SAFETY IMPACTS OF BICYCLE INFRASTRUCTURE: A CRITICAL REVIEW

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SAFETY IMPACTS OF BICYCLE INFRASTRUCTURE: A CRITICAL REVIEW

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This thesis is dedicated to my wife, Katelyn, whose unfailing support and encouragement have helped bring me through graduate school and the thesis writing process. This thesis is also dedicated to my parents, who have have loved me, helped me, and encouraged me to give my best at everything. Finally, this thesis is dedicated to everyone who wants to make their community a better place to ride a bicycle.

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TABLE OF CONTENTS

ACKNOWLEDGEMENTS . . . . **iv**

LIST OF TABLES . . . . **vii**

LIST OF FIGURES . . . . **viii**

LIST OF ABBREVIATIONS . . . . **ix**

SUMMARY . . . . **x**

I INTRODUCTION AND BACKGROUND **1**

1.1 Safety in active transportation 1

1.2 Planning and designing for safety 1

1.3 Motivation of thesis 2

1.3.1 The Highway Safety Manual and the safety research method 3

1.3.2 The Highway Safety Manual research method for bicycle and pedestrian countermeasures 4

1.4 Current research methods 5

1.4.1 Typical study formats 5

1.4.2 Typical outcome measures 7

1.4.3 Principles behind non-motorized roadway safety treatments 7

1.4.4 Interactions of safety design principles 8

1.4.5 The challenge in interpreting findings 9

1.5 Outline of thesis 10

II REVIEW OF THE LITERATURE **11**

2.1 Master list of treatments included in review 11

2.1.1 Strategy for literature search and review 11

2.1.2 Prioritization 12

2.1.3 Review and analysis 13

2.2 Synthesis 13

2.3 Study details 30

III INDICATIONS OF EFFECTIVENESS **42**

3.1 Indications from studies 42

3.1.1 Access management . . . 42
3.1.2 Bicycle boulevard . . . 42
3.1.3 Bike box . . . 43
3.1.4 Bike lanes . . . 44
3.1.5 Cycle tracks . . . 47
3.1.6 Increase bicycling levels in community . . . 48
3.1.7 Multi-use path in separate right-of-way . . . 48
3.1.8 Neighborhood traffic circle . . . 49
3.1.9 On-street parking removal . . . 49
3.1.10 Raised bicycle crossing . . . 51
3.1.11 Roundabouts . . . 52
3.1.12 Shared lane marking . . . 52
3.1.13 Shoulder pavement width . . . 54
3.1.14 Shoulder rumble strips . . . 54
3.1.15 Street lighting . . . 55
3.1.16 Two-stage turn queue box . . . 55
3.1.17 Wide curb lanes . . . 56
3.1.18 Other route characteristics . . . 56
3.2 Data issues and needs . . . 56
3.2.1 Number of crashes . . . 56
3.2.2 Injury severity . . . 57
3.2.3 Crash causation . . . 57
3.2.4 Exposure data collection and maintenance . . . 57
IV CONCLUSIONS . . . 59
4.1 Literature survey results and the need for better data . . . 59
4.2 Highway safety research and its applications . . . 60
4.3 Design decision support for Georgia . . . 60
4.4 Future work . . . 61
REFERENCES . . . 63

LIST OF TABLES

1 Bike Study Results . . . 16
1 Bike Study Results (continued) . . . 17
1 Bike Study Results (continued) . . . 18
1 Bike Study Results (continued) . . . 19
1 Bike Study Results (continued) . . . 20
1 Bike Study Results (continued) . . . 21
1 Bike Study Results (continued) . . . 22
1 Bike Study Results (continued) . . . 23
1 Bike Study Results (continued) . . . 24
1 Bike Study Results (continued) . . . 25
1 Bike Study Results (continued) . . . 26
1 Bike Study Results (continued) . . . 27
1 Bike Study Results (continued) . . . 28
1 Bike Study Results (continued) . . . 29
2 Study Details Legend . . . 32
3 Study Details I . . . 33
3 Study Details I (continued) . . . 34
3 Study Details I (continued) . . . 35
4 Study Details II . . . 36
4 Study Details II (continued) . . . 37
4 Study Details II (continued) . . . 38
4 Study Details II (continued) . . . 39

LIST OF FIGURES

1 Study result ranges for all interventions 15

2 Risk ratios associated with bicycle boulevard treatment 43

3 Risk ratios associated with bike box treatment 44

4 Risk ratios associated with bike lanes 45

5 Risk ratios associated with cycle tracks 47

6 Risk ratios associated with multi-use trails 49

7 Risk ratios associated with neighborhood traffic circles 50

8 Risk ratios associated with on-street parking removal 50

9 Risk ratios associated with raised bicycle crossings 51

10 Risk ratios associated with general roundabout installation 53

11 Risk ratios associated with roundabout installation with dedicated bicycle facilities 53

12 Risk ratios associated with night-time roadway lighting 55

LIST OF ABBREVIATIONS

AASHTO	American Association of State Highway and Transportation Officials.
BL	bike lane.
CA	California.
CMF	crash modification factor.
FHWA	Federal Highway Administration.
FL	Florida.
ft	feet.
HSM	Highway Safety Manual.
ITE	Institute of Transportation Engineers.
MA	Massachusetts.
MUTCD	Manual on Uniform Traffic Control Devices.
MV	motor vehicle.
NACTO	National Association of City Transportation Officials.
NC	North Carolina.
OECD	Organisation for Economic Cooperation and Development.
OR	Oregon.
TRB	Transportation Research Board.
TRID	An integrated database combining records from TRB's Transportation Research Information Services (TRIS) database and OECD's International Transport Research Documentation (ITRD) Database.
TX	Texas.
U.K.	United Kingdom.
U.S.	United States.
VMT	vehicle miles traveled.
VT	Vermont.
WA	Washington.
WCL	wide curb lane.

SUMMARY

This thesis takes a critical look at the present state of bicycle safety research, highlighting data needs and some conclusions researchers have already drawn using the data available to them. In particular, this thesis examines safety literature relating to 22 bicycle treatments, synthesizing findings, study methodologies, and data sources used in the studies. The current body of bicycle safety literature points toward some defensible conclusions regarding the safety of certain bicycle treatments such as bike lanes and removal of on-street parking; however, many treatments are still in need of rigorous research. Also, there are fundamental questions about data that need to be answered, and data availability issues need to be addressed. Among them are what constitutes appropriate exposure measures for bicycles, how to obtain accurate crash and exposure data for bicycles, and what impact safety treatments have on injury severity.

CHAPTER I

INTRODUCTION AND BACKGROUND

"Active transportation" uses human-powered means to move from place to place and encompasses a variety of modes including walking, bicycling, or using other human-powered devices. Increased used of active transportation can make direct and indirect contributions toward addressing both the health concerns arising from sedentary lifestyles and other issues related to over-reliance on automobiles for transportation including congestion, environmental, and equity problems [7, 72, 92, 98, 113]. Providing for active transportation is not only a legitimate goal in its own right, but it can also support the roles of public transit systems and increase economic activity [16, 20, 41, 63].

1.1 Safety in active transportation

Unfortunately, walking and bicycling are not free of risk. While 10.9% of trips in the United States were made by walking or by bicycle during 2009 [88], those modes made up 14% of all traffic fatalities nationally during the same year [82, 84]. This suggests that walking and biking are over-represented in crash fatalities, in that more of these fatalities happen while walking or biking than for other types of trips. However, quantifying the risk associated with walking and cycling is difficult without an accurate way to measure exposure for active travel modes [89].

1.2 Planning and designing for safety

For walking and biking to be the viable, healthy modes they should be, travelers choosing those modes should be able to do so without either the fear or reality of excessive danger associated with their choice. Safety for non-motorized road users is the responsibility of multiple parties, including the user, other travelers, law enforcement, and transportation planners and engineers [74]. Facility design can have a major influence on safety [1], which is why the role of planners and engineers is so important. This thesis focuses on the safety research used to discern appropriate designs and countermeasures that enhance bicycle safety.

Local governments and transportation agencies are constantly making decisions about how best to achieve their goals with the limited resources available to them. When faced with the decision of how to design or re-design a facility to improve bicycle or pedestrian safety, knowing the expected safety performance of the alternatives can help decision-makers gain support and feel confident in their resource allocation decisions. In the absence of data or past research to evaluate a treatment, jurisdictions may decide to implement a treatment experimentally in hope that it will address a specific safety concern.

In contrast, when substantial information about the expected effects of a safety treatment is available for a general context, those effects can be calibrated to the local situation. The expected safety performance can then be estimated to make better decisions about appropriate design and treatments. This is the foundation of the research method used for the Highway Safety Manual [1]; however, most pedestrian and bicycle safety research does not satisfy the data requirements for this method, and the Highway Safety Manual does not provide crash modification factors for any pedestrian or bicycle treatments.

1.3 Motivation of thesis

The Georgia Department of Transportation sponsored a project[1] to investigate the effectiveness of bicycle and pedestrian safety treatments in the absence of their representation in the Highway Safety Manual. The goal of the project was to use existing literature on bicycle and pedestrian treatments, combined with observational studies to fill in gaps in the available knowledge, to support the development of bicycle and pedestrian design policy for the state of Georgia. This thesis is an outworking of the project and summarizes literature related to bicycle treatment safety. The project is still underway as of the writing of this thesis, and a companion document on pedestrian treatment safety is planned to follow as well.

[1] GDOT research project No. 13-17, "Bicycle and Pedestrian Safety in the Highway Safety Manual"

1.3.1 The Highway Safety Manual and the safety research method

The Highway Safety Manual (HSM) is based on a simple method for assessing roadway safety treatment effectiveness based on data inputs and analytical study [1]. In the highway safety method, safety performance is a function of a base rate multiplied by a series of "crash modification factors" (CMFs), such that

$$\text{Safety Performance} = (\text{Base Rate}) \times (\text{CMF})_1 \times (\text{CMF})_2 \times ... \times (\text{CMF})_n \tag{1}$$

where the "base rate" term represents the expected number of crashes in the absence of special safety treatments, encompassing both risk and exposure. Each CMF term is a multiplier that modifies the number of expected crashes from the base rate according to the expected safety effectiveness of a specific treatment. CMFs less than 1 indicate an expected safety improvement (crash decrease), while CMFs greater than 1 indicate an expected safety decrease (increase in crashes). CMFs equal to 1 indicate no expected change in safety. The number of CMF terms for different countermeasures may range from one to five or more, depending on the situation and their availability. This method of combining CMFs assumes that their effects are multiplicative; however, this has not been proven [32]. Equation 1 can be re-written as

$$\text{Safety Performance} = A[e^{\alpha+(\text{CMF})_1+(\text{CMF})_2+...+(\text{CMF})_n}] \tag{2}$$

where A is primarily related to exposure, and e^{α} is primarily related to risk. Exposure may be expressed in a variety of ways, including number of trips, vehicle miles traveled (VMT), hours of exposure, or number of road crossings (in the case of pedestrians). For bicycle and pedestrian safety analysis, it is possible that multiple exposure types are valid and could be used in combination to better quantify safety performance. Risk is expressed as the probability of a crash occurring per unit of travel (distance, time, trips, etc.).

For most automobile-related safety research, VMT (sometimes adjusted by volume) is an adequate measure of exposure. The Highway Safety Manual provides a wide variety of CMFs describing safety interventions for automobiles; applying them is then a simple matter of multiplying the desired CMFs by the base rate which comes from VMT and a base rate factor. The HSM does not, however, include CMFs for bicycle and pedestrian treatments. Moreover, CMFs would be quite difficult to apply to bicycle and pedestrian interventions due to the lack and ambiguity of necessary exposure values. Meaningful exposure data is critical for both development and application of CMFs using the HSM method.

1.3.2 The Highway Safety Manual research method for bicycle and pedestrian countermeasures

In order to develop or use crash modification factors pursuant to the method of the Highway Safety Manual, it is necessary to have reliable crash rates and exposure measures to calculate an accurate base rate. Crash data and motor vehicle volume counts are collected regularly by transportation agencies, and these are often available in the sample sizes necessary for developing and using CMFs for automobile-related safety interventions. However, limited sample sizes and uncertainty about what even constitutes accurate pedestrian and bicycle exposure data continues to prevent the development and use of HSM-type CMFs for pedestrian and bicycle countermeasures.

One issue is the unreliability of officially-recorded crash data at estimating the rate of bicycle and pedestrian crashes in a given area. Elvik and Mysen [24] found the average rate at which fatal crashes are reported to be about 95%, compared to 70% for serious injuries, 25% for slight injuries, and 10% for very slight injuries. Since most crashes do not result in fatalities, this means that most crash types are grossly underreported. To exacerbate the issue of underreporting, bias also exists in crash reporting rates such that certain groups of people are less likely to report crashes than others. Bicyclists and pedestrians in particular are less likely than other users to report crashes [17, 71], but reporting levels also vary by age group and injury severity [17].

Even larger than the crash rate issue is the problem of measuring and representing exposure. It is all too easy to conduct a naïve before-after study on a safety treatment, find an increase in crashes or no change at all, and conclude that the treatment was ineffective. But without knowledge of cyclist or pedestrian exposure, there is no way of knowing that risk did not decrease on a per-cyclist or per-pedestrian basis due to an increase in cyclist or pedestrian volume. The inverse is also true for crash decreases.

As revealed in the bicycle safety treatment literature review described in the following chapters, some studies have found creative ways to control for cyclist exposure in the study's scenario, which is to be applauded. Examples include interviewing cyclists involved in injury crashes about the infrastructure characteristics along their routes [46, 104], and controlling for motor vehicle occupant injuries as a surrogate for traffic danger along the routes studied [69]. However, to develop CMFs that can be applied anywhere, transferable exposure data needs to be collected. This is true for both bicycle and pedestrian safety research.

1.4 Current research methods

In the absence of base crash rate data necessary for the HSM method (shown in Equations 1 and 2), many researchers and transportation agencies have developed other research methods to estimate safety effects of bicycle and pedestrian safety treatments. Some studies employ naïve before-after methodology, possibly incorporating a comparison group to control for area-wide changes in risk or exposure. Such studies do not incorporate data on exposure and crash risk for specific treatment locations and may also be susceptible to regression-to-the-mean bias or confounding factors, which can lead to incorrect judgments about the true effects of a safety countermeasure. Other studies overcome some of these issues by controlling for changes in exposure and risk while minimizing regression-to-the-mean effects and confounding factors. Even more sophisticated study designs such as cross-sectional or before-after studies with controls or even case-crossover studies cannot fully account for exposure data in a way that is transferable in a crash modification factor, because these studies still do not present a solution to the problem of adequately describing bicycle and pedestrian exposure. This is partly due to the challenges of small samples sizes and self-selection among non-motorized users.

1.4.1 Typical study formats

Typical study methods for highway safety research include:

- Simple before/after
- Full Bayes

- Empirical Bayes
- Regression cross-section
- Non-regression cross-section
- Case-control
- Cohort
- Meta-analysis

These are the typical study formats described in *A Guide to Developing Quality Crash Modification Factors* [43] and the CMF Clearinghouse site's glossary of terms [38]. Studies reviewed in this thesis used all the methods on the list above except the last two, case-control and cohort. There were a few studies that used methods not listed above (see Tables 2 and 3 for methodologies used in the reviewed studies).

Before/after (intervention) studies are generally preferred over cross-sectional (non-intervention) studies [43]. Simple before/after, full Bayes, and empirical Bayes are three types of before/after studies (though full Bayes can be applied to cross-sectional studies as well [43]). Simple before/after studies may control for changes in traffic, exposure, and other confounding factors, but not all do. Full Bayes and Empirical Bayes methods are considered the strongest, because they control for exposure and possible regression-to-the-mean effects caused by random variations in data.

