- Number of studies: 1.
- Number of CMFs: 7.
- Average CMF value: 0.93.
- CMF value range: 0.72–1.28.
- Average CMF rating: 1.6.
- CMF rating range: 1–2.
- Available crash-type CMFs: vehicle/pedestrian, vehicle/bicycle.
- Most severe crash severity CMF: KA.

Safe Routes to School is an approach that promotes walking and bicycling to school via infrastructure improvements, enforcement, tools, safety education, and incentives to encourage walking and bicycling to school. Figure 85 students walking as part of a Safe Routes to School initiative.

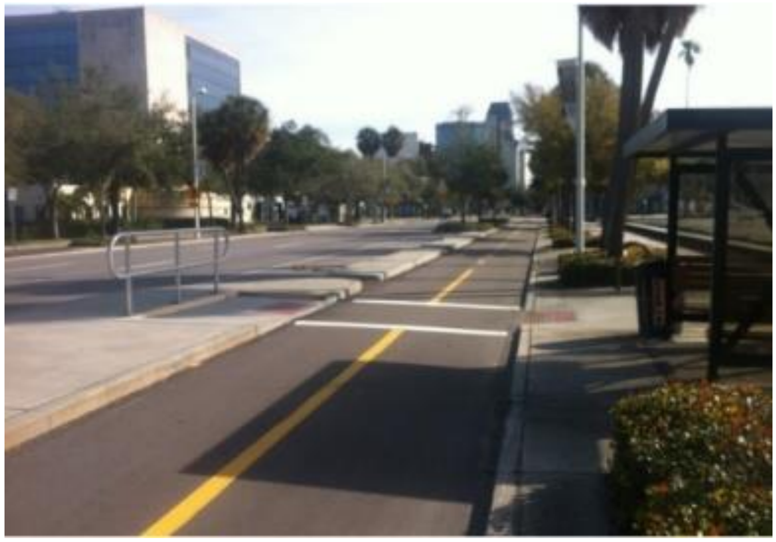
Figure 85. Photograph. Safe Routes to School.

ADD SEPARATED BIKE LANE

The project team identified three studies that developed CMFs for adding separated bike lanes (Jensen 2008; Nosal and Miranda-Moreno 2012; Schepers et al. 2011). CMF scores for adding separated bike lanes were the following:

- Number of studies: 3.
- Number of CMFs: 7.
- Average CMF value: 0.82.
- CMF value range: 0.27–1.75.
- Average CMF rating: 2.3.
- CMF rating range: 2–3.
- Available crash-type CMFs: vehicle/bicycle, vehicle/pedestrian.
- Most severe crash severity CMF: ABC.

Goodman et al. (2015) note that this treatment is also often called a protected bike lane. Separated bike lanes are exclusive facilities for bicyclists located within or directly adjacent to the roadway and are physically separated from motor vehicle traffic with a vertical element. These lanes are differentiated from shared use paths (and side paths) by their more proximate relationship to the adjacent roadway and the fact that they are bike-only facilities. Figure 86 provides an example of a separated bike lane.



Source: FHWA.

Figure 86. Photograph. Example of a separated bike lane (Goodman et al. 2015).

ADD SHARED-LANE MARKING (SHARROW)

The project team did not identify any studies that developed CMFs for adding a shared-lane marking (sharrow). Goodman et al. (2015) defined this treatment as a shared roadway with pavement markings providing wayfinding guidance to bicyclists and alerting drivers that bicyclists are likely to be operating in mixed traffic. Figure 87 provides an example of a shared-lane marking (sharrow).

Source: FHWA.

Figure 87. Photograph. Example of a shared-lane marking (Goodman et al. 2015).

INCREASE SHOULDER WIDTH

The project team identified three studies that developed CMFs for increased shoulder width (Bahar et al. 2009; Gross and Jovanis 2007; Park, Abdel-Aty, and Lee 2014). CMF scores for increasing shoulder width were the following:

- Number of studies: 3.
- Number of CMFs: 13.
- Average CMF value: 0.83.
- CMF value range: 0.56–1.01.
- Average CMF rating: 3.3.
- CMF rating range: 3–4.
- Available crash-type CMFs: all, run off road, SV.
- Most severe crash severity CMF: KABC.

Figure 88 provides an example of a wide shoulder.

Source: FHWA.

Figure 88. Photograph. Example of a wide shoulder (Stein and Nueman 2007).

ADD OR ENHANCE SIDEWALK

The project team identified two studies that developed CMFs for adding or enhancing sidewalk as part of their Complete Streets improvements (Alluri et al. 2017; Raihan et al. 2019). CMF scores for adding or enhancing sidewalk were the following:

- Number of studies: 2.
- Number of CMFs: 6.
- Average CMF value: 1.90.

- CMF value: 0.41–3.09.
- Average CMF rating: 2.70.
- CMF rating range: 2–3.
- Available crash-type CMFs: vehicle/bicycle.
- Most severe crash severity CMF: KA.

Sidewalks separated from the roadway are the preferred accommodation for pedestrians (Redmon 2010). Sidewalks provide many benefits that include safety, mobility, and healthier communities. Figure 89 provides an example of a sidewalk.

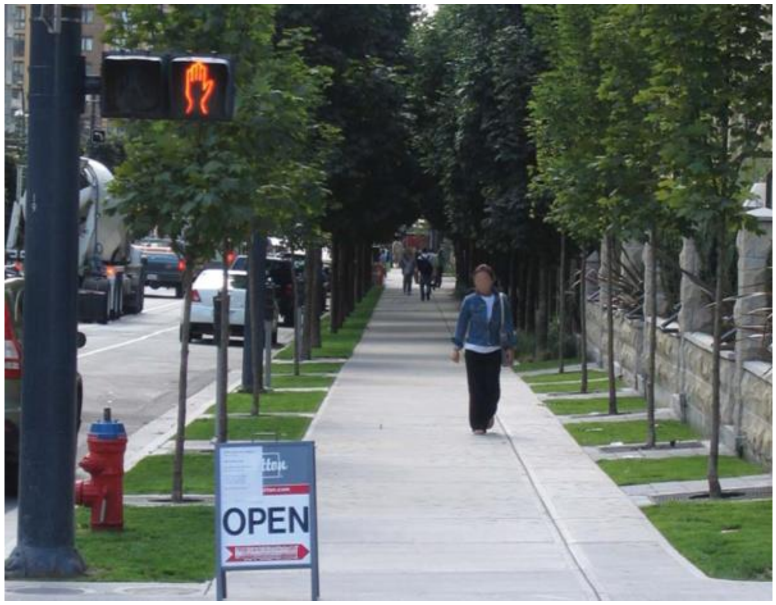
Figure 89. Photograph. Example of a sidewalk.

INCREASE SIDEWALK WIDTH

The project team identified two studies that developed CMFs for increasing the sidewalk width (Elvik and Vaa 2004; Oh et al. 2008). CMF scores for increasing the sidewalk width were the following:

- Number of studies: 2.
- Number of CMFs: 2.
- Average CMF value: 1.12.
- CMF value range: 1.12.
- Average CMF rating: 3.0.
- CMF rating range: 3.
- Available crash-type CMFs: all, vehicle/bicycle.
- Most severe crash severity CMF: ABC.

Figure 90 provides an example of a sidewalk with increased width.



Source: FHWA.

Figure 90. Photograph. Example of wide sidewalk (Redmon 2010).

IMPROVE SIGNING

The project team identified one study that developed a CMF for improving signing as part of Complete Streets improvements (Le, Gross, and Harmon 2017). CMF scores for improving signing were the following:

- Number of studies: 1.
- Number of CMFs: 1.
- Average CMF value: 0.92.
- CMF value range: 0.92.
- Average CMF rating: 4.0.
- CMF rating range: 4.
- Available crash-type CMFs: all.
- Most severe crash severity CMF: all.

Figure 91 provides an example of improved signing at a crosswalk.

Source: FHWA.

Figure 91. Graphic. Example of improved signing (FHWA 2021a).

REDUCE SPEED LIMIT

The project team identified seven studies that developed CMFs for reducing the speed limit (Abdelnaby et al. 2014; Al Marafi, Somasundaraswaran, and Bullen 2010; De Pauw et al. 2012; Islam and El-Basyouny 2015; Parker Jr. 1997; Raihan et al. 2019; Stokes et al. 2016). CMF scores for reducing the speed limit were the following:

- Number of studies: 7.
- Number of CMFs: 36.
- Average CMF value: 0.83.
- CMF value: 0.50–1.17.
- Average CMF rating: 3.4.
- CMF rating range: 2–5.
- Available crash-type CMFs: all, vehicle/bicycle, nonintersection, other.
- Most severe crash severity CMF: K.

Figure 92 provides an example of a reduced speed limit.

Source: FHWA.

Figure 92. Photograph. Example of a reduced speed limit (Warren, Xu, and Srinivasan 2013).

IMPROVE STORMWATER/DRAINAGE

The project team did not identify any studies that developed CMFs for improved stormwater/drainage. Improvements to stormwater systems and drainage may include replacing stormwater infrastructure, improving curb and gutter for drainage, adding drainage basin, adding rain garden, and providing stormwater management. See Add landscaping/streetscaping/hardscaping definition for related information. Figure 93 provides an example of an improved stormwater drain.

Source: FHWA.

Figure 93. Photograph. Example of an improved stormwater drain (Woronick and Sylvester 2023).

ADD STREETCAR

The project team did not identify any studies that developed CMFs for adding a streetcar. A streetcar is a type of light-rail public transportation that operates mostly in mixed traffic on rail lines embedded in streets and highways (Mallett 2014). Streetcar service is typically provided by single cars with electric power delivered by overhead wires known as catenaries, although streetcars can also draw power from underground cables or from batteries. Figure 94 provides an example of a streetcar.

Source: Federal Transit Administration.

Figure 94. Photograph. Example of a streetcar (Federal Transit Administration 2016).

ADD TRAFFIC-CALMING DEVICES

The project team identified one study that developed CMFs for adding traffic-calming devices (Elvik and Vaa 2004). CMF scores for adding traffic-calming devices were the following:

- Number of studies: 1.
- Number of CMFs: 13.
- Average CMF value: 0.79.
- CMF value range: 0.64–0.97.
- Average CMF rating: 3.0.
- CMF rating range: 3.
- Available crash-type CMFs: all.
- Most severe crash severity CMF: ABC.

FHWA (n.d.i) defines traffic-calming devices as treatments used to increase the quality-of-life in urban, suburban, and rural areas by reducing automobile speeds and traffic volumes on neighborhood streets. Figure 95 provides an example of a traffic-calming device.

Source: FHWA.

Figure 95. Photograph. Example of a traffic-calming device (FHWA n.d.i).

ADD TRAFFIC SIGNAL

The project team identified 13 studies that developed CMFs for adding a traffic signal (Abdel-Aty et al. 2014; L. Chen, C. Chen, and Ewing 2012; Davis and Aul 2007; De Pauw et al. 2014; Harkey et al. 2008a; McGee, Taori, and Persaud 2003; Pernia et al. 2002; Sacchi, Sayed, and El-Basyouny 2016; Schultz et al. 2014; Srinivasan, Lan, and Carter 2014; Wang and Abdel-Aty 2014; Wang et al. 2015; Yue et al. 2019). CMF scores for adding a traffic signal were the following:

- Number of studies: 13.
- Number of CMFs: 69.
- Average CMF value: 0.85.
- Maximum CMF value: 0.23–2.43.
- Average CMF rating: 3.0.
- CMF rating range: 1–5.
- Available crash-type CMFs: all, angle, rear end, left-turn, vehicle/pedestrian, head-on, sideswipe, left-turn same roadway, left-turn different roadway, rear to rear, right-turn, sideswipe.
- Most severe crash severity CMF: K.

Adding a traffic signal can have several safety benefits relevant to Complete Streets goals, including safely accommodating bicycle and pedestrian crossing movements. Figure 96 provides an example of a traffic signal.

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Figure 96. Photograph. Example of a traffic signal.

UPGRADE TRAFFIC SIGNAL

The project team identified 12 studies that developed CMFs for upgrading a traffic signal (El-Basyouny et al. 2012; Eustace, Griffin, and Hovey 2010; Jami et al. 2012; Khattak and Fontaine 2018; Le, Gross, and Harmon 2017; McGee, FHWA, and Institute of Transportation Engineers 2002; Polanis 1999; Rodegerdts, Nevers, and Robinson 2004; Sayed, Leur, and Pump 2005; Schattler et al. 2015; Srinivasan et al. 2008; Srinivasan et al. 2013). CMF scores for upgrading a traffic signal were the following:

- Number of studies: 12.
- Number of CMFs: 20.
- Average CMF value: 0.95.
- CMF value range: 0.51–1.71.
- Average CMF rating: 3.4.
- CMF rating range: 1–5.
- Available crash-type CMFs: all, angle, nighttime, daytime, left-turn/opposing through, left-turn related.
- Most severe crash severity CMF: KABC.

The team defined this treatment as upgrades to existing traffic signals, such as reconfiguring signal phasing for different turning movements or adding reflective backplates. Figure 97 provides an example of an upgraded traffic signal.

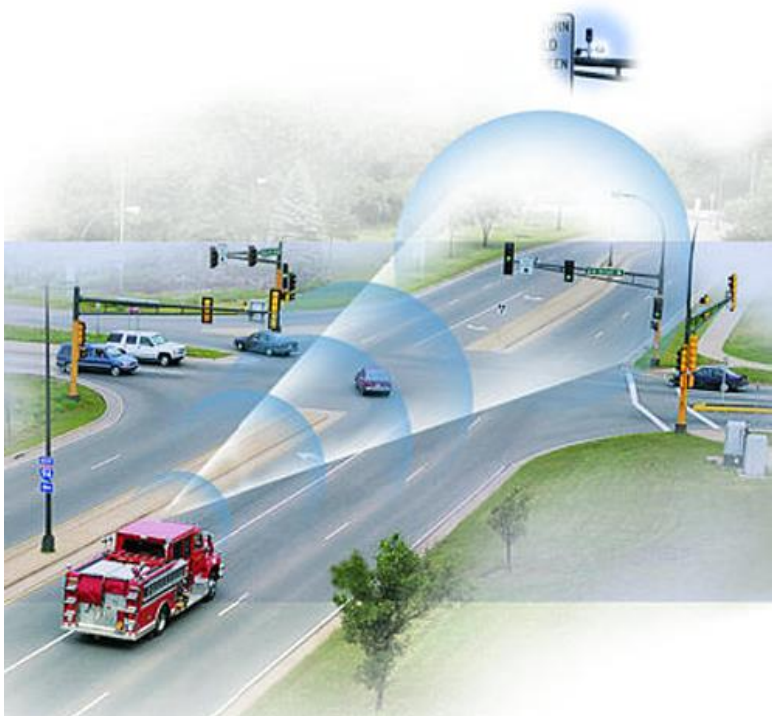
Figure 97. Photograph. Example of an upgraded traffic signal (NYSDOT 2022).

ADD TRANSIT SIGNAL PRIORITY (TSP)

The project team identified five studies that developed CMFs for adding TSP (Ali et al. 2021; Alluri et al. 2020; Naznin et al. 2015; Shalah et al. 2009; Song and Noyce 2018). CMF scores for adding TSP were the following:

- Number of studies: 5.
- Number of CMFs: 17.
- Average CMF value: 0.99.
- Maximum CMF value: 0.78–1.52.
- Average CMF rating: 3.8.
- CMF rating range: 3–5.
- Available crash type CMFs: all, angle, rear end, sideswipe.
- Most severe crash severity CMF: KABC.

TSP is an operational strategy applied to reduce the delay that transit vehicles experience at traffic signals (FHWA 2021k). TSP involves communication between transit vehicles (e.g., buses or light rail) and traffic signals so that a signal can alter its timing to give priority to transit operations. Figure 98 is an example of TSP.



Source: FHWA.

Figure 98. Graphic. Example of TSP (FHWA 2021k).

ADD TREE BELTS

The project team did not identify any studies that developed CMFs for adding tree belts. A tree belt is “a strip of ground lying between the sidewalk line and the curb line, usually turfed, and commonly planted with shade trees” (Merriam Webster n.d.). Figure 99 provides an example of a tree belt.

Source: FHWA.

Figure 99. Photograph. Example of a tree belt (FHWA 2006e).

ADD TWLTL

The project team identified seven studies that developed CMFs for adding a TWLTL (AASHTO 2010; Haleem and Abdel-Aty 2011; Hovey and Chowdhury 2005; Persaud et al. 2007; Persaud et al. 2008; Sun and Rahman 2019; X. Li et al. 2021). This treatment has CMFs that are included in the first edition of the HSM (AASHTO 2010). CMF scores for adding a TWLTL were the following:

- Number of studies: 7.
- Number of CMFs: 15.
- Average CMF value: 0.77.
- CMF value range: 0.53–1.45.
- Average CMF rating: 3.5.
- CMF rating range: 2–5.
- Available crash-type CMFs: all, rear end, nonintersection.
- Most severe crash severity CMF: KABC.

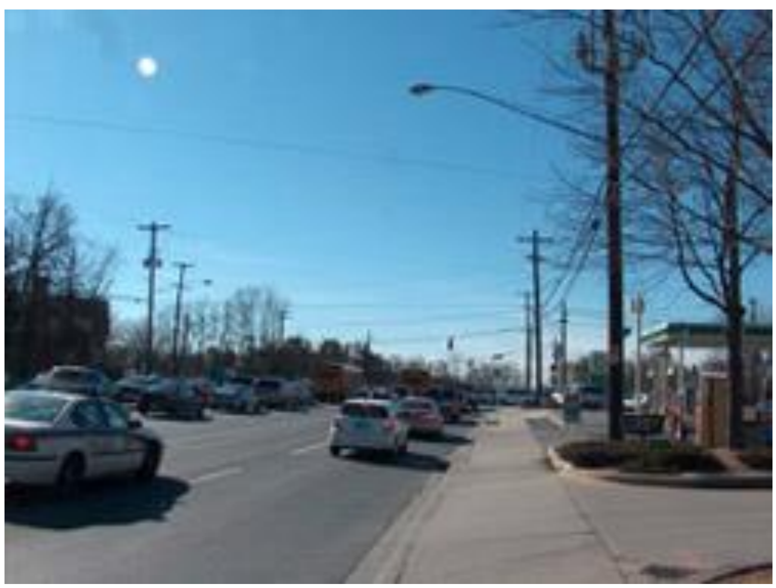
A TWLTL is a center lane that allows vehicles a space to wait for an acceptable gap before turning left (Persaud et al. 2007). Figure 100 provides an example of a TWLTL.

Source: FHWA.

Figure 100. Photograph. Example of a TWLTL (Persaud et al. 2007).

UPGRADE OR RELOCATE UTILITIES

The project team did not identify any studies that developed CMFs for upgrading or relocating utilities. This treatment includes replacing water, sewer, electrical, and other utility infrastructure. Figure 101 provides an example of relocated utilities.



Source: FHWA.

Figure 101. Photograph. Example of utility poles that were relocated further from the curb to make room for a sidewalk (FHWA 2018d).

APPENDIX B. METHODS FOR COMBINING CMFS

ESTIMATING THE COMBINED EFFECT OF MULTIPLE TREATMENTS

Transportation projects often involve more than one design feature or treatment that has estimable safety impacts. While estimating the impacts of one such treatment on a single facility is a relatively straightforward process, capturing the effects of multiple different treatments applied simultaneously to the same facility is not yet a standardized procedure. A number of CMFs were developed for commonly occurring simultaneous treatments, but these CMFs represent a fraction of the over 8,000 CMFs presently listed in the CMF Clearinghouse (FHWA 2023a). The sheer number of available CMFs makes development of new CMFs to fit all possible treatment combinations an unreasonable task. To circumvent the lack of available empirical data, researchers have explored 11 methods for estimating the combined effects of multiple different treatments using CMFs applied to a single facility. These 11 analysis methods are described in greater detail in the following sections of this report and draw heavily from *NCHRP Report 991: Guidelines for the Development and Application of Crash Modification Factors* (Carter et al. 2022). Several methods, but not all, rely on some amount of professional judgment, and each method has known limitations.

In no particular order, 11 established methods for estimating the combined effect of multiple safety-related treatments for a single facility are as follows:

- Additive effects.
- Additive effects with systematic reduction of subsequent CMFs.
- Dominant effect.
- Multiplicative.
- Limited multiplicative.
- Multiplicative with generalized reduction of combined effort.
- Multiplicative with systematic reduction of subsequent CMFs.
- Multiplicative with empirical-based reduction of combined effect.
- Dominant common residuals.
- Dominant effect for overlapping crash types.
- Estimate the combined effect when interaction is unknown.

Method 1: Additive Effects

This approach assumes the impacts of all applied CMFs are entirely independent. One example where this assumption may be reasonable is a project that involves installing rumble strips along the outside edge line and median barrier along the left side of a multilane freeway segment. These two treatments will affect two different crash types on two different regions of the road segment. However, the overarching assumption within this method would not hold true if the installation of rumble strips is combined with a shoulder-widening project, as both treatments may reasonably affect similar crash subsets occurring on the same side of the freeway. The treatments and associated CMFs must be entirely independent of one another for this approach to be viable, otherwise the method may overestimate or underestimate the treatment effects.

Figure 102 shows the calculation of the CMF for the combined treatment using the additive effects method.

$$CMF_t = 1 - [(1 - CMF_1) + (1 - CMF_2) + \cdots + (1 - CMF_n)]$$

Figure 102. Equation. Additive effects method.

Where:

CMF_t = CMF for the combined treatments

CMF_1 = CMF for the most effective treatment

CMF_2 = CMF for the second most effective treatment

CMF_n = CMF for the n^{th} most effective treatment

A primary limitation with this approach lies within the methodology of the approach itself; as the number or magnitude of CMFs increases, the combined effect will mathematically exceed 100 percent. Thus, this approach may only be reasonable for capturing effects of a small number of entirely independent CMFs.

Method 2: Additive Effects with Systematic Reduction of Subsequent CMFs

This method is the same as the additive effects method detailed previously but reduces the effect of each subsequent treatment by fixed percent. Specifically, the second treatment is assumed to be half as effective (divided by 2), the third treatment is assumed to be one-third as effective (divided by 3), and so on. This method may underestimate or overestimate the combined effects of multiple treatments if the applied treatments are not entirely independent.

The primary limitation with this method, as with the additive effects method, again lies within the methodology of the approach itself. As the number or magnitude of CMFs increases, the combined effect will mathematically exceed 100 percent.

Figure 103 shows the computation for the additive effects with systematic reduction of subsequent CMFs. Variables are defined in the discussion of method 1.

$$CMF_t = 1 - \left[(1 - CMF_1) + \left(\frac{1 - CMF_2}{2}\right) + \cdots + \left(\frac{1 - CMF_n}{n}\right)\right]$$

Figure 103. Equation. Additive effects with systematic reduction.

This method was among the most commonly used methods within the transportation industry at the time of the NCHRP Report 991 research (circa 2016) (Carter et al. 2022).

Method 3: Dominant Effect

The dominant effect method selects only the most effective (i.e., the lowest) CMF across a group of treatments for use in the analysis. For example, if curve warning signs, rumble strips, and a high friction surface treatment were all considered for application to the same curve, the safety impacts of installing the high friction surface treatment would be expected to provide the greatest measurable safety benefit and would be the only effect captured. This method eliminates the key assumption of complete independence among CMFs that is inherent to the additive effects methods outlined previously.

This method's limitation is that the potential impacts of other treatments are disregarded despite a possible greater safety benefit from implementing more than one treatment simultaneously.

Method 4: Multiplicative

Similar to the additive method, the multiplicative method makes a key assumption that all CMFs are independent. The combined effects are captured by multiplying all applicable individual CMFs. However, if the key assumption of CMF independence does not hold true, the resulting CMF may underestimate or overestimate the treatment effects.

Chapter 3 of the HSM first edition recommends the multiplicative method for estimating impacts of multiple treatments (AASHTO 2010). The HSM acknowledges the potential issues associated with the assumption of independence among CMFs and further states that this is a reasonable assumption based on then-current industry knowledge.

Figure 104 shows the computation for the multiplicative method. Variables are defined above in the discussion for method 1.

$$CMF_t = CMF_1 * CMF_2 * \ldots * CMF_n$$

Figure 104. Equation. Multiplicative method.

The multiplicative method was the most common method used in the transportation industry at the time of the NCHRP Report 991 research (circa 2016) (Carter et al., 2022).

Method 5: Limited Multiplicative

This method is the same as the multiplicative approach, but the number of CMFs is limited to two or three per facility. This approach minimizes the potential for overlapping, compounding effects. As with the multiplicative method, this method may underestimate or overestimate the treatment effects if the primary assumption of independence does not hold true.

This method limits the number of CMFs applied to the project at hand. Analysts use their professional judgment to select the number of CMFs to apply to the project.

Method 6: Multiplicative with Generalized Reduction of Combined Effect

This method is similar to the multiplicative approach, with the primary difference being the built-in reduction factor. For example, if the research team chose a one-fourth reduction factor, the resulting effect would be one-fourth of the effect derived using the multiplicative method. Figure 105 shows the calculation for the generalized reduction using the one-fourth example. The variables are defined in the discussion for method #1.

$$CMF_t = 1 - \left[\frac{1}{4}\left(1 - (CMF_1 * CMF_2 * \ldots * CMF_n)\right)\right]$$

Figure 105. Equation. Multiplicative with generalized reduction.

The primary issue with this method is the limited empirical evidence supporting the selected generalized reduction factor. Any reduction factor, whether arbitrary or based on data relevant to the project at hand, will have inherent limitations for extrapolation beyond the research dataset. The generalized reduction factor may also vary depending on the number of treatments selected. This method requires further research to refine the specific reductions.

Method 7: Multiplicative with Systematic Reduction of Subsequent CMFs

This method is similar to the additive effects with systematic reduction of subsequent CMFs method but replaces the additive methodology with the multiplicative methodology. The effects of subsequent treatment are reduced by a systematic amount, starting with one-half, then one-third, and so on. Figure 106 shows the calculation for the systematic reduction. The variables are defined in the discussion for method #1.

$$CMF_t = CMF_1 * \left(\frac{1 - CMF_2}{2}\right) * \ldots * \left(\frac{1 - CMF_n}{n}\right)$$

Figure 106. Equation. Multiplicative with systematic reduction.

The primary limitation with this method is the lack of empirical, evidence-based reasoning behind the systematic reduction factors. This method requires further research to refine the specific reductions.

