GEORGIA DOT RESEARCH PROJECT 13-17

FINAL REPORT

BICYCLE AND PEDESTRIAN SAFETY IN THE HIGHWAY SAFETY MANUAL

Georgia Department of Transportation

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An accurate understanding of the expected effectiveness of bicycle and pedestrian safety countermeasures is needed to support decisions about how to best allocate limited public resources to increase safety for non-motorized users. However, the kind of data necessary for developing Highway Safety Manual (HSM)–style safety performance functions for bicycle and pedestrian treatments are not currently available. Limited research has been done to date about the impact of bicycle and pedestrian treatments, and most studies are not robust enough to draw broad conclusions. Most agencies surveyed valued safety as a key component of their decision to implement infrastructure, but most did not collect enough exposure and crash data to adequately assess the safety impacts. The two major challenges in using crash records for bicycle safety research are that crashes in general and cyclist crashes specifically are underreported, and pedestrian and bicycle crashes are rare events. Therefore, GDOT should pursue case-control approaches in the immediate and build toward more robust data collection, including new sources for bicycle and pedestrian crash data, counts for exposure data, and site-specific before-and-after treatment data collection.</td></tr>
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BICYCLE AND PEDESTRIAN SAFETY IN THE HIGHWAY SAFETY MANUAL

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Executive Summary

The Georgia Department of Transportation (GDOT) sponsored this project to investigate the effectiveness of bicycle and pedestrian safety treatments in the absence of their representation in the Highway Safety Manual (HSM). The goal of the project is 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.

Based on the literature review, there were a few conclusions that could be drawn about the risk ratios of various treatments. However, the major finding was that very little research has been done to date about the impact of these treatments, and most studies are not robust enough to draw broad conclusions. Similarly, from the survey, there is a very wide range of data availability and preferences and planning techniques among regional and state bicycle and pedestrian transportation professionals relating to bicycle and pedestrian safety. Most agencies valued safety as a key component of their decision to implement infrastructure, but most did not collect enough exposure and crash data to adequately assess the safety impacts.

Based on previous literature review and expert surveys, the research team argues that agencies need to establish practices that are data-driven and evidence-based. Until agencies address the fundamental data needs required for quantitative-type analyses, the understanding of the safety impacts of bicycle and pedestrian designs is ambiguous at best, and can mislead the decisions to adopt these designs. To meet federal reporting requirements, state DOTs maintain a crash information database containing basic information (e.g., time, location, number of

vehicles, type of crash, injuries) regarding crashes and often maintain an archive with images of the police reports from which these data were drawn. Crash databases serve as a standard database in safety analysis. However, there are two major challenges in using crash records for bicycle safety research: (1) crashes in general and cyclist crashes specifically are underreported and (2) crashes are rare events, especially in places where pedestrian and bicycle activity levels are low.

An accurate understanding of the expected effectiveness of bicycle and pedestrian safety countermeasures is needed to support decisions about how to best allocate limited public resources to increase safety for non-motorized users. However, the kind of data necessary for developing HSM-style safety performance factors for bicycle and pedestrian treatments are not currently available.

The researchers encourage GDOT to pursue several practices to begin to transition to the use of HSM-type safety analysis in the long term and immediately begin to better understand safety impacts in the short term. First, case-control approaches are used where infrequent events preclude aggregate, top-down data assessment approaches. In case-control analysis, research teams focus on the individual events to identify the most-likely cause of the event and factors that contributed to the causality. The research team recommends that GDOT conduct a detailed study to assess the feasibility of implementing case-control analysis for fatal bicycle and pedestrian collisions, at a minimum, but preferably for all crashes that would currently be reported.