Cross-sectional (non-intervention) studies may be used when a before/after study is not an option. Regression and non-regression cross-section, case-control, and cohort are four types of cross-sectional studies (though full Bayes can be applied to cross-sectional studies as well [43]). Regression studies may use a variety of regression models to compare effects of different locations, while non-regression cross-sectional studies simply compare effects directly. Case-control and cohort methods are most common in epidemiological and similar studies, but they can also be applied to safety analysis by isolating locations in the case of case-control studies, or by isolating treatment status in the case of cohort studies.

Finally, meta-analysis can be used to combine outcomes from various studies. This method combines the results from multiple studies to produce a combined estimate of a treatment's safety effectiveness [38].

1.4.2 Typical outcome measures

The Highway Safety Manual includes only quantitative, crash-based outcome measures. Safety benefits reported in the HSM are therefore in terms of crash rate increases or decreases. These increases or decreases may be expressed in specific types of crashes—for example, fatal crashes, injury crashes, etc.—or they may be for all crash types combined. For some studies, sufficient crash data may not be available to directly observe a treatment's effect on numbers of crashes, and other measures may be used. Two of these are injury severity and conflicts. Injury severity examines the severity levels given that a crash has occurred. This can be useful, as some treatments may have a different effect on injury severity than they do on crashes overall. Conflict studies allow the researcher to examine changes in behavior that may precede crashes, even in the absence of any recorded crashes. These "near-miss" events are more frequent than actual crashes, but their exact relationship with crash occurrence may not be known [1]. Neither conflict outcomes not injury severity outcomes, however, produce CMFs that can be used in the HSM.

1.4.3 Principles behind non-motorized roadway safety treatments

While motor vehicles are not the only threat to pedestrian and bicyclist safety [6, 78, 79, 104], collisions with motor vehicles are the main cause of thousands of non-motorized road users' deaths each year, as well as many more injuries [82, 83, 84]. For this reason, most measures aimed at increasing safety for non-motorized users focus on safety from the dangers posed by conflicts with motorized traffic.

For contact with a motor vehicle to cause harm to a bicyclist or pedestrian, two prerequisites must be met. First, the two parties must at some point converge on the same space at the same time. Second, the speed differential between the two parties must be sufficient to cause a transfer of energy from the motor vehicle to the non-motorized traveler that results in harm to the non-motorized traveler. Typically, it is assumed that the non-motorized road user suffers the most substantial physical harm in a collision, because the non-motorized user often has less mass and is less protected than the motorized road user. Where this is true, non-motorized users are also referred to as "vulnerable road users."

For a safety treatment to reduce number or severity of collisions between a motor vehicle and a vulnerable road user, it must address at least one of the two prerequisites detailed above. Methods for addressing the prerequisites can be classified into three objectives [93]:

- separation from motor vehicles by time and space,
- increasing the visibility and conspicuity of non-motorized users, and
- reducing motor vehicle speeds.

While these objectives apply to both bicycle and pedestrian safety, this thesis will focus on treatments that address bicycle safety. For example, separation by space and/or time prevents the two parties from converging on one another; separated bikeways and bicycle signal phases separate cyclists from motor vehicles by space and time. Increasing visibility gives motorists more time to react and therefore avoid colliding with a vulnerable road user; colored bike lanes and bike boxes are both designed to increase cyclists' visibility at key locations. Reducing motor vehicle speeds both gives motorists more reaction time and can reduce the frequency and severity of collisions with non-motorized road users [64]; bicycle boulevards and roundabouts are both designed to decrease motor vehicle speeds.

1.4.4 Interactions of safety design principles

It might seem then that the goal of roadway safety design for non-motorized users would be to maximize the three criteria discussed in the previous section. In reality, there are complex interactions between the criteria, and roadway designers often have to seek compromises. For example, shared space schemes as employed in Auckland, New Zealand push separation between various road users to an absolute minimum in an effort to reduce motor vehicle speeds by adding complexity to the environment. Karndacharuk, Wilson, and Dunn observed positive results from this configuration [58]. On the other hand, separating bicyclists from motorized traffic by diverting them to multi-use trails may create a visibility issue at the locations where a road crossing is necessary. Furthermore, the constrained space of a multi-use trail shared with pedestrians, pets, and other trail users may increase a cyclist's risk of falling or being involved in a collision with another trail user [6]. Separation may also be inappropriate in locations where access to surrounding destinations is a main goal, as separation may limit non-motorized travelers' access. In some situations, however, vehicle speeds or volumes may be so great that separating cyclists from the rest of the traffic stream does indeed have a net positive impact on safety. It is difficult to overstate the centrality of context in good bicycle and pedestrian design.

1.4.5 The challenge in interpreting findings

It is the centrality of context, in part, that makes researching bicycle and pedestrian safety treatments such a challenge. The fact that a given treatment may work effectively in one context but not another makes it difficult to separate the effectiveness of the treatment from the context in which it exists. This means that transferring findings from one location to another is even more difficult without a clear understanding of how exactly a treatment interacts with its location.

Another challenge in interpreting observed crash modifications is knowing enough about accompanying changes in exposure to substantiate any apparent increases or decreases in crash rates. Several studies have shown an increase in bicyclist and pedestrian safety accompanying local increases in biking and walking [53, 39, 65, 95], a phenomenon referred to across the literature as "safety in numbers" [53, 39, 65, 95]. This idea of "safety in numbers" also puts an interesting perspective on how much emphasis should be placed on designing for safety alone versus designing facilities more people will want to use.

An understanding of crash causation is another important piece of the interpretation puzzle that is often missing in crash data. For automobile crashes, police reports include data that help researchers look for patterns in causation and address problem locations with approaches targeted at the cause of crashes. Much of the causation data found in crash reports is less relevant for non-motorized users, leaving critical gaps in information [59].

In summary, the lack of readily available data describing bicycle and pedestrian exposure, crash frequency, and crash causation makes it challenging to evaluate safety treatments and even more challenging to generalize findings. Nevertheless, there is an ever-growing body of literature on bicycle and pedestrian safety treatments and their observed effectiveness, and the observations in these studies are important in the absence of data that can be generalized more readily.

1.5 Outline of thesis

This thesis reviews literature related to bicycle safety treatments and their reported effectiveness. Studies are examined on the basis of methods, data sources, treatment details, and findings. A summary of the available literature is presented, and the attributes and results discussed. This thesis seeks to identify common trends and gaps in the existing bicycle safety research, including drawing inferences about treatment effectiveness and identifying where lack of data is an issue. Finally, this thesis compares the kinds of data available with what is necessary for the HSM method and then makes recommendations on how data issues could be addressed in the future. Only studies relating to bicycle safety are reviewed in this thesis; a companion document on existing pedestrian research is also being prepared for the Georgia Department of Transportation.

CHAPTER II

REVIEW OF THE LITERATURE

To search, prioritize, and organize literature for review, the author developed a master list of both bicycle and pedestrian treatments and found relevant literature relating to each treatment. Only the literature and analysis related to bicycle safety is included in this paper.[1] Sources which presented quantitative results for crash risk, injury risk, injury severity, or conflict outcomes were also tabulated to examine trends in study details and methodology. The following sections provide further explanation of the author's methods for creating the master treatment list, searching and reviewing literature, and conducting analysis.

2.1 Master list of treatments included in review

This study began with an initial list of bicycle-related treatments, developed by consulting the three major guidebooks on cycling infrastructure design:

- AASHTO's *Guide for the Development of Bicycle Facilities*, Fourth Edition [2];
- NACTO's *Urban Bikeway Design Guide*, Second Edition [81]; and
- ITE's *Traffic Calming State of the Practice* [26].

The author selected treatments from these guidebooks based on their relevance to the state of Georgia. Treatments that were too site- or application-specific to be studied in isolation were generally not selected. Selected treatments were included on the initial version of the master treatment list (final version reflected in Table 1).

2.1.1 Strategy for literature search and review

Once the initial treatment list was developed, the author began searching for relevant literature on the selected treatments. The author searched the following sources for relevant

[1] A companion document on existing pedestrian research is also being prepared for the Georgia Department of Transportation. See page 10.

literature:

- the TRID database hosted by TRB
- the National Technical Information Service database
- the Web of Science database
- Science Direct
- other literature reviews and lists of references from other papers.

The sources included in this review were limited to English language publications. This is an important limitation, as many European countries have been vanguards in bicycle infrastructure and have published safety research in other languages. A good deal of international bicycle infrastructure research was available in English nonetheless.

2.1.2 Prioritization

With the broad list of treatments selected for evaluation, the goal was to find the most relevant literature available for each treatment. In cases where much literature was available for a specific treatment, the author prioritized the most relevant sources as those that:

- were quantitative in nature
- had safety outcome measures relating to crash reduction, injury crash reduction, or injury severity reduction potential
- observed effects at 10 locations or more
- had a group of control locations
- discussed exposure
- included controls in the methodology and accounted for regression-to-the-mean bias
- were peer-reviewed
- conducted research within the last two decades

- examined locations in the United States.

The reason for prioritizing more recent literature over similarly-qualified literature from (sometimes) decades before is the underlying assumption that with long periods of time there are shifts in mode shares, infrastructure prevalence, and culture, such that newer studies of the comparable methodological integrity would give more relevant descriptions of today's conditions. For some treatments, none of the aforementioned criteria were met, so the author included whatever available literature dealt with those treatments. Some sources were not reviewed in-depth because they either did not meet the author's criteria [57, 68, 96, 103, 107, 110, 111] or were themselves reviews of other literature [44, 91, 94, 105].

2.1.3 Review and analysis

The author methodically reviewed articles and reports found during the literature search, making note of stated safety outcomes, treatment details, study design, sample size, controls, exposure data, statistical significance of results, and any other features of the study that made it unique. This literature review focuses on expected and stated safety outcomes by treatment and is found in Table 1 beginning on page 16.

For studies reporting quantitative safety outcome measures in the form of crash risk, injury risk, injury severity, or conflicts, reported results were plotted to show how outcomes compared to one another. Those plots are found in Figures 1 through 12 beginning on page 15 and continuing again on page 43. Study details were also tabulated in a standardized format developed by the author and his thesis committee. Tabulated study details are shown in Tables 3 and 4 on pages 33 and 36, respectively.

2.2 Synthesis

Using the criteria outlined above, literature on the effectiveness of each of the selected treatments was synthesized, and the results are shown in Table 1. Each treatment includes an image of the treatment, a description, a list of the safety goals the treatment is intended to address—separation, cyclist visibility, motor vehicle (MV) speeds, or other—and a synthesis of findings from the literature. For treatment photos taken in Georgia, the locations of the photos are noted beneath them.

Overall, quantitative safety outcomes (crash reduction, injury crash reduction, injury severity reduction, or conflict reduction) were reported in the literature for 14 of the 22 treatment types covered here. Figure 1 summarizes quantitative results of studies presented in the synthesis table (Table 1). The horizontal bars represent ranges of risk ratio values presented for *any* of the four safety outcome measures, all sharing an axis for overall comparison. A *risk ratio* represents the risk of an event happening *with* a treatment divided by the risk of that same event happening in the same situation *without* the treatment; risk ratios are much like a crash modification factor, but applicable to other outcome measures besides crashes. For example, if riding on a cycle track versus a parallel street has an injury crash risk ratio of 0.72, that means that the risk of having an injury crash on the cycle track is 0.72 times that of having an injury crash on the comparison street; this represents an improvement in the cycle track's case. Risk ratios presented in this thesis were either explicitly reported in the literature or were reported as percentages and converted to risk ratios for consistency. For more detailed breakdowns by individual treatments, see Figures 2 through 12 beginning on page 43.

Of the 14 treatments with study outcomes presented in Figure 1, only bike boxes, bike lanes, cycle tracks, and roundabouts had more than one quantitative study found by the author which described risk ratios associated with them. Bike boxes only had conflict-based studies (as opposed to crash- or injury-based); and bike lanes, cycle tracks, and roundabouts each had disagreement among their respective study results as to whether the treatment helped or harmed in terms of safety outcomes. These differences may be partly attributable to design differences in the facilities themselves, the way exposure was measured and tracked (if at all), crash reporting bias, location characteristics, study controls, or possibly even chance (see discussion on page 9). For a more in-depth discussion of each treatment and possible safety impacts as expressed in the literature, see pages 42 and following.

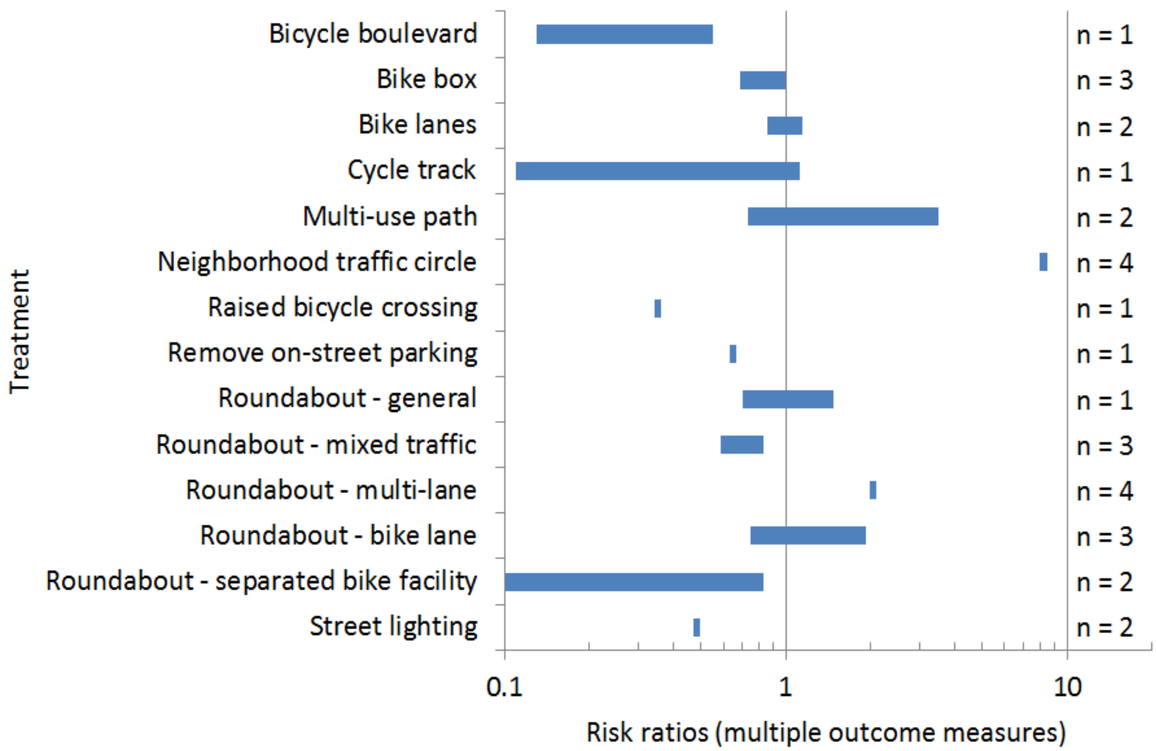


Figure 1: Study result ranges for all interventions, significant and non-significant. All outcome measures (crashes, injury crashes, injury severity, and conflicts) are combined into one graph and share an x-axis.