Method 8: Multiplicative with Empirical-based Reduction of Combined Effect

This method is equivalent to the multiplicative with generalized reduction of combined effect method, but the reduction factor is based on empirical research. Figure 107 through figure 109 represent this method using three alternative forms of the equation.

$$CMF_t = 1 - \left[\beta\left(1 - \prod_{i=1}^{n} CMF_i\right)\right]$$

Figure 107. Equation. Multiplicative with empirical-based reduction.

$$CMF_t = \beta_0 \prod_{i=1}^{n} CMF_i^{\beta_i}$$

Figure 108. Equation. Alternative form 1 of multiplicative with empirical-based reduction.

$$CMF_t = \beta_0 + \sum_{i=1}^{n} \beta_i * CMF_i$$

Figure 109. Equation. Alternative form 2 of multiplicative with empirical-based reduction.

Where:

β_0, β, and β_i are estimated parameters based on data relevant to the project at hand.

All other variables are defined in the discussion for method 1.

This method overcomes the primary limitation associated with methods 6 and 7 by basing the reduction factor on data relevant to the project at hand.

Method 9: Dominant Common Residuals

This approach is based on the multiplicative method. The difference is that the nonindependent CMFs (i.e., common residuals) are raised to the power of the most effective CMF. This logic is similar to that of the dominant effects methodology. Figure 110 shows the calculations for the dominant common residuals method. The variables are defined in the discussion for method 1. The equation assumes the variable CMF_1 is related to the most effective treatment (i.e., lowest CMF associated with the applied treatments).

$$CMF_t = (CMF_1 * CMF_2 * \ldots * CMF_n)^{CMF_1}$$

Figure 110. Equation. Dominant common residuals.

As with several other methods described previously, this method's primary limitation is the nature of assigning extra weight to the most effective treatment. That being said, this method is decisively more conservative than the more commonly used multiplicative method. A second issue with the dominant common residuals method is the mathematical limitations of such an approach. In cases where the combined CMFs are raised to a power greater than 1.0, the effects are accentuated, not minimized as intended. This method is therefore not applicable when selected CMFs have a value greater than 1.0, and the issue is even more apparent when the most effective CMF in the group of treatments is greater than 1.0.

Method 10: Dominant Effect for Overlapping Crash Types

Similar to the dominant effect method, this method includes only the most effective treatment (i.e., lowest CMF in a group of treatments) when the treatment effects are expected to overlap. This method removes a major limitation with the dominant effect method by capturing the safety impacts of multiple treatments for a single project. Analysts using this method must use their professional judgment to determine which CMFs to apply based on where the effects of treatments overlap and for which target crash group they apply to. Refer to NCHRP Report 991 for a detailed discussion of the dominant effect for overlapping crash types method with example applications (Carter et al. 2022).

NARROWING THE FOCUS

Of the 10 methods described in the previous section, the following five stand out as commonly implemented methods in the transportation industry (Massachusetts Department of Transportation 2021):

- Additive effects
- Dominant effect
- Multiplicative
- Limited multiplicative
- Dominant common residuals

The *Massachusetts Department of Transportation Safety Alternatives Analysis Guide* (MassDOT 2021) recommends four of the five listed methods. The limited multiplicative method is redundant for MassDOT, as the overarching premise of their methodology is limiting the number of CMFs applied to a single facility to a maximum of two. The guide provides a decision tree to simplify the choice between the additive effects, dominant effect, multiplicative, and dominant common residuals methods. Figure 111 provides a flowchart for reference.

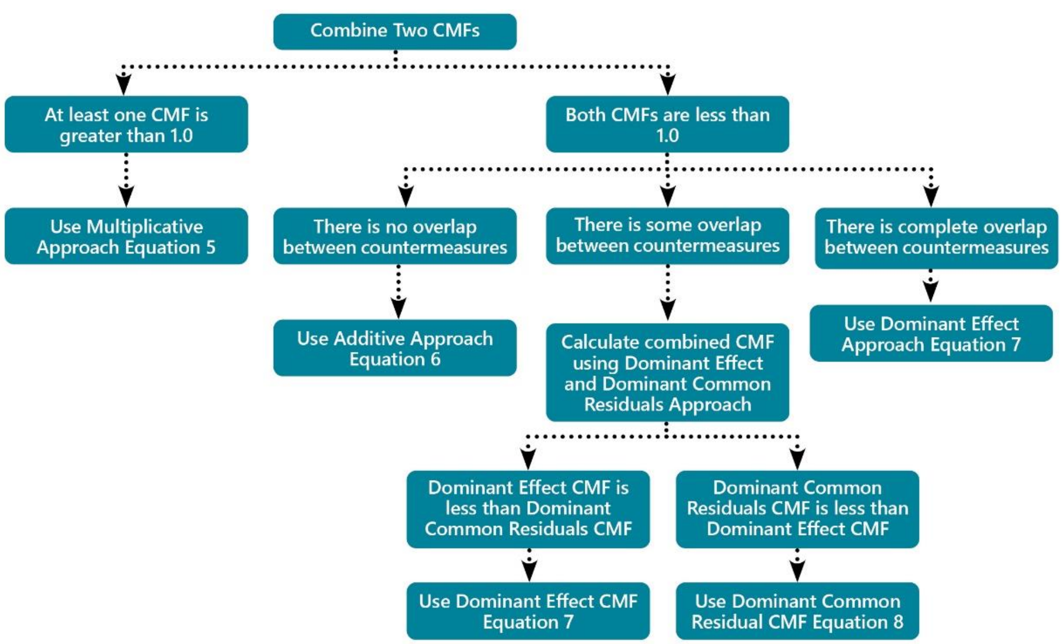


Figure 111. Graphic. Guide for selecting an evaluation method for application of two CMFs (MassDOT Safety 2021).

The decision points in figure 111 relate to CMF's magnitude (greater or less than 1.0), expected overlap in the treatment effects, and the results of the dominant common residuals and dominant effect methods. The dominant common residuals method follows method 9, the dominant effect method follows method 3, the multiplicative approach follows method 4, and the additive approach follows method 1 as described in the previous section of this report.

The decision tree in figure 111 helps to address limitations of individual methods for estimating effects of multiple treatments. This combination of methods allows agencies flexibility in the selected method based on relatively simple binary questions. While professional judgment is still required to determine if overlap among treatment effects exists, the decision tree helps to minimize the potential for exaggerated effects.

APPENDIX C. CASE STUDY DETAILS

INTRODUCTION

This appendix describes the five Complete Streets project case studies used to develop the recommendations and analysis guidelines in the primer. The remainder of this introduction section includes a brief overview of the selection process for the five case studies and an explanation of the analysis techniques. The sections that follow provide detailed descriptions of each case study project, the data collection process, the analysis considerations, and analysis results.

CASE STUDY SELECTION PROCESS

The project team gathered information on 85 unique Complete Streets projects from across the US, including location, area type, geometric and facility type descriptors, treatments applied, and year of construction. The team used this information to screen the full list of Complete Streets projects and select the five case studies. The selection criteria focused on projects with the following characteristics:

- Had at least three years of crash, traffic, and road data available before and after construction.
- Focused on improving pedestrian and/or bicyclist safety and connectivity.
- Had been constructed with two or more safety treatments for an individual site or project area.
- The project team also considered the following characteristics in selecting desirable case studies:
- Had been objectively evaluated and had shown a reduction in pedestrian and/or bicyclist crash frequency and/or severity after conversion.
- Had been found to have no or minimal negative impact on traffic operations after construction (e.g., did not increase or migrate congestion).

The project team was generally not able to objectively confirm these two criteria based on readily available project documentation and data. Agencies rarely circle back and conduct reliable before-after safety and operational performance evaluations of individual projects. The project team therefore searched for projects characterized as success stories with respect to meeting the project needs, based on the research team's knowledge of the projects combined with available project documentation.

Finally, since these projects served as a basis for testing methods of combining CMFs, the research team specified that the projects included treatments with known CMFs.

Based on these criteria, the research team selected the following projects as case studies:

- First Hill Streetcar, Seattle, WA.
- Greenough Boulevard, Cambridge, MA.
- Bench Boulevard, Billings, MT.
- Fletcher Avenue, Hillsborough County, FL.
- Highways 28, 29, and 104, Glenwood, MN.

CASE STUDY DATA COLLECTION OVERVIEW

For each of the case studies, the project team collected project information and data to perform both predictive and evaluative safety-performance analyses. This collected project information and data included project descriptions, locations, construction dates, before and after crash and traffic volume data, implemented safety treatments, and other roadway information. The project team divided each project into segments and intersections based on the segmentation process in the HSM Part C and assigned crash, traffic volume, geometric, and treatment data to the relevant segments and intersections. Table 15 and table 16 provide definitions for the intersection and segment types. Table 17 provides the definitions for the crash types and severity levels.

Table 15. Intersection type definitions.

Intersection Type	Definition
3ST	Unsignalized three-leg intersection (stop control on minor-road approaches)
3SG	Signalized three-leg intersection
4ST	Unsignalized four-leg intersection (stop control on minor-road approaches)
4SG	Signalized four-leg intersection
5SG	Signalized five-leg intersection
3AWST	Unsignalized three-leg intersection (stop control on all approaches)

Table 16. Segment type definitions.

Segment Type	Definition
2U	Two-lane undivided
2D	Two-lane divided
3T	Three-lane including a center TWLTL
3U	Three-lane undivided
3D	Three-lane divided
4U	Four-lane undivided
4D	Four-lane divided
4T	Four-lane including a center TWLTL
5T	Five-lane including center TWLTL

Table 17. Crash types and severity level definitions.

Crash Type and Severity	Definition	Crash Types Included
SV-KABC	SV fatal, suspected serious injury, suspected minor injury, or possible injury crashes	Collision with animal, overturned, ran off road, other SV crash
SV-O	SV no apparent injury or property damage only crashes	Collision with animal, overturned, ran off road, other SV crash
MV-KABC	MV fatal, suspected serious injury, suspected minor injury, or possible injury crashes	Angle collision, head-on collision, rear-end collision, sideswipe collision, other MV collision
MV-O	MV no apparent injury or property damage only crashes	Angle collision, head-on collision, rear-end collision, sideswipe collision, other MV collision
Ped-all	All pedestrian crashes	Collision with pedestrian
Bike-all	All bicycle crashes	Collision with bicycle

Crash Data Period Adjustments

As described in the specific case study sections, in two cases (Fletcher Avenue and Highways 28, 29, and 104), the research team was unable to obtain crash data for before and after periods of equal length. In these two cases, the period with fewer years of data available was adjusted up to provide an even comparison between before and after periods in terms of overall crash counts.

Volume Data Gaps and Assumptions

The project team worked to obtain as much volume data for the project corridors and cross-streets as possible. However, some gaps in the data remained following the data collection exercise. These gaps fell into one of three types:

1. Missing data for some but not all of the years in either the before or after period for one or more sites.
2. Missing data for all of either the before or after period for one or more sites.
3. Missing data for all of both the before and after period for one or more sites.

For missing data of type 1, the project team followed the recommendation in the chapter 4 primer and followed the interpolation procedure laid out in the HSM (AASHTO 2010). If the year with missing data for the location in question has years on either side with available data (i.e., before or after the missing year), the missing data is filled in using linear interpolation. If a period has data only for one year, that data is used to fill in the missing data for the other years. This technique is illustrated with the two site examples in table 18, where the interpolated data is shown in italics. For site 1, volume data was available for year 1 and year 3 but not year 2. The team used linear interpolation to fill in the missing data for year 2. For site 2, volume data was available for year 2 only, so that same value was used to fill in the missing data for year 1 and year 3.

Table 18. Example of Type 1 missing data interpolation.

Site ID	Year 1 ADT	Year 2 ADT	Year 3 ADT
Site 1	5,000	*6,000*	7,000
Site 2	*2,000*	2,000	*2,000*

Note: Italic text indicates interpolation was used to fill gaps.

For missing data of type 2, the project team used data from the period with available data to develop estimated data values for the period with missing data. The exact technique depended on whether the missing data was along the project corridor or the cross-streets. If the missing data was at sites from along the project corridor, then the research team estimated a volume using a proportion factor. The proportion factor was based on the volume data from the other period at that site and both the before and after volume data at a nearby site with available data in both periods and with similar characteristics. If the missing data was from the cross-street, the research team calculated a similar proportion that was based on the ratio of project corridor volume to cross-street volume.

For missing data of type 3, the project team used either an average of the volumes at several similar sites or the values from one chosen similar site.

In the volume data tables for each case study, the data gaps are indicated with italic text (for type 1 missing data) and bold text (for type 2 and type 3 missing data).

CMF SELECTION AND CONVERSION

The project team reviewed project documentation and other resources in detail to understand the treatments applied as part of each project (described in detail in the case study descriptions). CMFs for each treatment were selected on a case-by-case basis through detailed review of the CMF Clearinghouse and the specific characteristics of the treatment implementation (FHWA 2023a). In some cases, an applicable CMF was not available for a given treatment. Note that treatments for which the research team found no applicable CMF may have available CMFs, but the available CMFs were not applicable due to the project's specific conditions or characteristics.

If a selected CMF applied to a specific crash type or severity, the team used crash type and/or severity proportions from the HSM (AASHTO 2010) to convert the CMF to a total crash CMF.

ANALYSIS METHODS

The project team tested the two general applications of DDSA described in the chapter 4 primer for the five case studies:

- Predictive analysis.
- Safety effectiveness evaluation.

The predictive analysis estimates the safety performance of an unbuilt Complete Streets project, while the safety effectiveness evaluation determines the observed safety effects of a constructed Complete Streets project. Within each of these approaches, several different ways of conducting the analyses are possible. These variations are based on whether the analysis uses expected crashes, predicted crashes, and observed crashes and whether and how the analysis adjusts for changes in road-user volumes. The following sections detail the specific computations used for these case studies. In the case of all analysis methods, computation occurs at the individual segment or intersection level and is aggregated to the overall project level. Table 19 provides a summary of the analysis methods. The analyses used SPF AADT parameters as discussed in chapter 4 (AASHTO 2010). The project team used the coefficients found in the HSM (AASHTO 2010). Refer to chapter 4 of the report for more thorough discussion of the segmentation and analysis approaches.

Table 19. Summary of analysis methods.

Analysis Type	Analysis Method	Description
Predictive analysis	P1	Assumes no volume change from current period to future period
	P2	Projects future period volume by extrapolating the year-to-year trend from the current period
Safety effectiveness evaluation	E1	Assumes no volume change from before period to after period
	E2	Projects after-period volume by extrapolating the year-to-year trend from the before period
	E3	Uses observed after period volume

Predictive Analysis

The predictive analysis approach estimates the expected safety performance of the future no-build condition and then applies an appropriate CMF. As chapter 4 notes, the safety performance of the future no-build condition can be estimated using expected crashes, predicted crashes, or observed crashes. Due to limitations in both the data, available SPFs, and available CMFs (discussed more in the Conclusions and Recommendations section), the case study analyses used observed total crashes (total—all types and severities). The project team sought to mitigate some of the disadvantages of using observed crashes by using at least 5 yr of before crash data when these data were available. This approach corresponds to predictive analysis method 3 in the chapter 4 primer. However, the project team tried two variations: assuming no volume change from current to future no-build conditions (P1) and, projecting the current-period volume to the future period by continuing the year-to-year trends from the current period (P2).

The CMF applied to the observed crashes represented the effect of a combination of several individual treatments, each with individual CMFs.

The key variables used to describe the predictive analysis for the case studies are the following:

- $Observed\ Crashes_{current,WITHOUT}$: observed crashes in the current period (all crash types and severities).
- $AADT_{current,WITHOUT}$: observed traffic volume in the current period.

- $AADT_{future,WITHOUT}$: predicted future period AADT for the no-build condition, determined in the case studies by extrapolating the linear trend of the before-period ADT to the after period.
- *CMF*: CMF for combined treatment(s) as applicable to the individual segment or intersection.

Methods to Determine CMF for Treatment Combinations

The project team explored five methods for determining CMFs for treatment combinations because these methods were the most objective, repeatable, and commonly used. These methods are described in Appendix B. The project team expanded this list of five methods by introducing several variations for testing, which generated 15 variations. The methods and method variations tested were the following:

- CMF Method 1: Additive effects.
- Method 1a: Using all CMFs, including CMFs greater than one.
- Method 1b: Using the two most effective CMFs, including CMFs greater than one.
- Method 1c: Using the three most effective CMFs, including CMFs greater than one.
- Method 1d: Using all CMFs, excluding CMFs greater than one.
- Method 1e: Using the two most effective CMFs, excluding CMFs greater than one.
- Method 1f: Using the three most effective CMFs, excluding CMFs greater than one.
- CMF Method 3: Dominant effect.
- Method 3a: Including CMFs greater than one.
- Method 3b: Excluding CMFs greater than one.
- CMF Method 4: Multiplicative: Using all CMFs, including CMFs greater than one.
- CMF Method 5: Limited multiplicative.
- Method 5a: Using the two most effective CMFs.
- Method 5b: Using the three most effective CMFs.
- CMF Method 9: Dominant common residuals.
- Method 9a: Using the two most effective CMFs, including CMFs greater than one.
- Method 9b: Using the three most effective CMFs, including CMFs greater than one.
- Method 9c: Using the two most effective CMFs, excluding CMFs greater than one.
- Method 9d: Using the three most effective CMFs, excluding CMFs greater than one.

Prior to applying these methods for determining CMFs for treatment combinations, the project team converted all individual CMFs applicable to only specific crash types to total crash CMFs using crash-type proportions from the HSM for the closest applicable facility and site type (AASHTO 2010).

Table 20 provides a summary comparing the results of the predictive analysis with those of the safety effectiveness evaluation. The two metrics reported in the table are average percent difference and cumulative percent difference. Average percent difference is the average of the difference in percent crash reduction between the predictive analysis and the safety effectiveness evaluation across the five case studies. Cumulative percent difference is the sum of the difference in percent crash reduction between the predictive analysis and the safety effectiveness evaluation across the five case studies. Based on review of the analysis results for all 15 of these method variations, the project team narrowed the options to method 3a, method 4, and method 9b to report in the case study analysis results. The project team reports method 4 for comparative purposes as it represents the multiplicative approach common to Part C of the HSM (AASHTO 2010). Methods 3a and 9b provided consistent and accurate predictive analysis results when compared to the safety-evaluation results. Note that in the five case studies, all segments and intersections featured treatments with the most effective CMF being less than or equal to one.

Table 20. Comparison of predictive analysis results and safety effectiveness evaluation results for different CMF combination methods across the five case studies.

Method	P1–E1		P2–E2	
	Average Difference	Cumulative Difference	Average Difference	Cumulative Difference
1a	11%	53%	13%	64%
1b	14%	71%	16%	81%
1c	14%	71%	16%	81%
1d	16%	80%	18%	90%
1e	14%	71%	16%	81%
1f	16%	79%	18%	89%
3a	6%	32%	9%	43%
3b	6%	32%	9%	43%
4	9%	45%	11%	55%
5a	11%	57%	13%	67%
5b	11%	57%	13%	67%
9a	1%	5%	3%	15%
9b	1%	5%	3%	15%
9c	1%	5%	3%	15%
9d	2%	9%	4%	19%

Safety Effectiveness Evaluation

The safety effectiveness evaluation computes the observed change in safety performance of a constructed Complete Streets project. The key variables that describe the predictive analysis for the case studies are the following:

- $Observed\ Crashes_{before,WITHOUT}$: observed crashes in the before period (all crash types and severities).
- $Observed\ Crashes_{after,WITH}$: observed crashes in the after period.
- $AADT_{before,WITHOUT}$: observed traffic volume in the before period.
- $AADT_{after,WITHOUT}$: predicted after-period AADT for the no-build condition, determined by extrapolating the linear trend of the before-period ADT to the after-period.
- $AADT_{after,WITH}$: observed after-period AADT, accounting for the effect of the Complete Streets project on traffic volume.

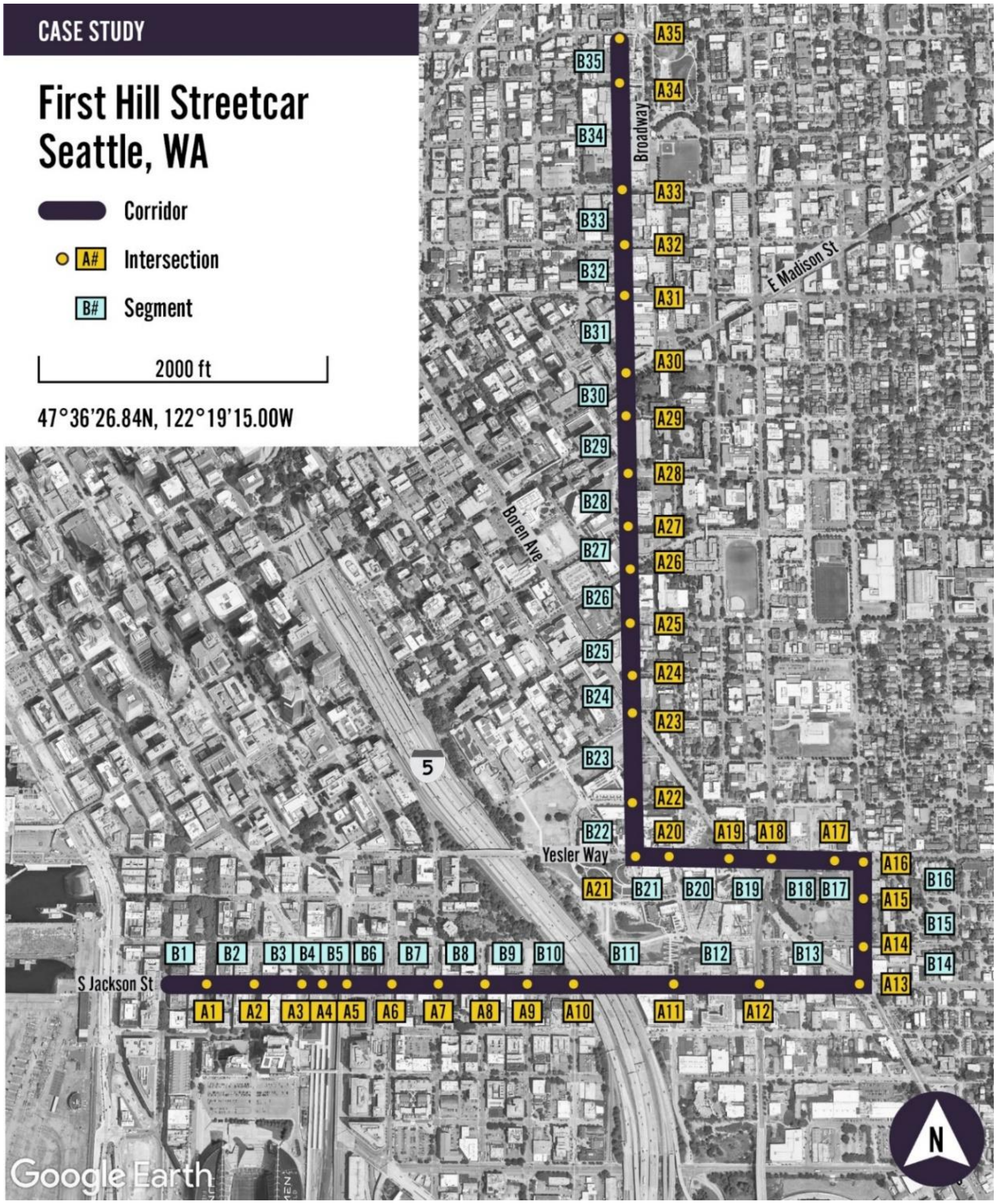
The project team applied safety effectiveness evaluation method 2 (observed crashes with traffic volume adjustment) and method 3 (observed crashes without traffic volume adjustment) as described in the chapter 4 primer. The case study documentation refers to these as E1 and E2, respectively.

CASE STUDY DESCRIPTIONS

The following sections discuss the data collection process, present the resulting data, and provide the analysis results for each case study project.

First Hill Streetcar Project, Seattle

The First Hill Streetcar project developed a streetcar line to link the Capitol Hill and International District neighborhoods in Seattle (see figure 112), an urbanized area. The project was funded as part of the Sound Transit 2 (ST2) mass transit expansion plan for the Puget Sound region. Roadway construction was completed in 2014 but the official streetcar operations were delayed until January 2016 due to supplier issues for the streetcars themselves. Design and construction of the First Hill Streetcar project included a Complete Streets approach along much of its 2.6-mi route: a two-way cycle track was built along most of the Broadway route, East Yesler Way was reduced from four lanes to two lanes, and southbound vehicle movements were disallowed on 14th Avenue South between East Yesler Way and South Jackson Street. Three median streetcar stops were built along Jackson Street, with one stop including a midblock crossing with a pedestrian-actuated traffic signal.



© 2011 Google. Modified by authors to highlight the First Hill Streetcar corridor, intersections, and segments.

Figure 112. Graphic. First Hill Streetcar project location.

Before the First Hill Streetcar project, Broadway's cross-section was generally either four-lane undivided or two-lane with a TWLTL. South Jackson Street was generally a four-lane undivided roadway with on-street parking on one side; some portions also had a TWLTL. Figure 113 through figure 116 show typical views of the project corridor before and after construction.

© 2011 Google Street View.

Figure 113. Photograph. Cross-section of Broadway north of East Pine Street pre-construction in 2011 (Google Maps 2011a).

