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16. ABSTRACT
Developing quality California-specific CMFs for bicycle-related safety countermeasures will support practitioners in making more informed decisions about infrastructure improvement projects. The researchers identified a comprehensive list of countermeasures, identified existing CMFs and reviewed their quality and applicability to California, determined key bicycle injury and fatality crash patterns in the state, prioritized potential bicycle safety countermeasures for study, and identified potential study sites.

The results show there is limited availability of relevant and high quality CMFs. Analysis of severe and fatal bicycle crashes point to the need for study of segment bicycle safety treatments, like Class IV bicycle lanes, because of the prevalence of segment parallel path and overtaking crashes, especially among fatal crashes. The researchers compiled a data set of existing and planned Class IV bicycle lanes, which are increasingly common throughout California, and identified existing bicycle count data collected on those facilities.

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Development of Crash Reduction Factors for Bicycle-Related Safety Countermeasures

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Berkeley SafeTREC
SAFE TRANSPORTATION RESEARCH AND EDUCATION CENTER

THE UNIVERSITY OF NORTH CAROLINA
HIGHWAY SAFETY
RESEARCH CENTER

Contents

Chapter 1: Introduction

Communities across California are looking to alternatives to the motor vehicle as the primary means of transportation to, from, and between activities. Investments in bicycling infrastructure, education, and enforcement have improved, and continue to have the potential to improve the quality of life in communities large and small. Furthermore, there is an increasing interest in improving safety for vulnerable road users and advancing the goals of Vision Zero to eliminate traffic fatalities and serious injuries. A transportation network with safe bicycle facilities means less car traffic, more physical activity, and reduced carbon emissions, making bicycling a solution to many pressing concerns.

Caltrans is responding to this shift by adopting new policies intended to encourage bicycling and emphasize safety, livability, and sustainability for all. This approach is aligned with Caltrans's current mission to "Provide a safe, sustainable, integrated and efficient transportation system to enhance California's economy and livability," its vision toward "a performance-driven, transparent and accountable organization that values its people, resources and partners, and meets new challenges through leadership, innovation and teamwork." It is also consistent with the first of five goals to "provide a safe transportation system for workers and users, and promote health through active transportation and reduced pollution in communities."

As communities and transportation agencies confront an increasing demand for bicycle infrastructure and programs, there is a need for information about the effectiveness of such facilities. Crash reduction factors (CRFs) and crash modification factors (CMFs) play a crucial role in providing the quantitative data that is needed by practitioners engaged in bicycle safety improvements to ascertain expected safety effectiveness of various designs to improve bicycle access and connectivity.

"A crash reduction factor (CRF) is the percentage crash reduction that might be expected after implementing a given countermeasure at a specific site. Expected countermeasure effectiveness is also commonly expressed as a crash modification factor (CMF). A CMF is a multiplicative factor used to compute the expected number of crashes after implementing a given countermeasure at a specific site." The terms CRF and CMF are used interchangeably in this document. Mathematically stated, CMF = 1 - (CRF/100). For example, if a particular countermeasure is expected to reduce the number of crashes by 32% (i.e., the CRF is 32), the CMF will be 1 - (32/100) = 0.68. On the other hand, if the treatment is expected to increase the number of crashes by 12% (i.e., the CRF is -12), the CMF will be = 1 - (-12/100) = 1.12.

This study had three main goals:

1. Understand the current availability and quality of CMFs for bicycle-related safety countermeasures.
2. Prioritize countermeasures that currently don't have high quality CMFs, especially California-specific CMFs, which would best support practitioners in making more informed decisions about infrastructure improvement projects.
3. Recommend data collection standards for new bicycle infrastructure projects that can be used for future CMF development.

We identified a comprehensive list of countermeasures, identified existing CMFs and reviewed their quality and applicability to California, determined key bicycle injury and fatality crash patterns in the state, prioritized potential bicycle safety countermeasures for study, and identified potential study sites.

Chapter 2: Existing CMFs

This chapter documents background on existing CRFs, including those catalogued in the publicly available Federal Highway Administration (FHWA) Crash Modification Factor (CMF) Clearinghouse, hosted at HSRC. The objective of the work was to conduct a comprehensive review, and provide recommendations on data needs and analysis methods for the future development of California-specific CRFs for bicycle safety countermeasures for common crash types and roadway types on the state highway system.

The project team identified a comprehensive list of more than 70 existing bicycle safety countermeasures (Table 1). We loosely categorized the countermeasures according to different design or operational types (e.g. access management, signalized locations, along the road / facilities), and indicated if they are likely to have safety impacts (which could be positive or negative or in opposite directions) at intersections, segments, or both (Y means yes; P for possibly was used for situations where the data and information are lacking or unclear, but logic suggests potential effects; D for depends on type, situation). (We also noted those measures that might not be appropriate for rural roads (but could be considered for rural villages).

Table 1. Comprehensive List of Safety Countermeasures that can Impact Bicycle Safety

Countermeasures	May not be Applicable to Rural	May affect safety at Intersections	May affect safety at Segments
Access Management			
Access Management (include continuous medians - see next)	X	P	Y
Driveway Improvements	X		
Median treatments (barriers: Install various median treatment: median fencing, sidewalk fencing, median brick planters, pedestrian islands) - could be grouped under "Access Management"		P	Y
Bike (Turn) Pockets - Median cut-through where motorist through is prevented		Y	
Traffic Diversion		Y	Y
Bike Facilities / Along the Road			
Advisory Bike Lanes (https://www.advisorybikelanes.com/)			Y
Parking Treatments (Back-in Angle, etc.)			
Bike Lanes		Y	Y
Bike Boulevards (there are many 'branded' names for these streets including neighborhood greenways), which may include combinations of signing, lack of centerlines, speed calming, and traffic diversion/management to achieve low-speed, shared 'bicycle-friendly' streets [may also be listed under "Traffic Diversion" as in BikeSafe	X	Y	Y
Bridge Access			Y
Combination (Bike-Bus) Lanes	X	Y	Y

Countermeasures	May not be Applicable to Rural	May affect safety at Intersections	May affect safety at Segments
Contra-flow Bike Lanes	X	Y	Y
Cycle Tracks / Protected Bike Lanes / Separated Bike Lanes / Buffered Bike Lanes		Y	Y
Increase Bike Lane Width			Y
Paved Shoulders			Y
Reduce Number of Lanes (Road Diet) (also under Speed Management)		Y	Y
Shared Lane Markings (Sharrows)		Y	Y
Tunnel Access			Y
Wide Curb Lanes			Y
Intersection Design			
Bike Box		Y	
Curb Radii Revisions		Y	
Installation of high quality markings for bicycle crossings with cyclist priority at intersections		Y	
Mini Circles (Mini Traffic Circles)	X	Y	
Median/Crossing Island		Y	
Mixing zone treatments		Y	
Parking Restrictions (at Intersections - could also be applied to other crossings)	X	Y	
Porkchop pedestrian island			
Protected Intersection Design		Y	
Roundabouts		Y	
Sight Distance Improvements at Intersections		Y	
Two Stage Bicycle Turn Queue Boxes		Y	
Other/ Unsignalized Junctions / Conflict Areas			
Interchange Treatments		Y	
Merge Area Redesign		Y	Y
Advanced Stop/Yield Lines (unsignalized, multi-lane crossings)		Y	
Path Intersection Treatments		Y	
Pedestrian Hybrid Beacon (unsignalized, multi-lane crossings)		Y	
Rectangular Rapid Flash Beacons (RRFB) (unsignalized, multi-lane crossings)		Y	
Red Pavement and Cyclist Priority at Intersections (unsignalized, multi-lane crossings)		Y	
Underpass / Overpass (of road crossing)		Y	
Speed Management - Traffic Calming			
Chicanes	X		Y
Raised Bicycle Crossing		Y	
Reduce Lane Width		P	Y

Countermeasures	May not be Applicable to Rural	May affect safety at Intersections	May affect safety at Segments
Speed Tables/Humps/Cushions	X	Y	Y
Traffic Calming (others - shifts in parking alignment, bulb-outs)		Y	Y
Visual Narrowing at Intersection	X	Y	
Surfaces / Quality			
Major Maintenance		Y	Y
Pavement Marking Improvements (skid resistance, visibility, placement)		Y	Y
Repetitive/Short Term Maintenance		Y	Y
Hazard Identification Program		Y	Y
Rail/ Light Rail / Streetcar Track Crossing Improvements		Y	Y
Roadway Surface Improvements		Y	Y
Traffic Signal Treatments			
Install Signal		Y	
Bicycle Detection at Signalized Intersections		Y	
Bicycle Detection at Signalized Intersections with feedback to cyclists		Y	
Bicycle Signal Heads	X	Y	
"Green Wave" (bike progression signal timing)	X	Y	Y
Leading Bicycle (Pedestrian) Interval		Y	
Left Turn Prohibition	X	Y	Y
Optimize Signal Timing for Bikes (clearance, etc.)		Y	
Restricted Left Turn Phasing		Y	
Right Turn on Red restriction/treatments (ped actuated device)	X	Y	
Traffic Signal Backplates (signals) to minimize sun glare		Y	
Turning Restrictions	X	Y	
Miscellaneous Others			
Aesthetics/Landscaping		Y	P
Bicyclist/Motorist Education		Y	Y
Law Enforcement		Y	Y
Roadway / Facility Lighting - general			Y
Enhance Lighting - site specific (crossings, etc.)		Y	Y
School Zone Improvements		D	D
Separate Mixed Use Path		Y	Y
Share the Trail Treatments			
Sign Improvements		D	D
Transit Access		P	P
Wayfinding	Y	P	P

Bicycle CMFs

From the extensive list of bicycle safety countermeasures presented in the previous section, the project team was able to identify CRFs from the CMF Clearinghouse for only 9 of these countermeasures. CRFs express the expected decrease in crashes due to implementation of a countermeasure. However, most road safety applications are now built on CMFs. Hereafter, the term CMF is used, which is a multiplicative function or estimate of the proportion of crashes expected after implementing a countermeasure, compared with if no change was made. CMFs are always positive, with CMFs greater than 1 indicating an increase in crashes compared to the baseline. (A CRF = 100*(1-CMF) as a percentage, but since there are frequently measures that increase the expected crashes, CRFs may lead to stating crash effects as a negative reduction, which is really an increase.) A total of 76 CMFs from 14 studies looked at the impact of these 9 countermeasures on vehicle/bicycle crash.