Second, in the absence of death or significant physical injury, bicycle and pedestrian crashes typically go unreported to the police. The study team proposes a pilot study to assess two possible means to collect improved crash data, via bicycle shops and via the Cycle Atlanta application. The Cycle Atlanta app could allow the pin-pointing of “near miss” or incident locations for cyclists to designate locations they feel are less than safe based on their own cycling experience. Because bicycles generally need to be professionally repaired after a crash, an opportunity to collect objective data exists for unreported crashes. Unreported bicycle crashes could also be identified by giving bicycle repair technicians a form for patrons to fill out as they are having their bicycle repaired to report any incident with a vehicle that led to the need for the repair. The survey would allow users to self-report the map location and details associated with the incident, and researchers could use the data to supplement information available in the Fatality Analysis Reporting System (FARS) and Georgia Electronic Accident Reporting System (GEARS) databases. Together, these new sources of data could substantially add to current crash records, and pilot studies to develop the sources are necessary.

Third, even in well-controlled, statistically rigorous studies, the common denominator in data need is quantifiable exposure data. Therefore, permanent count stations and monitoring systems for traffic volumes, speeds, and prevailing cycling and walking conditions should be deployed along high-traffic routes, as well as rotating sampling stations in low-volume locations. A comprehensive data collection program cannot be achieved in a timeframe that would be reasonable for the immediate analysis of bicycle and pedestrian safety. However, without it, GDOT will not progress toward eventual measurement of safety improvements along the lines of the Highway Safety Manual procedures.

Finally, the research team recommends that site-specific before-and-after data collection and analysis should be employed to help gather data to analyze locations where bicycle and pedestrian treatments are being implemented. All locations where treatments are being installed should be part of a data collection program to ensure proper exposure and crash data are collected in the before and after situations.

1 Background

Increased use of active transportation can make direct and indirect contributions toward addressing both the health concerns arising from sedentary lifestyles and other societal transportation issues including congestion, pollution, and equity problems (Barnes and Schlossberg, 2013; MacDonald, 2007; Pucher and Renne, 2003; Saelensminde, 2004; WHO, 2002). While 10.9% of trips in the United States were made by walking or by bicycling during 2009 (PBIC, 2010), those modes made up 14% of all traffic fatalities nationally during the same year (NHTSA, 2014a; 2014b). The data suggest an over-representation of walking and biking in crash fatalities; however, quantifying the risk associated with walking and cycling is difficult (PBIC, 2014).

Roadway design in the US has been traditionally geared toward fulfilling motorized travel needs that are different from the needs of pedestrians and bicyclists, and at times, in conflict with the requirements of safe biking and walking. However, in recent years, local and federal transportation agencies have placed an increased emphasis on promoting non-motorized transportation through the implementation of design policies that address the unique needs of these modes of travel. For biking and walking to be viable, healthy modes, travelers choosing the 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 and other travelers, but also transportation planners and engineers through facility design (Metroplan, 2010; AASHTO, 2010). Therefore, this project focuses on the safety research used to discern appropriate designs and countermeasures that enhance bicycle and pedestrian safety.

For state departments of transportation (DOTs) and local agencies responsible for deciding how to improve bicycle or pedestrian safety, knowing the expected safety performance of the alternatives can help decision makers allocate resources and gain support. With greater information about the range of effects of a safety treatment, planners can calibrate those effects to the local situation and estimate the expected safety performance. This is the foundation of the research method used for the Highway Safety Manual (HSM) (AASHTO, 2010); however, to date, most pedestrian and bicycle safety research does not satisfy the data requirements for this method, and the HSM does not provide crash modification factors for any pedestrian or bicycle treatments.

As stated in the newly approved GDOT Complete Streets Design Policy (2012), "It is the policy of the Georgia Department of Transportation (GDOT) to routinely incorporate bicycle, pedestrian, and transit (user and transit vehicle) accommodations into transportation infrastructure projects as a means for improving mobility, access, and safety for the traveling public." However, implementation of this policy is hampered by limited guidance currently available on the safety implications of most bicycle and pedestrian infrastructure projects. This study will serve to synthesize existing practice and current research on the impacts of bicycle and pedestrian facilities on bicycle and pedestrian volumes, accident frequency, accident severity, and other factors that impact the system usability measures of these modes.