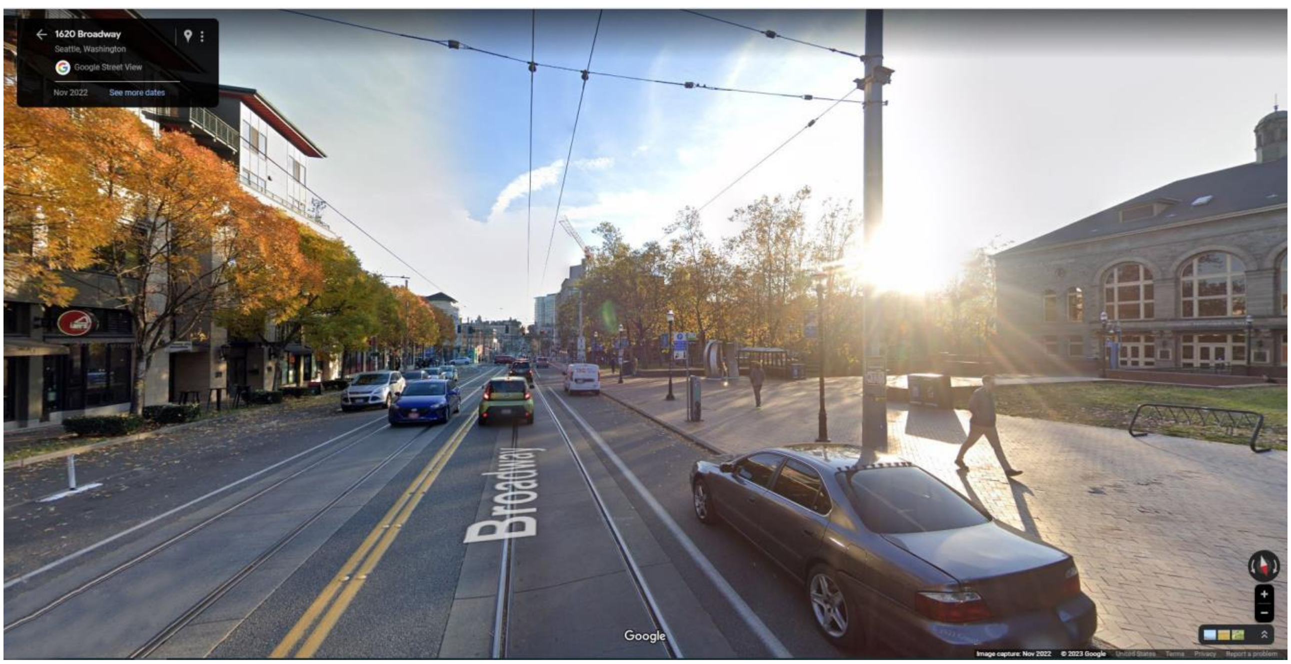


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Figure 114. Photograph. Cross-section of Broadway north of East Pine Street post-construction in 2014 (Google Maps 2022a).

Figure 115. Photograph. Cross-section of South Jackson Street west of 12th Avenue South pre-construction in 2011 (Google Maps 2011b, modified by FHWA).

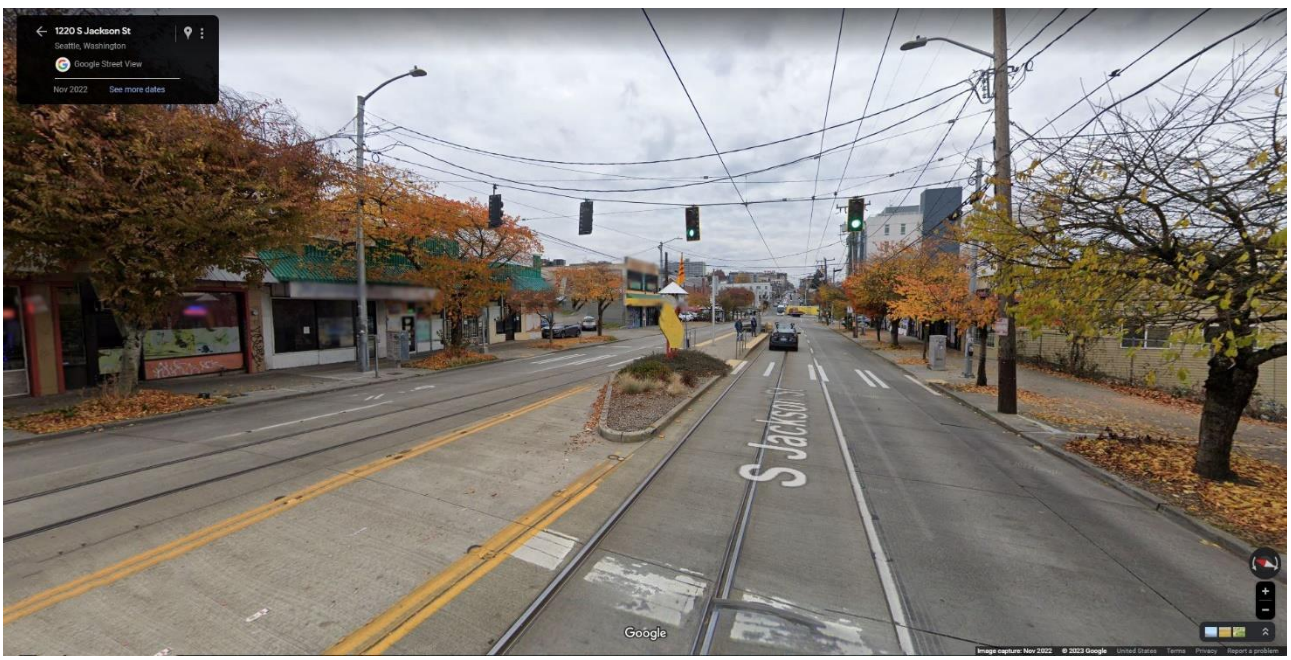


Figure 116. Photograph. Cross-section of South Jackson Street west of 12th Avenue South post-construction in 2014 (Google Maps 2022b).

The research team segmented the First Hill Streetcar project corridor and collected data for each segment and intersection. Table 21 and table 22 summarize the intersections and segments along the project.

Table 21. Summary of intersections along First Hill Streetcar project.

Intersection ID	Intersecting Road Names	Intersection Type	
		Before Construction	After Construction
A1	S Jackson St & Occidental Ave S	3SG	3SG
A2	S Jackson St & 2nd Ave S	4SG	4SG
A3	S Jackson St & 3rd Ave S	3SG	3SG
A4	S Jackson St & 2nd Ave Ext S	4SG	4SG
A5	S Jackson St & 4th Ave S	4SG	4SG
A6	S Jackson St & 5th Ave S	4SG	4SG
A7	S Jackson St & 6th Ave S	4SG	4SG
A8	S Jackson St & Maynard Ave S	4SG	4SG
A9	S Jackson St & 7th Ave S	4SG	4SG
A10	S Jackson St & 8th Ave S	3SG	3SG
A11	S Jackson St & 10th Ave S	4ST	4ST
A12	S Jackson St & 12th Ave S	4SG	4SG
A13	S Jackson St & Rainier Ave S / 14th Ave S	5SG	5SG
A14	14th Ave S & South Main St	4ST	4ST
A15	14th Ave S & S Washington St	3ST	3AWST*
A16	E Yesler Way & 14th Ave S	4SG	4SG
A17	E Yesler Way & 13th Ave	3ST	3ST
A18	E Yesler Way & 12th Ave S	4SG	4SG
A19	E Yesler Way & Boren Ave	4SG	4SG
A20	E Yesler Way & 10th Ave	4ST	4ST
A21	E Yesler Way & Broadway	3SG	3SG
A22	Broadway & E Fir St	3ST	3ST
A23	Broadway & Boren Ave	4SG	4SG
A24	Broadway & E Terrace St	3ST	3SG*
A25	Broadway & E Jefferson St / Minor Ave	4SG	4SG
A26	Broadway & E James Way / James St	4SG	4SG
A27	Broadway & Cherry St	4SG	4SG
A28	Broadway & E Columbia St	4SG	4SG
A29	Broadway & Marion St	3ST	3ST
A30	Broadway & Madison St / Harvard Ave	4SG	4SG
A31	Broadway & E Union St	4SG	4SG
A32	Broadway & E Pike St	4SG	4SG
A33	Broadway & E Pine St	4SG	4SG
A34	Broadway & E Howell St	3ST	3SG*
A35	Broadway & E Denny Way	4SG	4SG

Note: * indicates a change in intersection type between the before and after construction periods.

Table 22. Summary of segments along First Hill Streetcar corridor.

Segment ID	Road Name	Segment Limits	Segment Length (mi)	Roadway Type	
				Before Construction	After Construction
B1	S Jackson St	from Nord Alley to Occidental Ave S	0.06	2U	2D*
B2	S Jackson St	from Occidental Ave S to 2nd Ave S	0.06	2U	4T*
B3	S Jackson St	from 2nd Ave S to 3rd Ave S	0.06	4U	4U
B4	S Jackson St	from 3rd Ave S to 2nd Ave Ext S	0.03	4U	4U
B5	S Jackson St	from 2nd Ave Ext S to 4th Ave S	0.03	4U	4U
B6	S Jackson St	from 4th Ave S to 5th Ave S	0.06	4U	4U
B7	S Jackson St	from 5th Ave S to 6th Ave S	0.06	4U	4D*
B8	S Jackson St	from 6th Ave S to Maynard Ave S	0.06	4U	4U
B9	S Jackson St	from Maynard Ave S to 7th Ave S	0.06	4U	4U
B10	S Jackson St	from 7th Ave S to 8th Ave S	0.06	4U	4D*
B11	S Jackson St	from 8th Ave S to 10th Ave S	0.13	5T	5T
B12	S Jackson St	from 10th Ave S to 12th Ave S	0.11	5T	5T
B13	S Jackson St	from 12th Ave S to 14th Ave S / Rainier Ave S	0.15	4U	4D*
B14	14th Ave S	from S Jackson St to S Main St	0.06	2U	2U
B15	14th Ave S	from S Main St to S Washington St	0.06	2U	2U
B16	14th Ave S	from S Washington St to E Yesler Way	0.06	2U	2U
B17	E Yesler Wy	from 14th Ave S to 13th Ave S	0.04	2U	2U
B18	E Yesler Wy	from 13th Ave S to 12th Ave S	0.09	2U	2U
B19	E Yesler Wy	from 12th Ave S to Boren Ave	0.05	4U	2U*
B20	E Yesler Wy	from Boren Ave to 10th Ave	0.08	4U	2U*

Segment ID	Road Name	Segment Limits	Segment Length (mi)	Roadway Type	
				Before Construction	After Construction
B21	E Yesler Wy	from 10th Ave to Broadway	0.05	2U	2U
B22	Broadway	from E Yesler Way to E Fir St	0.07	2U	2U
B23	Broadway	from E Fir St to Boren Ave	0.13	2U	2U
B24	Broadway	from Boren Ave to E Terrace St	0.05	3T	3T
B25	Broadway	from E Terrace St to E Jefferson St / Minor Ave	0.07	3T	2D*
B26	Broadway	from E Jefferson St to E James Way / James St	0.07	3T	2D*
B27	Broadway	from E James Way / James St to E Cherry St	0.06	3T	2D*
B28	Broadway	from E Cherry St to E Columbia St	0.08	3T	3T
B29	Broadway	from E Columbia St to Marion St	0.08	4U	3T*
B30	Broadway	from Marion St to E Madison St / Harvard Ave	0.07	4U	2D*
B31	Broadway	from E Madison St / Harvard Ave to E Union St	0.13	4U	2D*
B32	Broadway	from E Union St to E Pike St	0.08	4U	3T*
B33	Broadway	from E Pike St to E Pine St	0.08	4U	2U*
B34	Broadway	from E Pine St to E Howell St	0.16	3T	2U*
B35	Broadway	from E Howell St to E Denny Way	0.08	3T	2U*
-	-	**Total Length**	**2.63**	–	–

Note: * indicates a change in roadway type between the before and after construction periods;– = not applicable.

Crash Data

The research team obtained crash data from the City of Seattle Open Data Portal (SDOT 2023). Table 23 summarizes the crash data by intersection or segment and disaggregates crash counts by crash type: SV, MV, pedestrian, and bicyclist. The table also distinguishes between KABC and non-injury crashes (O) for the single- and multiple-vehicle crash types. In total, 816 crashes occurred in the before period and 694 crashes occurred in the after period.

Table 23. Before and after crash data by segment or intersection for the First Hill Streetcar project.

Location ID	Before Construction Crashes (2007–2011)							After Construction Crashes (2014–2018)						
	SV-KABC	SV-O	MV-KABC	MV-O	Ped-all	Bike-all	Total	SV-KABC	SV-O	MV-KABC	MV-O	Ped-all	Bike-all	Total
A1	0	4	0	0	0	0	**4**	0	1	0	0	0	0	**1**
A2	0	0	2	8	2	1	**13**	0	0	2	4	3	2	**11**
A3	0	0	0	1	0	0	**1**	0	0	0	0	0	1	**1**
A4	0	0	4	11	2	1	**18**	0	0	0	11	3	1	**15**
A5	0	0	8	17	2	0	**27**	0	1	15	17	3	1	**37**
A6	0	0	1	5	9	0	**15**	2	1	4	6	8	1	**22**
A7	0	0	3	8	1	2	**14**	0	0	3	3	5	2	**13**
A8	0	0	2	3	2	0	**7**	0	1	1	1	0	0	**3**
A9	1	0	1	2	1	1	**6**	0	0	2	4	2	1	**9**
A10	0	1	2	4	3	0	**10**	0	0	0	2	1	2	**5**
A11	0	0	0	3	2	1	**6**	0	0	4	4	5	1	**14**
A12	0	0	5	14	3	2	**24**	0	0	5	12	6	1	**24**
A13	0	0	6	20	1	2	**29**	0	1	6	14	2	2	**25**
A14	0	0	0	0	0	0	**0**	0	0	0	1	0	0	**1**
A15	0	0	0	0	3	0	**3**	0	0	0	2	0	0	**2**
A16	0	0	3	4	0	2	**9**	0	0	5	2	3	0	**10**
A17	0	0	0	0	0	0	**0**	0	0	1	0	0	1	**2**
A18	0	2	10	16	1	3	**32**	0	0	14	16	1	6	**37**
A19	1	1	3	10	2	1	**18**	0	1	6	7	3	0	**17**
A20	0	0	1	1	0	0	**2**	0	0	0	1	1	0	**2**
A21	0	0	2	4	1	0	**7**	0	0	0	0	0	0	**0**
A22	0	0	1	0	0	0	**1**	0	0	0	1	0	0	**1**
A23	0	0	3	8	0	0	**11**	0	0	4	1	0	0	**5**
A24	0	0	0	4	0	1	**5**	0	0	1	0	0	1	**2**
A25	0	0	4	4	1	0	**9**	0	1	0	3	1	2	**7**
A26	0	0	8	7	4	0	**19**	0	0	4	3	1	0	**8**
A27	0	0	1	0	1	0	**2**	0	0	0	0	1	0	**1**
A28	1	0	2	0	1	0	**4**	0	0	1	2	0	1	**4**

Location ID	Before Construction Crashes (2007–2011)							After Construction Crashes (2014–2018)						
	SV-KABC	SV-O	MV-KABC	MV-O	Ped-all	Bike-all	Total	SV-KABC	SV-O	MV-KABC	MV-O	Ped-all	Bike-all	Total
A29	0	0	0	3	0	0	**3**	0	0	0	0	1	0	**1**
A30	1	0	7	10	4	2	**24**	0	1	10	14	3	0	**28**
A31	0	1	2	7	2	2	**14**	0	0	0	6	2	6	**14**
A32	0	0	5	13	4	2	**24**	1	0	1	17	7	1	**27**
A33	0	0	3	10	2	0	**15**	0	2	2	7	6	0	**17**
A34	0	0	0	1	2	2	**5**	1	0	0	0	0	1	**2**
A35	0	0	2	12	5	4	**23**	0	0	3	3	2	0	**8**
B1	0	0	0	4	0	1	**5**	1	2	1	2	0	0	**6**
B2	0	0	3	9	0	0	**12**	0	2	1	2	0	0	**5**
B3	0	0	0	5	0	1	**6**	0	1	0	5	0	2	**8**
B4	1	0	1	1	1	0	**4**	0	0	2	2	0	0	**4**
B5	0	0	2	1	0	1	**4**	0	0	1	4	0	0	**5**
B6	0	0	0	13	2	1	**16**	0	0	1	8	0	2	**11**
B7	1	0	3	12	0	0	**16**	1	1	1	4	0	0	**7**
B8	0	0	3	5	1	1	**10**	0	0	1	4	0	0	**5**
B9	0	0	0	7	0	0	**7**	0	0	2	3	0	2	**7**
B10	0	0	3	3	0	3	**9**	0	0	2	3	0	0	**5**
B11	0	0	6	9	1	0	**16**	1	2	1	11	1	0	**16**
B12	1	0	7	16	4	2	**30**	1	0	5	12	1	1	**20**
B13	1	1	8	20	0	1	**31**	0	1	1	20	3	2	**27**
B14	0	0	1	4	0	0	**5**	0	1	1	2	0	1	**5**
B15	0	0	0	1	0	0	**1**	0	0	1	0	0	0	**1**
B16	0	0	1	1	0	0	**2**	0	0	2	1	0	0	**3**
B17	0	0	0	3	0	0	**3**	0	0	0	5	0	1	**6**
B18	0	0	2	5	1	0	**8**	0	0	4	5	0	0	**9**
B19	0	0	2	2	0	0	**4**	0	0	3	0	0	1	**4**
B20	1	3	0	4	0	0	**8**	1	0	1	6	0	0	**8**
B21	0	0	2	1	0	0	**3**	0	0	0	3	0	0	**3**
B22	0	1	0	4	0	0	**5**	0	0	0	3	0	0	**3**

Location ID	Before Construction Crashes (2007–2011)							After Construction Crashes (2014–2018)						
	SV-KABC	SV-O	MV-KABC	MV-O	Ped-all	Bike-all	Total	SV-KABC	SV-O	MV-KABC	MV-O	Ped-all	Bike-all	Total
B23	0	0	0	3	1	0	**4**	0	0	2	2	0	0	**4**
B24	0	1	1	4	0	0	**6**	0	0	1	6	0	0	**7**
B25	0	0	3	5	0	1	**9**	0	0	0	4	0	0	**4**
B26	0	1	3	14	0	0	**18**	0	0	0	5	0	0	**5**
B27	0	0	3	13	0	0	**16**	0	0	2	6	0	0	**8**
B28	0	0	3	7	0	0	**10**	0	0	1	4	0	0	**5**
B29	0	0	0	4	0	0	**4**	0	0	1	3	0	1	**5**
B30	0	0	1	4	0	1	**6**	0	0	1	3	0	1	**5**
B31	0	1	8	21	0	0	**30**	0	1	4	7	0	2	**14**
B32	0	0	4	27	1	0	**32**	0	0	3	21	2	2	**28**
B33	0	0	3	24	0	1	**28**	1	3	3	17	1	3	**28**
B34	1	1	6	24	0	2	**34**	1	1	7	14	1	4	**28**
B35	1	0	1	7	0	1	**10**	0	1	3	4	0	1	**9**
Total	**11**	**18**	**171**	**497**	**73**	**46**	**816**	**11**	**26**	**153**	**365**	**79**	**60**	**694**

Volume Data

The research team obtained AADT data from traffic count maps available in the Seattle DOT (SDOT) Open Data Portal (SDOT 2023). Figure 117 shows the segments for which SDOT had AADT estimates, and table 25 summarizes the traffic data for the intersections and segments along the corridor. Note that SDOT estimates annual average weekday traffic (AAWDT) as opposed to AADT. However, for the purpose of this analysis, the research team elected to use this data because it covers most of the corridor and will still allow for the relative comparison between the before and after periods.

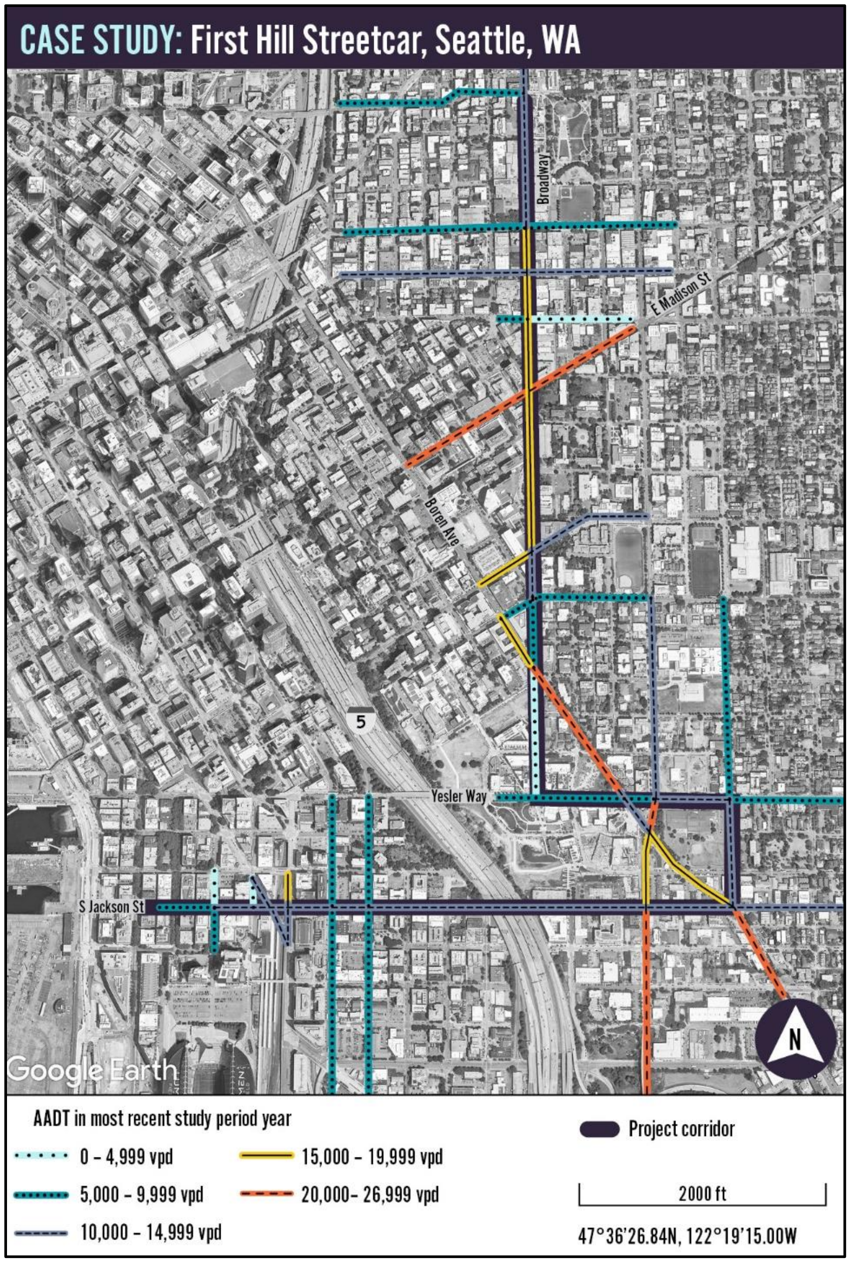


Figure 117. Graphic. Location of AADT segments in the First Hill Streetcar project area.

Table 24. AADT for intersections along First Hill Streetcar corridor.

Int. ID	Before Construction Study Corridor AADT/Intersecting Road AADT (veh/day)					After Construction Study Corridor AADT/Intersecting Road AADT (veh/day)				
	2007	2008	2009	2010	2011	2014	2015	2016	2017	2018
A1	14,600 / **1,223**	13,900 / **1,164**	14,100 / **1,180**	13,600 / **1,139**	12,800 / **1,072**	13,700 / **1,000**	6,600 / **1,000**	6,600 / **1,000**	6,600 / **1,000**	6,600 / **1,000**
A2	14,600 / **7,390**	13,900 / **7,035**	14,100 / **7,137**	13,600 / **6,883**	12,800 / **6,479**	13,700 / *4,950*	8,800 / 4,950	8,800 / 4,950	8,800 / 4,950	8,800 / 4,950
A3	14,600 / **1,223**	13,900 / **1,164**	14,100 / **1,180**	13,600 / **1,139**	12,800 / **1,072**	13,700 / *1,000*	11,500 / 1,000	11,500 / 1,000	11,500 / 1,000	11,500 / 1,000
A4	14,600 / 16,100	13,900 / 15,200	14,100 / 14,800	13,600 / 15,100	12,800 / 15,000	13,700 / 15,400	11,000 / 12,000	11,000 / 12,000	11,000 / 12,000	11,000 / 12,000
A5	14,600 / 26,400	13,900 / 24,000	14,100 / 25,800	13,600 / 21,600	12,800 / 26,600	13,700 / 27,000	12,000 / 15,000	12,000 / 15,000	12,000 / 15,000	12,000 / 15,000
A6	14,600 / **7,834**	13,900 / **7,458**	14,100 / **7,565**	13,600 / **7,297**	12,800 / **6,868**	13,700 / *6,900*	12,650 / 6,900	12,650 / 6,900	12,650 / 6,900	12,650 / 6,900
A7	14,600 / **7,266**	13,900 / **6,918**	14,100 / **7,018**	13,600 / **7,018**	12,800 / **6,769**	13,700 / *6,500*	12,900 / 6,500	12,900 / 6,500	12,900 / 6,500	12,900 / 6,500
A8	14,600 / **5,770**	13,900 / **5,493**	14,100 / **5,572**	13,600 / **5,374**	12,800 / **5,058**	13,700 / *5,000*	14,500 / 5,000	14,500 / 5,000	14,500 / 6,667	14,500 / 6,667
A9	14,600 / **7,181**	13,900 / **6,836**	14,100 / **6,935**	13,600 / **6,689**	12,800 / **6,295**	13,700 / *6,500*	14,500 / 6,500	14,500 / 6,500	14,500 / 7,882	14,500 / 7,882
A10	14,600 / **6,475**	13,900 / **6,165**	14,100 / **6,253**	13,600 / **6,032**	12,800 / **5,677**	13,700 / **5,750**	14,500 / **5,750**	14,500 / **5,750**	14,500 / **7,275**	14,500 / **7,275**
A11	14,600 / **6,475**	13,900 / **6,165**	14,100 / **6,253**	13,600 / **6,032**	12,800 / **5,677**	13,700 / **5,750**	14,500 / **5,750**	14,500 / **5,750**	14,500 / **7,275**	14,500 / **7,275**
A12	14,600 / 18,800	13,900 / 18,900	14,100 / 19,200	13,600 / 21,000	12,800 / 11,500	13,700 / 17,800	13,000 / 19,150	13,000 / 19,150	13,000 / 19,150	13,000 / 19,150
A13	14,600 / 24,900	13,900 / 23,850	14,100 / 25,150	13,600 / 25,750	12,800 / 26,000	13,700 / 25,550	11,000 / 20,666	11,000 / 20,666	11,000 / 20,666	11,000 / 20,666
A14	8,100 / **6,102**	7,700 / **5,870**	8,100 / **5,954**	11,800 / **6,022**	8,300 / **5,649**	*10,000* / **5,975**	10,000 / **5,975**	10,000 / **5,975**	10,000 / **6,382**	10,000 / **6,302**