Table 2 provides a collective summary and is followed by a brief description of CMFs for each countermeasure. Citations for studies of interest from the CMF Clearinghouse are listed in Appendix A and detailed information about all the specific CMFs is presented in the Appendix B.

Table 2. CMF Ranges by Countermeasure

Countermeasure	No. of CMFs	CMF Range	CMFs > 1	CMFs < 1
Median Treatments	2	0.14 - 1.12	1	1
Bike Boulevard	1	0.37	0	1
Bike Box	1	0.65	0	1
Bike Lane	27	0.40 - 2.03	17	10
Cycle Tracks / Protected Bike Lanes, Separated Bike Lanes	34	0 - 6.67	22	12
Increase Bike Lane Width	3	CMFunctions	0	3
Raised Bicycle Crossing	2	0.49 - 1.09	1	1
Red Color and/or High Quality Pavement Markings and Cyclist Priority at Intersections	4	0.61 - 2.53	3	1
Visual Narrowing at Intersection	2	0.54 - 1.37	1	1

Table 2 illustrates that two treatments have received the most study (bicycle lanes and separated bicycle lanes), but have not resulted in consensus on whether they reduce or increase crashes. For this reason, even though much study has been done, additional study and higher quality study is still needed on these treatments. Both intersection and segment-related crashes may be affected by these bicycle facilities and related intersection treatments.

Median Treatments

- One study developed CMFs for median treatments.
- Data used from Maryland.
- Two CMFs were developed.
    - One CMF for Total (KABCO) vehicle/bicycle and vehicle/pedestrian crashes.
        - Shows an increase in Total (KABCO) vehicle/bicycle and vehicle/pedestrian crashes.

    - One CMF for Fatal (K) vehicle/bicycle and vehicle/pedestrian crashes.
        - Shows a decrease in Fatal (K) vehicle/bicycle and vehicle/pedestrian crashes.

Install Bike Boulevard

- One study developed a CMF for installing bike boulevards.
- Data used from Berkeley, California.
- One CMF was developed.
    - One CMF for Total (KABCO) vehicle/bicycle crashes.
        - Shows a decrease in Total (KABCO) vehicle/bicycle crashes.

Provide Bike Box

- One study developed a CMF for providing a bike box.
- Data used from Copenhagen, Denmark.
- One CMF was developed.
    - One CMF for Total (KABCO) vehicle/bicycle crashes.
        - Shows a decrease in Total (KABCO) vehicle/bicycle crashes.

Install Bike Lanes

- Seven studies developed CMFs for installing bike lanes.
  Data used from New York City; Florida; Copenhagen, Denmark; Adelaide, Australia; and Christchurch, New Zealand.
    - Four studies developed CMFs for installing bike lanes at intersections.
    - Six studies developed CMFs for installing bike lanes at road segments.
- Seventeen CMFs were developed for installing bike lanes at intersections.
    - Fifteen CMFs for Total (KABCO) vehicle/bicycle crashes.
        - Ten CMFs show an increase in Total (KABCO) vehicle/bicycle crashes.
        - Five CMFs show a decrease in Total (KABCO) vehicle/bicycle crashes.
    - One CMF for Fatal and Injury (KABC) vehicle/bicycle crashes.
        - Shows an increase in Fatal and Injury (KABC) vehicle/bicycle crashes.
    - One CMF for Fatal and Serious Injury (KAB) vehicle/bicycle crashes.
        - Shows an increase in Fatal and Serious Injury (KAB) vehicle/bicycle crashes.
- Ten CMFs were developed for installing bike lanes at road segments.
    - Six CMFs for Total (KABCO) vehicle/bicycle crashes.
        - Three CMFs show an increase in Total (KABCO) vehicle/bicycle crashes.
        - Three CMFs show a decrease in Total (KABCO) vehicle/bicycle crashes.
    - Four CMFs for Fatal and Injury (KABC) vehicle/bicycle crashes.
        - Two CMF show an increase in Fatal and Injury (KABC) vehicle/bicycle crashes.
        - Two CMF show a decrease in Fatal and Injury (KABC) vehicle/bicycle crashes.

Install Cycle Tracks / Protected Bike Lanes / Separated Bike Lanes

- Three studies developed CMFs for installing cycle tracks / protected bike lanes / separated bike lanes.
- Data used from California; Washington, D.C.; Florida; Illinois; Montana; New York; Oregon; Texas; Copenhagen, Denmark; and Montreal, Canada.
- Thirty-Four CMFs were developed.

- Twenty-Three CMFs for Total (KABCO) vehicle/bicycle crashes.
  - Twenty CMFs show an increase in Total (KABCO) vehicle/bicycle crashes.
  - Three CMFs show a decrease in Total (KABCO) vehicle/bicycle crashes.
- Three CMFs for Fatal and Injury (KABC) vehicle/bicycle crashes.
  - Two CMFs show an increase in Fatal and Injury (KABC) vehicle/bicycle crashes.
  - One CMF shows a decrease in Fatal and Injury (KABC) vehicle/bicycle crashes.
- Eight CMFs for Serious and Minor Injury (ABC) vehicle/bicycle crashes.
  - Eight CMFs show a decrease in Serious and Minor Injury (ABC) vehicle/bicycle crashes.

Increase Bike Lane Width

- One study developed CMFunctions for increasing bike lane width.
- Data used from Florida.
- Three CMFunctions were developed.
  - One CMFunction for Total (KABCO) vehicle/bicycle crashes.
    - Shows a decrease in Total (KABCO) vehicle/bicycle crashes as the bike lane width is increased (using 2 feet as base width as a minimum, even if no bike lane/shoulder was present).
  - One CMFunction for Fatal and Injury (KABC) vehicle/bicycle crashes.
    - Shows a decrease in Fatal and Injury (KABC) vehicle/bicycle crashes as the bike lane width is increased (using 2 feet as base width).
  - One CMFunction for Fatal and Serious Injury (KAB) vehicle/bicycle crashes.
    - Shows a decrease in Fatal and Serious Injury (KAB) vehicle/bicycle crashes as the bike lane width is increased (using 2 feet as base width).

Install Raised Bike Crossings

- Two studies developed CMFs for installing raised bike crossings.
- Data used from Netherlands.
- Two CMFs were developed.
  - One CMF for Total (KABCO) vehicle/bicycle crashes.
    - Shows a decrease in Total (KABCO) vehicle/bicycle crashes.
  - One CMF for Serious and Minor Injury (ABC) vehicle/bicycle crashes.
    - Shows an increase in Serious and Minor Injury (ABC) vehicle/bicycle crashes.

Install Red Color and/or High Quality Pavement Markings and Cyclist Priority at Intersections

- Two studies developed CMFs for installing red color and/or high quality pavement markings and cyclist priority at intersections.
- Data used from Netherlands and Christchurch New Zealand.
- Four CMFs were developed.
  - Four CMFs for Total (KABCO) vehicle/bicycle crashes.
    - Three CMFs show an increase in Total (KABCO) vehicle/bicycle crashes.
    - One CMF shows a decrease in Total (KABCO) vehicle/bicycle crashes.

Provide Visual Narrowing at Intersections

- One study developed CMFs for providing visual narrowing at intersections.
- Data used from Netherlands.
- Two CMFs were developed.
    - Two CMFs for Total (KABCO) vehicle/bicycle crashes.
        - One CMF shows an increase in Total (KABCO) vehicle/bicycle crashes.
        - One CMF shows a decrease in Total (KABCO) vehicle/bicycle crashes. (Appendix B offers details on the differences in the data used between the two CMFs)

Discussion of CMF Quality

The CMF Clearinghouse uses a star quality rating system that indicates the quality or confidence in the results of the study producing the CMF. The star rating is based on a scale of 1 to 5, where a 5 indicates the highest and most reliable rating. Five categories are considered for each study – study design, sample size, standard error, potential biases, and data source – to determine the star rating for each CMF.

A star rating of 5 would mean that the study used a statistically rigorous study design (e.g. Empirical Bayes or Full Bayes before-after), a large sample with multiple years and diverse sties, and controls for all sources of known potential biases. Conversely, a star rating of 1 would mean that the study conducted a simple before-after analysis with a limited homogenous sample and no consideration of potential biases. More details about the star ratings can be found on the CMF Clearinghouse.

Of the 76 CMFs corresponding to the countermeasures as discussed in the previous section, 21 CMFs had a three-star rating, 49 had a two-star rating, 5 had a one-star rating, and 1 CMF cannot be rated. None of the CMFs had a four- or a five-star rating. A few main reasons behind this was that the majority of the studies used cross sectional (both regression and non-regression) or simple before-after analysis with a limited sample, and provided minimal consideration for potential biases.

Table 3 provides a breakdown of CMF star ratings for each countermeasure. It should be noted that even though many studies include bicycle lanes and separated bicycle lanes, only 3, three-star CMFs have been developed for bicycle lanes and only 10, three-star CMFs have been developed for separated bicycle lanes. Of the 3, three-star CMFs developed for bicycle lanes, 2 CMFs show an increase in vehicle/bicycle crashes and 1 CMF shows a decrease in vehicle-bicycle crashes. On the other hand, of the 10, three-star CMFs developed for separated bicycle lanes, 3 CMFs show an increase in vehicle/bicycle crashes and 7 CMFs show a decrease in vehicle-bicycle crashes. Given these results, there is still a lack of clarity about effectiveness of these treatment for bicyclist safety, especially under different treatment conditions and assumptions.

Table 3. CMF Star Ratings by Countermeasure

Countermeasure	No. of CMFs	3 Star	2 Star	1 Star
Median Treatments	2	2	0	0
Bike Boulevard	1	1	0	0
Bike Box	1 (not rated)	0	0	0
Bike Lane	27	3	24	0
Cycle Tracks / Protected Bike Lanes, Separated Bike Lanes	34	10	20	4
Increase Bike Lane Width	3	3	0	0
Raised Bicycle Crossing	2	1	0	1
Red Color and/or High Quality Pavement Markings and Cyclist Priority at Intersections	4	1	4	0
Visual Narrowing at Intersection	2	0	2	0

Applicability of CMFs

CMFs based on data from sites outside of California will likely be less applicable for use within the state. Of the 76 CMFs identified above, 75 were from studies where source jurisdictions were identified. Table 4 summarizes the CMFs by location. Only one CMF, for bicycle boulevards, includes sites exclusively in California. It is a three-star CMF, so potentially of sufficient quality, but this countermeasure is intended for low-volume local residential streets and not appropriate for a state highway facility. One study that produced 20 CMFs related to cycle tracks, protected bike lanes, and separated bike lanes included sites in California as well as other U.S. states, but it is unclear which sites were included in each CMF. These CMFs were rated 2 stars.