Table 1: Bike Study Results

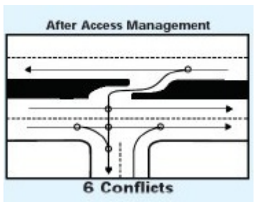
Treatment	Purpose	Description	Measured effects on safety
Access management  *Source: [27]*	☑ **Separate by time or space** ☐ Increase cyclist visibility ☐ Decrease MV speeds ☐ Other	Access management is a set of techniques to control access to highways, roads, and streets by limiting driveways and turning movements. Goals for using access management include improvement of traffic flow and reduction in crashes and conflicts [31].	An in-depth study by Hunter et al. [51] examined bike lanes (BLs) and wide curb lanes (WCLs) in Santa Barbara, CA, Austin, TX, and Gainesville, FL, with the goal of comparing the two treatments on the basis of bicyclist safety. As part of the study, high-conflict sites were analyzed for patterns, and the authors found that drivers pulling across the BL or WCL was one of the predominate sources of conflict, suggesting that access management along roadways could reduce conflicts and crashes between bicycles and motor vehicles.
Bicycle boulevard  *Source: [36]*	☐ Separate by time or space ☐ Increase cyclist visibility ☑ **Decrease MV speeds** ☐ Other	Bicycle boulevards are streets that use signs, pavement markings, and speed and volume control measures to prioritize bicycle travel over motorized traffic. These streets discourage cut-through motor vehicle traffic and promote safe, convenient travel by bicycle both midblock and at intersections [81].	Minikel examined bicycle boulevards in Berkeley, CA to compare bicycle crash risk on bicycle boulevards with that of their parallel arterial streets [75]. The study examined seven bicycle boulevards and nine parallel arterials and found risk ratios of 0.13 to 0.55 for bicycle crashes on bicycle boulevards compared with their parallel arterial streets, and these results were significant.

Table 1: Bike Study Results (continued)

Treatment	Purpose	Description	Measured effects on safety
Bike box  ***Atlanta, GA.*** *Source: [14]*	☐ Separate by time or space ☑ **Increase cyclist visibility** ☐ Decrease MV speeds ☑ **Other**[2]	A bike box, or advanced stop line, is a designated area ahead of the stop bar at signalized intersections for bicyclists to queue in during the red signal phase [81]. Bike boxes are typically marked by white painted borders and/or colored paint.	Bike boxes were examined by Hunter in 2000 [48] and by Dill, Monsere, and McNeil in 2012 [22]. Dill, Monsere, and McNeil [22] studied 10 signalized intersections in Portland, OR before and after installation of bike boxes, observing 174 cyclists in the “before” period and 124 in the “after” period. The study showed a 400–500% increase in drivers yielding to cyclists, 31% decrease in conflicts, and a 9–21% increase in motorists encroaching in the bike lane between the before and after periods. The after period also showed 76% motorist compliance for not encroaching in the bike box. Hunter [48] studied one signalized intersection in Eugene, OR before and after installation of a bike box treatment. Hunter observed 10 conflicts in the “before” period and 10 in the “after” period, out of 747 bicyclists before and 686 after. While there was not net change in conflicts, Hunter notes that there were not conflicts in the after period resulting from “proper” use of the bike box. Observations by Loskorn et al. [67] echo those noted above. Loskorn et al. also report a positive change in bicyclists stopping in the field of vision of motor vehicles at red lights.

[2] Bike boxes can also facilitate bicycle left turns (when the cyclists arrives at a red indication) and reduce signal delay for bicycles.

Table 1: Bike Study Results (continued)

Treatment	Purpose	Description	Measured effects on safety
Bike lanes  ***Whitfield County, GA.*** *Source: [112]*	☑ **Separate by time or space** ☐ Increase cyclist visibility ☐ Decrease MV speeds ☑ **Other**[3]	Bike lanes designate a portion of the roadway for preferential or exclusive use by bicyclists through use of pavement markings and signage. Bike lanes typically run on the right-hand side of general travel lanes and in the same direction as motor vehicle travel [81, 2]. Bike lanes discussed in this section were either not buffered (see *Buffered bike lanes*) or the source did not mention whether they were buffered.	In a case-crossover study of bicyclist injuries in Toronto and Vancouver, Canada, Teschke et al. [104] compared injury crashes on major routes with no parked cars and no bike lanes to the same route types *with* bike lanes. They found a bicyclist injury crash risk ratio of 0.86 for locations with bike lanes, and this risk reduction was significant at the 0.05 level in the unadjusted model but just shy of significant in the adjusted model. Hunter et al. [51] compared bicycle conflicts at 8 bike lane (BL) sites and 8 wide curb lane (WCL) sites across the U.S. in which 369 conflicts were examined. The study did not find a significant difference between overall conflicts at BL vs. WCL sites, but it did find BL sites to have significantly less wrong-way riding (including on sidewalks) than WCL sites. The study also found proportionally more bicyclists turning properly, more obedience to traffic laws, and fewer bicycle-pedestrian conflicts (due to less sidewalk riding) at BL sites (all significant). However, this may have been a result of site characteristics. Metroplan Orlando [74] performed a bicycle crash study in Florida's Orange, Seminole, and Osceola Counties during 2003 and 2004 in which it estimated that 7–15% of current bicycle crashes could be prevented by installing bike lanes for cyclists riding in the street; it also suggested the potential to aggravate frequency of "right-hook" crashes. Studies by both Van Houten and Seiderman [108] and Duthie et al. [23] found that bike lanes have the potential to influence bicyclists to ride further away from parked cars. A study by Jensen [54] examining bike lane installations in Denmark found that installing bike lanes had the potential to increase crashes; however, overall crash frequency changes were not statistically significant in the study. Three older studies found decreases in crash risk associated with bike lanes [68, 78, 79], while one other found an increase [103].

[3]The striped lines on the pavement delineating the bike lane can also have the effect of guiding cyclists along a safer riding path (e.g. outside the "door zone" of parked cars) when properly placed [23, 108].

Table 1: Bike Study Results (continued)

Treatment	Purpose	Description	Measured effects on safety
Buffered bike lanes  ***Atlanta, GA.*** *Source: [21]*	☑ **Separate by time or space** ☐ Increase cyclist visibility ☐ Decrease MV speeds ☐ Other	Buffered bike lanes share the same characteristics as conventional bike lanes (described above), except that they are separated from the rest of traffic by additional buffer space. The buffer between the bike lane and other traffic lanes should be marked with two parallel white lines and may range in width up to several feet. When buffers are 3 feet wide or greater, they should be filled with diagonal or chevron striping [81].	No quantitative studies were found dealing with crash, injury, or conflict outcomes associated with buffered bike lanes. One study by Monsere, McNeil, and Dill [77] compared user perceptions of buffered bike lanes at a site in Portland, OR to perceptions of "before" conditions (no bike lanes) and conventional bike lanes. Respondents overwhelmingly preferred the new buffered bike lanes and felt safer from motorized traffic and from being "doored" by a parked motor vehicle. Survey and video data indicated that motorists turning right was a source of some conflicts and confusion among drivers and cyclists. Cyclist volumes also increased 77–271% after installation of the lanes.
Colored bike lanes  *Source: [99]*	☑ **Separate by time or space** ☑ **Increase cyclist visibility** ☐ Decrease MV speeds ☐ Other	Colored pavement in bike lanes may be used to identify potential conflict areas, reinforce bicyclist priority, and increase bicyclist visibility; the treatment may be applied along the whole length of a facility or at specific points [81]. Use of colored pavement in bike lanes received interim approval from the MUTCD [66].	Three studies were found which examined bicyclist and driver operations surrounding installation of colored bicycle facilities [97, 49, 50, 55]. Sadek, Dickason, and Kaplan [97] examined green bike lanes marked across an interchange area in South Burlington, VT; Hunter et al. examined blue pavement markings at 10 selected bike lane conflict points in Portland, OR; and Hunter, Srinivasan, and Martell examined a weaving area with green pavement markings in St. Petersburg, FL. Additionally, Jensen examined the installation of blue bicycle crossing paths through major intersections in Copenhagen, Denmark, for crash risk. Of the three operational studies, one found an increase in cyclists scanning their surroundings for nearby vehicles [50] at sites with colored bike lanes, while two found a decrease [49, 97]. Two of the studies found an increase in motorists yielding to cyclists [49, 50], while one found the opposite [97]. One found an increase in drivers signaling their intentions before making a maneuver [50], while one found the opposite [49]. Surveys of drivers and cyclists showed positive perceptions of safety increases for colored bike lanes from both parties [49, 97]. Finally, the study that examined crashes at major intersections found mixed results, where installing one colored bicycle crossing was associated with increased safety, while installing more than one was associated with decreased safety [55].

Table 1: Bike Study Results (continued)

Treatment	Purpose	Description	Measured effects on safety
Combined bike lane/turn lane  *Source: [85]*	☐ Separate by time or space ☑ **Increase cyclist visibility** ☐ Decrease MV speeds ☑ **Other**[4]	Combined bike lanes/turn lanes continue a bike lane's trajectory through a turn lane such that they overlap. Through cyclists' suggested path is marked for the length of the turn lane, lining up with a continued bike lane on the far side [81].	Hunter [47] conducted an evaluation of a combined bike lane/right turn lane site in Eugene, OR and compared it to a nearby intersection on the same street with a full-width bike lane carried between the through lane and the right turn lane. No conflicts were recorded at either site. Most surveyed bicyclists either felt the combined lane design was safer than the comparison location or no different in safety. Combined bike lanes/turn lanes are included in the *Oregon Bicycle and Pedestrian Design Guide* [85].
Contra-flow bike lanes  *Source: [12]*	☑ **Separate by time or space** ☐ Increase cyclist visibility ☐ Decrease MV speeds ☑ **Other**[5]	Contra-flow bike lanes convert a one-way street to a two-way street, where motor vehicles and bicycles are permitted in one direction, and only bicycles are permitted in the other. The two directions are separated by a yellow line [81].	No studies were found which examined the safety effects of implementing contra-flow bike lanes on one-way streets. Patterson [87] performed an international literature review on allowing cyclists to contra-flow *without* a marked contra-flow lane on low-speed, low-volume one-way streets. She concluded that such allowances appeared to produce safety benefits rather than hazards where they were implemented.

[4]The main purpose of this treatment is to guide cyclists along the safest path through the intersection and toward the bike lane on the other side.

[5]This treatment allows bikeways and/or cyclists to follow a more direct route by using one-way streets against the main flow of traffic, adding convenience and potentially reducing exposure to other hazards involved with going the longer way.

Table 1: Bike Study Results (continued)

Treatment	Purpose	Description	Measured effects on safety
Cycle track  ***Atlanta, GA.*** *Source: [5]*	☑ **Separate by time or space** ☐ Increase cyclist visibility ☐ Decrease MV speeds ☐ Other	Cycle tracks are exclusive bicycle facilities that are physically separated from motorized traffic by curbs, parked cars, planters, delineators etc. but are distinct from sidewalks. Cycle tracks may allow one-way or two-way bicycle traffic, depending on how they are configured [81].	In a case-crossover study of bicyclist injuries in Toronto and Vancouver, Canada, Teschke et al. [104] found a risk ratio of 0.11 for injury crashes on cycle tracks (significant at 0.05 level) compared to the reference case of "major street routes with parked cars and no bike infrastructure." It appears that all the cycle tracks in the Teschke et al. study were one-way facilities [46]. Lusk et al. [69] examined 6 cycle tracks in Montreal, Quebec, comparing them to nearby reference streets bearing similar characteristics but no cycle tracks. Overall, the study found 28% lower injury crash rate (significant at 0.05 level) on the streets with cycle tracks versus their reference streets. While some streets showed an increased risk compared to their reference streets, risk was decreased on average. A later study by Lusk et al. [70] used crash data and bicycle count data at known cycle track locations across the U.S. to find a national cycle track crash rate per kilometer. The resulting rate was 2.1 crashes per million bicycle kilometers, which is low compared to most published U.S. bicycle crash rates [70]. A study by Jensen examining cycle track installations in Denmark [54] suggested that installing cycle tracks has the potential to increase crashes. While overall crash frequency changes were not statistically significant in this study, there was an 18% significant increase in crashes reported in intersections after installation, as well as a slight non-significant increase in crashes overall. Thomas and DeRobertis [105] reviewed urban cycle track literature and noted that one-way cycle tracks appear to be safer at intersections than two-way cycle tracks. They concluded that, with careful treatment at intersections, both one-way and two-way cycle tracks can reduce crashes and injuries on busy streets.

Table 1: Bike Study Results (continued)

Treatment	Purpose	Description	Measured effects on safety
Increase bicycling levels in community  ***Atlanta, GA.*** *Source: [101]*	☐ Separate by time or space ☑ **Increase cyclist visibility** ☐ Decrease MV speeds ☐ Other	Bicycling levels in a community may be measured by mode share (of total trips, commuting trips, etc.), distance, or number of trips [53].	Though not an infrastructure treatment, increased levels of bicycling have been associated with safety outcomes. Jacobsen compared locations and time periods by levels of walking and biking vs. injury data using thousands of data points, including time series, from California, the U.K., and Europe [53]. The results indicate that bicycle and pedestrian crashes are expected to increase on a 0.4 power function with increasing levels of walking or bicycling in a community. By extension, injury rates (per user) decrease with increased levels of walking and bicycling. Other studies support such an effect [39, 65, 95].
Multi-use path in separate right-of-way  ***Silver Comet Trail, GA.*** *Source: [86]*	☑ **Separate by time or space** ☐ Increase cyclist visibility ☐ Decrease MV speeds ☐ Other	Multi-use or shared-use paths are physically separated from motorized traffic by either open space or barriers and are designed for use by bicyclists, pedestrians, inline skaters, and other non-motorized users (AASHTO, 2012). These paths can serve a variety of purposes from transportation to recreation or both. Their separation from roadways makes conflicts with motor vehicles at non-intersection locations far less probable.	In the Metroplan Orlando 2003–2004 crash type study [74], the authors saw no evidence that multi-use paths would or did influence bicyclist crash risk. Teschke et al. included multi-use paths in their bicycle infrastructure and crash risk case-crossover study [104]. The results indicated a slight decrease in injury crash risk associated with riding on multi-use paths, but the findings were not statistically significant. Aultman-Hall and Kaltenecker used surveys to collect past exposure data, crash events, and injuries from 1196 commuter cyclists in Toronto, Canada [6]. They concluded that off-road paths had 3.5 times higher collision rates per kilometer compared to roads and 1.8 times higher injury rates per kilometer (both significant), but differences between different injury severities were not significant. Moritz found a similar crash risk for multi-use trails among surveyed League of American Bicyclists members [79].

Table 1: Bike Study Results (continued)

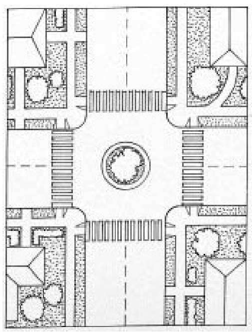
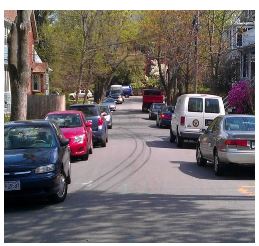
Treatment	Purpose	Description	Measured effects on safety
Neighborhood traffic circle  *Source: [33]*	☐ Separate by time or space ☐ Increase cyclist visibility ☑ **Decrease MV speeds** ☐ Other	A neighborhood traffic circle, also known as an intersection island, consists of a raised island in the middle of an intersection around which traffic circulates. Islands are often landscaped and usually circular, and the intersection is typically controlled by stop or yield signs. The purpose of neighborhood traffic circles is to prevent drivers from speeding through intersections by impeding the straight-through movement [26].	A study by Harris et al. [46] examined bicycle injury crashes at intersections and non-intersection locations in Vancouver and Toronto, Canada using the same respondents and case-crossover methodology as Teschke et al. [104]. Results included a marked increase in risk for intersections with neighborhood traffic circles compared to the reference case, which was a signalized intersection with no bicycle controls (statistically significant risk ratio of 7.89). Consistent with conclusions by Harris et al., Ewing also states anecdotally in *Traffic Calming: State of the Practice* that more than one-third of near-accidents reported to a "Close Call Hotline" for Boulder, CO during 1996 were at traffic circles on a particular collector street in the town and mostly involved bicyclists [26].
On-street parking removal  *Source: [37]*	☑ **Separate by time or space** ☐ Increase cyclist visibility ☐ Decrease MV speeds ☐ Other	On-street parking means allowing cars to be parked on the edge of a street either during specific times of day or all the time. On-street parking can act as a means of convenient access to businesses (by car) and as a buffer between streets and sidewalks or cycle tracks [81, 102].	Teschke et al. in a case-crossover study of bicycle injury crashes in Vancouver and Toronto, Canada, observed that roads without on-street parking were safer for cyclists than those that had it. More specifically, roads with no on-street parking and no bicycle facilities had a lower risk of being an injury site than roads with on-street parking but without bicycle facilities (risk ratio 0.65, statistically significant at 0.05 level) [104]. These results agree with observations by Hunter et al. who found that motor vehicles entering and leaving on-street parking spaces were a major source of conflict in the high-conflict locations in the study [51].