Int. ID	Before Construction Study Corridor AADT/Intersecting Road AADT (veh/day)					After Construction Study Corridor AADT/Intersecting Road AADT (veh/day)				
	2007	2008	2009	2010	2011	2014	2015	2016	2017	2018
A15	8,100 / **6,102**	7,700 / **5,870**	8,100 / **5,954**	11,800 / **6,022**	8,300 / **5,649**	*10,000 /* **5,975**	10,000 / **5,975**	10,000 / **5,975**	10,000 / **6,382**	10,000 / **6,302**
A16	9,300 / 8,100	8,600 / 7,700	8,000 / 8,100	8,000 / 11,800	7,900 / 8,300	7,500 / 13,500	9,150 / 8,850	9,150 / 8,850	9,150 / 8,850	9,150 / 8,850
A17	9,300 / **6,102**	8,600 / **5,870**	8,000 / **5,954**	8,000 / **6,022**	7,900 / **5,649**	7,500 / **5,975**	10,000 / **5,975**	10,000 / **5,975**	10,000 / **6,382**	10,000 / **6,302**
A18	9,300 / 12,900	8,600 / 13,100	8,000 / 12,300	8,000 / 12,600	7,900 / 14,800	7,500 / 13,700	9,950 / 12,550	9,950 / 12,550	9,950 / 12,550	9,950 / 12,550
A19	9,300 / 20,800	8,600 / 18,100	8,000 / 20,200	8,000 / 19,800	7,900 / 18,100	7,500 / 19,400	9,000 / 17,250	9,000 / 17,250	9,000 / 17,250	9,000 / 17,250
A20	**10,373** / **6,102**	**10,373** / **5,870**	**10,373** / **5,954**	**10,373** / **6,022**	**10,373** / **5,649**	*9,000 /* **5,975**	9,000 / **5,975**	9,000 / **5,975**	9,000 / **6,382**	9,000 / **6,302**
A21	**9,508** / **4,610**	**9,508** / **4,610**	**9,508** / **4,610**	**9,508** / **4,610**	**9,508** / **4,610**	*8,250 / 4,000*	8,250 / 4,000	8,250 / 4,000	8,250 / 4,000	8,250 / 4,000
A22	**4,610** / **5,487**	**4,610** / **5,487**	**4,610** / **5,487**	**4,610** / **5,487**	**4,610** / **5,487**	*4,000 / 5,000*	4,000 / 5,000	4,000 / 5,000	4,000 / 5\,000	4,000 / 3,804
A23	**15,559** / 20,800	**15,559** / 18,100	**15,559** / 20,200	**15,559** / 19,800	**15,559** / 18,100	*13,500 /* 19,400	13,500 / 18,600	13,500 / 18,600	13,500 / 18,600	13,500 / 18,600
A24	**10,949** / **6,102**	**10,949** / **5,870**	**10,949** / **5,954**	**10,949** / **6,022**	**10,949** / **5,649**	*9,500 /* **5,975**	9,500 / **5,975**	9,500 / **5,975**	9,500 / **6,382**	9,500 / **6,302**
A25	**12,966** / **6,051**	**12,966** / **6,051**	**12,966** / **6,051**	**12,966** / **6,051**	**12,966** / **6,051**	*11,250 / 5,250*	11,250 / 5,250	11,250 / 5,250	11,250 / 5,250	11,250 / 5,250
A26	*17,000 / 7,900*	*17,000 / 7,900*	*17,000 / 7,900*	*17,000 / 7,900*	17,000 / *7,900*	*14,750 / 17,000*	14,750 / 17,000	14,750 / 17,000	14,750 / 17,000	14,750 / 17,000
A27	*17,000 /* **8,784**	*17,000 /* **8,784**	*17,000 /* **8,784**	*17,000 /* **8,784**	17,000 / **8,784**	*16,500 / 8,526*	16,500 / 8,526	16,500 / 8,526	16,500 / 8,526	16,500 / 8,526
A28	*17,000 /* **6,102**	*17,000 /* **5,870**	*17,000 /* **5,954**	*17,000 /* **6,022**	17,000 / **5,649**	*16,500 /* **5,975**	16,500 / **5,975**	16,500 / **5,975**	16,500 / **6,382**	16,500 / **6,302**
A29	*17,000 /* **6,102**	*17,000 /* **5,870**	*17,000 /* **5,954**	*17,000 /* **6,022**	17,000 / **5,649**	*16,500 /* **5,975**	16,500 / **5,975**	16,500 / **5,975**	16,500 / **6,382**	16,500 / **6,302**

Int. ID	Before Construction Study Corridor AADT/Intersecting Road AADT (veh/day)					After Construction Study Corridor AADT/Intersecting Road AADT (veh/day)				
	2007	2008	2009	2010	2011	2014	2015	2016	2017	2018
A30	18,200 / 22,454	15,800 / 21,300	17,100 / 22,750	23,500 / 22,600	17,000 / 24,650	15,300 / 26,150	15,750 / 19,400	15,750 / 19,050	15,750 / 19,050	15,750 / 19,050
A31	18,200 / **7,855**	15,800 / **6,819**	17,100 / **7,380**	23,500 / **10,143**	17,000 / **7,337**	15,300 / *6,500*	15,000 / 6,500	15,000 / 6,500	15,000 / 6,500	15,000 / 6,500
A32	18,200 / 11,500	15,800 / 12,200	17,100 / 12,200	23,500 / 13,100	17,000 / 11,100	15,300 / 12,400	15,500 / 10,450	15,500 / 10,450	15,500 / 10,450	15,500 / 10,450
A33	18,200 / 11,500	15,800 / 12,500	17,100 / 11,900	23,500 / 12,800	17,000 / 11,700	15,300 / 14,400	15,300 / 9,650	15,300 / 9,650	15,300 / 9,650	15,300 / 9,650
A34	18,200 / **6,102**	15,800 / **5,870**	17,100 / **5,954**	23,500 / **6,022**	17,000 / **5,649**	15,300 / **5,975**	14,600 / **5,975**	14,600 / **5,975**	14,600 / **6,382**	14,600 / **6,302**
A35	18,200 / **13,000**	15,800 / **11,286**	17,100 / **12,214**	23,500 / **16,786**	17,000 / **12,143**	15,300 / *9,500*	12,800 / 9,500	12,800 / 9,500	12,800 / 9,500	12,800 / 9,500

Note: Int. ID = Intersection Identifier; Italic text indicates interpolation was used to fill gaps. Bold text indicates proportions were used to fill gaps. SDOT estimates AAWDT, as opposed to AADT. AADT along the study corridor is displayed first in the table and may not necessarily be the major road AADT.

Table 25. AADT for segments along First Hill Streetcar corridor.

Seg. ID	Before Construction AADT (veh/d)					After Construction AADT (veh/d)				
	2007	2008	2009	2010	2011	2014	2015	2016	2017	2018
B1	14,600	13,900	14,100	13,600	12,800	13,700	6,600	6,600	6,600	6,600
B2	14,600	13,900	14,100	13,600	12,800	13,700	6,600	6,600	6,600	6,600
B3	14,600	13,900	14,100	13,600	12,800	13,700	11,000	11,000	11,000	11,000
B4	14,600	13,900	14,100	13,600	12,800	13,700	12,000	12,000	12,000	12,000
B5	14,600	13,900	14,100	13,600	12,800	13,700	10,000	10,000	10,000	10,000
B6	14,600	13,900	14,100	13,600	12,800	13,700	14,000	14,000	14,000	14,000
B7	14,600	13,900	14,100	13,600	12,800	13,700	11,300	11,300	11,300	11,300
B8	14,600	13,900	14,100	13,600	12,800	13,700	14,500	14,500	14,500	14,500
B9	14,600	13,900	14,100	13,600	12,800	13,700	14,500	14,500	14,500	14,500
B10	14,600	13,900	14,100	13,600	12,800	13,700	14,500	14,500	14,500	14,500
B11	14,600	13,900	14,100	13,600	12,800	13,700	14,500	14,500	14,500	14,500
B12	14,600	13,900	14,100	13,600	12,800	13,700	14,500	14,500	14,500	14,500
B13	14,600	13,900	14,100	13,600	12,800	13,700	11,500	11,500	11,500	11,500
B14	8100	7700	8100	11,800	8300	*10,000*	10,000	10,000	10,000	10,000
B15	8100	7700	8100	11,800	8300	*10,000*	10,000	10,000	10,000	10,000
B16	8100	7700	8100	11,800	8300	*10,000*	10,000	10,000	10,000	10,000
B17	9,300	8,600	8,000	8,000	7,900	7,500	10,000	10,000	10,000	10,000
B18	9,300	8,600	8,000	8,000	7,900	7,500	10,000	10,000	10,000	10,000
B19	9,300	8,600	8,000	8,000	7,900	7,500	9,000	9,000	9,000	9,000
B20	**9,273**	**9,273**	**9,273**	**9,273**	**9,273**	*9,000*	9,000	9,000	9,000	9,000
B21	**9,273**	**9,273**	**9,273**	**9,273**	**9,273**	*9,000*	9,000	9,000	9,000	9,000
B22	**4,121**	**4,121**	**4,121**	**4,121**	**4,121**	*4,000*	4,000	4,000	4,000	4,000
B23	**4,121**	**4,121**	**4,121**	**4,121**	**4,121**	*4,000*	4,000	4,000	4,000	4,000
B24	**9,788**	**9,788**	**9,788**	**9,788**	**9,788**	*9,500*	9,500	9,500	9,500	9,500
B25	**9,788**	**9,788**	**9,788**	**9,788**	**9,788**	*9,500*	9,500	9,500	9,500	9,500
B26	**13,394**	**13,394**	**13,394**	**13,394**	**13,394**	*13,000*	13,000	13,000	13,000	13,000
B27	*17,000*	*17,000*	*17,000*	*17,000*	17,000	*16,500*	16,500	16,500	16,500	16,500
B28	*17,000*	*17,000*	*17,000*	*17,000*	17,000	*16,500*	16,500	16,500	16,500	16,500
B29	*17,000*	*17,000*	*17,000*	*17,000*	17,000	*16,500*	16,500	16,500	16,500	16,500
B30	*17,000*	*17,000*	*17,000*	*17,000*	17,000	*16,500*	16,500	16,500	16,500	16,500
B31	18,200	15,800	17,100	23,500	17,000	15,300	15,000	15,000	15,000	15,000
B32	18,200	15,800	17,100	23,500	17,000	15,300	15,000	15,000	15,000	15,000
B33	18,200	15,800	17,100	23,500	17,000	15,300	16,000	16,000	16,000	16,000
B34	18,200	15,800	17,100	23,500	17,000	15,300	14,600	14,600	14,600	14,600
B35	18,200	15,800	17,100	23,500	17,000	15,300	14,600	14,600	14,600	14,600

Note: Interpolated and extrapolated values shown in italics. Bold text indicates proportions were used to fill gaps. SDOT estimates AAWDT, as opposed to AADT.

Treatments and CMFs Applied

In addition to streetcar tracks and stations, the project implemented multiple treatments on the project. Not all treatments were installed at all intersections/segments. Generally, South Jackson

Street improvements were implemented at intersections and were related to signal timing. Improvements on Broadway were more extensive and generally included a two-way separated bike lane, a reduction in through lanes to one lane in each direction, and other intersection improvements. Table 26 details which treatments were applied to each segment and intersection.

The following are the treatments commonly implemented at intersections:

- Add traffic signal.
- Prohibit left turns.
- Add "No Turn on Red" sign.
- Convert through lanes to turn lanes.
- Change left-turn phasing from permissive to protected.
- Add bike box.
- Add green colored pavement.
- Add blank out sign (no right turn).
- Convert to all-way stop control.

Common treatments implemented on segments included the following:

- Remove two-way left-turn lane.
- Reduce number of lanes.
- Add median.
- Add two-way separated bike lane.
- Add bike lane.
- Add shared-lane marking (sharrow).
- Remove on-street parking.

Table 26. Treatments applied to each segment and intersection in the First Hill Streetcar project.

Location ID	Applied Treatment
A1	Prohibit left turns, add nearside transit stop, add streetcar
A2	Add left-turn lane, add bike box, add streetcar
A3	Add streetcar
A4	Add streetcar
A5	Add bike box, add streetcar
A6	Prohibit left turns, add farside transit stop, add "No Turn on Red" sign, add pedestrian refuge island, add streetcar
A7	Prohibit left turns, add farside transit stop, add "No Turn on Red" sign, add bike box, add pedestrian refuge island, add streetcar
A8	Add "No Turn on Red" sign, add bike box, add streetcar
A9	Add nearside transit stop, add farside transit stop, add "No Turn on Red" sign, add bike box, add pedestrian refuge island, add streetcar
A10	Add blank out sign (no right turn), add green colored pavement, add streetcar

Location ID	Applied Treatment
A11	Add streetcar
A12	Add “No Turn on Red” sign, add bike box, add streetcar
A13	Add bike box, add streetcar
A14	Add “Do Not Enter Except Streetcar” signs, add streetcar
A15	Prohibit left turns, add nearside transit stop, add farside transit stop, convert from minor-road stop control to all-way stop control, add crosswalk, add streetcar
A16	Prohibit left turns, add “Do Not Enter Except Streetcar” signs, add green colored pavement, add pedestrian refuge island, add streetcar
A17	Add streetcar
A18	Prohibit left turns, add “No Turn on Red” sign, add bike box, add green colored pavement, add streetcar
A19	Prohibit left turns, add green colored pavement, add streetcar
A20	Add streetcar
A21	Add “No Turn on Red” sign, add blank out sign (no right turn), add green colored pavement, add streetcar
A22	Add crosswalk, add green colored pavement, add streetcar
A23	Prohibit left turns, add “No Turn on Red” sign, prohibit right turns, add green colored pavement, reduce number of lanes, add streetcar
A24	Remove Two-Way Left-Turn Lane, add traffic signal, prohibit left turns, add “No Turn on Red” sign, add green colored pavement, add streetcar
A25	Convert to protected left-turn phasing, add “No Turn on Red” sign, add green colored pavement, add streetcar
A26	Add right-turn lane, add “No Turn on Red” sign, add bike box, add green colored pavement, add streetcar
A27	Convert to protected left-turn phasing, add bike box, reduce number of lanes, add green colored pavement, add streetcar
A28	Convert to protected left-turn phasing, reduce number of lanes, add green colored pavement, add streetcar
A29	Reduce number of lanes, add crosswalk, convert from minor-road stop control to signal control, add streetcar
A30	Prohibit left turns, add green colored pavement, add streetcar
A31	Add ‘No Turn on Red” sign, add green colored pavement, add streetcar
A32	Convert to protected left-turn phasing, add “No Turn on Red” sign, add bike box, reduce number of lanes, add green colored pavement, add streetcar
A33	Prohibit left turns, add right-turn lane, add “No Turn on Red” sign, add bike box, reduce number of lanes, add green colored pavement, add streetcar
A34	Remove Two-Way Left-Turn Lane, add traffic signal, add “No Turn on Red” sign, add blank out sign (no right turn), add green colored pavement, add streetcar
A35	Prohibit left turns, add “No Turn on Red” sign, add bike box, add diagonal pedestrian crossing, add “Do Not Enter Except Streetcar” sign, reduce number of lanes
B1	Add median, add streetcar stop, remove on-street parking, add streetcar
B2	Add shared-lane marking (sharrow), remove on-street parking, add streetcar

Location ID	Applied Treatment
B3	Add shared-lane marking (sharrow), add streetcar
B4	Add shared-lane marking (sharrow), add streetcar
B5	Add shared-lane marking (sharrow), add streetcar
B6	Add shared-lane marking (sharrow), add streetcar
B7	Add median, add shared-lane marking (sharrow), add streetcar stop, remove on-street parking, add streetcar
B8	Add shared-lane marking (sharrow), remove on-street parking, add streetcar
B9	Add shared-lane marking (sharrow), add streetcar
B10	Add median, add bike lane, add shared-lane marking (sharrow), Add streetcar stop, add streetcar
B11	Add separated bike lane, add shared-lane marking (sharrow), add green colored pavement, add streetcar
B12	Add shared-lane marking (sharrow), add two-way left-turn lane, remove on-street parking, add streetcar
B13	Add shared-lane marking (sharrow), remove on-street parking, add median, add streetcar stop, add midblock crossing, add pedestrian signal, add streetcar
B14	Add separated bike lane, remove on-street parking, add streetcar
B15	Add separated bike lane, add median, add streetcar stop, remove on-street parking, add streetcar
B16	Add separated bike lane, add median, remove on-street parking, add streetcar
B17	Add separated bike lane, add bike lane, remove on-street parking, add streetcar
B18	Add separated bike lane, add bike lane, remove on-street parking, add green colored pavement, add streetcar
B19	Add separated bike lane, add bike lane, add green colored pavement, reduce number of lanes, add streetcar
B20	Add separated bike lane, add bike lane, add green colored pavement, reduce number of lanes, add streetcar
B21	Add separated bike lane, add separated bike lane, add streetcar stop, remove on-street parking, add green colored pavement, add raised traffic separators, add streetcar
B22	Add two-way separated bike lane, add streetcar
B23	Add two-way separated bike lane, remove on-street parking, add green colored pavement, add streetcar
B24	Add two-way separated bike lane, add streetcar stop, remove on-street parking, add streetcar
B25	Add two-way separated bike lane, add streetcar stop, remove on-street parking, add streetcar
B26	Add two-way separated bike lane, remove on-street parking, add streetcar
B27	Add two-way separated bike lane, remove on-street parking, add streetcar
B28	Add two-way separated bike lane, add green colored pavement, add streetcar
B29	Add two-way separated bike lane, add streetcar stop, remove driveway, remove on-street parking, add streetcar

Location ID	Applied Treatment
B30	Add median, add two-way separated bike lane, remove on-street parking, add streetcar
B31	Add median, add two-way separated bike lane, add two-way left-turn lane, add streetcar stop, remove on-street parking, add raised traffic separators, add green colored pavement, add streetcar
B32	Add two-way separated bike lane, add two-way left-turn lane, remove on-street parking, add green colored pavement, add streetcar
B33	Add two-way separated bike lane, add streetcar stop, remove on-street parking, add green colored pavement, add streetcar
B34	Remove median, add two-way separated bike lane, remove on-street parking, add green colored pavement, add streetcar
B35	Add two-way separated bike lane, add streetcar stop, remove driveway, remove on-street parking, add green pavement, add streetcar

Table 27 displays the CMFs that were selected for use in the analysis.

Table 27. Selected CMFs for First Hill Streetcar case study analysis.

Treatment Name	CMF ID/Source	CMF Value (Crash/Severity Type)	Proportion (Source)	Total Crash CMF
Add "Do Not Enter Except Streetcar" sign	No Applicable CMF	–	–	–
Add "No Turn on Red" sign	HSM p. 12–44	0.922 (signalized)	–	0.922
	HSM p. 12–44	1.0 (unsignalized)	–	1.0
Add bike box	No Applicable CMF	–	–	–
Add bike lane	CMF ID 7838	0.68	–	0.68
Add blank out sign (no right turn)	No Applicable CMF	–	–	–
Add crosswalk	CMF ID 4123	0.6 (vehicle/pedestrian)	0.036 (HSM Table 12-8)	0.986
	CMF ID 4124	0.81 (3-leg stop-controlled)	0.664 (HSM Table 10-6)	0.874
Add diagonal pedestrian crossing	No Applicable CMF	–	–	–
Add farside transit stop	No Applicable CMF	–	–	–
Add green colored pavement	No Applicable CMF	–	–	–
Add green pavement	No Applicable CMF	–	–	–
Add left-turn lane	HSM Table 12-24	0.90	–	0.90

Treatment Name	CMF ID/Source	CMF Value (Crash/Severity Type)	Proportion (Source)	Total Crash CMF
Add median	CMF ID 2219	0.29	–	0.29
Add midblock crossing	CMF ID 11181	0.82	0.036 (HSM Table 12-8)	0.994
Add nearside transit stop	No Applicable CMF	–	–	–
Add pedestrian refuge island	No Applicable CMF	–	–	–
Add pedestrian signal	No Applicable CMF	–	–	–
Add raised traffic separators	No Applicable CMF	–	–	–
Add right-turn lane	HSM Table 12-26	0.96	–	0.96
Add separated bike lane	CMF ID 2134	0.37 (Vehicle/bicyclist)	0.018 (HSM Table 12-9)	0.989
Add shared-lane marking (sharrow)	No Applicable CMF	–	–	–
Add streetcar	No Applicable CMF	–	–	–
Add streetcar stop	No Applicable CMF	–	–	–
Add traffic signal	CMF ID 9144	0.84	–	0.84
Add two-way left-turn lane	CMF ID 2341	0.797	–	0.797
Convert from minor-road stop control to all-way stop control	CMF ID 310	0.25	0.082 (HSM Table 12-4)	0.939
Convert from minor-road stop control to signal control	HSM Table 14-7	0.95	–	0.95
Convert to protected left-turn phasing	HSM Table 12-25	0.884	–	0.884
Prohibit left turns	CMF ID 391	0.32	–	0.32
Prohibit right turns	No Applicable CMF	–	–	–
Reduce number of lanes	No Applicable CMF	–	–	–
Remove driveway	No Applicable CMF	–	–	–
Remove median	No Applicable CMF	–	–	–
Remove on-street parking	HSM Table 13-50	0.58	–	0.58

Treatment Name	CMF ID/Source	CMF Value (Crash/Severity Type)	Proportion (Source)	Total Crash CMF
Remove Two-Way Left-Turn Lane	No Applicable CMF	–	–	–

Note: – indicates that the field is not applicable or not available for the given treatment.

Analysis Results

The First Hill Streetcar case study analysis results are presented in table 28. The safety effectiveness evaluation without volume adjustment (E1) showed a 15 percent crash reduction in the study area. The predictive analysis (P1) results of 25–38 percent overpredicted this crash reduction. Several CMFs have low values (indicating high predicted crash reductions) of 0.29–0.68 that may have contributed to this overprediction; these CMFs include adding bike lanes, adding medians, prohibiting left turns, and removing on-street parking.

Based on the before-period traffic volume trend, the after-period volumes were expected to mostly decrease or remain constant, though some segments projected increased volumes. This overall projected volume decrease led to a lower crash reduction for E2 compared to E1. The E2 calculation recognized that the vehicle volumes were experiencing a decreasing trend and thus did not give sole credit to the Complete Streets project for decreasing the volume and corresponding crashes.

For both P1 and P2, the dominant common residuals method of determining a CMF for treatment combinations performed closest to the safety effectiveness evaluation. This result could be due to the dominant common residuals method tempering the influence of the very effective CMFs mentioned above, as compared to the dominant effect method.

Observed after period vehicle volumes decreased more than predicted in many cases, leading to a relatively low four percent crash reduction result for E3 (E3 assumes the full traffic volume would have occurred even without the Complete Streets project). This result may be due to the project converting the corridor's purpose from primarily serving motor vehicles to primarily serving transit vehicles and bicyclists.

Table 28. First Hill Streetcar case study analysis results.

Analysis Method	CMF Combination Method	Crash Reduction	Percent Reduction
E1	–	122	15
E2	–	88.2	11
E3	–	31.7	4
P1	Dominant Effect	288.0	35
	Multiplicative	314.0	38
	Dominant Common Residuals	206.5	25
P2	Dominant Effect	327.8	40
	Multiplicative	344.1	42
	Dominant Common Residuals	247.8	30

Note: – indicates that the safety effectiveness evaluations do not rely on CMFs and thus do not use CMF combination methods.

Greenough Boulevard Greenway Expansion, Cambridge

The Greenough Boulevard Greenway Expansion is a one-mile urbanized arterial corridor in Cambridge that was reconfigured to be a more balanced and appealing greenway along the Charles River. Figure 118 illustrates the project location. The project consisted of reducing the number of lanes from four to two, reducing the lane width, widening the shoulder and adding a bicycle lane on the shoulder in each direction, adding a shared use path along the river, and installing a tree lawn buffer between the roadway and shared use path.

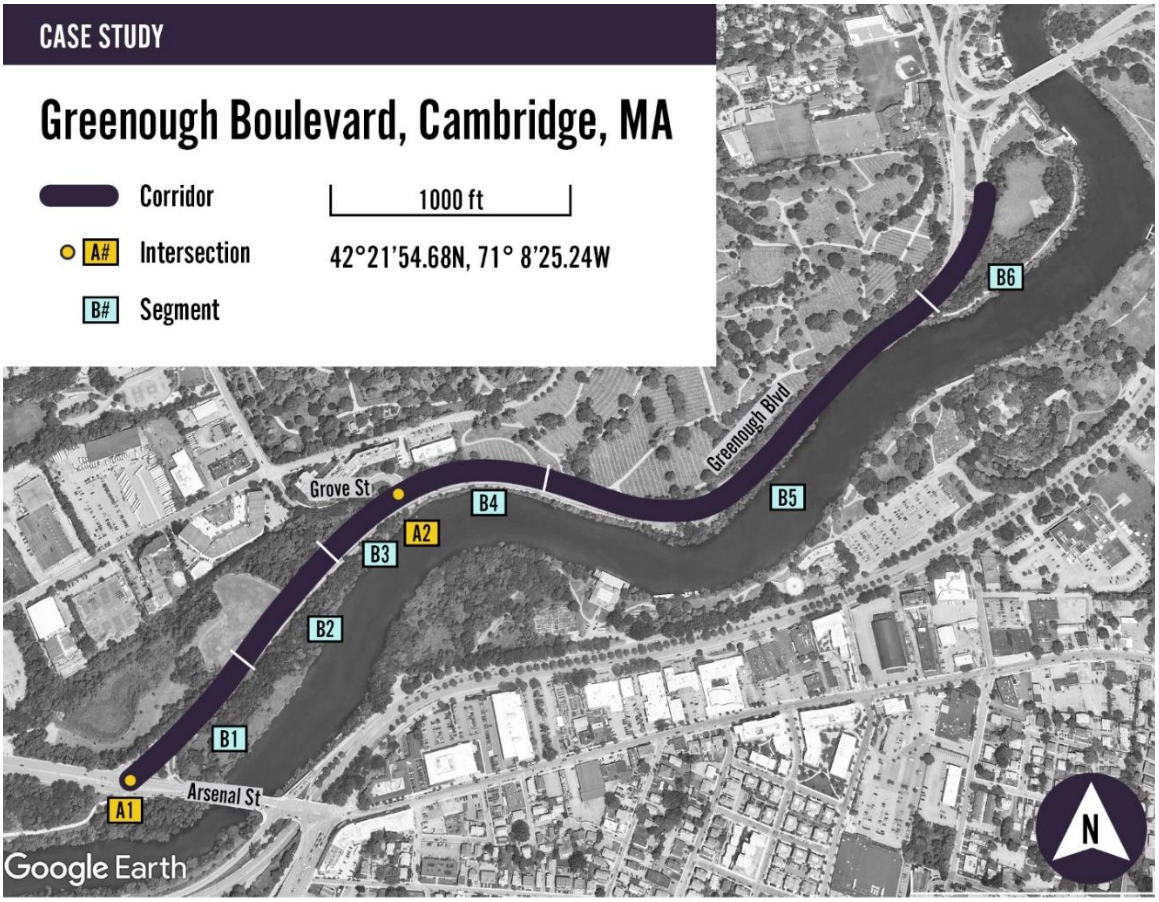


Figure 118. Graphic. Greenough Boulevard project location.