2 Research Objective and Significance

This research proposes to synthesize existing practice and current research on the impacts of bicycle and pedestrian facilities on bicycle and pedestrian volumes, accident frequency, accident severity, and other factors that measure the system usability of these modes. The objectives of this research are to (1) quantify the relationships between pedestrian safety and crossing treatments at uncontrolled locations, and (2) determine methods to develop crash modification factors by crash type and severity for unsignalized pedestrian crosswalk signs and pavement markings, high-intensity activated crosswalk (HAWK) signals, rectangular rapid flashing beacons, pedestrian refuge areas, curb extensions, in-pavement warning lights, high-visibility crosswalk marking patterns, etc. The final goal is to develop a design guideline for constructing new bicycle and pedestrian facilities in Georgia that are efficient and cost effective and will encourage more people to adopt these alternative and sustainable modes of transportation.

2.1 Research Tasks

The goal of this research is to provide a synthesis of current practice with regard to the design, implementation, and evaluation of pedestrian and bicycle treatments and to apply these findings in Georgia. This research consists of four primary tasks. The study began with a review of the applicable research specific to the effectiveness of individual bicycle and pedestrian measures in reducing accident frequency and severity, and encouraging use of facilities. In the second task, the team surveyed other state DOTs, metropolitan planning organizations (MPOs), and major municipal DOTs regarding the current practices in bicycle and pedestrian design policy. This survey asks how these agencies decide when pedestrian and bicycle accommodations in any form are warranted, when they use shared versus separated facilities, and how they evaluate the effectiveness of treatments and the community impacts of these treatments. In the third task, the team developed a cost–benefit analysis tool for pedestrian and bicycle treatments, including safety impacts. Finally, this research identifies the gaps and uncertainties that need to be evaluated in additional research.

2.2 Research Significance

The Centers for Disease Control estimates that 35.7% of US adults are obese (Ogden, et al., 2012). The US Department of Energy estimates that the transportation sector accounts for 28% of US greenhouse gases (Oak Ridge National Lab 2011). Yet, one of the main reasons citizens do not use the healthier, non-polluting modes of walking and cycling is a lack of safe infrastructure: dedicated bicycle routes, roads with bicycle lanes, safe crosswalks, and other designated facilities. GDOT has expressed a desire to integrate pedestrian and cycling infrastructure into roadway designs, but has limited information on how to best spend the money for improvements. Justification for various improvement strategies is needed based on projected safety improvements that depend on traffic volumes and other factors. The proposed research is significant not only as a synthesis of current practice with regard to bicycle and pedestrian infrastructure, but also for the cost–benefit analysis and the local application in a state with a limited bicycle and pedestrian culture.

3 Highway Safety Manual Method

In the United States, the predominant guide for assessing the effects of safety treatments is the Highway Safety Manual. The HSM employs a simple method for assessing roadway safety treatment effectiveness based on data inputs and analytical study (AASHTO, 2010). In the HSM method, safety performance is a function of a base rate multiplied by a series of crash modification factors (CMFs), such that:

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

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 in Equation (1) 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); CMFs greater than 1 indicate an expected safety decrease (increase in crashes). Exposure may be expressed in a variety of ways using a variety of data, including number of trips, vehicle miles traveled (VMT), hours of exposure, number of roads crossed, number of left turns made, etc. Risk is expressed as the probability of a crash occurring per unit of travel (i.e., distance, time, trips, turns, etc.) under specific conditions, presuming that the unit of travel under the set of conditions represents exposure.