Table 1: Bike Study Results (continued)

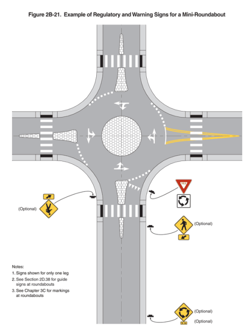
Treatment	Purpose	Description	Measured effects on safety
Raised bicycle crossing  *Source: [73]*	☐ Separate by time or space ☑ **Increase cyclist visibility** ☑ **Decrease MV speeds** ☐ Other	Raised bicycle crossings are continuations of raised cycle tracks or side paths across intersecting side streets and driveways without dropping the path to street level at each intersection. This design creates a raised crossing that intersecting drivers must traverse when entering or exiting the minor street [39].	In their 1998 study, Gårder, Leden, and Pulkkinen observed the effects of installing 44 raised bicycle crossings in Gothenburg, Sweden on bicycle volumes and safety from the "before" period to the "after." The team found a 50% increase in bicycle volumes on the corridor to which the treatments were applied and a 66% reduction crash rate for bicyclists. The team also observed a 40% decrease in turning motor vehicle speed and an increase in bicycle crossing speeds [39].
Roundabout  *Source: [80]*  *Source: [13]*	☐ Separate by time or space ☐ Increase cyclist visibility ☑ **Decrease MV speeds** ☐ Other	Roundabouts, specifically "modern" roundabouts as discussed here, are circular intersections with a center island in which traffic circulates counter-clockwise through the intersection to complete a movement. Entering traffic must yield to traffic already in the roundabout. Roundabouts may have one or more lanes and may have bicycle-specific facilities such as paths or lanes, or bicycles may operate in mixed traffic.	Several studies have examined the effects of roundabout conversion (from conventional intersections) on bicycle safety, and outcomes are somewhat mixed. Daniels et al. [19] examined 91 intersection in Flanders, Belgium before and after conversion to roundabouts and found a statistically significant 1.27 times higher risk of injury crashes after conversion, where the effect was even stronger inside built-up areas (risk ratio 1.48, also significant). Schoon and van Minnen [100] examined 181 intersections in the Netherlands before and after roundabout conversion and found an 8% reduction in bicyclist crash rate and a 30% reduction in injury crash rate in the "after" period. All the roundabouts in the study were single-lane. The same study also found a 41% reduction in crash rates for bicycles plus mopeds (treated together) in roundabouts where cyclists operate in mixed traffic only [100]. A study of 58 roundabouts in Sweden by Brüde and Larsson [10] found multi-lane roundabouts to be associated with about twice the crash risk and injury risk as "conventional" intersections based on a model of crash expectation calibrated to Sweden's other intersections. The study also found a lower-than-expected crash rate on single-lane roundabouts compared with "conventional" intersections.

Table 1: Bike Study Results (continued)

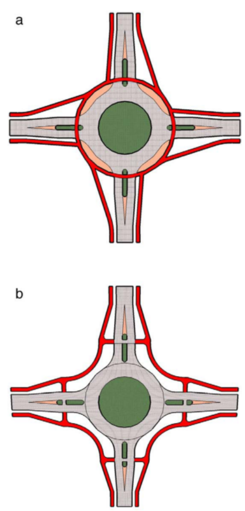
Treatment	Purpose	Description	Measured effects on safety
Roundabout with bicycle facilities  *Source: [18]*	☑ **Separate by time or space** ☐ Increase cyclist visibility ☑ **Decrease MV speeds** ☐ Other	Modern roundabouts (described above) may be constructed with facilities specifically designed for bicycles, including bike lanes in the roundabout and separated paths which follow outside the roundabout and cross each of its legs. Bicycle lanes in roundabouts typically run around the outside of the travel lane and may be separated by a striped line or painted a different color. Separated facilities are removed from the roadway by at least 3 feet and may require bicyclists to yield to motorists at leg crossings or vice versa. The images to the left show two different configurations for physically separated bicycle facilities at roundabouts: image (a) shows a configuration in which cyclists crossing the roundabout legs have the priority, while image (b) shows a configuration in which exiting motor vehicles have the priority at crossings.	Daniels et al. [18], using the same data as the aforementioned roundabout studies, found a statistically significant 1.93 times higher risk of bicycle injury crashes after conversion from "conventional" intersections for roundabouts constructed with bicycle lanes. The same study [18] found a non-significant 17% decrease in bicycle injury crash rate in roundabout conversions with separated bicycle facilities (removed from roadway by at least 3 ft) and a non-significant 17% decrease in bicycle injury crash rate in roundabouts where bicyclists operated in mixed traffic only. Schoon and van Minnen [100] found a 25% reduction in crash rates for bicycles plus mopeds (treated together) in roundabouts with bike lanes and a 90% reduction for roundabouts with separated bicycle facilities. However, those benefits may be mostly realized by moped riders, as mopeds tended to benefit more from roundabout conversion than cyclists [100]. Brüde and Larsson [10] found roundabouts with separated bicycle facilities to be associated with about half the crash risk as "conventional" intersections based on a model of crash expectation calibrated to Sweden's other intersections.

Table 1: Bike Study Results (continued)

Treatment	Purpose	Description	Measured effects on safety
Shared lane markings  ***Atlanta, GA.*** *Source: [25]*  ***Athens, GA.*** *Source: [8]*	☐ Separate by time or space ☑ **Increase cyclist visibility** ☐ Decrease MV speeds ☑ **Other**[6]	Shared lane markings, often called “sharrows,” are pavement markings used to indicate a shared lane environment for bicycles and automobiles [81]. They may be used to reinforce the legitimacy of bicycles using the lane, to recommend bicycle positioning in the lane, or to give cyclist wayfinding guidance [81].	No studies were found which addressed changes in crashes, injuries, or conflicts associated with addition of shared lane markings. However, five studies were found which used video recordings of bicycle and motor vehicle operations to assess their associated changes in potential safety indicators. Four studies observed decreases in sidewalk bicycling associated with sharrows [4, 9, 34, 90], and one observed a decrease in wrong-way bicycling [4]. All five studies noted increased operating space for bicyclists associated with sharrows; all five observed increased bicycle spacing from curbs and/or parked cars [4, 9, 34, 90, 99], and all but one observed increased space between bicyclists and passing motor vehicles [4, 9, 34, 99]. Two studies pointed out a strong trend in bicyclists positioning themselves over the path marked by the sharrows, which had a major influence on cyclists’ positioning relative to curbs and other vehicles measured by the researchers [9, 34]. Finally, a study which compared multiple sharrow marking designs found that the “bike-and-chevron” design (pictured left, top) performed better than the “bike-in-house” design (pictured left, bottom) or the “bike-and-separate-arrow” design [4].

[6]Much like bike lanes, the pavement markings can also have the effect of guiding cyclists along a safer riding path (e.g. outside the “door zone” of parked cars) when properly placed [9, 34].

Table 1: Bike Study Results (continued)

Treatment	Purpose	Description	Measured effects on safety
Shoulder pavement width  *Source: [30]*	☑ **Separate by time or space** ☐ Increase cyclist visibility ☐ Decrease MV speeds ☐ Other	Paved highway shoulders are most often found on rural roadways. They extend the service life of the road, provide temporary storage space for disabled vehicles, and provide space for bicycles to operate with some separation from higher-speed traffic [2].	Metroplan Orlando's crash type study suggested that paved highway shoulders could mitigate 7–15% of crashes for cyclists in the roadway [74]. An analysis of bicycle-motor vehicle crash data on North Carolina state roads by Klop and Khattak [62] suggested a positive correlation between absence of paved shoulder (or not known if present) and injury severity, but it was not statistically significant. Klop and Khattak did find a significant ($p < 0.10$) correlation among paved shoulder width, speed limit, and injury severity, where increasing speed limits required increasing shoulder widths for injury severity to remain constant. Abdel-Rahim and Sonnen [3] plotted crash data for two-lane rural highways in Idaho and found that most bicycle crashes happened where paved shoulders were less than 3 ft or greater than 8 ft. The report did not mention controlling for bicyclist exposure.
Shoulder rumble strip placement that accommodates bicycles  *Source: [28]*	☑ **Separate by time or space** ☐ Increase cyclist visibility ☐ Decrease MV speeds ☐ Other	Shoulder rumble strips are raised or indented patterns in the pavement that provide noise and tactile feedback when drivers drive onto them. They have been shown to reduce run-off-road crashes for drivers on high-speed roadways; however, they can be difficult or unpleasant for bicycles to traverse [2].	No studies were found which attempted to measure the safety effects of bicyclists riding in locations with shoulder rumble strips versus those without. Gårder combined bicycle crash data with motor vehicle run-off-road-type crashes to develop a theoretical bicycle-motor vehicle crash risk that could be averted by "waking up" drivers. He used this as an argument for including rumble strips along highway edge lines, so long as there is sufficient space remaining in the shoulder for bicycles to operate free from rumble strips, debris, or other hazards. Gårder concluded that shoulder rumble strips could solve safety problems for bicyclists by "waking up" errant and dozing drivers [40]. Moeur recognized the safety benefits to drivers of having rumble strips on roadway shoulders as well as the difficulty to cyclists in traversing them. He conducted an analysis including live test subjects to recommend a preferred gap pattern which allows bicyclists to cross from one side of the rumble strip to the other (e.g. to cross from the shoulder to a travel lane or vice versa) without hitting the strip itself [76]. The recommended gap length was 12 ft, recurring every 40 or 60 ft.

Table 1: Bike Study Results (continued)

Treatment	Purpose	Description	Measured effects on safety
Street lighting  *Source: [18]*	☐ Separate by time or space ☑ **Increase cyclist visibility** ☐ Decrease MV speeds ☐ Other	Illumination of streets by means of street lights increases visibility at night for road users.	Kim et al. [61] examined data from 2,934 bicycle crashes in North Carolina from 1997–2002 and developed a model describing which factors were associated with increases or decreases in safety for bicyclists. One factor examined in the study was light condition, which was significantly associated with injury severity. The study suggested that crashes in dark, non-lighted areas had a 111% greater chance of being fatal than those in daylight or in dark areas with lighting.
Two-stage turn queue box  ***Atlanta, GA.*** *Source: [60]*	☑ **Separate by time or space** ☐ Increase cyclist visibility ☐ Decrease MV speeds ☐ Other	Two-stage turn queue boxes, also known as Copenhagen left turns, offer bicyclists a way to make left turns (or in some cases right turns) at multi-lane signalized intersections without the need to merge across traffic to enter the left-turn lane [81]. To make a left turn using a two-stage turn queue box, the bicyclist rides through the signalized intersection on the right-hand side during a green signal phase, arrives at the turn queue box in the far-right corner, and waits until the green signal phase for the cross-street to complete the "turn."	No studies were found which examined safety performance of two-stage turn queue boxes. One study [15] examined them operationally based on traffic simulation, but the focus was on reducing delay to automobile traffic. The authors concluded that when used, two-stage left turn queue boxes could reduce automobile delay (compared to that caused by cyclists making left turns all the way from a bike lane). The authors cautioned that bicyclist "compliance" with two-stage turns may be low at some intersections where it is more convenient to make a vehicular-style left turn.

Table 1: Bike Study Results (continued)

Treatment	Purpose	Description	Measured effects on safety
Wide curb lanes  *Source: [51]*	☑ **Separate by time or space** ☐ Increase cyclist visibility ☐ Decrease MV speeds ☐ Other	A wide curb lane exists when the lane closest to the curb is wider than a standard lane, leaving enough room for bicycles and motor vehicles to share the lane. They may be present on two-lane or multi-lane roadways [51].	Wide curb lanes (WCLs) can potentially mitigate crashes caused by drivers overtaking cyclists riding in the street by allowing more space for passing within the lane [74]. The crash type study conducted by Metroplan Orlando [74] estimates that about 6% of cyclist crashes in the Orlando region could be mitigated by WCLs. Hunter et al. compared WCLs to bike lanes (BLs) in a national study of conflicts and behavior occuring in both types of facilities [51]. The study found that both facilities provided benefits to cyclists and had similar conflict rates overall, but WCL sites in the study had a significantly higher incidence wrong-way riding (including on sidewalks), pedestrian-bicycle conflicts (due to riding on sidewalks), and disobedience to traffic laws compared with BL sites. However, this may have been a result of site characteristics. Harkey and Stewart [45] also compared WCLs with BLs and paved shoulders and found them to have similar operational and "comfort" characteristics for drivers and cyclists. Their results found that drivers gave more space while passing cyclists in wide curb lanes versus bike lanes and paved shoulders, but drivers gave adequate space in both circumstances. They also found cyclists riding closer to the roadway edge in WCL situations, which can potentially pose a danger to cyclists due to debris, obstructions, and drain grates [2, 76].

2.3 Study details

For studies that derived safety outcomes for individual bicycle treatments, the details of their investigations were tabulated in Tables 3 and 4 for summary and comparison. Table 3 gives an overview of study design characteristics, while Table 4 gives specific information relating to the strength of each study. For definitions of the abbreviations in Tables 3 and 4, see Table 2.

Table 3 compares aspects of the study designs, treatments, and data types each study summarized into numeric and categorical data elements. The first two columns give the treatment and citation for the studies. The next three deal with the study design, listing the outcome measures, study format, and analysis methods used. The next six columns give location details where available, including road cross-section width, number of lanes, one-way or two-way operation, traffic speeds, roadway functional class, and whether the locations were urban, rural, or both. The next column group gives sample size information, including numbers of treatment and comparison locations and duration of before periods (where applicable), transition periods (where applicable), and after periods for data collection. Finally, the last column group lists data sources related to base rate determination, including crash rate determination and sources as well as exposure types and sources.

Table 4 lists information related to the strength of each study, including whatever treatment details were provided, the crash rate source, study controls, statistical significance, and a rating of the study's overall strength as evaluated by the author of this paper. Possible ratings for study strength were "Lacking in sample size, study depth, or controls," indicating that the study likely failed to control for key factors or had a very small sample size (less than 10 locations); "Fairly robust, but still lacking in depth or completeness," indicating that the study controlled for at least some important factors and had a relatively large sample size but still lacked in some controls, detail descriptions, or transferability; and "Informative but not conclusive," indicating that the study was quantitative, did not claim to present a causal relationship, but still provided informative background information. There was a fourth category, "Excellent," for studies with sufficient sample sizes, controls, and a strong, known base rate whose results could be transferred predictably to other situations; however, no study in this review fit that category.