Figure 119 and figure 120 show cross-sections of the project location before and after construction. Construction occurred in 2015 and 2016. In the before period, Greenough Boulevard was a four-lane undivided roadway along the majority of the project location. The cross-section became a two- or three-lane undivided road in the after period. The segments are divided approaching intersections.

Figure 119. Photograph. Cross-section of Greenough Boulevard pre-construction in 2015 (Google Maps 2014).

Figure 120. Photograph. Cross-section of Greenough Boulevard post-construction in 2017 (Google Maps 2017a).

The research team segmented the project corridor into six segments (B1–B6) and two intersections (A1–A2) and collected data by segment and intersection, as shown in figure 118. Table 29 and table 30 summarize the intersections and segments in the study area.

Table 29. Summary of intersections along Greenough Boulevard.

Intersection ID	Intersecting Road Name	Intersection Type	
		Before Construction	After Construction
A1	Arsenal St	3SG	3SG
A2	Grove St	3SG	3SG

Table 30. Summary of segments along Greenough Boulevard.

Segment ID	Segment Limits	Segment Length	Roadway Type	
			Before Construction	After Construction
B1	From Arsenal St to 670 ft north of Arsenal St	0.12	4D	3D*
B2	From 670 ft north of Arsenal St to 530 ft south of Grove St	0.10	4U	3U*
B3	From 530 ft south of Grove St to Grove St	0.10	4D	3D*
B4	From Grove St to 585 ft northeast of Grove St	0.11	4D	3D*
B5	From 585 ft northeast of Grove St to 1080 ft south of Greenough Blvd median cut-through	0.44	4U	2U*
B6	From 1080 ft south of Greenough Blvd median cut-through to Greenough Blvd median cut-through	0.13	4D	3D*
–	**Total Length**	**1.00**	–	–

Note: * indicates a change in roadway type between the before and after construction periods; – = not applicable.

Crash Data

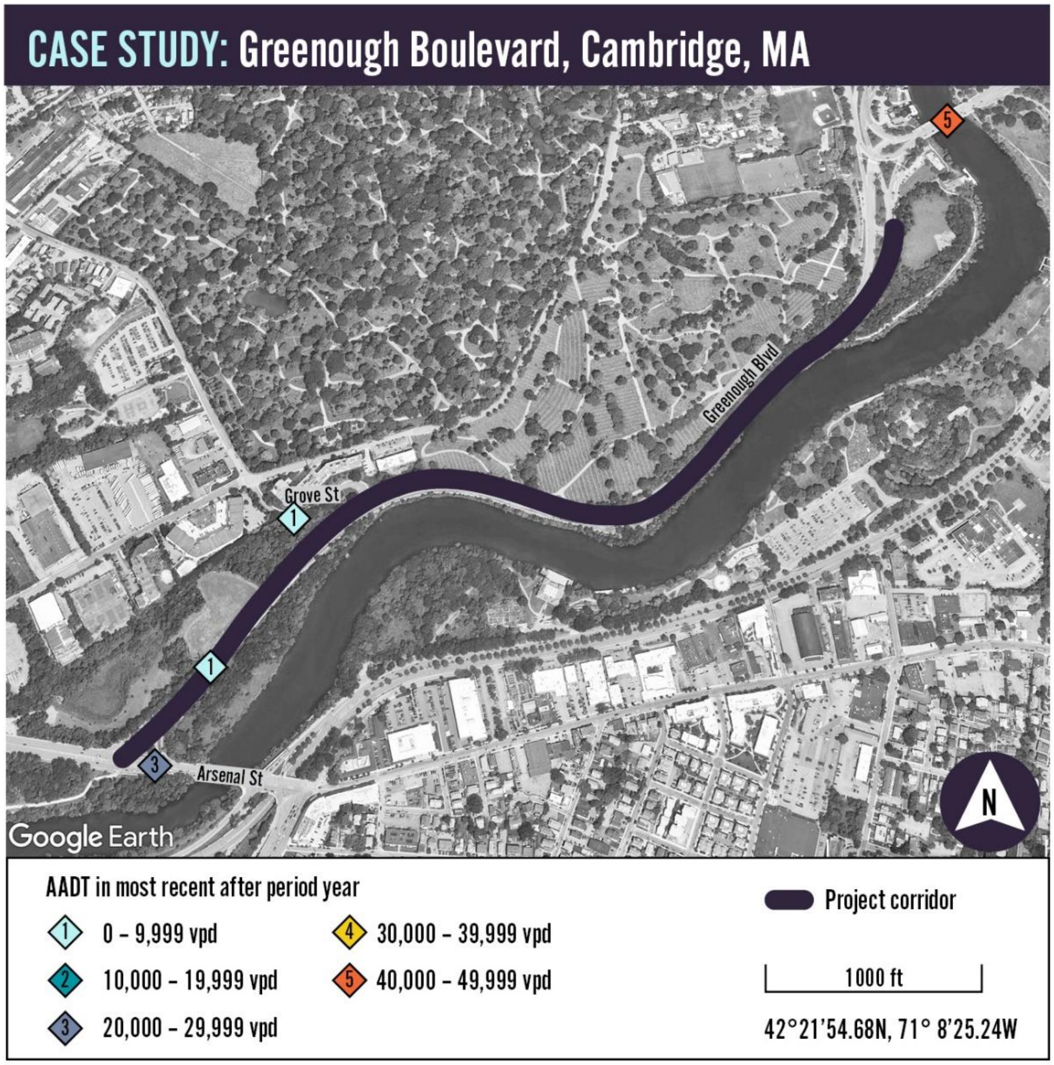
The research team used MassDOT's IMPACT tool (crash data portal) to download crash data for the before period (2010–2014) and after period (2017–2021) (MassDOT 2023a). Table 31 summarizes the crash data by intersection or segment and separates crash counts by type and severity. In total, 29 crashes occurred in the before period and 13 crashes occurred in the after period.

Table 31. Before and after crash data by segment or intersection for Greenough Boulevard.

Location ID	Before Construction Crashes (2010–2014)							After Construction Crashes (2017–2021)						
	SV-KABC	SV-O	MV-KABC	MV-O	Ped-all	Bike-all	Total	SV-KABC	SV-O	MV-KABC	MV-O	Ped-all	Bike-all	Total
B1	0	0	0	0	0	0	**0**	0	0	0	1	0	0	**1**
B2	0	0	0	0	0	0	**0**	0	0	0	1	0	0	**1**
B3	1	0	0	0	0	0	**1**	0	0	0	0	0	0	**0**
B4	0	0	0	0	0	0	**0**	0	0	0	0	0	0	**0**
B5	1	0	0	1	0	0	**2**	0	0	0	0	0	0	**0**
B6	0	0	0	0	0	0	**0**	0	0	0	0	0	0	**0**
A1	0	1	2	8	0	0	**11**	1	0	1	2	0	1	**5**
A2	0	4	5	5	0	1	**15**	1	1	2	2	0	0	**6**
Total	**2**	**5**	**7**	**14**	**0**	**1**	**29**	**2**	**1**	**3**	**6**	**0**	**1**	**13**

Volume Data

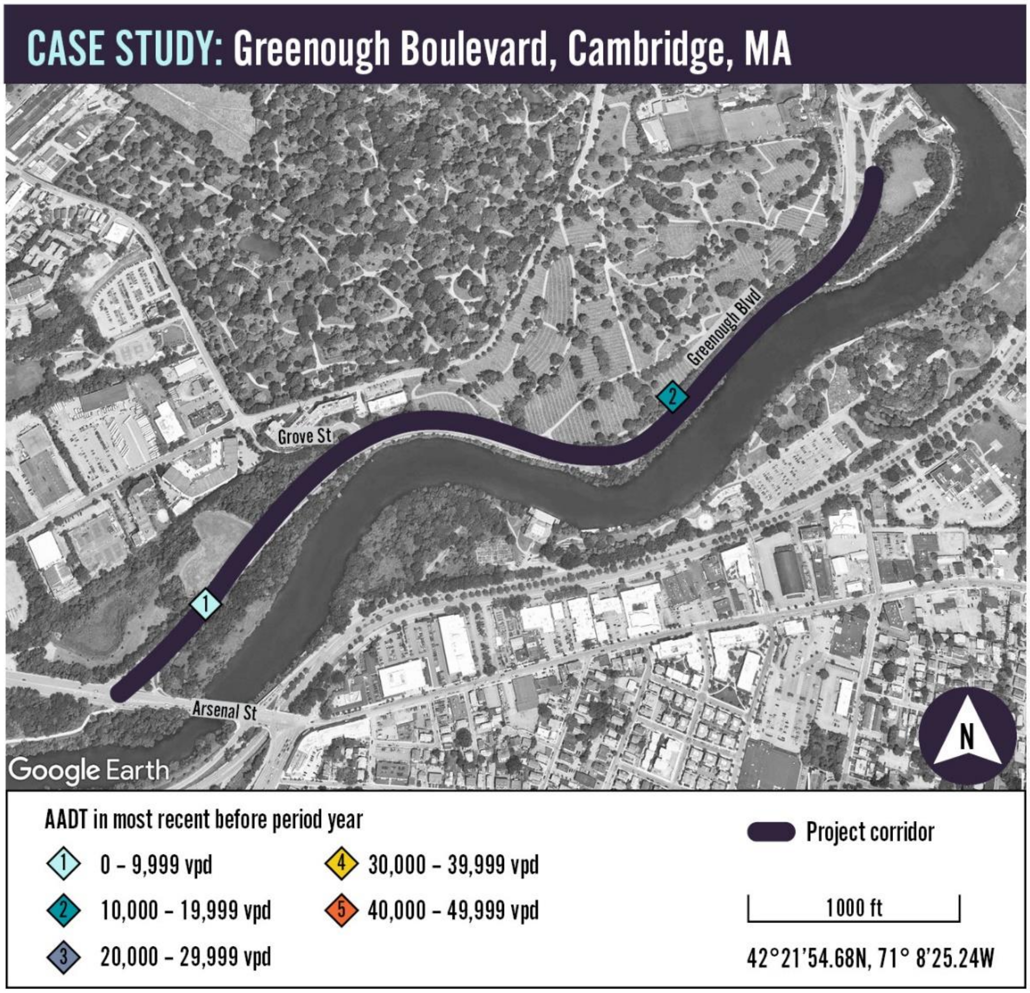
The research team used MassDOT's Transportation Data Management System to obtain AADT values for the segments and intersections for the after period (MassDOT 2023b). Figure 121 displays the AADT count locations in the project area from the MassDOT system for the after period. For the AADT values on the segments, the research team used the AADT from the traffic counter on the south end of Greenough Boulevard. For AADT values at the Greenough Boulevard and Arsenal Street intersection, the research team used the count on the east leg on Arsenal Street as the major AADT and the count on Greenough Boulevard as the minor AADT. For the AADT values at the Greenough Boulevard and Grove Street intersection, the research team used the count on the west leg on Greenough Boulevard as the major AADT and the count on the north leg on Grove Street as the minor AADT.



© 2022 Google. Modified by authors to highlight project corridor and AADT in various locations.

Figure 121. Graphic. Location of AADT count stations in the Greenough Boulevard project area for the after period.

No traffic counts exist for the before period (2010–2014) in MassDOT's Transportation Data Management System (MassDOT 2023b). For the AADT in the before period, the research team had existing traffic counts from the original project along the study period for one day in 2014 by direction (eastbound and westbound) at two different locations along Greenough Boulevard (east and west of Grove Street). Figure 122 illustrates these locations. The research team used the counts west of Grove Street for segments B1–B3 and east of Grove Street for segments B4–B6. For the Greenough Boulevard and Arsenal Street intersection, the research team used the count on Greenough Boulevard from the traffic counter west of Grove Street as the minor-road AADT. For the Greenough Boulevard and Grove Street intersection, the research team used the count on Greenough Boulevard from the traffic counter east of Grove Street for the major road AADT. The research team did not have major road AADT for the Greenough Boulevard and Arsenal Street intersection and minor-road AADT for the Greenough Boulevard and Grove Street intersection. Table 32 and table 33 display a summary of the AADT estimates.



© 2022 Google. Modified by authors to highlight the project corridor and AADT.

Figure 122. Graphic. Location of AADT count stations in the Greenough Boulevard project area for the before period.

Table 32. AADT for segments along Greenough Boulevard.

Segment ID	Before Construction AADT (veh/day)					After Construction AADT (veh/day)				
	2010	2011	2012	2013	2014	2017	2018	2019	2020	2021
B1	9,515	9,515	9,515	9,515	9,515	9,843	9,873	9,834	8,113	9,087
B2	9,515	9,515	9,515	9,515	9,515	9,843	9,873	9,834	8,113	9,087
B3	9,515	9,515	9,515	9,515	9,515	9,843	9,873	9,834	8,113	9,087

Segment ID	Before Construction AADT (veh/day)					After Construction AADT (veh/day)				
	2010	2011	2012	2013	2014	2017	2018	2019	2020	2021
B4	12,148	12,148	12,148	12,148	12,148	9,843	9,873	9,834	8,113	9,087
B5	12,148	12,148	12,148	12,148	12,148	9,843	9,873	9,834	8,113	9,087
B6	12,148	12,148	12,148	12,148	12,148	9,843	9,873	9,834	8,113	9,087

Table 33. AADT for intersections along Greenough Boulevard.

Int. ID	Before Construction Study Corridor AADT/Intersecting Road AADT (veh/day)					After Construction Study Corridor AADT/Intersecting Road AADT (veh/day)				
	2010	2011	2012	2013	2014	2017	2018	2019	2020	2021
A1	9,627/ **23,046**	9,627/ **23,046**	9,627/ **23,046**	9,627/ **23,046**	9,627/ **23,046**	9,843/ 23,564	9,873/ 23,635	9,834/ 23,540	8,113/ 19,421	9,087/ 21,753
A2	12,148/ **11,641**	12,148/ **11,641**	12,148/ **11,641**	12,148/ **11,641**	12,148/ **11,641**	9,843/ 9,433	9,873/ 9,461	9,834/ 9,423	8,113/ 7,774	9,087/ 8,707

Note: Bold text indicates proportions were used to fill gaps. AADT along the study corridor is displayed first in the table and may not necessarily be the major road AADT.

Treatments and CMFs Applied

The research team used project documents and Google Earth and Street View to identify the treatments applied to each segment and intersection as shown in table 34.

Table 34. Treatments applied to each segment and intersection in the Greenough Boulevard project.

Location ID	Applied Treatment
A1	Reduce number of lanes, reduce lane width, provide buffer/tree lawn, add shared-use path
A2	Reduce number of lanes, widen and convert shoulder to bike lane, provide buffer/tree lawn, add shared-use path
B1	Reduce number of lanes, reduce lane width, widen and convert shoulder to bike lane, provide buffer/tree lawn, add shared-use path
B2	Reduce number of lanes, reduce lane width, widen and convert shoulder to bike lane, provide buffer/tree lawn, add shared-use path
B3	Reduce number of lanes, reduce lane width, widen and convert shoulder to bike lane, provide buffer/tree lawn, add shared-use path
B4	Reduce number of lanes, widen and convert shoulder to bike lane, provide buffer/tree lawn, add shared-use path
B5	Reduce number of lanes, reduce lane width, widen and convert shoulder to bike lane, provide buffer/tree lawn, add shared-use path
B6	Reduce number of lanes, widen and convert shoulder to bike lane, provide buffer/tree lawn, add shared-use path

Table 35 displays the CMFs that were selected for use in the analysis.

Table 35. Selected CMFs for Greenough Boulevard case study analysis.

Treatment Name	CMF ID/Source	CMF Value (Crash/Severity Type)	Proportion (Source)	Total Crash CMF
Reduce number of lanes	CMF ID 11128	0.62 (segments)	–	0.62
	CMF ID 11133	0.65 (intersections)	–	0.65
Reduce lane width (12 ft to 11 ft)	CMF ID 8151	F(AADT)	–	F(AADT)
Widen and convert shoulder to on-street bike lane	No Applicable CMF	–	–	–
Provide buffer/tree lawn	No Applicable CMF	–	–	–
Add shared-use path	CMF ID 9250	0.75 (vehicle/bicycle)	0.002 (HSM p. 12-28)	0.9995

– not applicable.

Analysis Results

The Greenough Boulevard case study analysis results are shown in table 36. The safety effectiveness evaluation without volume adjustment (E1) showed a 55 percent crash reduction in the study area. The predictive analysis (P1) results of 21–35 percent underpredicted this crash reduction. This case study featured relatively fewer treatments and corresponding CMFs, and the CMFs available had a wide range of anticipated effectiveness (0.62–1.93). This variability and the presence of high CMF values may have contributed to the underprediction.

Based on the before-period traffic volume trend, the after-period volumes were expected to remain constant. This is why the results for E1 and E2 are equal and the results for P1 and P2 are equal.

For both P1 and P2, the dominant effect method of CMF combination performed closest to the safety effectiveness evaluation. This result could be due to the dominant effect method excluding the higher-value CMFs mentioned previously and minimizing the under-predictive tendencies associated with those CMFs.

Observed after-period vehicle volumes decreased due to the project converting the repurposed motor vehicle lanes as bicycle facilities and space for the improved shared-use path, which explains why the result for E3 is less than those for E1 and E2.

Table 36. Greenough Boulevard case study analysis results.

Analysis Method	CMF Combination Method	Crash Reduction	Percent Reduction
E1	–	16	55
E2	–	16.0	55

Analysis Method	CMF Combination Method	Crash Reduction	Percent Reduction
E3	–	11.1	38
P1	Dominant Effect	10.2	35
	Multiplicative	8.7	30
	Dominant Common Residuals	6.1	21
P2	Dominant Effect	10.2	35
	Multiplicative	8.7	30
	Dominant Common Residuals	6.1	21

Note: – indicates that the safety effectiveness evaluations do not rely on CMFs and thus do not use CMF combination methods.

Bench Boulevard Project, Billings

The Bench Boulevard project is a two-mile arterial corridor project that traverses the east side of Billings, an urbanized area between Hilltop Road and US 87/Highway 312 as shown in figure 123. The corridor runs parallel to US 87 and was reconstructed in 2015–2016 to provide safety and operational improvements. Prior to the project, Bench Boulevard was a two-lane road with gravel shoulders and attached sidewalk at intermittent intervals. The project added a center two-way left-turn lane, sidewalks (detached and attached), curb and gutter, ADA ramps, pedestrian refuge islands, curb bulb-outs, corridor lighting, improved signage and striping, on-street parking, auxiliary turn lanes (as needed), and a roundabout at the intersection of Bench Boulevard and Hilltop Road.

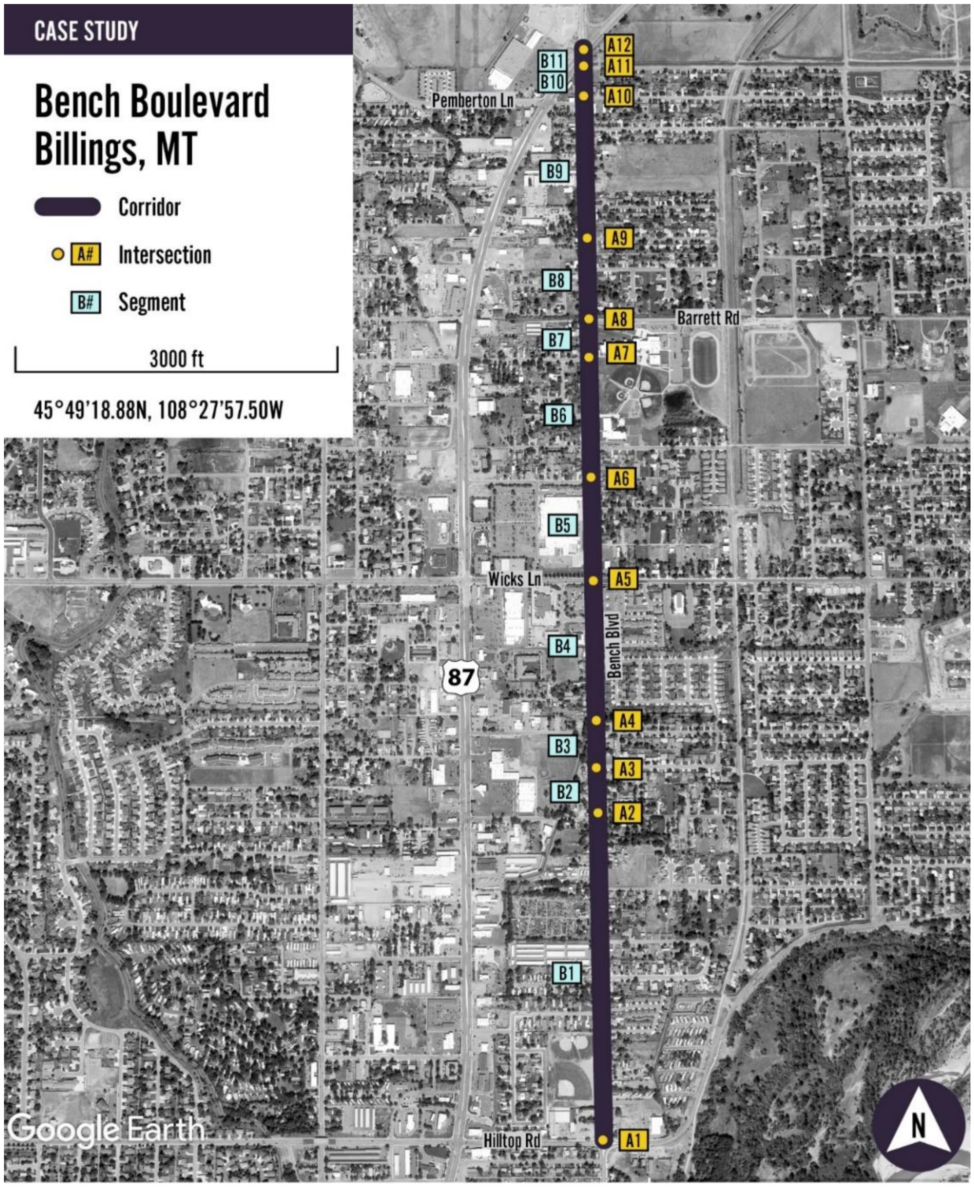


Figure 123. Graphic. Bench Boulevard project location.

Figure 124 through figure 129 show cross-sections of the project location before and after construction. During the before period, the roadway was a two-lane undivided roadway and was reconstructed to a three-lane with TWLTL facility with multimodal, safety, and stormwater improvements in the after period.

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Figure 124. Photograph. Cross-section of Bench Boulevard mid-corridor pre-construction in 2011 (Google Maps 2011c).

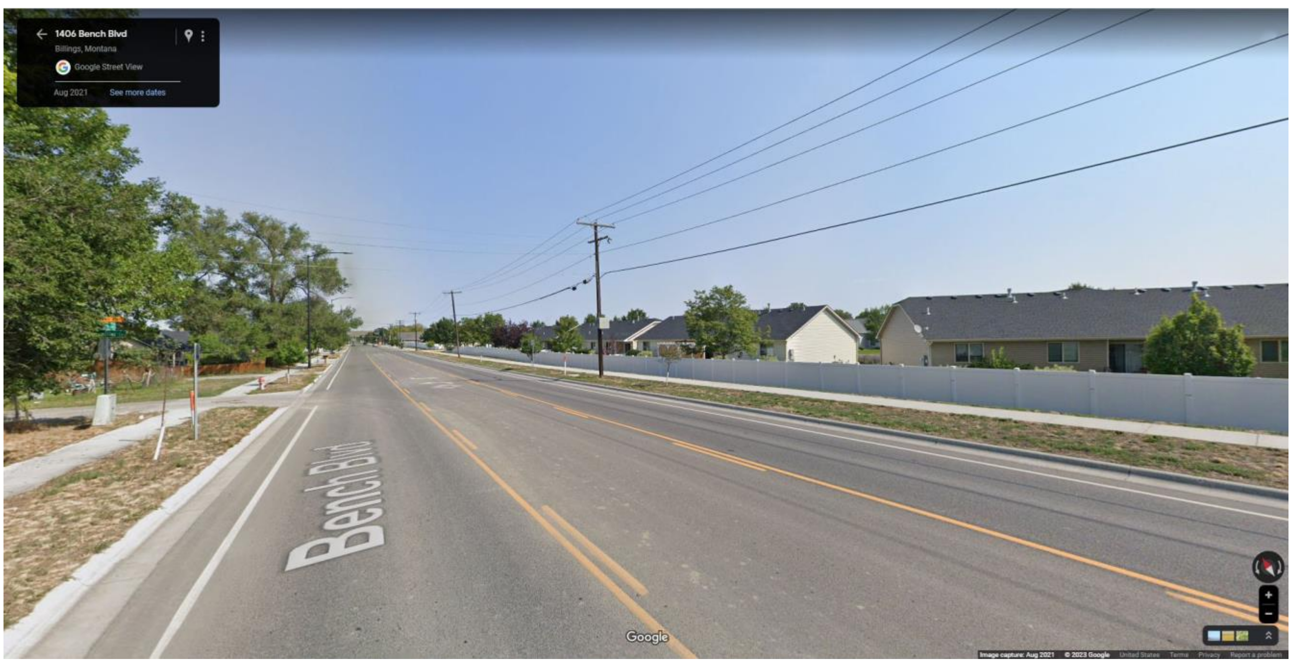

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Figure 125. Photograph. Cross-section of Bench Boulevard mid-corridor post-construction in 2017 (Google Maps 2021a).

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Figure 126. Photograph. Cross-section of Bench Boulevard near the US 87 intersection pre-construction in 2011 (Google Maps 2011d).