To develop or use crash modification factors, the HSM requires a significant amount of data for implementation of its quantitative approach to safety. These data needs can be classified into three main categories (AASHTO, 2010): crash data, exposure data, and roadway characteristics data. The HSM requires several specific attributes for crash data: year, location, type, severity level, relationship to intersection, and distance from intersection. For vehicular crashes, exposure data requires Average Annual Daily Traffic (AADT) data, as well as minor and major street AADT for safety evaluations occurring at intersections. The roadway characteristics data requirements are detailed, and the needs differ depending on facility type. All three data categories and their attributes need to be customized for pedestrian and bicycle safety research.

Motor vehicle traffic volumes and crash data are collected regularly by transportation agencies. The sample sizes necessary for developing and using CMFs for automobile-related safety interventions are often available, given the large traffic volumes, significant number of vehicle crashes, crash occurrences, and known facility design features. However, as discussed throughout this paper, cycle–vehicle collisions are fairly rare events compared to vehicle–vehicle crashes, few data sources are available for bicycle traffic volumes, and cyclist–vehicle exposure data (combined volumes by mode and relative movement data) are generally not readily available. These issues make the development of CMFs for vehicle–bicycle safety treatments difficult.

3.1 Current Research Methods

In the absence of base crash rate data necessary for the HSM method, many researchers and transportation agencies have developed other research methods to estimate safety effects of bicycle and pedestrian treatments. Some studies employ simple 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. 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.

A Guide to Developing Quality Crash Modification Factors (Gross, et al., 2010) and the CMF Clearinghouse site's glossary of terms (FHWA, 2010) describe the typical study methods for highway safety research:

- Simple before–after
- Full Bayes
- Empirical Bayes
- Regression cross section
- Non-regression cross section
- Case-control
- Cohort
- Meta-analysis

Before–after (intervention) studies are generally preferred over cross-sectional (non-intervention) studies. 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).

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 (Gross, et al., 2010).

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). 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 be applied to safety analysis as well by isolating locations in case-control studies, or by isolating treatment status in 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.

3.2 Principles Behind Non-motorized Roadway Safety Treatments

While motor vehicles are not the only threat to bicyclist safety (Aultman-Hall and Kaltenecker, 1999; Moritz, 1997; Moritz, 1998; Teshke, et al., 2012), collisions with motor vehicles are the main cause of thousands of non-motorized road users' deaths each year, as well as many more injuries (NHTSA, 2014a; 2014b). For this reason, most measures aimed at improving the safety of non-motorized users focus on mitigating the dangers posed by conflicts with motorized traffic.

For a safety treatment to reduce number or severity of collisions between a motor vehicle and a non-motorized road user, the treatment generally needs to address one or more of the following objectives (expanded from Retting, et al., 2003):

- Increasing the separation of bicycles and motor vehicles in time
- Increasing the separation of bicycles and motor vehicles in space
- Increasing the visibility and conspicuity of non-motorized users
- Improving lines of sight between the modes
- Reducing the number of interactions between modes (e.g., number of driveways)
- Reducing motor vehicle speeds

Maintaining a physical separation between bicycles and motor vehicles (space and/or time) will prevent the two modes from colliding. Separated bikeways and bicycle signal phases are employed to maintain a separation between modes in space and time. Increased separation in time and space at any given time will also increase the reaction time available to both modes to avoid an impending collision. Hence, bicycle lanes enhance this separation. Increasing bicycle and vehicle visibility gives motorists and cyclists more time to react and avoid a collision. For example, bike boxes that allow cyclists to proceed to the head of a queue at an intersection are designed to increase cyclists' visibility at key locations. Reducing motor vehicle speeds increases motorists' and cyclists' reaction time, reducing the frequency of collisions. When collisions do occur, the reduced speed differential between vehicle and cyclist reduces the severity of the collisions and probability of severe injury and death (Leaf and Preusser, 1999). A variety of traffic calming design measures, use of bicycle boulevards, and construction of roundabouts can decrease motor vehicle speeds (Brude and Larsson, 2000).