Table 2: Study Details Legend

Treatment	**Citation**	**Outcome measures**
(general)	n/a	Not applicable
	ns	Not specified
	nm	Not mentioned
	v	Varies
	m	Multiple
	o	Other
	N	None
Outcome measures[7]	CR	Crash rate
	cR	Conflict rate
	CS	Crash severity
	IR	Injury rate
	IS	Injury severity
	YR	Motor vehicle driver yielding rate
Study format	I	Intervention (before/after)
	NI	Non-intervention (cross-sectional, case-crossover, user survey, etc.)
Analysis method	B/A	Simple before/after
	FB	Full Bayes
	EB	Empirical Bayes
	R	Regression cross-section
	NR	Non-regression cross-section
	MA	Meta-analysis
One-way/two-way	1W	One-way
	2W	Two-way
	B	Both
Traffic speeds	L	Low
	M	Moderate
	H	High
	L-M	Low to moderate
	M-H	Moderate to high
	A	All
Functional class	L	Local
	C	Collector
	A	Arterial
Urban/rural	U	Urban
	R	Rural
	B	Both
Comparison group locations	#	Number of locations
	MM	Mathematical model (predictive based on other locations)
Crash rate determination	M	Measured
	E	Estimated
	S	Survey
Crash rate source type	CD	City database
	SD	State database
	ND	National database
Exposure type	BC	Bicycle counts
	MC	Motor vehicle counts
	BD	Bicycle distance traveled
Exposure source	MC	Manual counts
	AC	Automatic counts
	VC	Video counts
	EC	Estimated counts
	OP	Observed percentage

[7]Note: All crash- and injury-related measures apply to bicyclists unless otherwise noted.

Table 3: Study Details I

Study		Design			Treatment and loc. details						Sample size					Base rate						
Treatment	**Citation**	Outcome measures	Study format	Analysis method	Cross-section width	Cross-section lanes	One-way/two-way st	Traffic speeds	Functional class	Urban/rural	Treatment locations	Comparison locations	Before period (months)	Transition period (months)	After period (months)	Crash rate determination (treatment)	Crash rate determination (comparison)	Crash rate source type	Exposure 1 type	Exposure 1 source	Exposure 2 type	Exposure 2 source
Access management	Hunter et al., 1999 [51]	cR	NI	NR	ns	ns	ns	v	m	U	8	8	n/a	n/a	ns	n/a	n/a	n/a	nm	nm	nm	nm
Bicycle boulevard	Minikel, 2012 [75]	CR, CS	NI	R	ns	ns	ns	L	L	U	7	9	n/a	N	70	M	M	SD	BC	MC	n/a	n/a
Bike box	Dill, Monsere, McNeil, 2012 [22]	cR, YR, o[8,9]	I	B/A	ns	2-4	B	ns	ns	U	10	2	3	nm	3	n/a	n/a	n/a	BC	VC	MC	VC
	Hunter, 2000 [48]	cR	I	B/A	ns	3	1W	ns	ns	U	1	0	1	ns	5	n/a	n/a	n/a	BC	VC	nm	nm
Bike lanes	Jensen, 2008 [54]	CR, IR	I	o[10]	ns	ns	ns	ns	ns	U	5.6 km	112 km	12-60	nm	12-60	M	M	ns	BC	ns	MC	ns
	Teschke et al., 2012 [104]	IR	NI	R	ns	ns	ns	L-M	m	U	81	35	n/a	n/a	18	M	M	o[11]	BD	OP	o[11]	m
	Hunter et al., 1999 [51]	cR	NI	R	ns	ns	ns	v	m	U	8	8	n/a	n/a	ns	n/a	n/a	n/a	BC	VC	MC	VC
Cycle track	Jensen, 2008 [54]	CR, IR	I	o[10]	ns	ns	ns	ns	ns	U	20.6 km	110 km	12-60	nm	12-60	M	M	ns	BC	ns	MC	ns
	Lusk et al., 2011 [69]	CR	NI	NR	ns	ns	2W	ns	ns	U	6	8	n/a	nm	75	M	M	m	BD	m	o[12]	m
	Teschke et al., 2012 [104]	IR	NI	R	ns	ns	ns	ns	m	U	12	2	n/a	n/a	18	M	M	o[11]	BD	OP	o[11]	m

[8]"Before" was motor vehicles encroaching into crosswalk; "after" was motor vehicles encroaching into bike box.
[9]Motor vehicles encroaching into bike lane
[10]Comparison with site-specific correction factors
[11]As this was an interview-based case-crossover study, the participants provided the crash and exposure data.
[12]Rather than using motor vehicle volumes as an exposure measure, this study used motor vehicle occupant injuries as a surrogate for relative "traffic danger."

Table 3: Study Details I (continued)

Study		Design			Treatment and loc. details						Sample size					Base rate						
Treatment	**Citation**	Outcome measures	Study format	Analysis method	Cross-section width	Cross-section lanes	One-way/two-way st	Traffic speeds	Functional class	Urban/rural	Treatment locations	Comparison locations	Before period (months)	Transition period (months)	After period (months)	Crash rate determination (treatment)	Crash rate determination (comparison)	Crash rate source type	Exposure 1 type	Exposure 1 source	Exposure 2 type	Exposure 2 source
(Multiple)	Metroplan Orlando, 2010 [74]	CR	NI	NR	v	v	B	v	m	B	ns	n/a	n/a	n/a	24	M	n/a	SD	ns	ns	ns	ns
Multi-use path	Aultman-Hall & Kaltenecker, 2000 [6]	CR	NI	R	ns	ns	ns	ns	ns	ns	20	280	n/a	n/a	36	S	S	o[13]	BD	S	BD	S
		IR	"	"	"	"	"	"	"	"	12	170	"	"	12	"	"	"	"	"	"	"
Neighborhood traffic circle	Harris et al., 2013 [46]	IR	NI	R	9-11 m	2	2W	L	L	U	28	19	n/a	n/a	18	M	M	o[14]	BD	OP	o[14]	m
On-street parking	Hunter et al., 1999 [51]	cR	NI	NR	ns	ns	ns	v	m	U	8	8	n/a	n/a	ns	n/a	n/a	n/a	nm	nm	nm	nm
	Teschke et al., 2012 [104]	IR	NI	R	ns	ns	ns	L-M	m	U	230	118	n/a	n/a	18	S	S	o[14]	BD	OP	o[14]	m
Raised bicycle Xing	Gårder, Leden, Pulkkinen, 1998 [39]	CR	I	FB	ns	ns	ns	L	A	U	44	ns	67	nm	34	M	M	CD	BC	EC	N	n/a
Roundabout—bike lane	Daniels et al., 2009 [18]	IR	I	EB	n/a	n/a	n/a	M	ns	B	40	172	36	nm	12	M	M	ND	N	n/a	N	n/a
	Schoon & van Minnen, 1994 [100]	o[15]	I	B/A	n/a	n/a	n/a	ns	ns	B	104	0	64	7	24	M	nm	ND	nm	nm	nm	nm

[13] Survey participants were relied upon as a crash rate source for themselves.
[14] As this was an interview-based case-crossover study, the participants provided the crash and exposure data.
[15] Crash reduction for bicycles and mopeds combined

Table 3: Study Details I (continued)

Study		Design			Treatment and loc. details						Sample size					Base rate						
Treatment	**Citation**	Outcome measures	Study format	Analysis method	Cross-section width	Cross-section lanes	One-way/two-way st	Traffic speeds	Functional class	Urban/rural	Treatment locations	Comparison locations	Before period (months)	Transition period (months)	After period (months)	Crash rate determination (treatment)	Crash rate determination (comparison)	Crash rate source type	Exposure 1 type	Exposure 1 source	Exposure 2 type	Exposure 2 source
Roundabout—general	Daniels et al., 2008 [19]	IR	I	MA	n/a	n/a	n/a	M	ns	B	91	172	36	nm	12	M	M	ND	N	n/a	N	n/a
		IR	"	"	"	"	"	"	"	U	40	76	"	"	"	"	"	"	"	"	"	"
	Schoon & van Minnen, 1994 [100]	CR, IR	I	B/A	n/a	n/a	n/a	ns	ns	B	181	0	64	7	24	M	nm	ND	nm	nm	nm	nm
Roundabout—mixed traffic	Daniels et al., 2009 [18]	IR	I	EB	n/a	n/a	n/a	M	ns	B	9	172	36	nm	12	M	M	ND	N	n/a	N	n/a
	Schoon & van Minnen, 1994 [100]	CR	I	B/A	n/a	n/a	n/a	ns	ns	B	18	0	64	7	24	M	nm	ND	nm	nm	nm	nm
Roundabout—multi-lane	Brüde & Larsson, 2000 [10]	CR	NI	NR	n/a	n/a	n/a	v	ns	B	14	MM	n/a	n/a	48	M	nm	ns	BC	ns	MC	ns
Roundabout—separated bike facility	Brüde & Larsson, 2000 [10]	CR	NI	NR	n/a	n/a	n/a	v	ns	B	49	MM	n/a	n/a	48	M	nm	ns	BC	ns	MC	ns
	Daniels et al., 2009 [18]	IR	I	EB	n/a	n/a	n/a	M	ns	B	38	172	36	nm	12	M	M	ND	N	n/a	N	n/a
	Schoon & van Minnen, 1994 [100]	CR	I	B/A	n/a	n/a	n/a	ns	ns	B	59	0	64	7	24	M	nm	ND	nm	nm	nm	nm
Roundabout—single-lane	Brüde & Larsson, 2000 [10]	CR	NI	NR	n/a	n/a	n/a	v	ns	B	58	MM	n/a	n/a	48	M	nm	ns	BC	ns	MC	ns
Shoulder width	Abdel-Rahim & Sonnen, 2012 [3]	CR	NI	NR	v	2	2W	v	ns	R	5	n/a	n/a	n/a	216	M	n/a	SD	N	n/a	N	n/a
	Klop & Khattak, 1999 [62]	IS	NI	R	v	2	2W	v	ns	B	787	238	n/a	n/a	48	M	M	SD	N	n/a	N	n/a
Street lighting	Kim et al., 2007 [61]	IS	NI	R	v	v	B	v	m	B	ns	n/a	n/a	n/a	72	M	n/a	SD	N	n/a	N	n/a

Table 4: Study Details II

Treatment	Citation	Outcome measures	Treatment details	Crash rate source	Controls	Signif. at 0.05 level?	Overall strength
Access management	Hunter et al., 1999 [51]	cR	Striped BLs (widths vary), WCLs (4-4.6 m); location details vary.	n/a	ns	ns	Informative but not conclusive
Bicycle boulevard	Minikel, 2012 [75]	CR	v	California Statewide Integrated Traffic Records System	Segment length (between pairs), bicycle counts	Yes	Lacking in sample size, study depth, or controls
		CS	"	"	"	No	"
Bike box	Dill, Monsere, McNeil, 2012 [22]	cR	Adv. stop line, green thermoplastic marking (all but 3), bicycle stencil, regulatory signage, no RTOR, “WAIT HERE” stencil	n/a	Bicycle movement counts, motor vehicle movement counts	ns	Lacking in sample size, study depth, or controls
		YR	"	n/a	"	ns	"
		o[16]	"	n/a	"	Yes	"
		o[17]	"	n/a	"	Yes	"
	Hunter, 2000 [48]	cR	Continuation of a left-side BL. Apparently no colored paint.	n/a	Bicycle volume	ns	Lacking in sample size, study depth, or controls
Bike lanes	Jensen, 2008 [54]	CR	1.5-2 m wide, includes BLs behind parking lanes	ns	Bicycle volume, motor vehicle volume, crash trends, examination to prevent regression-to-the-mean	No	Lacking in sample size, study depth, or controls
		IR	"	"	"	No	Lacking in sample size, study depth, or controls
	Teschke et al., 2012 [104]	IR	ns	As this was an interview-based case-crossover study, the study participants were the crash rate source	Bicycle distance traveled, personal characteristics, route characteristics, exposure to traffic and infrastructure	Mixed	Fairly robust, but still lacking in depth or completeness

[16] “Before” was motor vehicles encroaching into crosswalk; “after” was motor vehicles encroaching into bike box.
[17] Motor vehicles encroaching into bike lane

Table 4: Study Details II (continued)

Treatment	**Citation**	**Outcome measures**	**Treatment details**	**Crash rate source**	**Controls**	**Signif. at 0.05 level?**	**Overall strength**
Bike lanes (continued)	Hunter et al., 1999 [51]	cR	Striped BLs (widths vary), WCLs (4-4.6 m); location details vary.	n/a	Bicycle counts, motor vehicle counts	Yes	Lacking in sample size, study depth, or controls
Cycle track	Jensen, 2008 [54]	CR	2-2.5 m wide, raised, one-way on both sides of street	ns	Bicycle volume, motor vehicle volume, crash trends, examination to prevent regression-to-the-mean	Mixed	Lacking in sample size, study depth, or controls
		IR	"	"	"	No	"
	Lusk et al., 2011 [69]	CR	Two-way cycle tracks on one side of street; separated from traffic by parking, planting strips, medians, curbs, delineator posts, or combination.	Police crash data and hospital injury data	Bicycle distance traveled, motor vehicle traffic & speed, "vehicular traffic danger"	Yes	Fairly robust, but still lacking in depth or completeness
	Teschke et al., 2012 [104]	IR	ns	As this was an interview-based case-crossover study, the study participants were the crash rate source	Bicycle distance traveled, personal characteristics, route characteristics, exposure to traffic and infrastructure	Yes	Fairly robust, but still lacking in depth or completeness
(Multiple)	Metroplan Orlando, 2010 [74]	CR	v	Local governments in Orange, Seminole, and Osceola counties, and Florida Department of Highway Safety and Motor Vehicles records	None	ns	Informative but not conclusive
Multi-use path	Aultman-Hall & Kaltenecker, 2000 [6]	CR	All off-road paths excl. sidewalks	Surveys	Cyclist experience and other personal characteristics, distance traveled	Yes	Fairly robust, but still lacking in depth or completeness
		IR	"	"	"	Yes	"
Neighborhood traffic circle	Harris et al., 2013 [46]	IR	Islands 6-8 m in diameter	As this was an interview-based case-crossover study, the study participants were the crash rate source	Bicycle distance traveled, personal characteristics, route characteristics, exposure to traffic and infrastructure	Yes	Fairly robust, but still lacking in depth or completeness

Table 4: Study Details II (continued)

Treatment	Citation	Outcome measures	Treatment details	Crash rate source	Controls	Signif. at 0.05 level?	Overall strength
On-street parking	Hunter et al., 1999 [51]	cR	Striped BLs (widths vary), WCLs (4-4.6 m); location details vary	n/a	ns	ns	Informative but not conclusive
	Teschke et al., 2012 [104]	IR	Major streets (arterials and collectors) without vs. with on-street parking	As this was an interview-based case-crossover study, the study participants were the crash rate source	Bicycle distance traveled, personal characteristics, route characteristics, exposure to traffic and infrastructure	Yes	Fairly robust, but still lacking in depth or completeness
Raised bicycle Xing	Gårder, Leden, Pulkkinen, 1998 [39]	CR	4-12 cm rise above side streets, red pavement in crossing	Gothenburg, Sweden police- and hospital-reported incidents database	Bicycle counts, comparison group	ns	Fairly robust, but still lacking in depth or completeness
Roundabout—bike lane	Daniels et al., 2009 [18]	IR	Most bike lanes were colored red	Flanders, Belgium Ministry of Mobility and Public Works	Comparison group helped control for general traffic trends and possible regression-to-the-mean bias	Yes	Lacking in sample size, study depth, or controls
	Schoon & van Minnen, 1994 [100]	o	One-lane with small (avg. 30 m) outside diameter and BLs	Netherlands national crash database	Corrects for temporal crash and injury rate trends across all intersections in the Netherlands but not exposure at the treatment intersections	ns	Lacking in sample size, study depth, or controls
Roundabout—general	Daniels et al., 2008 [19]	IR	Mostly single-lane; incl. ones w/ bike lanes and sep. paths.	Flanders, Belgium Ministry of Mobility and Public Works	Comparison group helped control for general traffic trends and possible regression-to-the-mean bias	Yes	Lacking in sample size, study depth, or controls
		IR	Only inside built-up areas: Mostly single-lane; incl. ones w/ bike lanes and sep. paths.	"	"	Yes	"
	Schoon & van Minnen, 1994 [100]	CR	One-lane with small (avg. 30 m) outside diameter; incl. BLs, mixed traffic, and sep. paths.	Netherlands national crash database	Corrects for temporal crash and injury rate trends across all intersections in the Netherlands but not exposure at the treatment intersections	ns	Lacking in sample size, study depth, or controls
		IR	"	"	"	ns	"