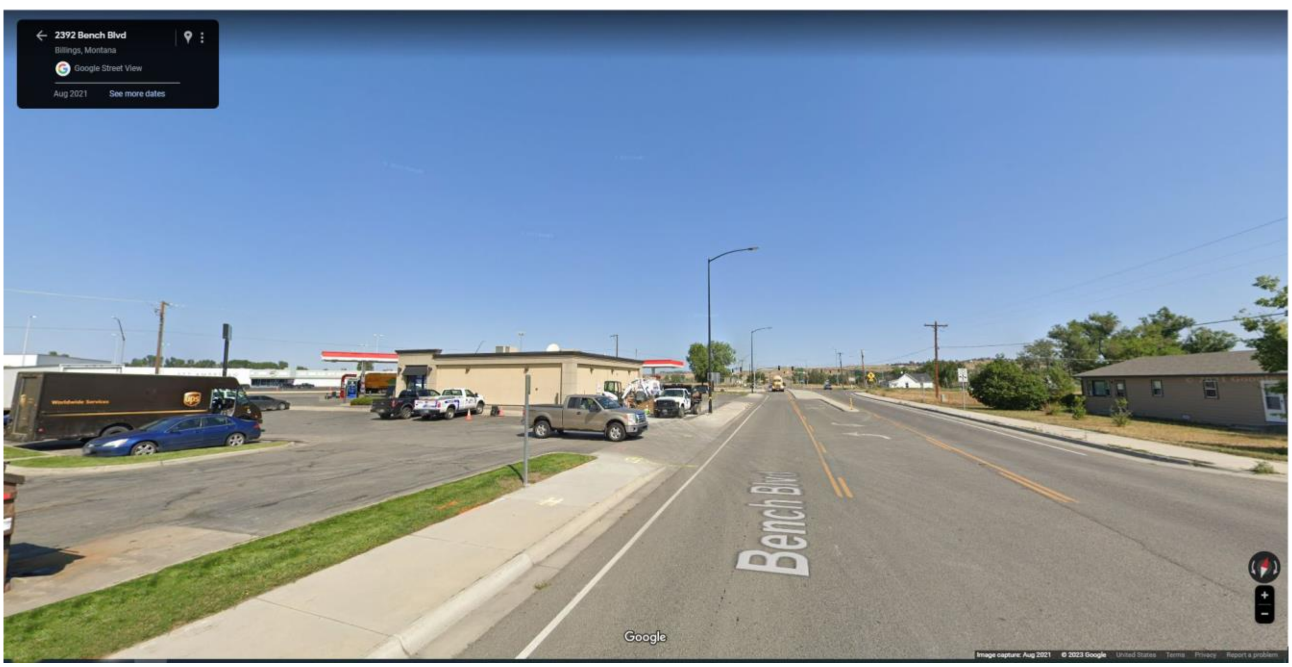

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Figure 127. Photograph. Cross-section of Bench Boulevard near the US 87 intersection post-construction in 2017 (Google Maps 2021d).

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Figure 128. Photograph. Cross-section of Bench Boulevard near the Hilltop Road intersection pre-construction in 2011 (Google Maps 2011e).

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Figure 129. Photograph. Cross-section of Bench Boulevard near the Hilltop Road intersection post-construction in 2017 (Google Maps 2017b).

The research team segmented the project into 11 segments (B1–B11) and 12 intersections (A1–A12) and collected data for the segments and intersections, as shown in figure 123. Table 37 and table 38 display the summary of the intersections and segments in the study area.

Table 37. Summary of intersections along Bench Boulevard.

Intersection ID	Intersecting Road Name	Intersection Type	
		Before Construction	After Construction
A1	Hilltop Rd	4ST	Roundabout*
A2	Logan Ln	4ST	4ST
A3	Ahoy Ave	3ST	3ST
A4	Anchor Ave	4ST	4ST
A5	Wicks Ln	4SG	4SG
A6	Mattson Ln	3ST	3ST
A7	Key City Dr	3ST	3ST
A8	Barrett Dr	4ST	4ST
A9	Kale Dr	3ST	3ST
A10	Crist Dr	3ST	3ST
A11	Mary St	4ST	3ST
A12	Highway 312 (Main St)	4ST	4SG*

Note: * indicates a change in intersection type between the before and after construction periods.

Table 38. Summary of segments along Bench Boulevard.

Segment ID	Segment Limits	Segment Length (mi)	Roadway Type	
			Before Construction	After Construction
B1	from Hilltop Rd to Logan Ln	0.57	2U	3T*
B2	from Logan Ln to Ahoy Ave	0.09	2U	3T*
B3	from Ahoy Ave to Anchor Ave	0.06	2U	3T*
B4	from Anchor Ave to Wicks Ln	0.28	2U	3T*
B5	from Wicks Ln to Mattson Ln	0.19	2U	3T*
B6	from Mattson Ln to Key City Dr	0.23	2U	3T*
B7	from Key City Dr to Barrett Dr	0.08	2U	3T*
B8	from Barrett Dr to Kale Dr	0.16	2U	3T*
B9	from Kale Dr to Crist Dr	0.28	2U	3T*
B10	from Crist Dr to Mary St	0.06	2U	3D*
B11	from Mary St to Highway 312 (Main St)	0.04	2U	4D*
	Total Length	**2.04**	–	–

Note: * indicates a change in roadway type between the before and after construction periods; – = not applicable.

Crash Data

The research team coordinated with the Montana Department of Transportation's (MDT's) Safety Office to gather crash data for the before period (2011–2014) and after period (2017–2020).[4] Table 39 summarizes the crash data by intersection or segment and separates crash counts by type and severity. In total, 90 crashes occurred in the before period and 88 crashes occurred in the after period.

Table 39. Before and after crash data by segment or intersection for Bench Boulevard.

Location ID	Before Construction Crashes (2011–2014)							After Construction Crashes (2017–2020)						
	SV-KABC	SV-O	MV-KABC	MV-O	Ped-all	Bike-all	Total	SV-KABC	SV-O	MV-KABC	MV-O	Ped-all	Bike-all	Total
A1	0	3	0	3	0	0	**6**	0	3	2	5	0	0	**10**
A2	0	1	1	0	0	0	**2**	0	0	0	0	0	0	**0**
A3	0	0	0	0	0	0	**0**	0	0	0	0	0	0	**0**
A4	0	0	0	0	0	0	**0**	0	0	0	3	0	0	**3**
A5	1	2	0	1	0	0	**4**	0	1	0	1	0	0	**2**
A6	0	0	0	1	0	0	**1**	0	0	0	0	0	0	**0**
A7	0	1	0	0	0	0	**1**	0	0	0	0	0	0	**0**
A8	1	0	0	0	0	0	**1**	0	0	0	0	0	0	**0**
A9	0	0	0	0	0	0	**0**	0	0	0	0	0	0	**0**
A10	0	0	0	0	0	0	**0**	0	0	0	0	0	0	**0**
A11	1	1	2	2	0	0	**6**	0	1	2	2	0	0	**5**
A12	1	2	4	10	0	1	**18**	2	2	3	11	0	1	**19**
B1	0	0	2	2	0	0	**4**	0	0	1	0	0	0	**1**
B2	0	1	1	1	0	0	**3**	0	0	0	0	0	0	**0**
B3	0	2	2	2	0	0	**6**	0	1	1	1	0	0	**3**
B4	0	0	0	3	0	0	**3**	0	0	13	11	0	0	**24**
B5	0	0	1	2	0	0	**3**	0	0	0	0	0	0	**0**
B6	0	1	0	0	0	0	**1**	0	0	1	1	0	0	**2**

[4]MDT shared crash data directly with the research team.

Location ID	Before Construction Crashes (2011–2014)							After Construction Crashes (2017–2020)						
	SV-KABC	SV-O	MV-KABC	MV-O	Ped-all	Bike-all	Total	SV-KABC	SV-O	MV-KABC	MV-O	Ped-all	Bike-all	Total
B7	1	0	0	0	0	0	**1**	0	0	0	1	0	0	**1**
B8	1	0	0	0	0	0	**1**	0	0	0	0	0	0	**0**
B9	0	1	0	0	0	0	**1**	0	0	0	0	0	0	**0**
B10	0	1	1	1	0	0	**3**	1	1	0	1	0	0	**3**
B11	0	0	9	16	0	0	**25**	0	1	6	8	0	0	**15**
Total	**6**	**16**	**23**	**44**	**0**	**1**	**90**	**3**	**10**	**29**	**45**	**0**	**1**	**88**

Note: Bold text indicates proportions were used to fill gaps. AADT along the study corridor is displayed first in the table and may not necessarily be the major road AADT.

Volume Data

The research team used MDTs online traffic data map to obtain AADT values for intersections and segments along the corridor for the before and after periods (MDT 2023). No counts for the minor roadways were provided, therefore volumes are shown primarily for the arterial corridor. Some crash reports contained estimated AADT for the minor roadways, and those values are provided as available. Figure 130 illustrates the AADT count locations in the project area from MDT's traffic data map. MDT has permanent counters within the project area along Bench Boulevard; counters are located at Bench Boulevard south of Shawnee Drive, Bench Boulevard between Ahoy Avenue and Logan Lane, Bench Boulevard between Wicks Lane and Lynch Drive, and Bench Boulevard between Barrett Road and Wagner Lane. Table 40 and table 41 display a summary of the AADT data by intersection and segment.

Figure 130. Graphic. Location of AADT count stations and segments in the Bench Boulevard project area.

Table 40. AADT for intersections along Bench Boulevard.

Intersection ID	Before Construction Study Corridor AADT/Intersecting Road AADT (veh/day)				After Construction Study Corridor AADT/Intersecting Road AADT (veh/day)			
	2011	2012	2013	2014	2017	2018	2019	2020
A1	4,280 / 4,785	4,240 / 5,774	4,010 / 5,460	5,894 / 7,462	5,390 / 5,739	7,582 / 4,927	7,627 / 4,718	7,233 / 5,301
A2	4,400 / *6,955*	4,360 / *6,955*	4,120 / 6,955	4,190 / *6,955*	6,555 / *6,468*	6,653 / 6,468	6,955 / *6,468*	6,468 / *6,468*
A3	4,400 / 740	4,360 / 740	4,120 / *740*	4,190 / *740*	6,555 / *668*	6,653 / *668*	6,955 / 668	6,468 / *668*
A4	4,400 / 740	4,360 / 740	4,120 / *740*	4,190 / *740*	6,555 / **1,137**	6,653 / **1,154**	6,955 / **1,206**	6,468 / **1,122**
A5	5,000 / 14,170	4,960 / 13,420	4,690 / 16,630	4,770 / 13,130	5,978 / 11,394	6,068 / 11,405	5,961 / 11,306	5,544 / 10,515
A6	5,000 / **4,372**	4,960 / **4,377**	4,690 / **4,380**	4,770 / **4,380**	5,978 / **3,468**	6,068 / **3,476**	5,961 / **3,289**	5,544 / **3,253**
A7	3,200 / **2,798**	3,170 / **2,797**	3,000 / **2,802**	3,050 / **2,801**	3,396 / **1,970**	3,447 / **1,974**	3,617 / **1,995**	3,364 / **1,974**
A8	3,200 / *1,960*	3,170 / 1,960	3,000 / 1,960	3,050 / *1,960*	3,396 / **2,144**	3,447 / **2,176**	3,617 / **2,283**	3,364 / **2,123**
A9	3,200 / *740*	3,170 / 740	3,000 / 740	3,050 / *740*	3,396 / **809**	3,447 / **822**	3,617 / **862**	3,364 / **802**
A10	3,200 / 740	3,170 / *740*	3,000 / *740*	3,050 / *740*	3,396 / **809**	3,447 / **822**	3,617 / **862**	3,364 / **802**
A11	3,200 / 1,990	3,170 / 1,517	3,000 / 1430	3,050 / 1,763	3,396 / 863	3,447 / 952	3,617 / 958	3,364 / 740
A12	3,200 / 12,250	3,170 / 13,705	3,000 / 12,355	3,050 / 12,785	3,396 / 13,417	3,447 / 12,849	3,617 / 12,757	3,364 / 12,427

Note: Italic text indicates interpolation was used to fill gaps. Bold text indicates proportions were used to fill gaps. AADT along the study corridor is displayed first in the table and may not necessarily be the major road AADT.

Table 41. AADT for segments on Bench Boulevard.

Segment ID	Before Construction AADT (veh/day)				After Construction AADT (veh/day)			
	2011	2012	2013	2014	2017	2018	2019	2020
B1	4,280	4,240	4,010	5,894	5,390	7,582	7,627	7,233
B2	4,400	4,360	4,120	4,190	6,555	6,653	6,955	6,468
B3	4,400	4,360	4,120	4,190	6,555	6,653	6,955	6,468
B4	4,400	4,360	4,120	4,190	6,555	6,653	6,955	6,468
B5	5,000	4,960	4,690	4,770	5,978	6,068	5,961	5,544
B6	5,000	4,960	4,690	4,770	5,978	6,068	5,961	5,544
B7	5,000	4,960	4,690	4,770	5,978	6,068	5,961	5,544
B8	3,200	3,170	3,000	3,050	3,396	3,447	3,617	3,364
B9	3,200	3,170	3,000	3,050	3,396	3,447	3,617	3,364
B10	3,200	3,170	3,000	3,050	3,396	3,447	3,617	3,364
B11	3,200	3,170	3,000	3,050	3,396	3,447	3,617	3,364

Treatments and CMFs Applied

The research team used project documents and Google Earth and Street View to identify the treatments applied to each segment and intersection, as shown in table 42.

Table 42. Treatments applied to each segment and intersection in the Bench Boulevard project.

Location ID	Applied Treatments
A1	Convert all-way stop control to roundabout, add sidewalk, add pedestrian refuge island, add crosswalk, add pedestrian warning signs, add ADA ramps, enhance lighting
A2	Add sidewalk, add ADA ramps, add lighting
A3	Add sidewalk, add ADA ramps, add lighting
A4	Add sidewalk, add ADA ramps, add lighting
A5	Add pedestrian signal head, add ADA ramps
A6	Add sidewalk, add ADA ramps, add lighting, add on-street parking
A7	Add sidewalk, add ADA ramps, add lighting, add on-street parking and pull-out parking area for school
A8	Add sidewalk, add crosswalk, add pedestrian/school crossing warning signs, add yield pavement markings (sharks teeth), add ADA ramps, add lighting, add on-street parking
A9	Add sidewalk, add ADA ramps, add lighting
A10	Add sidewalk, add ADA ramps, add lighting
A11	Add pedestrian refuge island, add pedestrian warning signs, add yield pavement markings (sharks teeth), add sidewalks, add ADA ramps, add lighting

Location ID	Applied Treatments
A12	Convert from minor-road stop control to traffic signal, add pedestrian refuge island, add crosswalk, add pedestrian signal heads and pushbuttons, add sidewalk, add ADA ramps, add lighting
B1	Add two-way left-turn lane, add sidewalk, add lighting, add on-street parking, reduce lane width
B2	Add two-way left-turn lane, add sidewalk, add lighting, add on-street parking, reduce lane width
B3	Add two-way left-turn lane, add sidewalk, add lighting, add on-street parking, reduce lane width
B4	Add two-way left-turn lane, add sidewalk, add lighting, reduce lane width
B5	Add two-way left-turn lane, add sidewalk, add lighting, add on-street parking, reduce lane width
B6	Add two-way left-turn lane, add sidewalk, add crosswalk, add yield markings (sharks teeth), add pedestrian warning sign, add "Yield Here to Pedestrians" sign, add lighting, add curb extension/bulb-out, add drop off lane, add on-street parking
B7	Add two-way left-turn lane, add sidewalk, add lighting, add on-street parking
B8	Add two-way left-turn lane, add sidewalk, add lighting, reduce lane width
B9	Add two-way left-turn lane, add sidewalk, add lighting, reduce lane width
B10	Add two-way left-turn lane, add median, add sidewalk, add lighting
B11	Add median, add sidewalk, add lighting

Table 43 displays the CMFs that were selected for use in the analysis.

Table 43. Selected CMFs for Bench Boulevard case study.

Treatment Name	CMF ID/Source	CMF Value (Crash/Severity Type)	Proportion (Source)	Total Crash CMF
Add "Yield Here to Pedestrians" sign.	CMF ID 9017	0.75	–	0.75
Add ADA ramps.	No Applicable CMF	–	–	–
Add crosswalk.	CMF ID 4123	0.6 (vehicle/pedestrian)	0.005 (HSM Table 12-8)	0.998
	CMF ID 4124	0.81	0.814 (HSM Table 10-6, 4-leg stop control)	0.845
			0.664 (HSM Table 10-6, 3-leg stop control)	0.874
Add curb extension/ bulb-out.	No Applicable CMF	–	–	–
Add drop off lane.	No Applicable CMF	–	–	–

Treatment Name	CMF ID/Source	CMF Value (Crash/Severity Type)	Proportion (Source)	Total Crash CMF
Add or enhance lighting.	CMF ID 11026	0.679 (nighttime)	0.316 (HSM Table 12-23)	0.899
Add median.	CMF ID 7789	0.81 (KABC)	0.679 (HSM Table 10-3)	0.871
Add on-street parking.	CMF ID 9253	0.48 (vehicle/pedestrian)	0.005 (HSM Table 12-8)	0.997
Add pedestrian signal heads and pushbuttons.	CMF ID 9025	F(Major Street AADT)	–	F(Major Street AADT)
Add pedestrian refuge island.	No Applicable CMF	–	–	–
Add pedestrian warning signs.	No Applicable CMF	–	–	–
Add school crossing warning signs.	No Applicable CMF	–	–	–
Add pull-out parking area for school.	No Applicable CMF	–	–	–
Add sidewalk.	CMF ID 10221	1.53 (vehicle/bicycle)	0.004 (HSM Table 12-9)	1.002
Add TWLTL.	CMF ID 2341	0.797	–	0.797
Add yield pavement markings (sharks teeth).	Included in the Add "Yield Here to Pedestrians" sign CMF	–	–	–
Convert all-way stop control to roundabout.	CMF ID 209	0.65	–	0.65
Convert from minor-road stop control to traffic signal.	CMF ID 5527	0.502	–	0.502
Reduce lane width.	CMF ID 8151	F(AADT)	–	F(AADT)

– not applicable

Analysis Results

The Bench Boulevard case study analysis results are shown in table 44. The safety effectiveness evaluation without volume adjustment (E1) showed a two percent crash reduction in the study area. The predictive analysis (P1) results of 23–31 percent overpredicted this crash reduction.

Based on the before-period traffic volume trend, the after-period no-build volumes were expected to mostly decrease without the Complete Streets project. This overall projected volume decrease led to an estimated crash increase for the Complete Streets project of two percent for E2 compared to the two percent reduction for E1. E2 in this case assigns the Complete Streets project as the cause for the volume increase and corresponding crash increase.

In other words, observed after-period vehicle volumes increased rather than decreased as predicted, as the improvements to the corridor made the corridor a more attractive facility for both vehicle and nonmotorized traffic. With such an upgrade in the facility that attracts more vehicle volume, continuing the before-period traffic volume trend “penalizes” the Complete Streets project for attracting more traffic. If a more advanced traffic forecasting method was used to show that the volume increases would have occurred even on the older facility, the safety effectiveness evaluation would have shown a 27 percent crash reduction (shown in table 44 as E3), much closer to the predictive analysis results.

For both P1 and P2, the dominant effect and dominant common residuals methods of CMF combination performed very similarly and somewhat better than the multiplicative method.

Table 44. Bench Boulevard case study analysis results.

Analysis Method	CMF Combination Method	Crash Reduction	Percent Reduction
E1	–	2	2
E2	–	-1.5	-2
E3	–	27.2	30
P1	Dominant Effect	20.8	23
	Multiplicative	28.2	31
	Dominant Common Residuals	21.6	24
P2	Dominant Effect	24.1	27
	Multiplicative	31.3	35
	Dominant Common Residuals	24.8	28

Note: – indicates that the safety effectiveness evaluations do not rely on CMFs and thus do not use CMF combination methods.

Fletcher Avenue Complete Streets Project, Hillsborough County

The Fletcher Avenue Complete Streets project is located on a 1.5-mi section of East Fletcher Avenue, an urbanized arterial roadway in Hillsborough County just outside the Tampa city limits. The section runs from the intersection with North Nebraska Avenue on the west end to Bruce B. Downs Boulevard on the east end. A mix of residential and retail land uses surrounds the project corridor. The project involved adding five midblock pedestrian crossings with RRFBs, one midblock pedestrian crossing with a traffic control signal, LED lighting, pedestrian refuge islands, bike lanes, raised traffic separators, and median landscaping while also reducing the speed limit along Fletcher Avenue from 45 mph to 35 mph. Additionally, the project included media outreach, education, and enforcement components. Figure 131 shows the project extents and the various intersections and segments included.

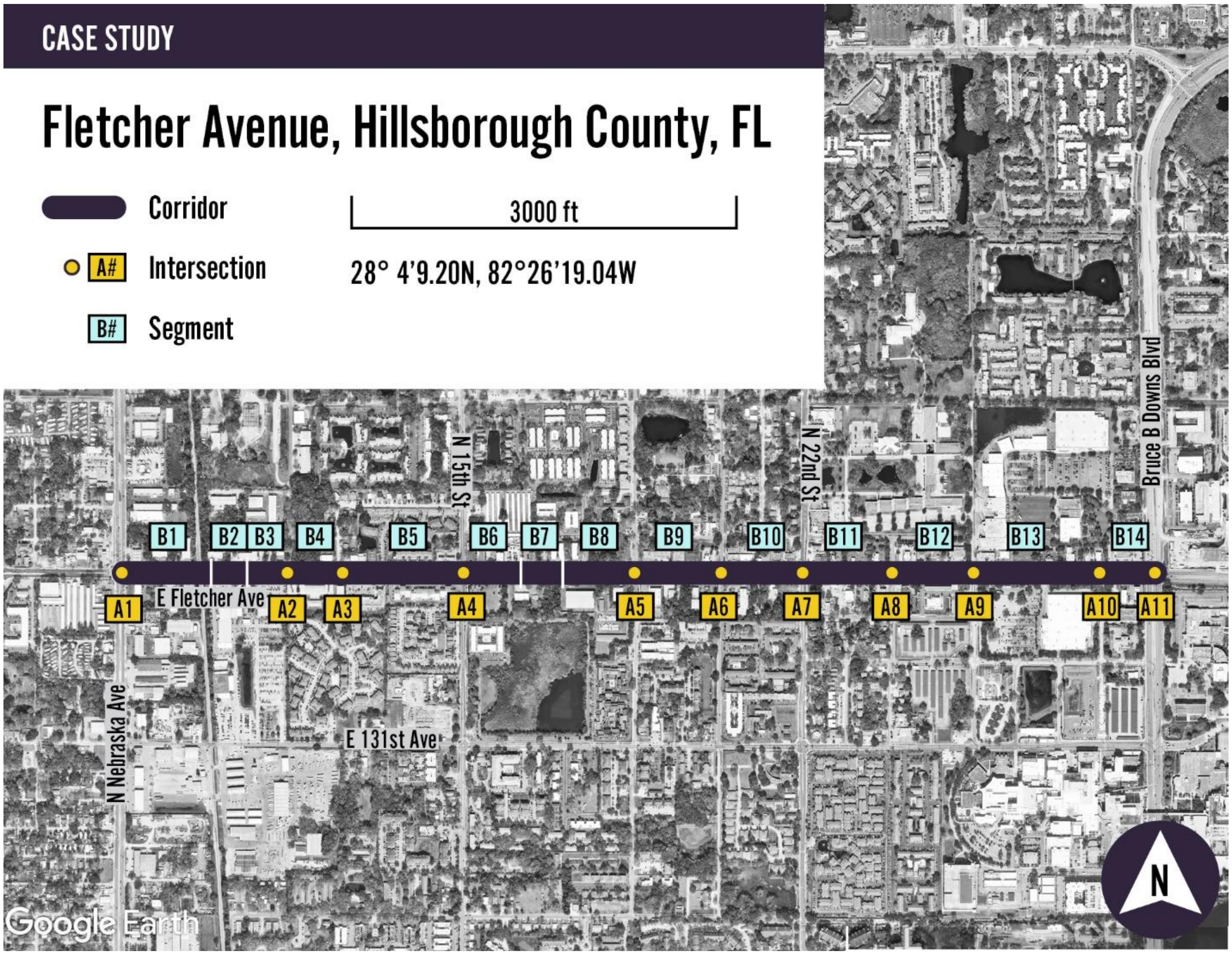

Figure 131. Graphic. Fletcher Avenue project location.

Prior to its construction in 2014 and early 2015, Fletcher Avenue through the project corridor was a five-lane cross-section with two through lanes in each direction and a two-way left-turn lane. The project mostly replaced the center turn lane with raised median and directional left-turn lanes. Figure 132 through figure 137 show before and after views of the project corridor.

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Figure 132. Photograph. Cross-section of Fletcher Avenue pre-construction in 2013 (Google Maps 2013a).

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Figure 133. Photograph. Cross-section of Fletcher Avenue post-construction in 2022 (Google Maps 2022c).

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Figure 134. Photograph. Segment between North 23rd Street and Livingston Avenue pre-construction in 2013 (Google Maps 2013b).

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Figure 135. Photograph. Segment between North 23rd Street and Livingston Avenue with midblock pedestrian crossing with RRFBs post-construction in 2022 (Google Maps 2022d).

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Figure 136. Photograph. Commercial driveway pre-construction in 2013 (Google Maps 2013c).

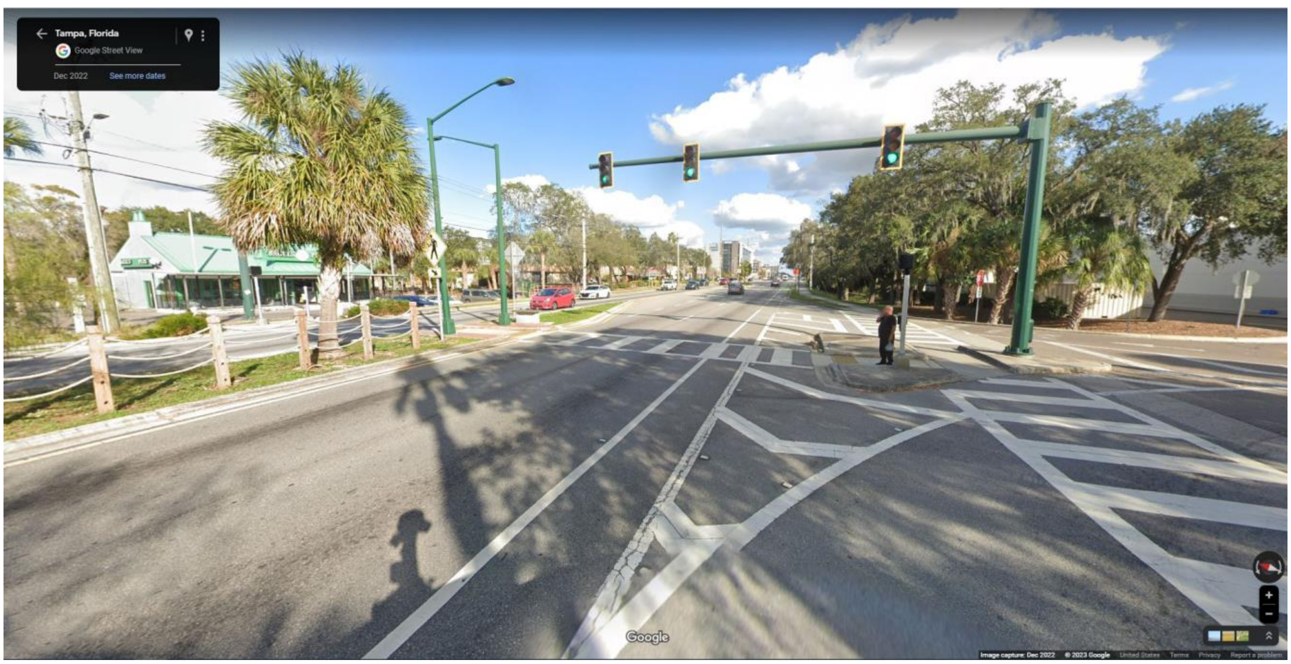

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Figure 137. Photograph. Commercial driveway with midblock pedestrian crossing and traffic signal post-construction in 2022 (Google Maps 2022e).