Table 4. Number of CMFs per Countermeasure by Source Jurisdiction

Countermeasure	California	North America	Outside North America
Median Treatments	0	2	0
Bike Boulevard	1	0	0
Bike Box	0	0	1
Bike Lane	0	10	17
Cycle Tracks / Protected Bike Lanes, Separated Bike Lanes	20*	8	6
Increase Bike Lane Width	0	3	0
Raised Bicycle Crossing	0	0	1
Red Color and/or High Quality Pavement Markings and Cyclist Priority at Intersections	0	0	4
Visual Narrowing at Intersection	0	0	2
Total	21	23	31

* Includes sites in other states and CA sites may not have been used for all CMFs.

Summary of CMF’s by Infrastructure Type

As mentioned in the previous sections, the project team was able to identify CMFs from the CMF Clearinghouse for 9 countermeasures. Also noted was that a total of 76 CMFs from 14 studies looked at the impact of these 9 countermeasures on vehicle/bicycle crashes.

Table 5 and Table 6 provide an insight into the number of studies and the number of CMFs per countermeasure by infrastructure type (i.e. intersections or road segments).

Table 5. Number of Studies per Countermeasure by Infrastructure Type

Countermeasure	Intersections	Road Segments
Median Treatments	0	1
Bike Boulevard	0	1
Bike Box	1	0
Bike Lane	4	6
Cycle Tracks / Protected Bike Lanes, Separated Bike Lanes	0	3
Increase Bike Lane Width	0	1
Raised Bicycle Crossing	2	0
Red Color and/or High Quality Pavement Markings and Cyclist Priority at Intersections	2	0
Visual Narrowing at Intersection	1	0

Table 6. Number of CMFs per Countermeasure by Infrastructure Type

Countermeasure	Intersections	Road Segments
Median Treatments	0	2
Bike Boulevard	0	1
Bike Box	1	0
Bike Lane	17	10
Cycle Tracks / Protected Bike Lanes, Separated Bike Lanes	0	34
Increase Bike Lane Width	0	3
Raised Bicycle Crossing	2	0
Red Color and/or High Quality Pavement Markings and Cyclist Priority at Intersections	4	0
Visual Narrowing at Intersection	2	0

Continuing Research Needs

Most bicycle treatments have not been evaluated for crash-based safety effects. Of more than 70 different bicycle safety treatments identified, only 9 have any CMFs for one or more types of bicycle-motor vehicle crashes. Among the 76 distinct bicycle-motor vehicle CMFs produced by 14 studies for one or the other of these nine treatments, only 21 of the CMFs are three-star; none were four-star or five-star. In addition, safety results are mixed, even for separated bike lanes—the most analyzed intervention—with some CMFs indicating increases in crashes and others indicating decreases. In addition, crashes at intersections and crashes along segments were frequently mixed in the prior analyses so it was challenging to understand the findings and potential for supporting interventions to mitigate potential crash increases.

For example, bike lanes and separated bikeways most often appear associated with increases in crashes at intersections. Twelve of 17 CMFs for implementing bike lanes found increases in crashes at intersections. The two three-star CMFs for bike lanes at intersections both found increases in crashes at intersections. Effects along segments appear to be a wash (half found increases and half found decreases in expected crashes), but if estimates of more severe injuries across intersection and segment locations combined, are reduced, (while accounting for possible differences in bicycle and traffic volume exposure) then bike lanes may provide an improvement in safety. In addition, the analyses of 'segment' effects in bike lane and separated bike lane studies often appeared to include both segment-related and intersection crashes, making it unclear if there is a safety benefit or disbenefit along segments and what the net effects may be. Understanding these issues is important to designing and implementing better treatments that safely accommodate cyclists riding in traffic, as well as crossing through intersections.

None of the other treatment types has enough consistent, high-quality evidence of effectiveness, especially of treatments applied in conditions similar to California's (many of the source locations for these studies were international) to eliminate them from need for further study. Therefore, as far as priorities go, any treatment considered promising to target the safety issues and crash types that are prevalent across California, or that help to achieve bicycle service goals, may be worthy of more safety evaluation.

The numbers of locations where different treatments have been or are to be implemented is also a key consideration for obtaining reliable and statistically significant results. Ideally, before-after study designs with comparison sites best allow detection of crash effects due to a treatment. Quality results are also dependent on crash history, numbers of treated sites, measures of ridership and traffic volume trends, and years of crash data available.

Chapter 3: Countermeasure Prioritization

While the review in the previous chapter did not narrow the list of bicycle-related safety countermeasures that would benefit from further study in California, there are other factors that can help to prioritize countermeasure selection. In the first section of this chapter, we present summary statistics that point to the most common types of bicycle crashes in California and then identify countermeasures that would best address them based on the design of the countermeasure and existing guidance. The subsequent section describes current availability of data necessary for the development of CMFs for these countermeasures.

Initial Prioritization of Countermeasures

We analyzed data from the Statewide Integrated Traffic Records System (SWITRS) on motor vehicle-bicycle injury crashes occurring between 2009 and 2018. Figure 1 shows that reported bicycle-involved crashes have decreased since 2012, but that most of the variation is in the minor crashes (other visible and complaint of pain). These data may be misleading because bicycle crashes are known to be underreported and this is more likely to occur with minor crashes.

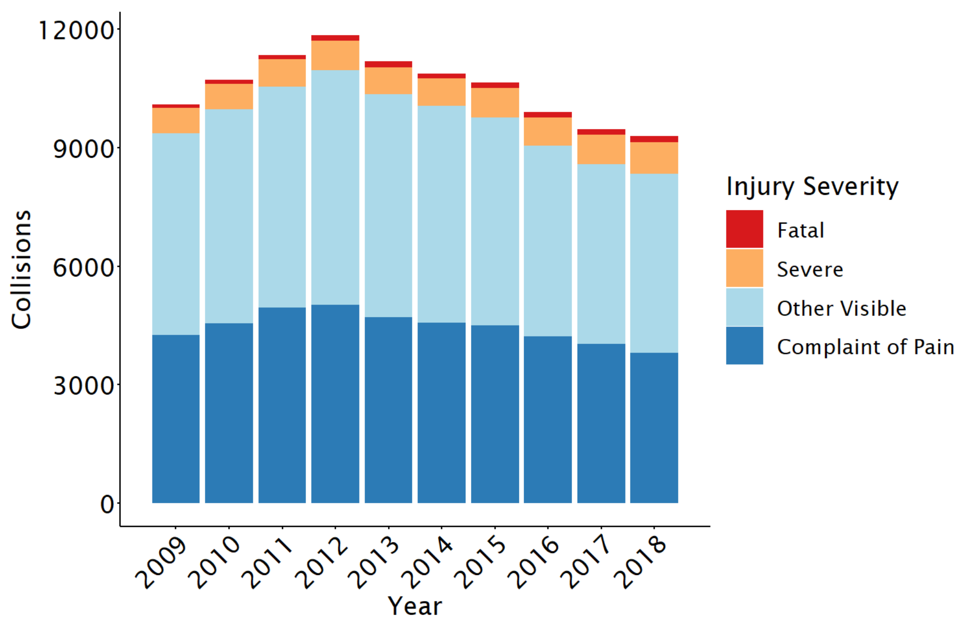

Figure 1. Severity of Motor Vehicle-Bicycle Crashes by Year (2009-2018)

The number of fatal and severe bicycle crashes has been increasing over time, as shown in Figure 2. There were 724 severe or fatal motor vehicle-bicycle crashes in 2009, and 948 such crashes in 2018, a 31 percent increase. This change could be related to increases in the popularity of cycling, steady increases in vehicle miles traveled (VMT) since the economic slump in 2008, or other unknown reasons. The data exploration in the subsequent figures is based on motor vehicle-bicycle crashes where a bicyclist was severely or fatally injured. Among these crashes, 7,382 involved one motor vehicle and 943 involved 2 or more motor vehicles.

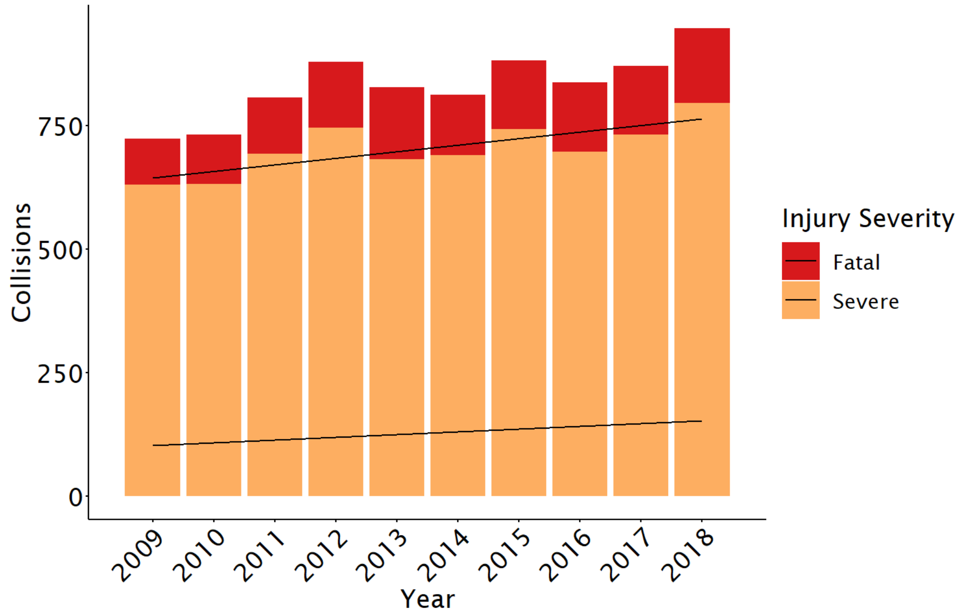

Figure 2. Fatal and Severe Motor Vehicle-Bicycle Crashes by Year (2009-2018)

Most fatal and severe bicyclist crashes occur at non-intersection locations, 64 percent in the 10-year period examined. Figure 3 shows the number of crashes by collision type and location type. Broadside crashes are the most common types of crashes at both intersection and non-intersection locations, and they represent the majority of all crashes occurring at intersections (52 percent). Parallel path collision types, like head-on, sideswipe, and rear end, occur much more commonly at non-intersection locations (81 percent).