Table 4: Study Details II (continued)

Treatment	Citation	Outcome measures	Treatment details	Crash rate source	Controls	Signif. at 0.05 level?	Overall strength
Roundabout—mixed traffic	Daniels et al., 2009 [18]	IR	Mostly single-lane	Flanders, Belgium Ministry of Mobility and Public Works	Comparison group helped control for general traffic trends and possible regression-to-the-mean bias	No	Lacking in sample size, study depth, or controls
	Schoon & van Minnen, 1994 [100]	CR	One-lane with small (avg. 30 m) outside diameter; no BLs or sep. paths	Netherlands national crash database	Corrects for temporal crash and injury rate trends across all intersections in the Netherlands but not exposure at the treatment intersections	ns	Lacking in sample size, study depth, or controls
Roundabout—multi-lane	Brüde & Larsson, 2000 [10]	CR	ns	ns	Number of entering motorists, number of entering cyclists	ns	Lacking in sample size, study depth, or controls
Roundabout—separated bike facility	Brüde & Larsson, 2000 [10]	CR	ns	ns	Number of entering motorists, number of entering cyclists	ns	Lacking in sample size, study depth, or controls
	Daniels et al., 2009 [18]	IR	Bike path sep. from lanes by at least 1 m	Flanders, Belgium Ministry of Mobility and Public Works	Comparison group helped control for general traffic trends and possible regression-to-the-mean bias	No	Lacking in sample size, study depth, or controls
	Schoon & van Minnen, 1994 [100]	CR	One-lane with small (avg. 30 m) outside diameter and sep. paths	Netherlands national crash database	Corrects for temporal crash and injury rate trends across all intersections in the Netherlands but not exposure at the treatment intersections	ns	Lacking in sample size, study depth, or controls
Roundabout—single-lane	Brüde & Larsson, 2000 [10]	CR	One-lane with diameters greater than 10 m	ns	Number of entering motorists, number of entering cyclists	ns	Lacking in sample size, study depth, or controls
Shoulder width	Abdel-Rahim & Sonnen, 2012 [3]	CR	Varying right shoulder widths	Idaho state database for crashes on state highways	None?	ns	Lacking in sample size, study depth, or controls
	Klop & Khattak, 1999 [62]	IS	Varying shoulder widths and speed limits	North Carolina HSIS (Highway Safety Information System) database 1990-1993	Vertical and horizontal curvature, traffic volumes, speed limit, light conditions, and others	No	Informative but not conclusive
Street lighting	Kim et al., 2007 [61]	IS	ns	North Carolina state crash database 1997-2002	Speeds, helmet use, time, weather, driver/cyclist characteristics, and others	Yes	Informative but not conclusive

The studies represented in Tables 3 and 4 show a wide range of variability in design, controls, and depth. Of the 18 treatments and 18 studies shown, 14 of the outcome measures were crash reductions, 12 were injury crash reductions, and the remainder were conflict reductions, yielding rates, and injury severities. From Table 3, 14 of the outcome measures were results of before-after studies, while 18 were derived using non-intervention study methods. The most common analysis methods were various forms of regression with 10 outcome measures derived using these methods. There were nine outcome measures derived using a simple before-after approach, four of which accounted for exposure while the remaining five did not. Eight outcome measures were a result of simply comparing rates from different sites, with some studies controlling for more variables than others. The empirical Bayes method was employed by one study for three outcome measures, and one other study used other Bayesian methods. Of all the approaches, simply comparing sites or results before and after a treatment is the simplest; however, it requires that assumptions be made about what variables to control for; without proper controls, simple comparison methods are weak compared to the others. However, any method is substantially weakened without appropriate controls.

Few of the studies examined provided detailed treatment descriptions—probably due in part to variations among treatments within each study. Treatment details are important for the transferability of the results to other sites. One of the outcome measures had a cross-section width associated with it, while five had cross-section lane counts. Ten (10) of the outcome measures named whether they were on a one-way or two-way street or multiple, while the rest did not specify. Traffic speeds were specified for 10 of the outcome measures, functional class was specified for four outcome measures, and 37 outcome measures specified whether they were in an urban or rural location or both. Of these, 20 were urban, one was rural, and 18 were both.

Twenty-seven (27) outcome measures used at least 10 treatment locations in the study; only 14, however, used more than 20 treatment sites. Fifteen (15) of the 39 outcome measures used fewer than 10 comparison sites. Of the studies that mentioned a crash rate source, 19 were measured, and 3 came from a survey. Of the measured ones, one came from a city database, six came from state databases, and 10 came from national databases. Twenty-two (22) of the outcome measures had sources that mentioned controlling for any kind of exposure in the study, and 14 came from studies that controlled for more than one type of exposure. Most of the exposure types were bicycle counts and motor vehicle counts, but a few were surveys and percentages. Exposure data were usually counts from the studies themselves, but some were past data collected by a local government. Of the 14 outcome measures investigated using before-after studies, only one study specified leaving a transition period after the treatment's installation before collecting data.

From Table 4, 14 of the 39 outcome measures had studies reporting statistically significant results for them at the 0.05 level. Of the remaining, nine were reported as statistically non-significant, while significance was not specified for the other 16. On the author's scale of study robustness, none was "excellent," eight were "fairly robust," 20 were "lacking in sample size, study depth, or controls," and five were "informative but not conclusive." Overall, many of the studies examined lacked key controls which rendered their outcomes less defensible. Those that were well-controlled still lacked treatment details, re-producible exposure data, sample size depth, or some other element that would be needed for transferability of results.

CHAPTER III

INDICATIONS OF EFFECTIVENESS

3.1 Indications from studies

The following sections discuss study outcomes on a treatment-by-treatment basis. Each section discusses results from the literature in light of the merits and limitations of the studies in a broader context. For treatments with quantitative safety outcome measures, plots are presented to compare and contrast what different studies have found with regards to treatment effectiveness. When a study reports multiple results for a single countermeasure and measure of effectiveness, only the upper and lower values for that study are plotted.

3.1.1 Access management

Access management techniques are known for their potential safety benefits for automobile traffic [29]. Though the literature reviewed in this paper does not say much to quantitatively support access management as a bicycle safety measure, it may be worth considering as a bicycle crash countermeasure based on the principle of eliminating conflict points to prevent crashes. Hunter et al. observed that sites with many conflict points, specifically those with on-street parking and driveways, had high occurrences of car-bicycle conflicts [51]. Based on an older study, intersections and driveways account for three fourths of all bicycle crashes [52]. Access management may not be a traditional tool in the bicycle safety coordinator's toolkit, but perhaps more consideration should be given in light of this observation.

3.1.2 Bicycle boulevard

Bicycle boulevards appear to offer safety benefits to cyclists by facilitating travel on roads where traffic speeds and volumes are low. Minikel's study [75] was the only one found during the literature search that evaluated bicycle boulevards for bicyclist safety. Risk ratios from Minikel's study are plotted in Figure 2. Minikel decidedly did not control for vehicle volumes at all, because he saw low vehicle volumes as one of the defining characteristics of bicycle boulevards [75]. The study controlled for distance-based exposure only by pairing streets, so exposure cannot translate to other streets or other locations. More study should be given to bicycle boulevards with an eye for specific treatment details involved.

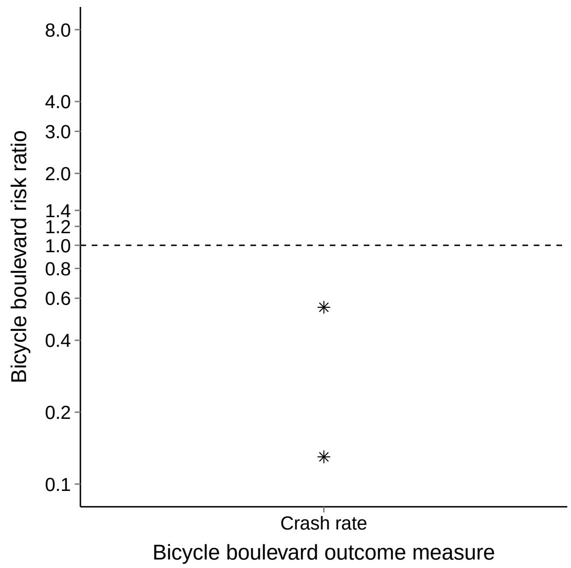


Figure 2: Study results for risk ratios associated with bicycle boulevard treatment. Results significant at the 0.05 level are marked by (∗); non-significant results or those with unknown significance are marked by (•).

3.1.3 Bike box

Bike boxes appear to be effective in reducing bicycle-motor-vehicle conflicts in some circumstances but potentially unhelpful or possibly dangerous in others. While no controlled, academic studies into crash outcomes of bike boxes were found, several were found which analyzed conflicts before and after with positive results [22, 48, 67]. Results are plotted in Figure 3. Planners and engineers should keep in mind that bike boxes are not a panacea for bicyclists' problems or dangers at intersections. In a letter from the City of Portland traffic engineer to the Federal Highway Administration regarding experimental use of bike boxes in Portland, Oregon, the city traffic engineer reported a doubling of bicycle right-hook crashes with motor vehicles at the intersections where bike boxes had been installed. These crashes were mostly concentrated at a few locations with steep downhill grades, high bicycle speeds, and high rates of bicyclists overtaking motor vehicles on the right next to the intersection

[11]. Such findings underscore the importance of examining the context of crashes.

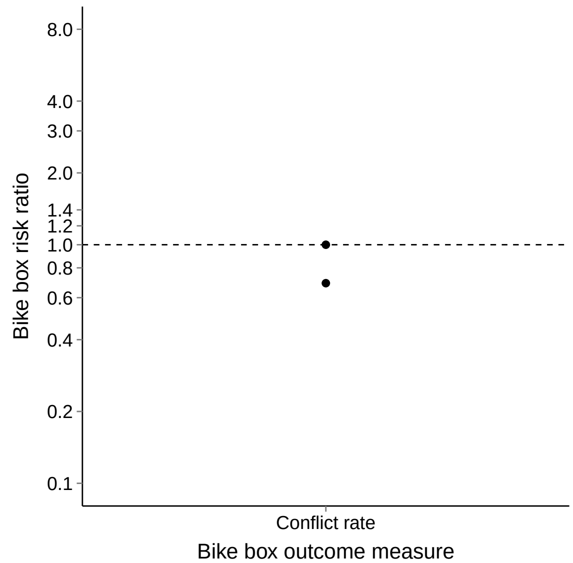


Figure 3: Study results for risk ratios associated with bike box treatment. Results significant at the 0.05 level are marked by (∗); non-significant results or those with unknown significance are marked by (•).

3.1.4 Bike lanes

Bike lanes appear to be somewhat beneficial for safety in some situations but not in others, according to the risk ratios in Figure 4. While much literature is available on bike lane safety impacts, there seem to be relatively few studies with tight controls and statistically significant results. This may be due to the relevantly high prevalence of bike lanes in the United States (compared to other bicycle-specific infrastructure) and the resulting wide variety of street types on which bike lanes are installed. The variability in the *almost*-significant beneficial bike lane results from the Teschke et al. study [104] suggest that despite there being many bike lane locations in the United States, the design details and surroundings vary so much that it is impossible to say for *all* situations that bike lanes are helpful or not. Bike lane design details were scarce in all the bike lane studies besides some mentioning standard ranges of widths.

In Jensen's study that pointed to a decrease in safety associated with bike lanes [54], overall crash frequency changes were not statistically significant. Furthermore, bike lane

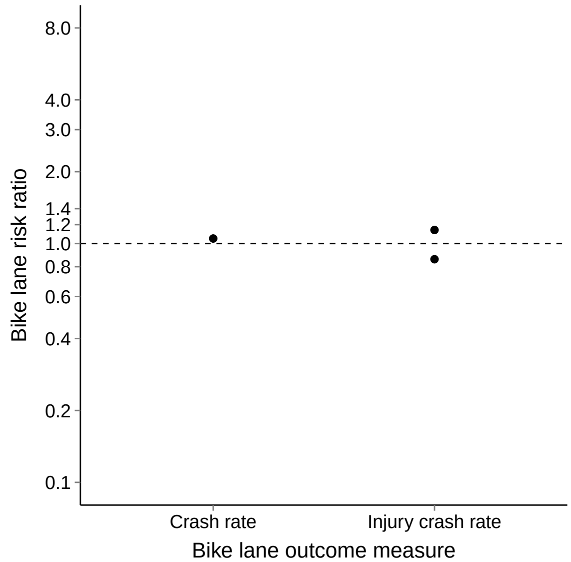


Figure 4: Study results for risk ratios associated with bike lane treatment. Results significant at the 0.05 level are marked by (∗); non-significant results or those with unknown significance are marked by (•).

designs are different in Denmark than in the United States (as evidenced by the picture in Jensen's paper showing a bike lane occupying a space between a curb and parked cars) [2, 54]. Still, the results underscore the importance of appropriate selection and design of treatments. An older study by Smith and Walsh [103] (older than this review's normal inclusion criteria) noted an increase in crashes but also that crashes after the first year of bike lane installation were not statistically significant, and furthermore that much of the crash risk was traceable to one location where the bike lane was on the left side of a one-way street. This is an interesting finding, as left-side bike lanes can be found in the NACTO *Urban Bikeway Design Guide* [81].

While there is little agreement on bike lane safety impacts *overall*, there is evidence from multiple sources that bike lanes have the potential to influence bicycle and motor vehicle positioning adjacent to on-street parking. When properly placed, bike lanes have the potential to influence cyclists to stay out of the dangerous “door zone” of parked cars [23, 108], which can be a frequent and serious hazard to cyclists [56]. Finally, bike lanes appear to be valued highly by cyclists [51, 106], which could also contribute to “safety in numbers” benefits [53, 91] while making cycling more attractive.

3.1.4.1 Buffered bike lanes

Although no crash- or injury-specific studies were found for buffered bike lanes, the "safety in numbers" effect may play into improving safety for individual bicyclists if adding buffered bike lanes attracts more cyclists [53, 91], a possibility indicated in a study by Monsere, McNeil, and Dill [77]. In some ways, buffered bike lanes used in urban areas may also bear some functional similarities to wide highway shoulders used as bicycle facilities in rural areas. For more discussion on shoulders as bicycle facilities, see the *Shoulder pavement width* section of the review in Table 1 and section 3.1.13 below.

3.1.4.2 Colored bike lanes

It is not clear whether colored bike lanes have safety benefits to cyclists or not. The literature regarding them was somewhat conflicting, where some sources cited increases in drivers' and cyclists' awareness and improvement in interactions, while other sources cited the opposite.

3.1.4.3 Combined bike lane/turn lane

Little is known about combined bike lanes/turn lanes from a safety perspective. Based on results from van Houten and Seiderman [108], pavement markings have an influence on bicycle positioning. If "taking the lane" and riding closer to through-traffic is safer than riding to the right side of a right turn lane, for instance (as some bicyclists may be wont to do), it follows that such striping that could direct them in a safer path through the intersection could have safety benefits.