As shown in figure 131, the research team segmented the project corridor into 11 intersections (A1–A11) and 14 segments (B1–B14). Table 45 and table 46 summarize the segments and intersections in the study area.

Table 45. Summary of intersections along Fletcher Avenue.

Intersection ID	Intersecting Road Name	Intersection Type	
		Before Construction	After Construction
A1	N Nebraska Ave	4SG	4SG
A2	N 12th St	4ST	4ST
A3	Cecilia Ave	3ST	3ST
A4	N 15th St	4SG	4SG
A5	N 19th St	4ST	4ST
A6	N 20th St	4ST	4ST
A7	N 22nd St	4SG	4SG
A8	N 23rd St	4ST	4ST
A9	Livingston Ave	4SG	4SG
A10	N 29th St	3ST	3ST
A11	Bruce B Downs Blvd	4SG	4SG

Table 46. Summary of segments along Fletcher Avenue.

Segment ID	Segment Limits	Segment Length (mi)	Roadway Type	
			Before Construction	After Construction
B1	from N Nebraska Ave to east of RR crossing	0.14	5T	4D*
B2	from east of RR crossing to west of N 12th St	0.06	5T	5T
B3	from west of N 12th St to N 12th St	0.06	5T	4D*
B4	from N 12th St to Cecilia Ave	0.07	5T	4D*
B5	from Cecilia Ave to N 15th St	0.18	5T	4D*
B6	from N 15th St to east of N 15th St	0.08	5T	4D*
B7	from east of N 15th St to Winward Dr driveway	0.05	5T	5T
B8	from Winward Dr driveway to N 19th St	0.13	5T	4D*
B9	from N 19th St to N 20th St	0.13	5T	4D*
B10	from N 20th St to N 22nd St	0.12	5T	4D*
B11	from N 22nd St to N 23rd St	0.13	5T	4D*
B12	from N 23rd St to Livingston Ave	0.12	5T	4D*
B13	from Livingston Ave to N 29th St	0.19	5T	4D*
B14	from N 29th St to Bruce B Downs Blvd	0.08	4U	4D*
-	**Total Length**	**1.54**	-	-

Note: * indicates a change in roadway type between the before and after construction periods; – = not applicable.

Crash Data

The research team obtained crash data from the Florida Department of Transportation's (FDOT's) Signal Four Analytics system (FDOT 2023). Due to recent FDOT purges of its older data, the Signal Four Analytics database contained data only going back to 2012. The research team downloaded all crash data on the corridor from 2012 through 2021. Because the download only provided 2 yr of crash data for the before period, the research team scaled the before period crash totals by multiplying the totals by three to provide an even comparison with the after-period crash totals. Table 47 summarizes the crash data by intersection or segment and separates crash counts by type and severity. In total, 1,986 crashes occurred in the before period and 1,776 crashes occurred in the after period.

Table 47. Before and after crash data by segment or intersection for Fletcher Avenue.

Location ID	Before Construction Crashes (2012–2013)*							After Construction Crashes (2016–2021)						
	SV-KABC	SV-O	MV-KABC	MV-O	Ped-all	Bike-all	Total	SV-KABC	SV-O	MV-KABC	MV-O	Ped-all	Bike-all	Total
A1	*3*	*0*	*84*	*84*	*9*	*9*	***189***	1	2	70	98	5	1	**177**
A2	*0*	*0*	*9*	*27*	*0*	*0*	***36***	0	1	10	18	0	1	**30**
A3	*0*	*0*	*6*	*9*	*0*	*0*	***15***	0	1	0	3	0	0	**4**
A4	*0*	*3*	*27*	*54*	*6*	*6*	***96***	0	0	28	58	9	2	**97**
A5	*3*	*0*	*27*	*12*	*0*	*3*	***45***	0	0	22	36	2	2	**62**
A6	*3*	*0*	*12*	*9*	*3*	*3*	***30***	1	0	14	29	0	2	**46**
A7	*0*	*0*	*24*	*21*	*0*	*3*	***48***	0	0	25	54	4	4	**87**
A8	*0*	*0*	*3*	*12*	*0*	*0*	***15***	0	0	12	25	2	0	**39**
A9	*0*	*0*	*27*	*57*	*3*	*0*	***87***	0	1	36	71	2	3	**113**
A10	*0*	*0*	*6*	*9*	*0*	*0*	***15***	0	1	1	10	1	0	**13**
A11	*0*	*0*	*60*	*105*	*6*	*0*	***171***	2	0	42	163	1	3	**211**
B1	*0*	*0*	*60*	*117*	*6*	*3*	***186***	0	1	46	136	0	2	**185**
B2	*3*	*0*	*21*	*27*	*0*	*0*	***51***	1	0	7	20	0	0	**28**
B3	*3*	*0*	*12*	*18*	*0*	*3*	***36***	0	2	9	12	1	0	**24**
B4	*3*	*0*	*15*	*21*	*3*	*3*	***45***	0	3	8	18	1	0	**30**
B5	*0*	*6*	*48*	*84*	*12*	*6*	***156***	3	1	28	61	3	2	**98**
B6	*0*	*0*	*30*	*48*	*3*	*0*	***81***	1	1	5	24	2	1	**34**
B7	*0*	*6*	*0*	*15*	*0*	*0*	***21***	0	2	12	18	6	3	**41**
B8	*0*	*0*	*0*	*27*	*6*	*0*	***33***	0	2	9	23	3	3	**40**
B9	*0*	*0*	*30*	*27*	*6*	*0*	***63***	0	2	23	31	3	5	**64**
B10	*0*	*0*	*30*	*39*	*3*	*3*	***75***	1	1	18	33	1	0	**54**
B11	*0*	*3*	*45*	*120*	*3*	*12*	***183***	1	0	18	50	2	6	**77**
B12	*3*	*0*	*18*	*42*	*0*	*0*	***63***	0	1	22	42	2	4	**71**
B13	*0*	*0*	*51*	*93*	*9*	*3*	***156***	0	2	10	31	3	0	**46**
B14	*0*	*0*	*12*	*75*	*3*	*0*	***90***	2	1	17	80	3	2	**105**
Total	***21***	***18***	***657***	***1,152***	***81***	***57***	***1,986***	**13**	**25**	**492**	**1144**	**56**	**46**	**1,776**

Note: * Before-period crash data was available from FDOT Signal Four Analytics for 2012–2013. These crash totals were multiplied by three to provide even comparison with the after period. Scaled crash totals shown in italics.

Volume Data

The research team obtained vehicle volume data from FDOT's Florida Traffic Online tool, which includes historical counts from both portable and permanent traffic monitoring sites and segment ADT estimates (FDOT 2021). Figure 138 shows the data availability and count station locations in the vicinity of the study area, and table 48 and table 49 summarize the data for the intersections and segments along the corridor.

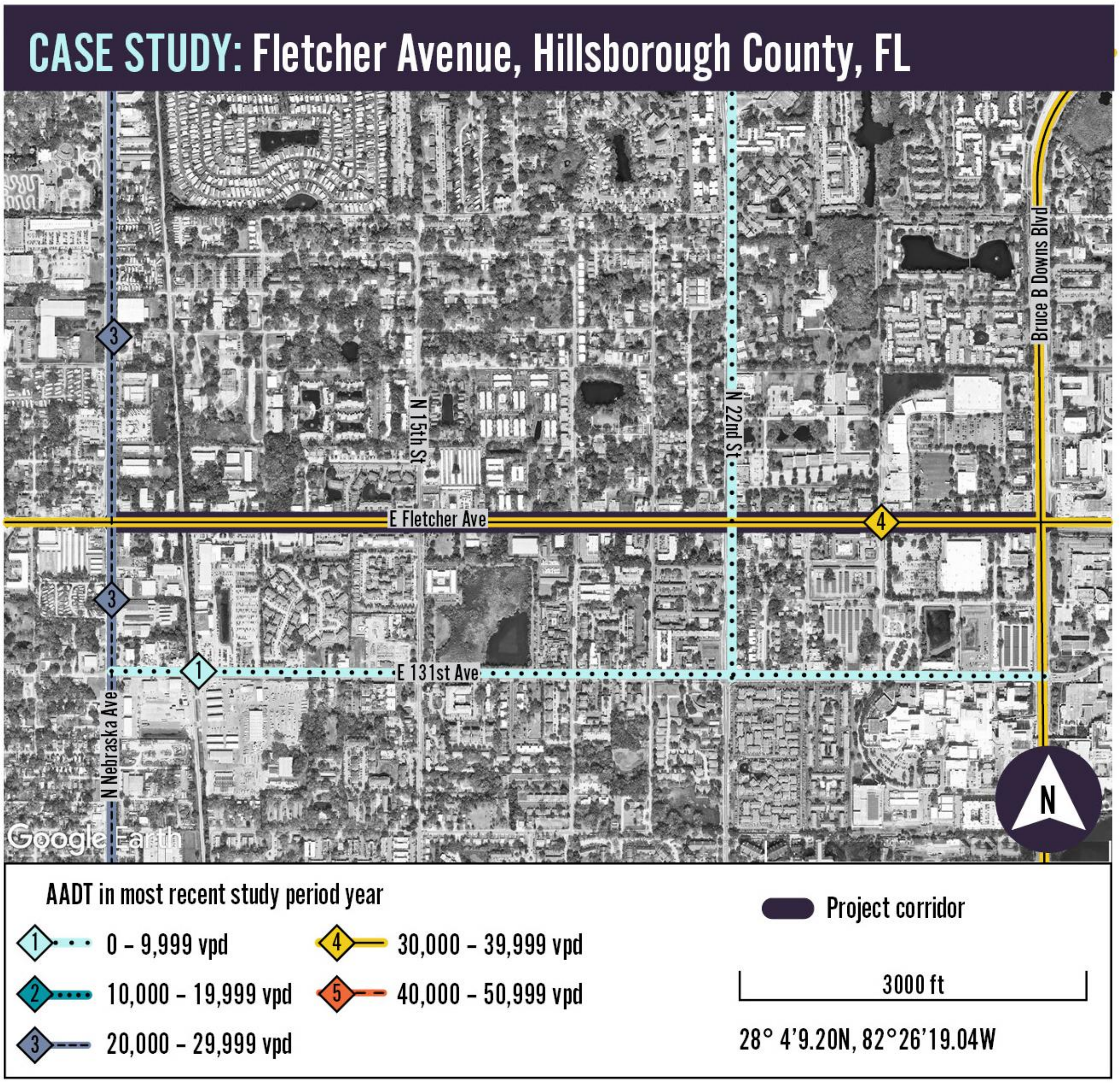

Figure 138. Graphic. Location of AADT count stations and segments in the Fletcher Avenue project area.

Table 48. AADT for intersections along Fletcher Avenue.

Int. ID	Before Construction Study Corridor AADT/Intersecting Road AADT (veh/day)						After Construction Study Corridor AADT/Intersecting Road AADT (veh/day)				
	2009	**2010**	**2011**	**2012**	**2013**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**
A1	44,000 / 24,500	42,000 / 26,500	46,500 / 27,000	44,000 / 24,000	41,500 / 25,000	43,000 / 24,000	44,500 / 25,000	41,500 / 24,000	42,500 / 25,000	39,000 / 22,500	44,500 / 27,000
A2	44,000 / **6,998**	42,000 / **6,998**	46,500 / **6,998**	44,000 / **6,998**	41,500 / **6,998**	43,000 / **6,991**	44,500 / **7,184**	41,500 / **6,998**	42,500 / **7,143**	39,000 / **6,710**	44,500 / **7,984**
A3	44,000 / **6,998**	42,000 / **6,998**	46,500 / **6,998**	44,000 / **6,998**	41,500 / **6,998**	43,000 / **6,991**	44,500 / **7,184**	41,500 / **6,998**	42,500 / **7,143**	39,000 / **6,710**	44,500 / **7,984**
A4	44,000 / *8,296*	42,000 / 8,296	46,500 / *8,296*	44,000 / *8,296*	41,500 / *8,296*	43,000 / **8,182**	44,500 / **8,467**	41,500 / **7,896**	42,500 / **8,087**	39,000 / **7,421**	44,500 / **8,467**
A5	44,000 / **6,998**	42,000 / **6,998**	46,500 / **6,998**	44,000 / **6,998**	41,500 / **6,998**	43,000 / **6,991**	44,500 / **7,184**	41,500 / **6,998**	42,500 / **7,143**	39,000 / **6,710**	44,500 / **7,984**
A6	44,000 / **6,998**	42,000 / **6,998**	46,500 / **6,998**	44,000 / **6,998**	41,500 / **6,998**	43,000 / **6,991**	44,500 / **7,184**	41,500 / **6,998**	42,500 / **7,143**	39,000 / **6,710**	44,500 / **7,984**
A7	44,000 / *5,700*	42,000 / *5,700*	46,500 / 5,700	44,000 / 5,700	41,500 / 5,700	43,000 / 5,800	44,500 / 5,900	41,500 / 6,100	42,500 / 6,200	39,000 / 6,000	44,500 / 7,500
A8	44,000 / **6,998**	42,000 / **6,998**	46,500 / **6,998**	44,000 / **6,998**	41,500 / **6,998**	43,000 / **6,991**	44,500 / **7,184**	41,500 / **6,998**	42,500 / **7,143**	39,000 / **6,710**	44,500 / **7,984**
A9	44,000 / **6,998**	42,000 / **6,998**	46,500 / **6,998**	44,000 / **6,998**	41,500 / **6,998**	43,000 / **6,991**	44,500 / **7,184**	41,500 / **6,998**	42,500 / **7,143**	39,000 / **6,710**	44,500 / **7,984**
A10	44,000 / **6,998**	42,000 / **6,998**	46,500 / **6,998**	44,000 / **6,998**	41,500 / **6,998**	43,000 / **6,991**	44,500 / **7,184**	41,500 / **6,998**	42,500 / **7,143**	39,000 / **6,710**	44,500 / **7,984**
A11	44,000 / *43,000*	42,000 / *43,000*	46,500 / 43,000	44,000 / 43,000	41,500 / 43,000	43,000 / 44,000	44,500 / 45,000	41,500 / 46,500	42,500 / 49,500	39,000 / 49,500	44,500 / 50,500

Note: Italic text indicates interpolation was used to fill gaps. Bold text indicates proportions were used to fill gaps. AADT along the study corridor is displayed first in the table and may not necessarily be the major road AADT.

Table 49. AADT for segments along Fletcher Avenue.

Segment ID	Before Construction AADT (veh/day)					After Construction Major AADT (veh/day)					
	2009	**2010**	**2011**	**2012**	**2013**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**
B1	44,000	42,000	46,500	44,000	41,500	43,000	44,500	41,500	42,500	39,000	44,500
B2	44,000	42,000	46,500	44,000	41,500	43,000	44,500	41,500	42,500	39,000	44,500
B3	44,000	42,000	46,500	44,000	41,500	43,000	44,500	41,500	42,500	39,000	44,500
B4	44,000	42,000	46,500	44,000	41,500	43,000	44,500	41,500	42,500	39,000	44,500
B5	44,000	42,000	46,500	44,000	41,500	43,000	44,500	41,500	42,500	39,000	44,500
B6	44,000	42,000	46,500	44,000	41,500	43,000	44,500	41,500	42,500	39,000	44,500
B7	44,000	42,000	46,500	44,000	41,500	43,000	44,500	41,500	42,500	39,000	44,500
B8	44,000	42,000	46,500	44,000	41,500	43,000	44,500	41,500	42,500	39,000	44,500
B9	44,000	42,000	46,500	44,000	41,500	43,000	44,500	41,500	42,500	39,000	44,500
B10	44,000	42,000	46,500	44,000	41,500	43,000	44,500	41,500	42,500	39,000	44,500
B11	44,000	42,000	46,500	44,000	41,500	43,000	44,500	41,500	42,500	39,000	44,500
B12	44,000	42,000	46,500	44,000	41,500	43,000	44,500	41,500	42,500	39,000	44,500
B13	44,000	42,000	46,500	44,000	41,500	43,000	44,500	41,500	42,500	39,000	44,500
B14	44,000	42,000	46,500	44,000	41,500	43,000	44,500	41,500	42,500	39,000	44,500

Note: Italic text indicates interpolation was used to fill gaps. Bold text indicates proportions were used to fill gaps. AADT along the study corridor is displayed first in the table and may not necessarily be the major road AADT.

Treatments and CMFs Applied

The research team used project documentation available from Plan Hillsborough, the Hillsborough County Transportation Planning Organization, and a desktop review of satellite and Street View imagery to identify the treatments applied to each segment and intersection along the project corridor. Table 50 summarizes these treatments.

Table 50. Treatments applied to each segment and intersection in the Fletcher Avenue project.

Location ID	Applied Treatment
A1	Enhance lighting
A2	Enhance lighting
A3	Enhance lighting
A4	Add median, enhance lighting
A5	Enhance lighting
A6	Enhance lighting
A7	Enhance lighting
A8	Enhance lighting
A9	Add median, enhance lighting
A10	Enhance lighting
A11	Enhance lighting
B1	Add bike lane, decrease lane width, reduce speed limit, enhance lighting
B2	Add bike lane, decrease lane width, reduce speed limit, enhance lighting
B3	Add median, add bike lane, decrease lane width, reduce speed limit, enhance lighting
B4	Add median, add bike lane, decrease lane width, reduce speed limit, enhance lighting, improve signing
B5	Add midblock crossing, add RRFB, add pedestrian refuge island, add Danish offset (Redmon 2011) to refuge island, add median, add bike lane, decrease lane width, reduce speed limit, enhance lighting, improve signing
B6	Add median, add bike lane, decrease lane width, reduce speed limit, enhance lighting, improve signing
B7	Add bike lane, decrease lane width, reduce speed limit, enhance lighting, improve signing
B8	Add midblock crossing, add RRFB, add pedestrian refuge island, add Danish offset (Redmon 2011) to refuge island, add median, add bike lane, decrease lane width, reduce speed limit, enhance lighting, improve signing
B9	Add midblock crossing, add RRFB, add pedestrian refuge island, add Danish offset (Redmon 2011) to refuge island, add median, add bike lane, decrease lane width, reduce speed limit, enhance lighting, improve signing
B10	Add median, add bike lane, decrease lane width, reduce speed limit, enhance lighting
B11	Add midblock crossing, add RRFB, add pedestrian refuge island, add Danish offset (Redmon 2011) to refuge island, add median, add bike lane, decrease lane width, reduce speed limit, enhance lighting, improve signing

Location ID	Applied Treatment
B12	Add midblock crossing, add RRFB, add pedestrian refuge island, add Danish offset (Redmon 2011) to refuge island, add median, add bike lane, decrease lane width, reduce speed limit, enhance lighting, improve signing
B13	Add midblock crossing, add pedestrian traffic signal, add pedestrian refuge island, add median, add bike lane, decrease lane width, reduce speed limit, enhance lighting, improve signing
B14	Add median, add bike lane, decrease lane width, reduce speed limit, enhance lighting

Table 51 displays the CMFs that were selected for use in the analysis.

Table 51. Selected CMFs for Fletcher Avenue case study.

Treatment Name	CMF ID/Source	CMF Value (Crash/Severity Type)	Proportion (Source)	Total Crash CMF
Improve existing street lighting	CMF ID 11027	0.581 (nighttime)	0.41 (HSM Table 12-23)	0.828
Add LED lighting at midblock crosswalk	CMF ID 436	0.97 (nighttime)	0.41 (HSM Table 12-23)	0.988
Add median (minor)–4SG	CMF ID 10984	0.72 (KABC)	0.66 (HSM Table 10-5)	0.815
Add median (major)–3ST	CMF ID 10985	0.58 (KABC)	0.585 (HSM Table 10-5)	0.754
Add median (major)–4ST	CMF ID 10985	0.58 (KABC)	0.569 (HSM Table 10-5)	0.761
Add median (major)–4SG	CMF ID 10985	0.58 (KABC)	0.66 (HSM Table 10-5)	0.723
Add median	CMF ID 7789	0.81 (KABC)	0.679 (HSM Table 10-3)	0.871
Add bike lane	CMF ID 7840	0.42 (vehicle/bicycle)	0.005 (HSM Table 12-9)	0.997
Decrease lane width	CMF ID 8157	1.28	–	1.28
Reduce speed limit	CMF ID 1239	0.96	–	0.96
Improve signing	No Applicable CMF	–	–	–
Add midblock crossing	CMF ID 11181	0.82 (vehicle/pedestrian)	0.019 (HSM Table 12-8)	0.997
Add RRFB	CMF ID 9024	0.526 (vehicle/pedestrian)	0.019 (HSM Table 12-8)	0.991
Add pedestrian refuge island	CMF ID 175	0.54 (vehicle/pedestrian)	0.019 (HSM Table 12-8)	0.991

Treatment Name	CMF ID/Source	CMF Value (Crash/Severity Type)	Proportion (Source)	Total Crash CMF
Add Danish offset to refuge island (Redmon 2011)	No Applicable CMF	–	–	–
Add pedestrian traffic signal	CMF ID 8480	F (Major Road AADT, Minor-Road AADT, Area Type, Number of Years Since Treatment Installation)	–	F (Major Road AADT, Minor-Road AADT, Area Type, Number of Years Since Treatment Installation)

– not applicable

Analysis Results

Table 52 shows the case study analysis results. The safety effectiveness evaluation without volume adjustment (E1) showed an 11 percent crash reduction in the study area. The predictive analysis (P1) results of 20–26 percent overpredicted this crash reduction.

Based on the before-period traffic volume trend, the after-period volumes were expected to mostly decrease or remain constant. This overall projected volume decrease led to a lower crash reduction for E2 compared to E1, as the E2 calculation took away the credit for the crash reduction that belonged to the expected reduction in crash volumes based on the volume trend prior to construction of the project.

For both P1 and P2, the dominant effect and multiplicative methods of CMF combination performed closer to the safety effectiveness evaluation. This performance could be due to all CMFs being less than one, whereas the dominant common residuals method seemed to perform better when some CMFs are greater than one.

Observed after period vehicle volumes decreased somewhat but not as much as predicted in many cases.

Table 52. Fletcher Avenue case study analysis results.

Analysis Method	CMF Combination Method	Crash Reduction	Percent Reduction
E1	–	210	11
E2	–	98.2	5
E3	–	160.6	8
P1	Dominant Effect	394.2	20

Analysis Method	CMF Combination Method	Crash Reduction	Percent Reduction
	Multiplicative	392.0	20
	Dominant Common Residuals	518.6	26
P2	Dominant Effect	484.1	24
	Multiplicative	482.5	24
	Dominant Common Residuals	601.5	30

Note: – indicates that the safety effectiveness evaluations do not rely on CMFs and thus do not use CMF combination methods.

Highways 28, 29, and 104 Project, Glenwood

Highways 28, 29, and 104 is reconstruction project stretching 1 mi along the rural principal arterial known as Minnesota Avenue W in Glenwood, shown in figure 139. The project reconstructed the roadway and included a Complete Streets redesign in the downtown area to improve safety, provide opportunities for active transportation, and offer economic benefits. The Complete Streets treatments include bike lanes, a Road Diet, adding or improving sidewalks, curb extensions, landscaping, enhanced lighting, street furniture, and improved street parking.

© 2022 Google Earth. Modified by authors to highlight the project corridor, intersections, and segments.

Figure 139. Graphic. Highways 28, 29, and 104 project location.

Figure 140 and figure 141 show cross-sections of the project location before and after construction, which occurred in 2018.

Figure 140. Photograph. Cross-section of Highways 28, 29, and 104 pre-construction in 2015 (Google Maps 2015).

Figure 141. Photograph. Cross-section of Highways 28, 29, and 104 post-construction in 2021 (Google Maps 2021c).

As shown in figure 139, the research team segmented the corridor into 16 intersections (A1–A16) and 15 segments (B1–B15) and collected data by segment and intersection. Table 53 and table 54 display summaries of the intersections and segments in the study area.

Table 53. Summary of intersections along Highways 28, 29, and 104.

Intersection ID	Intersecting Road Name	Intersection Type	
		Before Construction	After Construction
A1	4th St NW	4 ST	4 ST
A2	Minnesota Ave W	3 ST	3 ST
A3	2nd St SW	3 ST	3 ST
A4	1st St SW/NW	4 ST	4 ST
A5	Franklin St S	4 SG	4 SG
A6	1st St SE/NE	4 ST	4 ST
A7	2nd St SE/NE	4 ST	4 ST
A8	3rd St SE/NE	4 ST	4 ST
A9	4th St SE/NE	4 ST	4 ST
A10	5th St NE	3 ST	3 ST
A11	5th St SE	3 ST	3 ST
A12	6th St NE	3 ST	3 ST
A13	6th St SE	3 ST	3 ST
A14	7th St NE	3 ST	3 ST
A15	Minnesota Ave E (connection)	3 ST	3 ST
A16	Highway 28 (connection)	3 ST	3 ST

Table 54. Summary of segments along Highways 28, 29, and 104.

Segment ID	Segment Limits	Segment Length (mi)	Roadway Type	
			Before Construction	After Construction
B1	4th St NW to Minnesota Ave W	0.12	2U	2D*
B2	Minnesota Ave W to 2nd St SW	0.08	4U	3T*
B3	2nd St SW to 1st St SW	0.08	4U	3T*
B4	1st St SW to Franklin St S	0.08	4U	3T*
B5	Franklin St S to 1st St SE	0.08	4U	3T*
B6	1st St SE to 2nd St SE	0.08	4U	3T*
B7	2nd St SE to 3rd St SE	0.08	4U	3T*
B8	3rd St SE to 4th St SE	0.08	3U	3T*
B9	4th St SE to 5th St NE	0.08	3U	2U*
B10	5th St NE to 5th St SE	0.03	3U	3U
B11	5th St SE to 6th St NE	0.04	3U	3U
B12	6th St NE to 6th St SE	0.04	3U	3U
B13	6th St SE to 7th St NE	0.04	3U	3U
B14	7th St NE to Minnesota Ave E (connection)	0.04	2U	2U
B15	7th St NE to Minnesota Ave E (connection)	0.05	3U	3U
–	**Total Length**	**1.00**	–	–

Note: * indicates a change in roadway type between the before and after construction periods; – = not applicable.