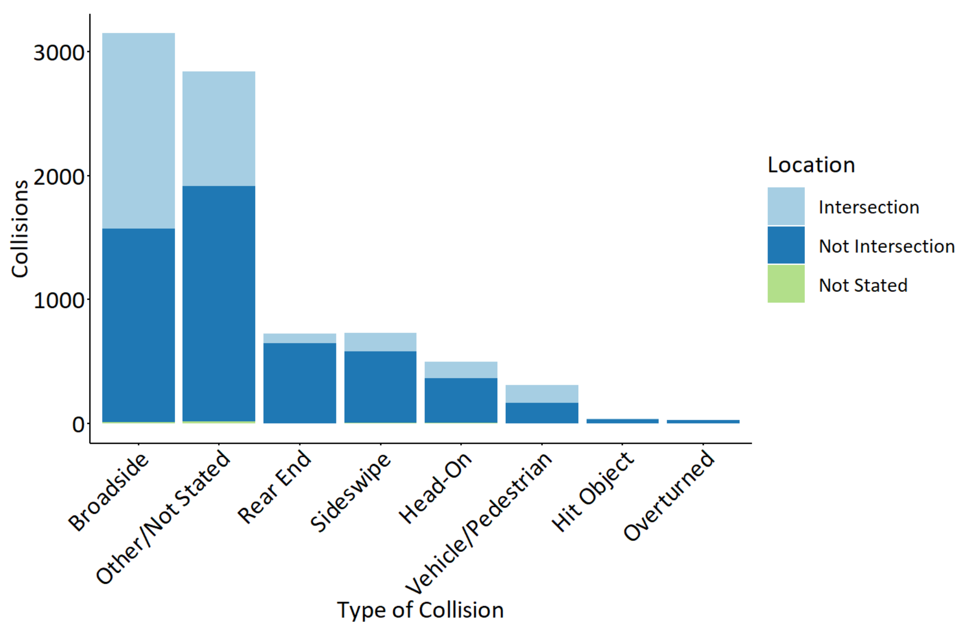

Figure 3. Fatal and Severe Motor Vehicle-Bicycle Crashes by Collision Type and Location (2009-2018)

As shown in Table 7, both motorists and bicyclists were proceeding straight in over one third of severe and fatal, 2-party, motor vehicle-bicycle crashes (35 percent). In 92 percent of crashes, at least one party was preceding straight. Crashes where the motor vehicle is proceeding straight can be more serious because the driver may not have slowed down, as they would before a turn. Turning left and turning right are the next most prevalent driver movements preceding crashes. These may be cases where the driver fails to detect or check for the bicyclist before turning.

Table 7. Motor vehicle (MV) by bicycle movement preceding collision for severe and fatal, 2-party, motor vehicle-bicycle collisions (2009-2018)

Movement Preceding Collision	Bicycle Slowing/ Stopped	Bicycle Proceeding Straight	Bicycle Turning Right	Bicycle Turning Left	Bicycle Changing Lanes	Bicycle Entering Traffic	Bicycle Traveling Wrong Way	Bicycle Other
MV Slowing/ Stopped	19	134	7	8	5	8	16	29
MV Proceeding Straight	52	2,615	80	402	162	521	264	525
MV Turning Right	14	595	12	8	0	33	113	32
MV Turning Left	13	825	5	22	0	19	17	25
MV Changing Lanes	1	41	0	0	7	3	3	2
MV Entering Traffic	0	90	2	1	0	2	40	8
MV Traveling Wrong Way	0	14	0	2	0	0	4	0
MV Other	4	471	6	19	2	5	11	64

Table 8 shows the common combinations of motor vehicle and bicycle movements preceding collisions cross-tabulated with intersection and generalized collision type (broadside, parallel path, and other). The most prevalent combination of movements is both parties preceding straight. At intersections, these collisions are mostly broadside, and at non-intersections, they are more commonly parallel path, but broadsides are also common.

Table 8. Movements Preceding Collision for Motor Vehicle and Bicyclist by Location Type and Generalized Collision Type for Severe and Fatal, 2-Party, Motor Vehicle-Bicycle Collisions (2009-2018)

Motor Vehicle – Bicycle Movements Preceding Collision	Inter. Broadside	Inter. Parallel Path	Inter. Other	Non-inter. Broadside	Non-inter. Parallel Path	Non-inter. Other
Proceeding Straight - Changing Lanes	6	7	3	38	53	53
Proceeding Straight - Entering Traffic	53	8	45	223	49	140
Proceeding Straight - Proceeding Straight	695	88	400	390	530	499
Proceeding Straight - Traveling Wrong Way	28	4	26	46	67	91
Proceeding Straight - Turning Left	101	23	69	106	32	70
Proceeding Straight - Other	27	16	37	132	113	196
Turning Left - Proceeding Straight	329	56	155	143	38	99
Turning Right - Proceeding Straight	136	54	97	141	66	98
Other - Proceeding Straight	10	20	21	22	190	205
Other	138	49	129	245	182	252

Note: Parallel path is head-on, sideswipe, and rear end.

FARS Data Analysis

Fatality Analysis Reporting System (FARS) data between 2014 and 2017 include crash types from FHWA's Pedestrian and Bicycle Crash Analysis Tool (PBCAT) method for bicyclists struck in a crash in which one or more people were killed. Figure 4 shows crashes by the PBCAT crash groups. By far the most common crash group among bicyclists killed is motorist overtaking bicyclist. These are crashes that mostly occur on segments. Figure 5 shows the crash prevalence by PBCAT types within the motorist overtaking bicyclist group. The largest group is other/unknown, but misjudged space and undetected bicyclist, both situations where a driver makes an error, are also common.

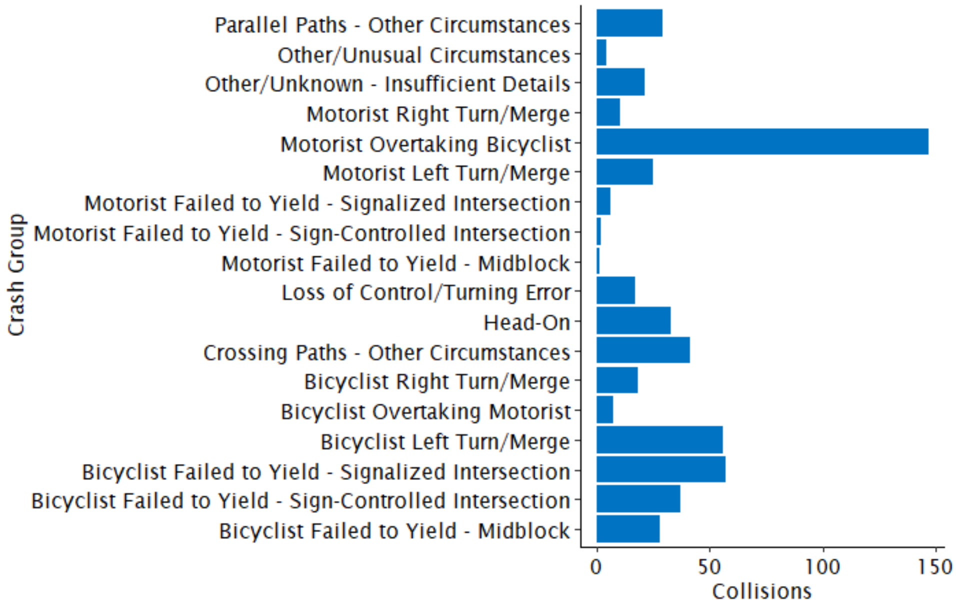

Figure 4. PBCAT Crash Groups for Fatal Crashes 2014-2017 (FARS)

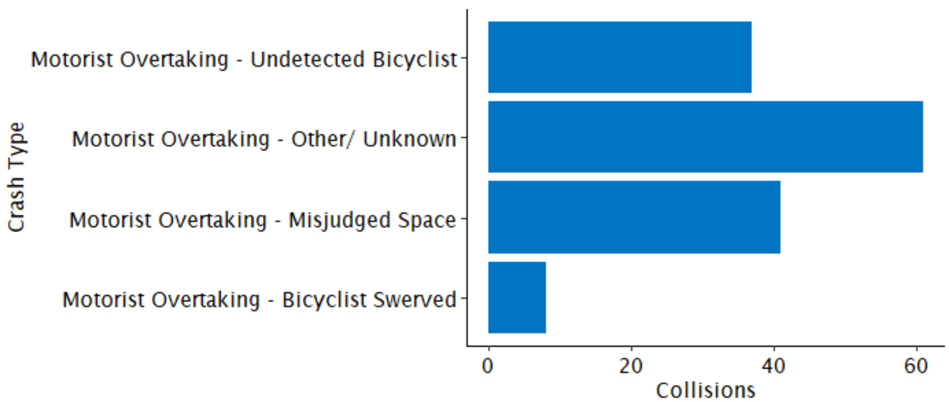

Figure 5. PBCAT Types within Motorist Overtaking Crash Group for Fatal Crashes 2014-2017 (FARS)

The prevalence of non-intersection parallel path collision types in SWITRS data and motorist overtaking crashes in FARS data point to the need for improved bicycling facilities on road segments. While Class II bicycle lanes have become common in cities across the state, these facilities do not provide any physical protection to bicyclists and cannot prevent overtaking crashes caused by inattentive drivers. Increasingly, advocates are calling for and cities are installing buffered bicycle lanes and Class IV protected bicycle lanes. These facilities make bicyclists feel safer (Griswold et al, 2018), but as shown in Chapter 2, there is limited evidence that they improve safety for bicyclists. The increasing number of Class IV facilities provides an opportunity for California to study their safety on its own roads.