3.1.4.4 Contra-flow bike lanes

Contra-flow bike lanes seem to offer safety benefits when they allow cyclists to circumvent awkward traffic maneuvers, thus reducing bicyclist exposure to motor vehicle traffic. Since wrong-way riding has been shown to worsen crash risk [74, 109], it would seem that contra-flow bike lanes should be placed very judiciously. Patterson and NACTO both recommend allowing contra-flow cycling only on quiet streets.

3.1.5 Cycle tracks

Cycle tracks appear to offer safety benefits to cyclists when they provide an opportunity to ride separately from the rest of traffic on crowded arterial streets. These benefits seem to be due in large part to protecting cyclists from the conflicts that arise while riding next to on-street parking and while being overtaken by motor vehicles. Arguments have been made against cycle tracks on the basis of crash increases, comparing riding on cycle tracks to riding on multi-use paths, sidewalks, and other off-road facilities where increased crash risk has been reported [6, 35]. Off-road crash increases, however, are largely made up of falls and crashes with pedestrians and animals [6], which should be far less common on cycle tracks which are designated for exclusive use by cyclists.

However, care should be exercised in designing cycle track intersections that do not lead to crash increases like those in Jensen's study [54]. This means being especially careful when designing intersections involving two-way cycle tracks, as contra-flowing cyclists may come as a surprise to others using the intersection [81]. Care should also be taken to design intersections and driveways of one-way cycle tracks to prevent "right hook" and driver-pulling-out crashes.

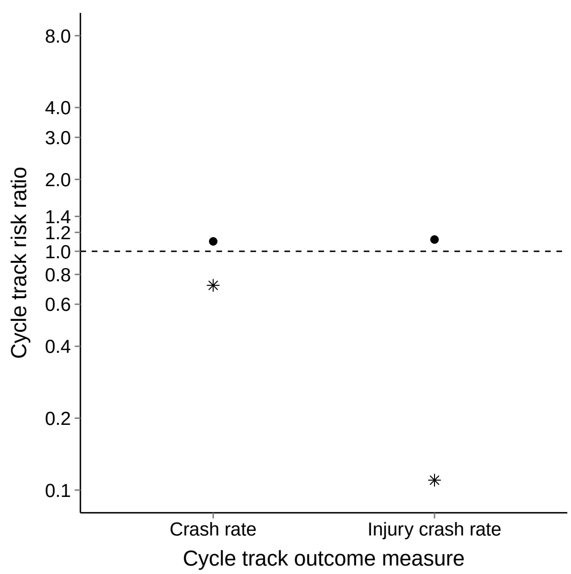


Figure 5: Study results for risk ratios associated with cycle track treatment. Results significant at the 0.05 level are marked by (∗); non-significant results or those with unknown significance are marked by (•).

While the AASHTO Bicycle Facilities guide cautions against facilities that encourage cycling against traffic [2], Lusk et al. still found a crash risk decrease associated with two-way cycle tracks (see Figure 5). This decrease was not as great as the one recorded by Teschke et al. and Harris et al., who said, "At the time of the study, none of the route infrastructure in Vancouver or Toronto mandated cycling in the direction opposite to traffic" [46], suggesting that all the cycle tracks used by study participants were one-way only.

3.1.6 Increase bicycling levels in community

Increasing bicycling levels in a community has been found in multiple studies to increase safety on a per-cyclist basis [53, 65, 95]. Gårder, Leden, and Pulkkinen found this to be the case in their study of raised bicycle crossing installations in Gothenburg, Sweden [39]. An interesting corollary, then, is that increasing cycling numbers can be a means to increase safety [53, 91]. Therefore, facilities which appear to offer modest safety increases but attract new cyclists may in fact lead to better-than-expected safety outcomes.

3.1.7 Multi-use path in separate right-of-way

Multi-use paths seem to be associated with higher crash rates for cyclists in general, as reflected in Figure 6. This may have to do with the constrained space of a multi-use trail shared with pedestrians, pets, and other trail users that may increase a cyclist's risk of falling or being involved in a collision with another trail user [6]. However, with the degree of variation that exists from one multi-use trail design to another, it would be presumptuous to say that all multi-use trails decrease safety. While Aultman-Hall and Kaltenecker found a significantly higher crash and injury risk associated with commuting on "off-road trails" compared to on roads [6], detail is not given as to the trails' width, whether they were paved, the intersection density, or other design details, making it difficult to transfer findings to other multi-use trails. The results do underscore the importance of refraining from assuming that one route type is safer only because it "feels" safer. In some situations, however, vehicle speeds or volumes may be so great that separating cyclists from the rest of the traffic stream does indeed have a net positive impact on safety.

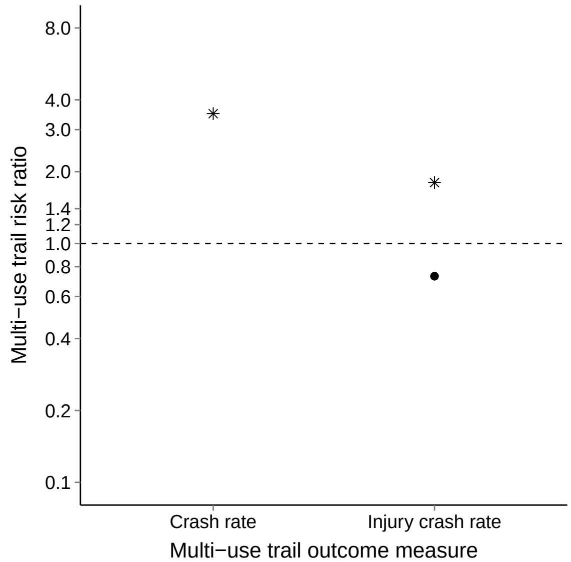


Figure 6: Study results for risk ratios associated with multi-use trail treatment. Results significant at the 0.05 level are marked by (∗); non-significant results or those with unknown significance are marked by (•).

3.1.8 Neighborhood traffic circle

Neighborhood traffic circles seem to do more harm than good overall for cyclists. Though they do not appear to be the subject of extensive study, their significant crash risk as reported by Harris et al. [46], paired with the anecdotal evidence given by Ewing [26], makes a case for using them sparingly, as the traffic calming effect on safety may be overcome when bicyclists actually enter a traffic circle. Figure 7 shows the risk ratio associated with traffic circles from Harris et al. [46].

3.1.9 On-street parking removal

On-street parking appears to be a perennial hazard to cyclists due to cars crossing the cyclist's space to enter or leave a space, and also because of the potential of having a car door open directly in the cyclist's path. Figure 8 shows a risk ratio associated with cycling in the absence of on-street parking versus alongside it. Besides its potential economic benefits, the presence of on-street parking may also be an important element in traffic calming schemes [26, 102]. Part of the potential danger, however, comes in cycling too close to parked vehicles and colliding with open doors which is a fairly common crash type and can even

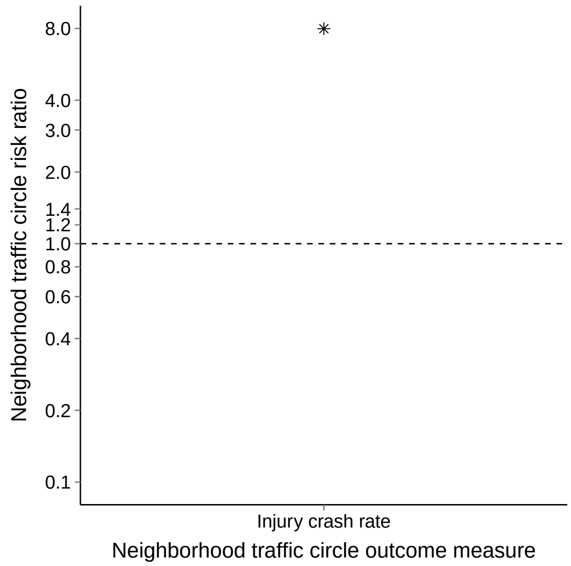


Figure 7: Study results for risk ratios associated with neighborhood traffic circle treatment. Results significant at the 0.05 level are marked by (∗); non-significant results or those with unknown significance are marked by (•).

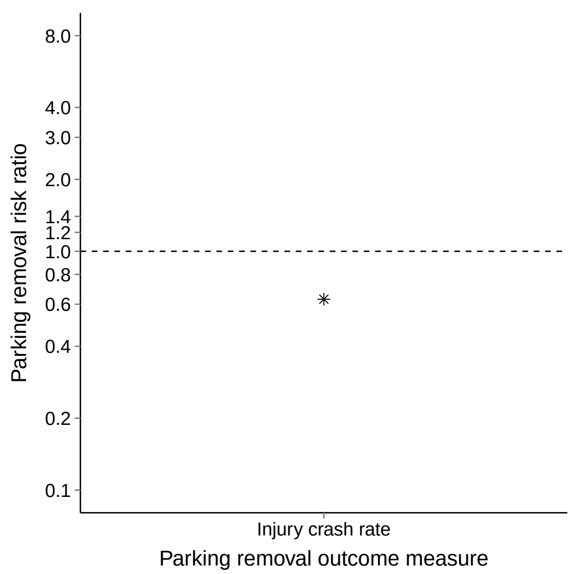


Figure 8: Study results for risk ratios associated with on-street parking removal. Results significant at the 0.05 level are marked by (∗); non-significant results or those with unknown significance are marked by (•).

be fatal [51, 56]. Whether or not removing on-street parking is an option, striping a bike lane or a shared lane marking appropriately may help mitigate some of those dangers by influencing bicyclists' positioning and bringing them further from the dangerous "door zone" [4, 9, 23, 34, 90, 108].

3.1.10 Raised bicycle crossing

Raised bicycle crossings are not very common in the United States, and that is likely in part because cycle tracks and side paths are not very common, either. However, the raised bicycle crossings described by Gårder, Leden, and Pulkkinen appear to be effective in preventing crashes by simultaneously reducing vehicle speeds and increasing cyclist visibility, as shown in Figure 9. Gårder, Leden, and Pulkkinen point out that bicycle speeds and motor vehicle speeds should both be regulated in complex environments [39]. While raised bicycle crossings were associated with decreased turning motor vehicle speeds, increased bicycle speeds can also diminish some of the safety benefits of any treatment. This treatment appears to have potential for use at conflict points in cycle track crossings in North America, in addition to the usual colored paint treatments, so long as bicycle speeds are also managed.

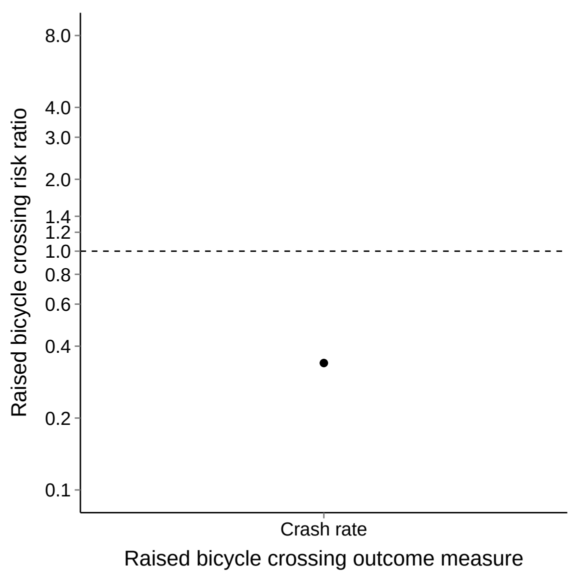


Figure 9: Study results for risk ratios associated with raised bicycle crossing treatment. Results significant at the 0.05 level are marked by (∗); non-significant results or those with unknown significance are marked by (•).

3.1.11 Roundabouts

In the case of roundabouts, the design seems to be the deciding factor between one that is benign or hazardous for cyclists. While roundabouts with one lane and mixed traffic or a separated facility may even offer safety benefits to cyclists compared to signalized intersections, those with bike lanes inside the intersection or with more than one travel lane carried through seem to decrease safety substantially. Figures 10 and 11 show results for multiple roundabout designs.

According to AASHTO, multi-lane roundabouts can be difficult to manage for bicyclists because of difficulty changing lanes and the risk of being cut off by exiting drivers [2]. For this reason, the AASHTO *Guide for the Development of Bicycle Facilities* recommends a prevention measure for newly constructed roundabouts: if the design year traffic volumes require a two-lane roundabout but current volumes only require one, only open one lane to begin with, and add the additional lane only if and when the design year volumes are realized [2].

In Schoon and van Minnen's study, where moped and bicycle safety were combined, mopeds tended to benefit more from crash reductions [100]. This means that some of the reductions claimed for bicyclists *and* mopeds may really have a better effect for mopeds than for bicyclists, which tends to agree more with findings by Daniels et al. who found safety decreases associated with roundabout bike lanes.

Finally, it may be startling that Daniels et al. found such a high danger to cyclists associated with roundabout conversion. It is important to note, however, that the roundabout sample studied by Daniels et al. had a large proportion of roundabouts with bike lanes [19], which were shown to increase crash risk for cyclists by Daniels et al. in a later study [18].

3.1.12 Shared lane marking

Shared lane markings, or "sharrows," seem to have a strong ability to influence cyclist positioning on roadways. Sharrow studies reviewed had no coverage of crash or injury outcomes and minimal treatment of conflicts. Instead, investigators chose to focus on lane positioning of bicyclists in relation to curbs and parked and passing motor vehicles. Although the four

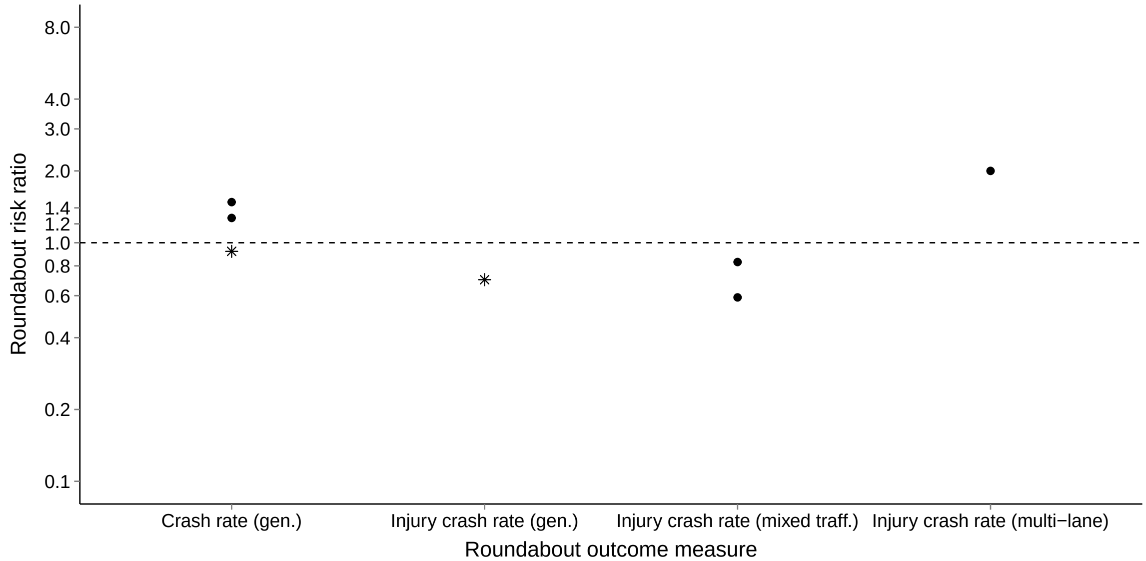


Figure 10: Study results for risk ratios associated with roundabout installation compared with "conventional" intersections. This figure includes results from a group of roundabouts in general (with many designs including those with dedicated bicycle facilities), a group of roundabouts where bicycles are expected mix with automobile traffic, and a group with multiple lanes. Results significant at the 0.05 level are marked by ($\ast$); non-significant results or those with unknown significance are marked by (●).