Crash Data

The Minnesota Department of Transportation (MnDOT) provided crash data for the before period (2013–2017) and after period (2019–2022). Because the before period is 5 yr and the after period is 4 yr, the research team scaled the after-period crash totals by multiplying the totals by 1.25 to provide an even comparison with the before-period crash totals.

Table 55 summarizes the crash data by intersection or segment and separates crash counts by type and severity. In total, 48 crashes occurred in the before period and 24 crashes occurred in the after period.

Table 55. Before and after crash data by segment or intersection for Highways 28, 29, and 104.

Location ID	Before Construction Crashes (2013-2017)							After Construction Crashes (2019-2022)*						
	SV-KABC	SV-O	MV-KABC	MV-O	Ped-all	Bike-all	Total	SV-KABC	SV-O	MV-KABC	MV-O	Ped-all	Bike-all	Total
B1	0	0	0	2	0	0	**2**	*0*	*0*	*0*	*3.75*	*0*	*0*	***3.75***
B2	0	0	0	3	0	0	**3**	*0*	*0*	*0*	*1.25*	*0*	*0*	***1.25***
B3	0	0	0	0	0	0	**0**	*0*	*0*	*0*	*2.5*	*0*	*0*	***2.5***
B4	0	0	0	3	1	0	**4**	*0*	*0*	*0*	*2.5*	*0*	*0*	***2.5***
B5	0	1	1	13	0	0	**15**	*1.25*	*0*	*2.5*	*5*	*0*	*0*	***8.75***
B6	0	0	1	4	1	0	**6**	*0*	*0*	*0*	*0*	*0*	*0*	***0***
B7	0	0	1	0	0	0	**1**	*0*	*0*	*0*	*0*	*0*	*0*	***0***
B8	1	0	0	2	0	0	**3**	*0*	*0*	*0*	*0*	*0*	*0*	***0***
B9	0	0	0	0	0	0	**0**	*0*	*0*	*0*	*1.25*	*0*	*0*	***1.25***
B10	0	0	1	0	0	0	**1**	*0*	*0*	*0*	*0*	*0*	*0*	***0***
B11	0	0	0	1	0	0	**1**	*0*	*0*	*0*	*0*	*0*	*0*	***0***
B12	0	0	0	0	0	0	**0**	*0*	*0*	*0*	*0*	*0*	*0*	***0***
B13	0	0	1	0	0	0	**1**	*0*	*0*	*0*	*1.25*	*0*	*0*	***1.25***
B14	0	0	0	2	0	0	**2**	*1.25*	*0*	*0*	*0*	*0*	*0*	***1.25***
B15	0	0	0	0	0	0	**0**	*0*	*0*	*0*	*0*	*0*	*0*	***0***
A1	0	0	0	0	0	0	**0**	*0*	*0*	*0*	*0*	*0*	*0*	***0***
A2	0	0	0	0	0	0	**0**	*0*	*0*	*0*	*0*	*0*	*0*	***0***
A3	0	0	0	0	0	0	**0**	*0*	*0*	*0*	*0*	*0*	*0*	***0***
A4	0	0	0	0	0	0	**0**	*0*	*0*	*0*	*0*	*0*	*0*	***0***
A5	0	0	0	2	0	0	**2**	*0*	*0*	*1.25*	*1.25*	*0*	*0*	***2.5***
A6	0	0	0	2	0	0	**2**	*0*	*0*	*0*	*3.75*	*0*	*0*	***3.75***
A7	0	0	0	0	0	0	**0**	*0*	*1.25*	*0*	*0*	*0*	*0*	***1.25***
A8	0	0	0	1	0	0	**1**	*0*	*0*	*0*	*0*	*0*	*0*	***0***
A9	0	0	0	1	0	0	**1**	*0*	*0*	*0*	*0*	*0*	*0*	***0***
A10	0	0	0	0	0	0	**0**	*0*	*0*	*0*	*0*	*0*	*0*	***0***
A11	0	0	0	0	0	0	**0**	*0*	*0*	*0*	*0*	*0*	*0*	***0***
A12	0	1	0	0	0	0	**1**	*0*	*0*	*0*	*0*	*0*	*0*	***0***
A13	0	0	0	0	0	0	**0**	*0*	*0*	*0*	*0*	*0*	*0*	***0***

Location ID	Before Construction Crashes (2013-2017)							After Construction Crashes (2019-2022)*						
	SV-KABC	**SV-O**	**MV-KABC**	**MV-O**	**Ped-all**	**Bike-all**	**Total**	**SV-KABC**	**SV-O**	**MV-KABC**	**MV-O**	**Ped-all**	**Bike-all**	**Total**
A14	0	0	0	0	0	0	**0**	*0*	*0*	*0*	*0*	*0*	*0*	***0***
A15	0	1	0	1	0	0	**2**	*0*	*0*	*0*	*0*	*0*	*0*	***0***
A16	0	0	0	0	0	0	**0**	*0*	*0*	*0*	*0*	*0*	*0*	***0***
Total	**1**	**3**	**5**	**37**	**2**	**0**	**48**	***2.5***	***1.25***	***3.75***	***22.5***	***0***	***0***	***30***

Note: * Because the before period was 5 yr and the after period was 4 yr, after-period crash totals were multiplied by 1.25 to provide even comparison with the before period. Scaled crash totals are shown in italics.

Volume Data

The research team used MnDOT's Traffic Mapping Application to obtain AADT values along the corridor for the before and after time periods (MnDOT 2023). Figure 142 displays the count stations along the study corridor. As shown on the map, AADT data are not available for the majority of minor intersecting roads. MnDOT also did not have AADT data for 2014, 2016, 2020, and 2022. The research team estimated AADT for 2014 by interpolating AADT values from 2013 and 2015, estimated 2016 by interpolating AADT values from 2015 and 2017, and estimated 2020 by interpolating AADT values from 2019 and 2021. The research team used the AADT value from 2021 as the AADT for 2022.

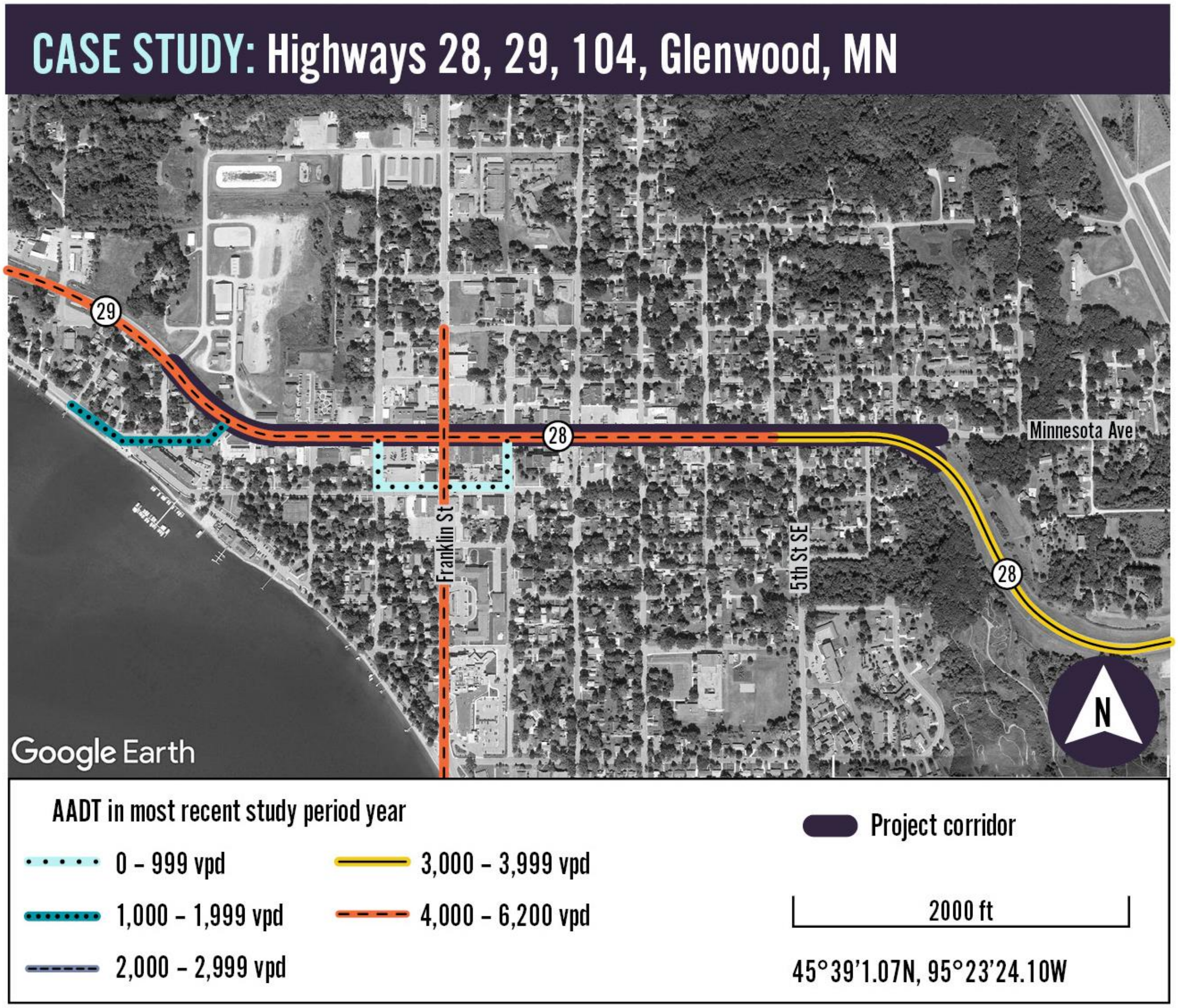

Figure 142. Graphic. Location of traffic count stations and segments in the Highways 28, 29, and 104 project area.

Table 56 and table 57 display the AADT for the intersection and segments, respectively.

Table 56. AADT for segments on Highways 28, 29, and 104.

Segment ID	Before Construction AADT (veh/day)					After Construction AADT (veh/day)			
	2013	2014	2015	2016	2017	2019	2020	2021	2022
B1	7,700	*7,500*	7,300	*7,600*	7,900	7,400	*6,766*	6,132	*6,132*
B2	7,700	*7,500*	7,300	*7,600*	7,900	7,400	*6,766*	6,132	*6,132*
B3	7,700	*7,500*	7,300	*7,600*	7,900	7,400	*6,766*	6,132	*6,132*
B4	7,700	*7,500*	7,300	*7,600*	7,900	7,400	*6,766*	6,132	*6,132*

Segment ID	Before Construction AADT (veh/day)					After Construction AADT (veh/day)			
	2013	2014	2015	2016	2017	2019	2020	2021	2022
B5	6,100	*6,150*	6,200	*6,450*	6,700	7,000	*6,114*	5,227	*5,227*
B6	6,100	*6,150*	6,200	*6,450*	6,700	7,000	*6,114*	5,227	*5,227*
B7	6,100	*6,150*	6,200	*6,450*	6,700	7,000	*6,114*	5,227	*5,227*
B8	6,100	*6,150*	6,200	*6,450*	6,700	7,000	*6,114*	5,227	*5,227*
B9	6,100	*6,150*	6,200	*6,450*	6,700	7,000	*6,114*	5,227	*5,227*
B10	5,100	*5,000*	4,900	*5,100*	5,300	4,950	*4,258*	3,565	*3,565*
B11	5,100	*5,000*	4,900	*5,100*	5,300	4,950	*4,258*	3,565	*3,565*
B12	5,100	*5,000*	4,900	*5,100*	5,300	4,950	*4,258*	3,565	*3,565*
B13	5,100	*5,000*	4,900	*5,100*	5,300	4,950	*4,258*	3,565	*3,565*
B14	5,100	*5,000*	4,900	*5,100*	5,300	4,950	*4,258*	3,565	*3,565*
B15	5,100	*5,000*	4,900	*5,100*	5,300	4,950	*4,258*	3,565	*3,565*

Note: Italic text indicates interpolation was used to fill gaps.

Table 57. AADT for intersections on Highways 28, 29, and 104.

Intersection Number	Before Construction Study Corridor AADT/Intersecting Road AADT (veh/day)					After Construction Study Corridor AADT/Intersecting Road AADT (veh/day)			
	2013	**2014**	**2015**	**2016**	**2017**	**2019**	**2020**	**2021**	**2022**
A1	7,700 / **2,082**	*7,500* / **2,109**	7,300 / **2,136**	*7,600* / **2,011**	7,900 / **1,886**	7,400 / **2,316**	*6,766* / **2,112**	6,132 / **1,911**	*6,132* / **1,911**
A2	7,700 / *1,350*	*7,500* / *1,350*	7,300 / 1,350	*7,600* / *1,350*	7,900 / *1,350*	7,400 / **1,314**	*6,766* / **1,202**	6,132 / **1,089**	*6,132* / **1,089**
A3	7,700 / **2,082**	*7,500* / **2,109**	7,300 / **2,136**	*7,600* / **2,011**	7,900 / **1,886**	7,400 / **2,316**	*6,766* / **2,112**	6,132 / **1,911**	*6,132* / **1,911**
A4	7,700 / *640*	*7,500* / *640*	7,300 / 640	*7,600* / *640*	7,900 / *640*	7,400 / 760	*6,766* / *760*	6,132 / *760*	*6,132* / *760*
A5	7,700 / 5,100	*7,500* / *5,250*	7,300 / 5,400	*7,600* / *4,900*	7,900 / 4,400	7,400 / 6,300	*6,766* / *5,555*	6,132 / 4,809	*6,132* / *4,809*
A6	6,100 / *980*	*6,150* / *980*	6,200 / 980	*6,450* / *980*	6,700 / *980*	7,000 / 840	*6,114* / *840*	5,227 / *840*	*5,227* / *840*
A7	6,100 / **1,649**	*6,150* / **1,729**	6,200 / **1,814**	*6,450* / **1,707**	6,700 / **1,600**	7,000 / **2,190**	*6,114* / **1,908**	5,227 / **1,629**	*5,227* / **1,629**
A8	6,100 / **1,649**	*6,150* / **1,729**	6,200 / **1,814**	*6,450* / **1,707**	6,700 / **1,600**	7,000 / **2,190**	*6,114* / **1,908**	5,227 / **1,629**	*5,227* / **1,629**
A9	6,100 / **1,649**	*6,150* / **1,729**	6,200 / **1,814**	*6,450* / **1,707**	6,700 / **1,600**	7,000 / **2,190**	*6,114* / **1,908**	5,227 / **1,629**	*5,227* / **1,629**
A10	6,100 / **1,649**	*6,150* / **1,729**	6,200 / **1,814**	*6,450* / **1,707**	6,700 / **1,600**	7,000 / **2,190**	*6,114* / **1,908**	5,227 / **1,629**	*5,227* / **1,629**
A11	5,100 / **1,379**	*5,000* / **1,406**	4,900 / **1,434**	*5,100* / **1,350**	5,300 / **1,266**	4,950 / **1,549**	*4,258* / **1,329**	3,565 / **1,111**	*3,565* / **1,111**
A12	5,100 / **1,379**	*5,000* / **1,406**	4,900 / **1,434**	*5,100* / **1,350**	5,300 / **1,266**	4,950 / **1,549**	*4,258* / **1,329**	3,565 / **1,111**	*3,565* / **1,111**
A13	5,100 / **1,379**	*5,000* / **1,406**	4,900 / **1,434**	*5,100* / **1,350**	5,300 / **1,266**	4,950 / **1,549**	*4,258* / **1,329**	3,565 / **1,111**	*3,565* / **1,111**
A14	5,100 / **1,379**	*5,000* / **1,406**	4,900 / **1,434**	*5,100* / **1,350**	5,300 / **1,266**	4,950 / **1,549**	*4,258* / **1,329**	3,565 / **1,111**	*3,565* / **1,111**

Intersection Number	Before Construction Study Corridor AADT/Intersecting Road AADT (veh/day)					After Construction Study Corridor AADT/Intersecting Road AADT (veh/day)			
	2013	2014	2015	2016	2017	2019	2020	2021	2022
A15	**5,100** / 1,379	**5,000** / 1,406	**4,900** / 1,434	**5,100** / 1,350	**5,300** / 1,266	**4,950** / 1,549	**4,258** / 1,329	**3,565** / 1,111	**3,565** / 1,111
A16	5,100 / **1,379**	*5,000* / **1,406**	4,900 / **1,434**	*5,100* / **1,350**	5,300 / **1,266**	4,950 / **1,549**	*4,258* / **1,329**	3,565 / **1,111**	*3,565* / **1,111**

Note: Italic text indicates interpolation was used to fill gaps. Bold text indicates proportions were used to fill gaps. AADT along the study corridor is displayed first in the table and may not necessarily be the major road AADT.

Treatments and CMFs Applied

The research team used project documents and Google Earth and Street View to identify the treatments applied to each segment and intersection, shown in table 58. Not all segments and intersections received all Complete Streets treatments.

Table 58. Treatments applied to each segment and intersection in the Highways 28, 29, and 104 project.

Location ID	Applied Treatment
A1	Realign intersection (realign one minor-road approach to remove offset between both minor-road approaches), add crosswalk, add sidewalk, add right-turn lane, enhance lighting, enhance marking
A2	Realign intersection (reduce skew), add crosswalk, add and enhance sidewalk, add right-turn lane, enhance lighting, improve pavement marking, add pedestrian/bicyclist warning signs
A3	Add crosswalk, enhance sidewalk, reduce number of lanes, add two-way left-turn lane, enhance lighting, improve pavement marking, add curb extension/bulb-out
A4	Enhance crosswalk, add and enhance sidewalks, reduce number of lanes, add two-way left-turn lane, enhance lighting, improve pavement marking, add curb extension/bulb-out
A5	Enhance crosswalk, enhance sidewalk, reduce number of lanes, add two-way left-turn lane, enhance lighting, improve pavement marking, add curb extension/bulb-out
A6	Add and enhance crosswalk, enhance sidewalk, reduce number of lanes, add two-way left-turn lane, enhance lighting, improve pavement marking, add curb extension/bulb-out
A7	Add and enhance crosswalk, enhance sidewalk, reduce number of lanes, add two-way left-turn lane, enhance lighting, improve pavement marking, add curb extension/bulb-out
A8	Add crosswalk, enhance sidewalk, reduce number of lanes, add two-way left-turn lane, enhance lighting, improve pavement marking, add curb extension/bulb-out
A9	Add crosswalk, enhance sidewalk, reduce number of lanes, add two-way left-turn lane, enhance lighting, improve pavement marking, add curb extension/bulb-out
A10	Add crosswalk, enhance sidewalk, enhance lighting, improve pavement marking
A11	Add crosswalk, enhance sidewalk, enhance lighting, improve pavement marking
A12	Add crosswalk, enhance sidewalk, enhance lighting, improve pavement marking
A13	Add crosswalk, enhance sidewalk, enhance lighting, improve pavement marking
A14	Add crosswalk, enhance sidewalk, enhance lighting, improve pavement marking
A15	Enhance sidewalk
A16	Add sidewalk, improve pavement marking
B1	Add sidewalk, enhance lighting, improve pavement marking, add median
B2	Add and enhance sidewalk, reduce number of lanes, add two-way left-turn lane, enhance lighting, improve pavement marking
B3	Enhance sidewalk, reduce number of lanes, add two-way left-turn lane, enhance lighting, improve pavement marking, add on-street parking, add separated bike lane
B4	Add and enhance sidewalks, reduce number of lanes, add two-way left-turn lane, enhance lighting, improve pavement marking, add on-street parking, add separated bike lane
B5	Enhance sidewalk, reduce number of lanes, add two-way left-turn lane, enhance lighting, improve pavement marking, add on-street parking, add separated bike lane

Location ID	Applied Treatment
B6	Enhance sidewalk, reduce number of lanes, add two-way left-turn lane, enhance lighting, improve pavement marking, add on-street parking, add separated bike lane
B7	Enhance sidewalk, reduce number of lanes, add two-way left-turn lane, enhance lighting, improve pavement marking, add on-street parking
B8	Enhance sidewalk, reduce number of lanes, add two-way left-turn lane, enhance lighting, improve pavement marking, add on-street parking
B9	Enhance sidewalk, reduce number of lanes, enhance lighting, improve pavement marking
B10	Enhance sidewalk, enhance lighting, improve pavement marking
B11	Enhance sidewalk, enhance lighting, improve pavement marking
B12	Enhance sidewalk, enhance lighting, improve pavement marking
B13	Enhance sidewalk, enhance lighting, improve pavement marking
B14	Enhance sidewalk
B15	Add crosswalk, add sidewalk, improve pavement marking

Table 59 displays the CMFs that were selected for use in the analysis.

Table 59. Selected CMFs for Highways 28, 29, and 104 case study.

Treatment Name	CMF ID/Source	CMF Value (Crash/Severity Type)	Proportion (Source)	Total Crash CMF
Added crosswalk	CMF ID 4123	0.6 (vehicle/pedestrian)	0.022 (HSM Table 12-8)	0.991
	CMF ID 4124	0.81	0.814 (HSM Table 10-6, 4-leg stop control)	0.845
			0.664 (HSM Table 10-6, 3-leg stop control)	0.874
Added sidewalk	CMF ID 10221	1.53 (vehicle/bicycle)	0.011 (HSM Table 12-9)	1.006
Added street parking	No Applicable CMF	–	–	–
Perform a Road Diet	CMF ID 2841	0.53	–	0.53
Changed minor roadway configuration at intersection	CMF ID 5188	F (Proposed Skew Angle, Existing Skew Angle)	–	F (Proposed Skew Angle, Existing Skew Angle)

Treatment Name	CMF ID/Source	CMF Value (Crash/Severity Type)	Proportion (Source)	Total Crash CMF
Curb extensions	No Applicable CMF	–	–	–
Improved lighting	CMF ID 11026	0.679 (nighttime)	0.37 (HSM Table 10-12)	0.881
Improved sidewalk	No Applicable CMF	–	–	–
Raised bike lanes	CMF ID 2134	0.37 (Vehicle/bicyclist)	0.011 (HSM Table 12-9)	0.993
Reduced lanes	Included in Road Diet CMF	–	–	–
Repainted crosswalk	No Applicable CMF	–	–	–
Repainted line striping	No Applicable CMF	–	–	–
Added right-turn lane	HSM Table 10-14	0.96 (4-leg unsignalized)	–	0.96
	HSM Table 10-14	0.74 (3-leg unsignalized)	–	0.74
Add median	CMF ID 7792	0.76 (KABC)	0.679 (HSM Table 10-3)	0.837
Add pedestrian/ bicyclist warning signs	No Applicable CMF	–	–	–

– not applicable

Analysis Results

Table 60 shows the Highways 28, 29, and 104 case study analysis results . The safety effectiveness evaluation without volume adjustment (E1) showed a 38 percent crash reduction in the study area. The predictive analysis (P1) results of 29–45 percent were in-line with this observed crash reduction. The dominant effect method of CMF combination in particular was very close (39 percent).

Based on the before-period traffic volume trend, the after-period volumes were expected to mostly increase slightly. This slight projected increase in volumes did not make a significant difference in the safety effectiveness evaluation results (E2) or the predictive analysis results (P2).

For both P1 and P2, the dominant effect method of CMF combination performed closest to the safety effectiveness evaluation.

In many cases, observed after-period vehicle volumes decreased rather than increased as predicted. This is why the results for E3 are lower than E2. E3 does not give credit to the Complete Streets project as the reason for the volume reduction.

Table 60. Highways 28, 29, and 104 case study analysis results.

Analysis Method	CMF Combination Method	Crash Reduction	Percent Reduction
E1	–	18	38
E2	–	19.2	39
E3	–	13.2	31
P1	Dominant Effect	18.7	39
	Multiplicative	21.7	45
	Dominant Common Residuals	13.9	29
P2	Dominant Effect	18.0	38
	Multiplicative	21.2	44
	Dominant Common Residuals	13.1	27

Note: – indicates that the safety effectiveness evaluations do not rely on CMFs and thus do not use CMF combination methods.

SUMMARY OF CASE STUDY ANALYSIS RESULTS

Table 61 shows the combined analysis results for all five case studies, revealing that the predictive analyses often overpredict the crash reduction when compared to the safety effectiveness evaluations. The Greenough Boulevard and Highways 28, 29, and 104 case studies were exceptions to overprediction; the results for these two case studies show that the predictions were generally in-line with the evaluations. The five case studies described in this appendix were not selected randomly and do not represent a sufficient sample to draw generalized conclusions. They serve as examples of how to carry out the analysis process described in chapter 4.

Table 61. Combined case study analysis results.

Analysis Method	CMF Combination Method	Result Type	First Hill Streetcar	Greenough Blvd	Bench Blvd	Fletcher Ave	Hwy 28, 29, and 104
E1	–	Reduction	122	16	2	210	18
		%	15	55	2	11	38
E2	–	Reduction	88.2	16.0	-1.5	98.2	19.2
		%	11	55	-2	5	39
E3	–	Reduction	31.7	11.1	27.2	160.6	13.2
		%	4	38	30	8	31
P1	Dominant Effect	Reduction	288.0	10.2	20.8	394.2	18.7
		%	35	35	23	20	39
	Multiplicative	Reduction	314.0	8.7	28.2	392.0	21.7
		%	38	30	31	20	45
	Dominant Common Residuals	Reduction	206.5	6.1	21.6	518.6	13.9
		%	25	21	24	26	29
P2	Dominant Effect	Reduction	317.5	10.2	24.1	484.1	18.0
		%	39	35	27	24	38
	Multiplicative	Reduction	344.1	8.7	31.3	482.5	21.2
		%	42	30	35	24	44
	Dominant Common Residuals	Reduction	238.2	6.1	24.8	601.5	13.1
		%	29	21	28	30	27

Note: – indicates that the safety effectiveness evaluations do not rely on CMFs and thus do not use CMF combination methods; Reduct. = reduction.

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The photo in figure 114 was modified. The original photo is the property of Google Maps and can be accessed from https://www.google.com/maps/@47.5991715,-122.3162418,3a,75y,72.27h,81.76t/data=!3m7!1e1!3m5!1s3Z82be1-csQnzvCf-NOeGQ!2e0!5s20110801T000000!7i13312!8i6656?entry=ttu (Google Maps 2011b). PII-containing signage was blurred by FHWA.

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