Existing Data Availability

As will be discussed in the subsequent chapter, data quality is one of the primary constraints limiting the quality of studies to develop CMFs. We conducted preliminary data collection to assess the quality of data available to study the safety of Class IV bicycle lanes in California. The main categories of data required for these studies are:

- Infrastructure data – Data about the location and installation date of the treatment is of primary concern, but other information about the attributes of the infrastructure at the treatment sites is also necessary. Depending on the study design, we may also need infrastructure data for similar sites without the treatment.
- Volume data – Count/volume/AADT data for both bicyclists and motor vehicles is necessary for any quality safety analysis. Depending on the study design, these data may be required over time to cover the before and after periods of the treatment installation.

We focused on the availability of data on the location of Class IV bicycle lanes in in California. First we identified bicycle facility data sets from cities, counties, and metropolitan planning organizations. The location information was generally available in either GIS shapefile, web map, or PDF map format. We identified 39 sources from the National Pedestrian and Bicycle Safety Data Clearinghouse (pedbikedata.org) and additional Google searches (See Appendix C). Of these sources, 8 contained existing or planned Class IV facilities. Only three data sets included installation date of the treatment. The Active Transportation Program (ATP) provided a list of all funded ATP grants that include Class IV facilities (Appendix D). These projects have mostly not been constructed yet, but are pending in 2020 or 2021.

We compiled a GIS shapefile with existing and planned Class IV projects from these data sources. We were not able to include some of the ATP projects because project data were unavailable online. Where installation dates were unavailable for existing facilities, we were able to estimate a range of dates for installation at some locations based on historic Google Streetview imagery. In total, we compiled 52 miles of existing Class IV facilities and 48 miles of planned projects. Most of these facilities are in urban areas, including San Francisco, Oakland, Sacramento, Los Angeles, and San Diego. There may be additional existing or planned projects besides the unmapped ATP project locations that we have not been able to identify. Additional efforts will be required to obtain precise installation date information from agencies, most likely by examining as-built drawings.

In addition to the infrastructure data, we have compiled over 7,000 bicycle count studies from agencies around California. Of those, 157 were conducted on existing or planned Class IV facilities we have mapped, although the studies may have been conducted before those facilities were installed. We identified 24 unique facilities where at least one count study has been conducted. For facilities with multiple counts, some included studies at multiple intersections along the facility and others included multiple studies at the same location. Precise installation dates for the facilities will be required to determine whether counts were conducted before or after facility construction. ATP-funded projects are asked to conduct counts before and after, so there will likely be count data available for additional locations in the future.

Countermeasure Recommendations

The crash data analysis in this chapter points to the need to develop CMFs for segment bicycle safety treatments. Class IV bicycle lanes, despite being relatively new to the U.S., are increasingly being installed throughout California and our data collection efforts suggest that there may be a sufficient number of these facilities to conduct a robust study of their safety. Class IV facilities are the highest priority for study because these facilities, by providing physical separation have such potential to reduce bicycle injuries and fatalities. We also recommend studying other types of on-road segment treatments, including traditional Class II bicycle lanes and buffered bicycle lanes, because there has been limited study of these facilities in California.

At the same time that segment treatments are important, installation of physical separation or protection on segments may move the conflicts and hazards to intersections, driveways, or other locations where there are breaks in the protection. While studying Class IV facilities, in particular, it is important to examine the intersection treatments and evaluate how they affect safety. Data on locations or geometrics of intersection treatments are not easily accessible and will likely require examination of imagery or as-built drawings.

Crucial to the development of bicycle-related CMFs is availability of quality data. In the next chapter, we present recommendations for data collection efforts to be conducted before and after installation of bicycle countermeasures.

Chapter 4: Evaluation Framework

Before-after assessments can help agencies assess whether an installed countermeasure resulted in any statistically significant change in crashes/risk at a given location. However, computing a robust estimate of this change requires significant data input of conditions before, during, and after the period of installation. Subject to the data availability, statistically robust techniques may (or may not) be readily applicable for inferring the before-after impact. This chapter documents the data requirements for approved countermeasure installations for site-specific evaluation and CMF and CRF calibration/estimation and the analytical approaches that can be used based on the constraints of data availability.

Recommended Data Collection

We recommend collection of the data below during ongoing and future bicycle countermeasure implementation in Caltrans to support CMF development.

1. Prior to/after installation (documented for a period of 3-5 years before, 2-3 years after):
    a. Counts:
        i. Duration: One week of counts preferred. If 1 week is not possible, at least 24 hours on a Tuesday, Wednesday, or Thursday and a Saturday.
        ii. Modes counted: bicyclists, automobiles, through and right and left turns major to minor, and pedestrians (for both on major and minor roads on intersections)
        iii. Dates and times of collection
        iv. Weather

    b. Infrastructure:
        i. For intersection-related
            1. Number of approaches
                a. Number of lanes
                b. 1-way or 2-way
                c. Divided or undivided
                d. Presence of right-turn and left-turn channelization
                e. Presence of bus stops
                f. Speed limits
                g. Curb extensions
                h. Presence of bicycle-specific infrastructure
                    i. Bicycle lane
                    ii. Bicycle box
                    iii. In-pavement sensors for bicyclists
                    iv. Protected intersection
            2. Type of signal control (signalized, stop control on minor or all streets)
            3. Type of signal phasing (fixed vs actuated, pedestrian signal head, lead pedestrian interval, restricted turn phasing, right turn on red restrictions)

        ii. For segment-related countermeasures:
            1. Divided or undivided
            2. Number of travel lanes

        3. Shoulder width
        4. Presence of on-street parking, 1 or both sides
        5. Presence of bus stops
        6. Number of driveways, commercial & residential

2. Details about the countermeasure installation:
    a. Location of installation: begin and end postmile
    b. Duration of installation: begin and end times of construction
    c. Features of the countermeasure:
        i. Design attributes (if relevant): width, length
        ii. Operational attributes (if relevant): type of bicycle phase
    d. Additional changes made to infrastructure at the same time

Analytical Approaches

There are two broad categories of study design: experimental and observational. Experimental studies are conducted like a randomized control trial, where treatment and control sites are selected at random. This study design is effective at determining the safety effect of a treatment, but it requires advance planning before the treatments are installed and can create liability issues. Observational studies are more common because they evaluate treatments that have been applied with the goal of improving safety on a facility. The two main types of observational study designs are:

- Before-and-after study
- Cross-sectional study

Before-and-After Study

Before-and-after studies look at a group of sites where a treatment has been applied, and compare how the safety at the site changed between the before and after periods. These studies require count and infrastructure data for the before and after periods at the treatment sites as well as the sites included in the comparison and reference groups. Simple before-and-after studies are vulnerable to potential sources of bias, including:

- Changes over time – other variables besides the presence of treatment, like traffic volume, weather or driver demographics, may change over time and impact the number of crashes at the site. A comparison group of sites with the same external effects, like weather and economic changes, can be used to account for historical trends.
- Regression-to-the-mean (RTM) – RTM is a phenomenon where unusually high or low crash counts are likely to return closer to the mean counts over time. If a site is selected for treatment in response to a high number of crashes, the analysis may overestimate the effect of the treatment. RTM can be accounted for by using a reference group of sites with similar traffic volume and geometric attributes that did not receive the treatment and the empirical Bayes or Full Bayes methodology.
- While reference groups and comparison groups can be used to account for other forms of bias, using unsuitable sites in these groups can bring in new bias. Spillover effects of a treatment and crash migration are common issues that can affect the suitability of a reference or comparison group site.

Cross-sectional study

Cross-sectional studies are generally used when before data are not available. These studies compare crashes rates at treatments sites to a group of similar sites without the treatment. Since finding suitable sites can be difficult, often regression models are used that predict crashes based on site characteristics. Some potential biases in cross-sectional studies include:

- Inappropriate functional form,
- Omitted variable bias, and
- Correlated and confounding variables.

Meta-analysis

When insufficient data are available to conduct new analysis, meta-analysis studies may be considered. These studies combine the knowledge from multiple relevant studies of the same countermeasure, while considering the quality of each study. This study design may be less appropriate for developing California-specific CMFs because most existing studies use data from different countries or regions where design standards and driving culture may be different.

Chapter 5: Conclusion

Developing quality California-specific CMFs for bicycle-related safety countermeasures will support practitioners in making more informed decisions about infrastructure improvement projects. We identified a comprehensive list of countermeasures, identified existing CMFs and reviewed their quality and applicability to California, determined key bicycle injury and fatality crash patterns in the state, prioritized potential bicycle safety countermeasures for study, and identified potential study sites.

Currently, there is limited availability of relevant and high quality CMFs. Analysis of severe and fatal bicycle crashes pointed to the need for study of segment bicycle safety treatments, like Class IV bicycle lanes, because of the prevalence of segment parallel path and overtaking crashes, especially among fatal crashes. We compiled a data set of existing and planned Class IV bicycle lanes, which are increasingly common throughout California, and identified existing bicycle count data collected on those facilities. We recommend that Class IV, traditional Class II, and buffered bicycle lanes be studied further to develop state-specific CMFs, and that intersection treatments on these facilities be included in any studies. However, the availability of quality data before and after installation of the treatments may determine the robustness of any CMF studies.