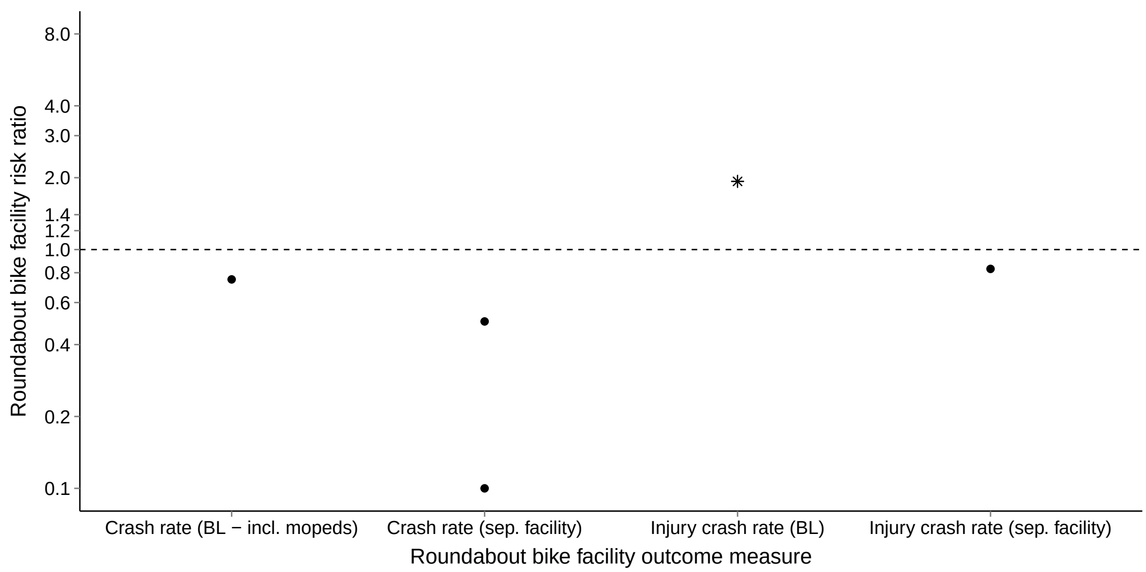


Figure 11: Study results for risk ratios associated with installation of roundabouts with dedicated bicycle facilities compared with "conventional" intersections. This figure includes results from a group of roundabouts with bike lanes carried through the circle and a group of roundabouts with separated bicycle facilities around the outside. Results significant at the 0.05 level are marked by ($\ast$); non-significant results or those with unknown significance are marked by (●).

sharrow studies were located all across the United States (Cambridge, MA [34], Chapel Hill, NC [34], Seattle, WA [34], Gainesville, FL [90], Austin, TX [9], and San Francisco, CA [4]), they all observed remarkably similar results. The most interesting result, perhaps, is the influence sharrows appear to have over the riding path of bicyclists, which could potentially be applied to many safety issues relating to bicyclist positioning on roadways such as staying clear of parked car doors.

3.1.13 Shoulder pavement width

Greater shoulder pavement width appears to have a very loose relationship with increased safety for cyclists. Shoulder width is one of the few rural treatments in this paper. The estimates by Metroplan Orlando and by Abdel-Rahim and Sonnen for potential crash modifications did not take exposure into account at all, or at least did not mention it [3, 74].

The study by Klop and Khattak was the most statistically rigorous; however, the most statistically significant variables in the model related to shoulder width were not highly explanatory. This study did not control for exposure directly, either, although it did control for many other things [62].

3.1.14 Shoulder rumble strips

Shoulder rumble strips have the potential to either render a shoulder un-rideable for a cyclist or to provide a noise-making barrier between the cyclist and the rest of traffic. While neither study observed safety outcomes such as crash or injury reductions, both studies make important points about rumble strips and bicyclists. Bicyclists do not need to be afraid of well-placed rumble strips, as they may have some benefit to the cyclist, too [40]. However, care should be exercised in placing the rumble strips so that they leave adequate operating space for bicyclists and do not force bicyclists to operate outside the shoulder. The AASHTO *Guide for the Development of Bicycle Facilities* specifies a clear path of 4 feet between the rumble strip and the outside edge of pavement, or 5 feet to the adjacent curb, guardrail, or other obstacle [2]. Leaving regular gaps in the rumble strip pattern can also minimize bicyclist difficulty or discomfort when crossing rumble strip channels [2, 76]. The AASHTO Guide also notes that centerline rumble strips can be a concern for cyclists, as the rumble strips may deter motorists from approaching the centerline to give cyclists adequate passing room. The Guide states that where centerline rumble strips are present, shoulder rumble strips should only be placed on full-width paved shoulders of at least 6 feet [2].

3.1.15 Street lighting

Roadway lighting appears to have a substantial positive effect on cyclist safety at night (see Figure 12). Kim et al. examined light conditions and other crash characteristics for their influence on crash severity. The authors hypothesized that darkness delays any evasive actions on the part of a cyclist or driver due to lack of visibility on both parts, which supports the significant increase in crash severity associated with darkness. Lighting roadways, it seems, could help reduce injury severity, but making bicycles themselves more visible by outfitting them with lights may have a positive effect as well [61].

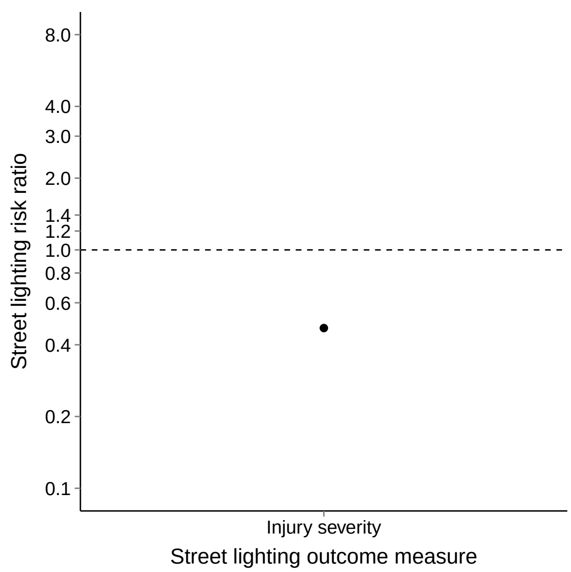


Figure 12: Study results for risk ratios associated with night-time roadway lighting treatment. Results significant at the 0.05 level are marked by (⁎); non-significant results or those with unknown significance are marked by (•).

3.1.16 Two-stage turn queue box

There is little to say at this point about two-stage turn queue boxes, because no literature was found that examined them based on safety. Providing them could be helpful in minimizing conflict points for bicyclists at multi-lane intersections, which could theoretically have safety benefits.

3.1.17 Wide curb lanes

Wide curb lanes appear to have many of the same benefits as bike lanes [51]. One positive aspect is absence of stripes on the pavement may encourage cyclists to "take the lane" when conditions would make such actions safer. According to van Houten and Seiderman, striped bike lanes have a significant influence on bicycle positioning within the lane, such that cyclists want to stay in it [108]. One potential disadvantage compared with bike lanes is that bicyclists have stated a preference for marked bike lanes [51, 106], which could also potentially interact with the "safety in numbers" effect.

3.1.18 Other route characteristics

At least two studies found significanly more danger to bicyclists on routes with slopes [62, 104]. Routes crossing train or streetcar tracks were also found to carry significantly more danger to bicyclists [104].

3.2 Data issues and needs

Despite the growing concern and effort toward improving the status of non-motorized transportation safety in North America, there are still missing pieces to the puzzle of understanding and justifying measures to increase safety for non-motorized users. Knowledge about true numbers of crashes, injury severity and crash causation are both necessary for selecting the right facility type. The literature available on bicycle safety treatments varies greatly in sample sizes, controls, statistical rigor, and use of exposure measures. Even in well-controlled, statistically rigorous studies, the common denominator in data need is quantifiable exposure data.

3.2.1 Number of crashes

Knowing the number, type, and severity of crashes is a significant problem for understanding the effectiveness of bicycle treatments. While Table 3 suggests that most studies were able to obtain some kind of crash data from local, state, and national governments, the quality of that data is often lacking due to problems of underreporting and reporting bias [17, 24, 71], which could lead to incorrect conclusions. Without more consistent crash data it is also difficult to capture the effects of a treatment when it causes a shift in severity but not overall crashes [1].

3.2.2 Injury severity

While studies with large sample sizes may be used to find relationships between infrastructure characteristics and injury severity, sample sizes of the magnitude needed to capture enough different levels of injury severity to measure the effect of a single treatment would be difficult to achieve. Some studies in this review examined injury severity exclusively [61, 62]. Others examined crash or injury crash frequency as well as injury severity but lacked sample sizes large enough for significant severity results [6, 19, 75]. At least one noted that it lacked data to assess change in injury severity [69]. However, a treatment's influence on injury severity may be important for quantifying the costs and benefits of infrastructure decisions.

3.2.3 Crash causation

Part of the exposure issue is knowing what types of activities even expose cyclists or pedestrians to risk. Karsch et al. [59] suggest that better data on crash causation for pedestrians and bicyclists could be captured by using standardized, automated crash reports specific to bicycle and pedestrian modes. If the report were electronic, it could be quite detailed and give automated instructions to officers on how to fill in specific portions. This may help answer questions about crash causation which could contribute to better exposure data. Research is needed in this area to determine what data would be best to include in pedestrian and/or bicycle crash reports [59].

3.2.4 Exposure data collection and maintenance

Besides knowing what puts non-motorized users at risk, there must be a way to know the extent to which users are exposed risk. From the studies shown in Tables 3 and 4, fewer than half of the outcome measures controlled for exposure in any way. This is a significant issue, as lack of exposure data makes it difficult to prove the effects of a treatment in either direction. Just as transportation agencies invest in collecting and keeping motor vehicle counts on road facilities, they must also invest in collecting and maintaining non-motorized user counts. A project funded by Caltrans worked on ways of counting pedestrians and bicyclists automatically, creating a state database, and making sense of the counts collected [42]. Another challenge that presents itself is determining if only one exposure measure is adequate—for example, if counts, distance walked and biked, or hours walking and biking can stand alone as exposure measures or whether multiple measures are necessary to fully describe exposure. These questions need to be answered.

CHAPTER IV

CONCLUSIONS

Walking and bicycling are active, low-cost means of transportation that have the potential to alleviate many of the health problems caused by sedentary lifestyles and the congestion, environmental, and equity problems caused by an over-reliance on automobiles for transportation [7, 72, 92, 98, 113]. For active transportation to effectively alleviate these problems, it needs to be safer. To make walking and bicycling safer, engineers and planners need to know what facility designs promote the safest interactions among pedestrians, cyclists, drivers, and other modes in a given situation and how effective they are expected to be.

4.1 Literature survey results and the need for better data

This paper reviewed other literature that presented evaluations of safety benefits associated specifically with bicycle safety treatments. Of the studies reviewed, some used very simple methodologies with few controls, while others developed more rigorous methods to control for confounding factors. Some treatment types had multiple studies which evaluated them, while others had none. Sometimes the studies were in agreement with one another about a treatment's safety benefits, and other times they were not.

One common theme among the studies in this review was a lack of standardized, transferable exposure data. While many of the researchers found creative ways to control for exposure (for example, interviewing cyclists involved in injury crashes about the infrastructure characteristics along their routes [46, 104], or controlling for motor vehicle occupant injuries as a surrogate for traffic danger along the routes studied [69]) and thus make their results more meaningful, standard methods of collecting, storing, and transferring exposure data are essential for understanding how many users will benefit from a facility as well as developing high-quality CMFs that can be applied anywhere.

4.2 Highway safety research and its applications

An accurate understanding of the expected effectiveness of bicycle and pedestrian safety countermeasures is greatly needed to support decisions about how to best allocate limited public resources to increase safety for non-motorized users. To the same end, knowing how many people are walking and biking on individual routes and facilities, how they are using them, and how many people are expected to benefit from a safety treatment are also necessary to support strong infrastructure decision making.

In some situations, a transportation agency or local government may be constructing or reconstructing a new facility, such as a road or bridge, and need a method for choosing designs that meet the needs of non-motorized users. While reliable crash, exposure data, and CMFs would certainly aid in making these types of decisions, transportation providers need not wait until such data is available to make good decisions about new infrastructure. The treatment reviews and concepts discussed in this paper can be used as guidelines, along with engineering judgment and local knowledge, to help develop standard accommodations and minimum accommodations for bicycles and pedestrians.

Often, however, transportation agencies and local governments are making decisions about how to retrofit existing facilities to better accommodate cyclists and pedestrians. These choices may have significant constraints on space or financial availability, and decision makers may want to focus on areas where the greatest risk reduction potential exists. Understanding the expected effectiveness of specific facilities, including how many people it would serve and where safety needs are, would help make an informed resource allocation decision.

4.3 Design decision support for Georgia

The evaluation presented in this paper is part of a larger project sponsored by the Georgia Department of Transportation to investigate safety benefits of pedestrian and bicycle treatments and how they can be applied to the state of Georgia. The project includes developing design policy recommendations for standard, minimum, and special bicycle and pedestrian accommodation, as well as a decision structure for selecting the appropriate accommodation level. The evaluation presented in this paper can be used as background knowledge to better understand the current state of bicycle safety treatments and their known effectiveness. This evaluation can then be used to develop specifications for standard and minimum bicycle accommodation for roadway facilities in Georgia. A follow-up report on pedestrian safety treatments will likewise be used to develop specifications for standard and minimum pedestrian accommodation.

For design situations that warrant neither minimum accommodation for pedestrians and cyclists, nor standard accommodation, this project will also develop a procedure for evaluating and selecting special accommodations in the future. Special accommodations may need to be applied at locations with high bicycle or pedestrian demand or a poor crash history. The procedure this project intends to develop will include collecting crash and exposure data, observing treatment effects, and developing CMFs.

4.4 Future work

The Highway Safety Manual (HSM) [1] presents a methodical way of quantifying and transferring safety benefits associated with infrastructure countermeasures. The HSM also publishes safety benefits that are already known in the form of crash modification factors (CMFs). However, the HSM does not include any CMFs for pedestrian or bicycle treatments. Moreover, the kinds of data necessary for developing HSM-style CMFs for bicycle or pedestrian treatments are not readily available.

Work is already being done in some places to develop methods of collecting and processing pedestrian and bicycle exposure data on a large scale [42]. However, more questions still need to be answered about how to apply the CMFs to non-motorized safety and how exposure ought to be quantified and collected. The HSM assumes that countermeasure CMFs are multiplicative and that multiple countermeasure benefits applied together have independently additive benefits [32]. While this may be the case sometimes, benefits may not be multiplicative for combinations of treatments designed to address the same safety concerns. For example, bicycle boulevards and roundabouts both have the potential to reduce motor vehicle speeds; however, constructing a bicycle boulevard and placing roundabouts at its intersections may not have a proportionally greater effect on vehicle speeds than simply constructing a bicycle boulevard.

Knowing the right exposure measures to collect and apply toward safety calculations is also a necessary consideration. For some linear facilities separated from traffic, such as cycle tracks and multi-use trails, distance-based exposure measures may make the most sense; for non-separated facilities, however, time-based exposure measures could make the most sense, since cyclists would be exposed to more passing automobile traffic as a function of time rather than their own distance traveled; even a combination of time and distance could make sense.

Collecting more detailed information surrounding bicycle- and pedestrian-related crashes could help answer the question of why crashes happen, which could in turn help inform how exposure should be quantified. Collecting crash data specific to pedestrian and bicycle crashes might be more feasible now thanks to automated crash reporting technology used by police forces. Investing in research and actions to work toward finding the answers is critical, and it has the potential to make a substantial difference in the reach of non-motorized safety research and its application to the safety and excellence of walking and cycling infrastructure for future generations.

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