Appendix A: Studies of Interest from the CMF Clearinghouse

Study ID	Study Citation
14	Elvik, R. and Vaa, T., "Handbook of Road Safety Measures." Oxford, United Kingdom, Elsevier, (2004)
82	Rodegerdts, L. A., Nevers, B., and Robinson, B., "Signalized Intersections: Informational Guide." FHWA-HRT-04-091, (2004)
124	Jensen, S.U. "Bicycle Tracks and Lanes: a Before-After Study." TRB 87th Annual Meeting Compendium of Papers CD-ROM. Washington, D.C., (2008).
221	Minikel, E., "Cyclist Safety on Bicycle Boulevards and Parallel Arterial Routes in Berkeley, California." Presented at the 90th Meeting of the Transportation Research Board, Washington, D.C., (2011).
230	Turner, S. A., Wood, G., Hughes, T., and Singh, R., "Safety Performance Functions for Bicycle Crashes in New Zealand and Australia." Presented at the 90th Annual Meeting of the Transportation Research Board, Washington, D.C., (2011).
259	J.P. Schepers, J.P., Kroeze, P.A., Sweers, W., and Wust, J.C., "Road Factors and Bicycle-Motor Vehicle Crashes at Unsignalized Priority Intersections." Accident Analysis and Prevention, Vol. 43, Issue 3, Elsevier Ltd., (2011) pp. 853-861.
274	Nosal, T. and L.F. Miranda-Moreno. "Cycle-tracks, bicycle lanes & on-street cycling in Montreal: a preliminary comparison of the cyclist injury risk." Presented at the 91st Annual Meeting of the Transportation Research Board, Washington, DC, (2012).
298	Chen, L., Chen, C., Srinivasan, R., McKnight, C. E., Ewing, R., and Roe, M., "Evaluating the Safety Effects of Bicycle Lanes in New York City," American Journal of Public Health, Vol. 102, No. 6, (2012).
433	Abdel-Aty, M.A., C. Lee, J. Park, J.Wang, M. Abuzwidah, and S. Al-Arifi. "Validation and Application of Highway Safety Manual (Part D) in Florida." Florida Department of Transportation. Tallahassee, Florida. (2014).
457	Koorey, G., and Parsons, J., "The Effect of Cycle Lanes on Cycling Numbers and Safety." Presented at the 95th Annual Meeting of the Transportation Research Board, Washington, D.C., (2016).
460	Rothenberg, H., D. Goodman, and C. Sundstrom, "Separated Bike Lane Crash Analysis." Presented at the 95th Annual Meeting of the Transportation Research Board, Washington, D.C., (2016).
476	Park, J. and M. Abdel-Aty. "Evaluation of safety effectiveness of multiple cross sectional features on urban arterials". Accident Analysis and Prevention, Vol. 92, (2016) pp. 245-255.

Study ID	Study Citation
502	Zhang, L., S. Ghader, A. Asadabadi, M. Franz, C. Xiong, and J. Litchford. "Analyzing the Impact of Median Treatments on Pedestrian/Bicyclist Safety." Report No. MD-17-SHA/UM/4-28. Maryland State Highway Administration. Baltimore, MD. (2017).
515	Alluri, P., Raihan, A., Saha, D., Wu, W., Huq, A., Nafis, S., and Gan, A. "Statewide Analysis of Bicycle Crashes." Florida Department of Transportation (2017).

Appendix B: Detailed Information about CMFs by Countermeasure

Countermeasure = Median Treatments (One Study; Two 3-Star CMFs)

Study ID	CMF ID	CMF	St. Error	Star Rating	Crash Type	Crash Severity (KABCO)	Source Jurisdiction	No of Sites/Miles
502	9122	1.12	0.18	3	Vehicle/Bicycle & Vehicle/Pedestrian	All (KABCO)	Maryland, USA	16 Segments
502	9123	0.14	0.07	3	Vehicle/Bicycle & Vehicle/Pedestrian	Fatal (K)	Maryland, USA	16 Segments

Countermeasure = Install Bike Boulevard (One Study; One 3-Star CMF)

Study ID	CMF ID	CMF	St. Error	Star Rating	Crash Type	Crash Severity (KABCO)	Source Jurisdiction	No of Sites/Miles
221	3092	0.37	0.052	3	Vehicle/Bicycle	All (KABCO)	Berkeley, CA, USA	7 Segments

Countermeasure = Provide Bike Box (One Study; One Unrated CMF)

Study ID	CMF ID	CMF	St. Error	Star Rating	Crash Type	Crash Severity (KABCO)	Source Jurisdiction	No of Sites/Miles
82	1718	0.65	n/a	Unrated	Vehicle/Bicycle	All (KABCO)	Copenhagen, Denmark	n/a

Countermeasure = Install Bike Lanes - Intersection Crashes (Four Studies; One 3-Star CMF, Sixteen 2-Star CMFs)

Study ID	CMF ID	CMF	St. Error	Star Rating	Crash Type	Crash Severity (KABCO)	Source Jurisdiction	No of Sites/Miles
298	4664	1.28	0.175	3	Vehicle/Bicycle	All (KABCO)	New York, NY, USA	43 miles on 61 streets
124	2184	1.57	0.385	2	Vehicle/Bicycle	Fatal & Injury (KABC)	Copenhagen, Denmark	5.6 km

Study ID	CMF ID	CMF	St. Error	Star Rating	Crash Type	Crash Severity (KABCO)	Source Jurisdiction	No of Sites/Miles
230	3246	1.37	n/a	2	Vehicle/Bicycle (all @ signalized intersections)	All (KABCO)	Adelaide, Australia	46 Intersections
230	3247	0.8	n/a	2	Vehicle/Bicycle (all @ signalized intersections)	All (KABCO)	Christchurch, New Zealand	56 Intersections
230	3248	0.63	n/a	2	Vehicle/Bicycle (crossing at 90 degrees - T-bone @ signalized intersections)	All (KABCO)	Adelaide, AUS & Christchurch, NZ	46 & 56 Intersections
230	3249	1.33	n/a	2	Vehicle/Bicycle (cyclist through - left turning vehicle* @ signalized intersections)	All (KABCO)	Adelaide, AUS & Christchurch, NZ	46 & 56 Intersections
230	3250	1.01	n/a	2	Vehicle/Bicycle (rear end, sideswipe, same direction @ signalized intersections)	All (KABCO)	Adelaide, AUS & Christchurch, NZ	46 & 56 Intersections
230	3251	2.03	n/a	2	Vehicle/Bicycle (cyclist through, right turning vehicle* in same direction @ signalized intersections)	All (KABCO)	Adelaide, Australia	46 Intersections
230	3252	0.42	n/a	2	Vehicle/Bicycle (cyclist through, right turning vehicle* in same direction @ signalized intersections)	All (KABCO)	Christchurch, New Zealand	56 Intersections
230	3253	1.02	n/a	2	Vehicle/Bicycle (other than those mentioned above @ signalized intersections)	All (KABCO)	Adelaide, AUS & Christchurch, NZ	46 & 56 Intersections
230	3254	1.4	n/a	2	Vehicle/Bicycle (all @ signalized intersections with shared through/right turn lanes)	All (KABCO)	Adelaide, Australia	n/a
230	3255	0.6	n/a	2	Vehicle/Bicycle (all @ signalized intersections with shared through/right turn lanes)	All (KABCO)	Christchurch, New Zealand	n/a
230	3256	1.36	n/a	2	Vehicle/Bicycle (all @ signalized intersections with exclusive right turn lanes)	All (KABCO)	Adelaide, Australia	n/a
230	3257	0.97	n/a	2	Vehicle/Bicycle (all @ signalized intersections with exclusive right turn lanes)	All (KABCO)	Christchurch, New Zealand	n/a
515	9261	1.27	n/a	2	Vehicle/Bicycle (all @ 4-leg signalized intersections)	All (KABCO)	Florida, USA	n/a

Study ID	CMF ID	CMF	St. Error	Star Rating	Crash Type	Crash Severity (KABCO)	Source Jurisdiction	No of Sites/Miles
515	9262	1.71	n/a	2	Vehicle/Bicycle (fatal & serious injury @ 4-leg signalized intersections)	Fatal & Serious Injury (KAB)	Florida, USA	n/a
515	9263	1.36	n/a	2	Vehicle/Bicycle (all @ 3-leg stop-controlled intersections)	All (KABCO)	Florida, USA	n/a

*Data is from Australia and New Zealand and the turning directions have been reversed to reflect right-side driving.

Countermeasure = Install Bike Lanes - Segment Crashes (Six Studies; Two 3-Star CMFs, Eight 2-Star CMFs)

Study ID	CMF ID	CMF	St. Error	Star Rating	Crash Type	Crash Severity (KABCO)	Source Jurisdiction	No of Sites/Miles
298	4659	1.51	0.583	3	Vehicle/Bicycle	All (KABCO)	New York, NY, USA	43 miles on 61 streets
515	9244	0.86	n/a	3	Vehicle/Bicycle (all @ urban 4-lane divided segments)	All (KABCO)	Florida, USA	616 miles
82	1719	0.65	0.2	2	Vehicle/Bicycle	Fatal & Injury (KABC)	Copenhagen, Denmark	n/a
124	2183	1.49	0.324	2	Vehicle/Bicycle (all motor vehicle and bicycle/moped @ intersections and segments)	Fatal & Injury (KABC)	Copenhagen, Denmark	5.6 km
124	2185	1.27	0.651	2	Vehicle/Bicycle (all motor vehicle and bicycle/moped @ all non-intersection locations)	Fatal & Injury (KABC)	Copenhagen, Denmark	5.6 km
433	7840	0.42	0.1	2	Vehicle/Bicycle (all @ urban multilane segments)	All (KABCO)	Florida, USA	29.509 miles
433	7841	0.4	0.09	2	Vehicle/Bicycle (fatal & injury @ urban multilane segments)	Fatal & Injury (KABC)	Florida, USA	29.509 miles
457	8216	0.77	0.24	2	Vehicle/Bicycle	All (KABCO)	Christchurch, New Zealand	12 Segments
515	9236	1.69	n/a	2	Vehicle/Bicycle (all @ urban 2-lane divided segments)	All (KABCO)	Florida, USA	126 miles
515	9258	2.24	n/a	2	Vehicle/Bicycle (all @ urban 4-lane undivided segments)	All (KABCO)	Florida, USA	5 miles

Countermeasure = Install Cycle Tracks / Protected Bike Lanes / Separated Bike Lanes (Three Studies; Ten 3-Star CMFS, Twenty 2-Star CMFs, Four 1-Star CMFs)

Study ID	CMF ID	CMF	St. Error	Star Rating	Crash Type	Crash Severity (KABCO)	Source Jurisdiction	No of Sites/Miles
124	2134	0.37	0.061	3	Vehicle/Bicycle (all motor vehicle and bicycle/moped)	All (KABCO)	Copenhagen, Denmark	20.6 km
124	2139	2.29	0.449	3	Vehicle/Bicycle (right turning vehicle with bicycle/moped)	All (KABCO)	Copenhagen, Denmark	20.6 km
124	2144	1.48	0.27	3	Vehicle/Bicycle (left turning vehicle with bicycle/moped)	All (KABCO)	Copenhagen, Denmark	20.6 km
124	2171	1.1	0.077	3	Vehicle/Bicycle (all motor vehicle and bicycle/moped)	Fatal & Injury (KABC)	Copenhagen, Denmark	20.6 km
124	2172	1.24	0.105	3	Vehicle/Bicycle (all motor vehicle and bicycle/moped @ intersections)	Fatal & Injury (KABC)	Copenhagen, Denmark	20.6 km
124	2173	0.87	0.107	3	Vehicle/Bicycle (all motor vehicle and bicycle/moped @ all non-intersection locations)	Fatal & Injury (KABC)	Copenhagen, Denmark	20.6 km
274	4097	0.26	n/a	3	Vehicle/Bicycle (physically separated bidirectional, no parking between cycle tracks and traffic, segment crashes)	Serious/Minor Injury (ABC)	Montreal, QC, Canada	11.75 km (CT) & 3.76 km (BL)
274	4098	0.27	n/a	3	Vehicle/Bicycle (physically separated bidirectional, no parking between cycle tracks and traffic, segment and intersection crashes)	Serious/Minor Injury (ABC)	Montreal, QC, Canada	11.75 km (CT) & 3.76 km (BL)
274	4102	0.41	n/a	3	Vehicle/Bicycle (physically separated bidirectional, with parking between cycle tracks and traffic, segment crashes)	Serious/Minor Injury (ABC)	Montreal, QC, Canada	11.75 km (CT) & 3.76 km (BL)
274	4103	0.41	n/a	3	Vehicle/Bicycle (physically separated bidirectional, with parking between cycle tracks and traffic, segment and intersection crashes)	Serious/Minor Injury (ABC)	Montreal, QC, Canada	11.75 km (CT) & 3.76 km (BL)

Study ID	CMF ID	CMF	St. Error	Star Rating	Crash Type	Crash Severity (KABCO)	Source Jurisdiction	No of Sites/Miles
274	4094	0.92	n/a	2	Vehicle/Bicycle (both physically separated bidirectional and unidirectional bike lanes adjacent to traffic, segment crashes)	Serious/Minor Injury (ABC)	Montreal, QC, Canada	11.75 km (CT) & 3.76 km (BL)
274	4095	0.85	n/a	2	Vehicle/Bicycle (both physically separated bidirectional and unidirectional bike lanes adjacent to traffic, segment and intersection crashes)	Serious/Minor Injury (ABC)	Montreal, QC, Canada	11.75 km (CT) & 3.76 km (BL)
274	4099	0.12	n/a	2	Vehicle/Bicycle (unidirectional bike lanes adjacent to traffic, segment crashes)	Serious/Minor Injury (ABC)	Montreal, QC, Canada	11.75 km (CT) & 3.76 km (BL)
274	4100	0.19	n/a	2	Vehicle/Bicycle (unidirectional bike lanes adjacent to traffic, segment and intersection crashes)	Serious/Minor Injury (ABC)	Montreal, QC, Canada	11.75 km (CT) & 3.76 km (BL)
460	8222	1.52	n/a	2	Vehicle/Bicycle (bike lane separated by a parking lane only)	All (KABCO)	CA, DC, FL, IL, MT, NY, OR, TX; USA*	11 Sites
460	8223	1.54	n/a	2	Vehicle/Bicycle (bike lane separated by more than a parking lane)	All (KABCO)	CA, DC, FL, IL, MT, NY, OR, TX; USA*	15 Sites
460	8224	0.84	n/a	2	Vehicle/Bicycle (bike lane separated by concrete/curb only)	All (KABCO)	CA, DC, FL, IL, MT, NY, OR, TX; USA*	5 Sites
460	8232	1.37	n/a	2	Vehicle/Bicycle (bike lane separated by concrete/curb plus)	All (KABCO)	CA, DC, FL, IL, MT, NY, OR, TX; USA*	14 Sites
460	8233	2.44	n/a	2	Vehicle/Bicycle (bike lane separated by plastic bollards only)	All (KABCO)	CA, DC, FL, IL, MT, NY, OR, TX; USA*	6 Sites
460	8234	1.56	n/a	2	Vehicle/Bicycle (bike lane separated by plastic bollards plus)	All (KABCO)	CA, DC, FL, IL, MT, NY, OR, TX; USA*	13 Sites
460	8239	1.37	n/a	2	Vehicle/Bicycle (bike lane separated by other - including other bollards - plus)	All (KABCO)	CA, DC, FL, IL, MT, NY, OR, TX; USA*	8 Sites
460	8241	1.31	n/a	2	Vehicle/Bicycle (intersection treatment is mixing zones plus)	All (KABCO)	CA, DC, FL, IL, MT, NY, OR, TX; USA*	10 Sites

Study ID	CMF ID	CMF	St. Error	Star Rating	Crash Type	Crash Severity (KABCO)	Source Jurisdiction	No of Sites/Miles
460	8244	1.31	n/a	2	Vehicle/Bicycle (intersection treatment is separate bike signals plus)	All (KABCO)	CA, DC, FL, IL, MT, NY, OR, TX; USA*	4 Sites
460	8245	1.39	n/a	2	Vehicle/Bicycle (intersection treatment is markings through intersections only)	All (KABCO)	CA, DC, FL, IL, MT, NY, OR, TX; USA*	15 Sites
460	8246	1.52	n/a	2	Vehicle/Bicycle (intersection treatment is markings through intersections plus)	All (KABCO)	CA, DC, FL, IL, MT, NY, OR, TX; USA*	12 Sites
460	8248	1.11	n/a	2	Vehicle/Bicycle (green pavement is provided only at conflict points)	All (KABCO)	CA, DC, FL, IL, MT, NY, OR, TX; USA*	13 Sites
460	8249	1.4	n/a	2	Vehicle/Bicycle (green pavement is provided except at conflict points)	All (KABCO)	CA, DC, FL, IL, MT, NY, OR, TX; USA*	8 Sites
460	8251	1.74	n/a	2	Vehicle/Bicycle (no green pavement is provided)	All (KABCO)	CA, DC, FL, IL, MT, NY, OR, TX; USA*	10 Sites
460	8252	1.56	n/a	2	Vehicle/Bicycle (bike lane in the before period)	All (KABCO)	CA, DC, FL, IL, MT, NY, OR, TX; USA*	16 Sites
460	8253	1.46	n/a	2	Vehicle/Bicycle (no bike lane in the before period)	All (KABCO)	CA, DC, FL, IL, MT, NY, OR, TX; USA*	30 Sites
460	8240	0	n/a	1	Vehicle/Bicycle (intersection treatment is mixing zones only)	All (KABCO)	CA, DC, FL, IL, MT, NY, OR, TX; USA*	3 Sites
460	8242	6.67	n/a	1	Vehicle/Bicycle (intersection treatment is lateral shift only)	All (KABCO)	CA, DC, FL, IL, MT, NY, OR, TX; USA*	2 Sites
460	8243	2.2	n/a	1	Vehicle/Bicycle (intersection treatment is lateral shift plus)	All (KABCO)	CA, DC, FL, IL, MT, NY, OR, TX; USA*	4 Sites
460	8247	1.67	n/a	1	Vehicle/Bicycle (continuous green pavement)	All (KABCO)	CA, DC, FL, IL, MT, NY, OR, TX; USA*	4 Sites

* The study used data from all the mentioned states, however, it is not clear which states were used for a particular CMF.

Countermeasure = Increase Bike Lane Width (One Study; Three 3-Star CMFunctions)

Study ID	CMF ID	CMF	St. Error	Star Rating	Crash Type	Crash Severity (KABCO)	Source Jurisdiction	No of Sites/Miles
476	8692	*	n/a	3	Vehicle/Bicycle (@ urban arterials)	All (KABCO)	Florida, USA	6240 Segments
476	8702	**	n/a	3	Vehicle/Bicycle (@ urban arterials)	Fatal & Injury (KABC)	Florida, USA	6240 Segments
476	8703	***	b/a	3	Vehicle/Bicycle (@ urban arterials)	Fatal & Serious Injury (KAB)	Florida, USA	6240 Segments

*

CMFunction:

$$CMF = \exp\{0.1172 \times (U_{BLW} - Base_{U_{BLW}})\}$$

Where:

$U_{BLW} = \ln\{47.24 + 11.859\,(PropBikeLaneWidth - 7) + 3.7\,(PropBikeLaneWidth - 7)^2\}$

$Base_{U_{BLW}} = \ln\{47.24 + 11.859\,(ExistBikeLaneWidth - 7) + 3.7\,(ExistBikeLaneWidth - 7)^2\}$

Where:

$PropBikeLaneWidth$ = Proposed bicycle lane width in feet

$ExistBikeLaneWidth$ = Base, or existing, bicycle lane width in feet

**

CMFunction:

$$CMF = \exp\{0.1155 \times (U_{BLW} - Base_{U_{BLW}})\}$$

Where:

$U_{BLW} = \ln\{47.24 + 11.859\,(PropBikeLaneWidth - 7) + 3.7\,(PropBikeLaneWidth - 7)^2\}$

$Base_{U_{BLW}} = \ln\{47.24 + 11.859\,(ExistBikeLaneWidth - 7) + 3.7\,(ExistBikeLaneWidth - 7)^2\}$

Where:

$PropBikeLaneWidth$ = Proposed bicycle lane width in feet

$ExistBikeLaneWidth$ = Base, or existing, bicycle lane width in feet

***

$$CMF = \exp\{0.1201 \times (U_{BLW} - Base_{U_{BLW}})\}$$

Where:

U_{BLW} = Bike Lane Width (feet)

$Base_{U_{BLW}}$ = Baseline Bike Lane Width (feet)

Countermeasure = Install Raised Bike Crossings (Two Studies; One 3-Star CMF, One 1-Star CMF)

Study ID	CMF ID	CMF	St. Error	Star Rating	Crash Type	Crash Severity (KABCO)	Source Jurisdiction	No of Sites/Miles
259	4039	0.49	0.114	3	Vehicle/Bicycle	All (KABCO)	Netherlands	852 site-years
14	419	1.09*	n/a	1	Vehicle/Bicycle	Serious/Minor Injury (ABC)	n/a	n/a

* Meta-analysis study

Countermeasure = Install Red Color and/or High Quality Pavement Markings and Cyclist Priority at Intersections (Two Studies; One 3-Star CMF, Three 2-Star CMFs)

Study ID	CMF ID	CMF	St. Error	Star Rating	Crash Type	Crash Severity (KABCO)	Source Jurisdiction	No of Sites/Miles
259	4038	2.53	0.788	3	Vehicle/Bicycle (red color and high quality markings for bicycle crossing with cyclist priority at intersections)	All (KABCO)	Netherlands	n/a
230	3258	0.61	n/a	2	Vehicle/Bicycle (colored bike lanes at signalized intersections)	All (KABCO)	Christchurch, New Zealand	38 Intersections
259	4036	1.47	0.412	2	Vehicle/Bicycle (red color for bicycle crossing with cyclist priority at intersections)	All (KABCO)	Netherlands	n/a
259	4037	1.74	0.618	2	Vehicle/Bicycle (high quality markings for bicycle crossing with cyclist priority at intersections)	All (KABCO)	Netherlands	n/a

Countermeasure = Provide Visual Narrowing at Intersections (One Study; Two 2-Star CMFs)

Study ID	CMF ID	CMF	St. Error	Star Rating	Crash Type	Crash Severity (KABCO)	Source Jurisdiction	No of Sites/Miles
259	4040	1.37	0.33	2	Vehicle/Bicycle (restricted visibility from vehicles on a minor road to approaching bicyclists at intersections with cyclist priority)	All (KABCO)	Netherlands	460 site-years
259	4041	0.54	0.337	2	Vehicle/Bicycle (very poor visibility from vehicles on a minor road to approaching bicyclists at intersections with cyclist priority)	All (KABCO)	Netherlands	136 site-years

Appendix C: Bicycle Infrastructure Data Sources

Name	Jurisdiction	Format	Date	Install Date	Contains Class IV
Regional Bike Map	Ventura County	Web map	Unk	No	Yes
Bike Paths	Milpitas	Web map	Unk	No	No
Hayward Bicycle Network	Hayward	Shapefile	6/26/2018	No	No
Bikeways (Existing)	Los Angeles (City)	Shapefile	3/19/20189	Yes	No
Bike Routes – SCAG Region	SCAG	Shapefile	11/18/2019	Some	Yes
LA County Bikeways Map	LADPW	Web map	2016	No	Yes
ATSP Project Data	Metro	Shapefile	2016	No	Unk
Regional Bike Facilities	MTC	Shapefile	10/3/2018	No	No
Gilroy Bike Map	Gilroy	PDF map	Unk	No	No
Bike Map	Mountain View	Web map	Unk	No	No
Bikeway and Trail	Pleasanton	Shapefile	Unk	No	No
Bikeways	Salinas	Web map	Unk	No	No
Bicycle Greenwave Streets	San Francisco	Shapefile	11/18/2019	No	N/A
SFMTA Bikeway Network	San Francisco	Shapefile	11/18/2019	Yes	Yes
SFMTA Bikeway Network Point Features	San Francisco	Shapefile	11/18/2019	Yes	N/A
Bikeway Projects	Oakland	Shapefile	10/14/2019	Yes	Yes
Existing and Proposed Bikeways	Oakland	Shapefile	8/13/2019	Yes	Yes
Bike Routes	SANDAG	Shapefile	5/31/2018	No	No
Bikepaths	Modesto	Web map	Unk	No	Yes
Bike Routes in Pasadena, CA	Pasadena	Shapefile	7/24/2014	No	No
Bike Plan Public	Rancho Cucamonga	Shapefile	10/15/2019	No	No
OC Bikeways Map	Orange County	PDF map	Unk	No	No
City of Sacramento Existing Bikeways	Sacramento	PDF map	3/24/2015	No	No
East Anaheim Existing and Proposed Bikeways	Anaheim	PDF map	11/9/2016	No	No
West Anaheim Existing and Proposed Bikeways	Anaheim	PDF map	11/9/2016	No	No
Citywide Bikeway Network	Stockton	PDF map	12/5/2017	No	No
Bikeways of Irvine	Irvine	Web map	Unk	No	No
Alameda County Bikeways	Alameda County	Shapefile	8/28/2016	No	No
Corona Bike Routes	Corona	Shapefile	11/20/2017	No	No
Existing Bicycle Facilities	Elk Grove	PDF map	Unk	No	No
Bicycle Transportation Existing	San Luis Obispo	Shapefile	4/26/2019	No	No
Bikeway	Shasta Regional Active Transportation	Web map	Unk	No	No
Biking in Tulare County	Tulare County	Web map	Unk	No	No
Bike Routes	SACOG	Shapefile	7/30/2018	No	Yes

Name	Jurisdiction	Format	Date	Install Date	Contains Class IV
Existing Bikeways and Trails	Rocklin	Shapefile	11/6/2017	No	No
Bikeways	SLOCOG	Shapefile	2014	No	No
Sonoma County Bicycle Plan	Sonoma County	Shapefile	9/2014	No	No
Monterey County Bike Map	Monterey County	Web map	2016?	No	No
Kern Bike Transportation	Kern County	Shapefile	4/10/2018	No	No

Appendix D: ATP-Funded Projects with Class IV Bike Lanes

ATP ID	Cycle	District	Agency Name	Project Name	Class IV (Linear Feet)
ATP1-05-071R	1	5	Monterey, City of	North Fremont Bike and Pedestrian Access and Safety Improvements	5,000
ATP3-07-001M	3	7	Los Angeles, City of	DTLA Arts District Pedestrian and Cyclist Safety Project	2,250
ATP3A-11-010M	3A	11	National City, City of	Euclid Avenue Bicycle and Pedestrian Enhancements	1,267
ATP3/3A-07-014M	3/3A	7	Pasadena, City of	Union Street Cycle Track	7,920
ATP3A-04-016S	3A	4	Oakland, City of	14th Street: Safe Routes in the City	10,200
ATP3A-07-018S	3A	7	Los Angeles, City of	Jefferson Boulevard Complete Street Project	3,315
ATP3A-04-023S	3A	4	Oakland, City of	Fruitvale Alive Gap Closure Project	10,200
ATP3A-07-049S	3A	7	Glendale, City of	Glendale Transportation Center 1st and Last Mile Regional Improvements Phase II	1,000
ATP3A-07-050S	3A	7	Palmdale, City of	City of Palmdale - Civic Center Complete Streets	1,000
ATP3-11-068M	3	11	Carlsbad, City of	Avenida Encinas Coastal Rail Trail and Pedestrian Improvements, Carlsbad	20,000
ATP3A-08-087M	3A	8	Redlands, City of	East Valley Corridor Bike Route Interconnect Project	5,737
ATP3-11-026S	3	11	San Diego Association of Governments (SANDAG)	Imperial Avenue Bikeway	11,950
ATP3A-07-080M	3A	7	Los Angeles County	Temple Avenue Complete Street Improvements	4,066
ATP3A-04-023M	3A	4	Alameda County Transportation Commission	I-80 and Gilman Interchange, C Bicycle, Pedestrian Overcrossing and Access Improvements	338
ATP3A-03-043M	3A	3	Yuba City, City of	Harter Parkway and Sutter Bike Path Gap Closure	1,900
ATP3A-07-074M	3A	7	Ventura, City of	Harmon Barranca Corridor Gap Closure for Montalvo and Portola Elementary School	600
ATP3A-12-048M	3A	12	Santa Ana, City of	City of Santa Ana - West Willits Street Protected Bicycle Lanes	4,000
ATP3-07-073M	3	7	Baldwin Park, City of	Maine Avenue and Pacific Avenue Corridor Complete Streets Improvements, Phase II	13,778
ATP3-04-035S	3	4	Alameda, City of	Central Avenue Complete Street Project	3,100

ATP ID	Cycle	District	Agency Name	Project Name	Class IV (Linear Feet)
ATP4-08-010S	4	8	San Bernardino County Transportation Authority	SBCTA Metrolink Station Accessibility Improvement Project - Phase II	18,000
ATP4-11-011S	4	11	National City, City of	Bayshore Bikeway - Segment 5	3,440
ATP4-10-014S	4	10	Stanislaus County	Airport Neighborhood Active Transportation Connectivity and Safety Project	1,850
ATP4-07-015S	4	7	Pomona, City of	Pomona Multi-Neighborhood Pedestrian and Bicycle Improvements	6,600
ATP4-05-019S	4	5	Santa Barbara, City of	Downtown De LaVina Street Safe Crosswalks and Buffered Bike Lanes	500
ATP4-10-023S	4	10	Stockton, City of	California Street Separated Bikeway Project	6,336
ATP4-07-025S	4	7	Long Beach, City of	Orange Avenue Backbone Bikeway and Complete Streets Improvements	7,392
ATP4-08-040S	4	8	Eastvale, City of	North/South Bike Network Gap Closure & Connectivity to North Eastvale	25,000
ATP4-04-048S	4	4	San Jose, City of	Better BikewaySJ - San Fernando Corridor	5,000
ATP4-05-051S	4	5	Santa Barbara, City of	U.S. 101 State Street Undercrossing Active Transportation Improvements	2,060
ATP4-06-063M	4	6	Fresno, City of	Southeast Fresno Cycle Track, First from Tulare to Ventura/Hazelwood	4,300
ATP4-06-068M	4	6	Fresno, City of	Maple Avenue Cycle Track and Pedestrian Scramble	4,500
ATP4-04-074M	4	4	San Jose, City of	Willow-Keyes Complete Streets Improvements	880
ATP4-03-077M	4	3	Sacramento, City of	Franklin Boulevard Complete Street Phase 2	8,800
ATP4-11-086M	4	11	San Diego Association of Governments	University Bikeway	13,000
ATP4-11-087M	4	11	National City, City of	8th Street and Roosevelt Avenue Active Transportation Corridor, National City	2,140
ATP4-07-092M	4	7	Los Angeles, City of	Broadway-Manchester Active Transportation Equity Project	21,023
ATP4-07-093M	4	7	Los Angeles, City	LA River Greenway, West San Fernando Valley Gap Closure	4,310
ATP4-12-095M	4	12	Costa Mesa, City of	Merrimac Way Multipurpose Street, Sidewalk and Bicycle Facility Project	4,800

ATP ID	Cycle	District	Agency Name	Project Name	Class IV (Linear Feet)
ATP4-12-096M	4	12	Santa Ana, City of	McFadden Avenue Protected Bike Lane and Bicycle Boulevard Project	15,050
ATP4-12-097M	4	12	Santa Ana, City of	Standard Avenue Protected Bike Lane and Protected Intersection Project	5,900
ATP4-08-099M	4	8	Palm Desert, City of	San Pablo Avenue Improvements from Fred Waring to Magnesia Falls	2,730