Given the arguments outlined above, the goal of roadway safety design for non-motorized users would seem to be to maximize the criteria discussed above. In reality, there are complex interactions between the criteria, and roadway designers often have to seek compromises. For example, increasing visual complexity in the roadway environment has been shown to decrease vehicle speeds. Shared space schemes employed in Auckland, New Zealand, actually are designed to minimize the separation between various road users in an effort to reduce motor vehicle speeds by adding complexity to the environment (Karndacharuk, et al., 2013). Hence, increased separation may increase vehicle speeds and collision severity.

Physically separating bicyclists from motorized traffic by diverting them to multi-use trails may create a visibility issue at locations where the trail crosses roads. The separation of motor vehicles and bicyclists can also be problematic at major intersections when bicycles are often merged with vehicles to cross busy streets. Diverting cyclist traffic to a multi-use trail that is 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 (Aultman-Hall and Kaltenecker, 1999). Separation may also be inappropriate from a transportation planning perspective when access to specific activities and surrounding destinations is the main goal of bicycle use (e.g., commuting to work, shopping, etc.) because the separation typically limits accessibility by the bicycle mode. It is difficult to balance the integration/separation of cyclist and vehicle traffic, while ensuring that the system provides positive mobility benefits to all users and also ensuring comparative safety for all system users.

3.3 Developing Crash Modification Factors

Over the past several decades, many studies have been conducted to evaluate the potential safety impacts of bicycle treatments. However, bicycle safety research conducted to date has been insufficient to support the development of crash modification factors for treatment installation because the research does not satisfy the data requirements outlined in the Highway Safety Manual (AASHTO, 2010). As noted earlier, cycle–vehicle collisions are fairly rare, extensive cycle activity monitoring is not undertaken, and solid cyclist–vehicle exposure data are generally not readily available. This report reviews a body of literature (i.e., technical reports, journal papers, and conference papers) related to bicycle safety treatments and the reported potential effectiveness. The research team reviewed the treatment details, research methods, data sources, findings, and research conclusions presented in each of these papers. This research seeks to identify common inferences in the literature related to treatment effectiveness, and identify gaps in existing bicycle safety data and methods that currently prevent the generation of statistically significant crash modification factors. Finally, this research identifies the kinds of data that will be necessary for generating bicycle intervention crash modification factors using the HSM method and recommends how data issues could be addressed in the future.

4 Literature Review of Bicycle Treatments

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

- AASHTO *Guide for the Development of Bicycle Facilities*, 4th Edition (2012)
- National Association of City Transportation Officials (NACTO) *Urban Bikeway Design Guide*, 2nd Edition (2012)
- Institute of Transportation Engineers (ITE) *Traffic Calming State of the Practice* (Ewing, 1999)

A literature scan was then undertaken to identify studies related to the treatments in the initial list. The sources included in this review were limited to English language publications. This is an important limitation of this study, as many European countries have been vanguards in development of bicycle infrastructure treatments and have published safety research in other languages. Nevertheless, much international bicycle infrastructure research was available in English for this study. In cases where a substantial amount of literature was available for a specific treatment, the authors prioritized the most relevant sources as those that:

- Were quantitative in nature
- Provided 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 including controls in the methodology and accounted for regression-to-the-mean bias
- Were peer-reviewed
- Conducted research within the last two decades

More recent literature is given priority due to the underlying assumption that there are shifts in mode shares, infrastructure prevalence, and culture over long periods of time. Newer studies of the comparable methodological integrity would give more relevant descriptions of today's conditions. For some treatments, none of these criteria were met, so the authors included whatever available literature addressed those treatments. Some sources were not reviewed in-depth because they either did not meet the methodological criteria for this review or were themselves reviews of other literature (Handy, et al., 2014; Pucher, et al., 2010; Reynolds, et al., 2009; Thomas and DeRobertis, 2103).

The authors methodically reviewed the journal articles and reports identified during the literature search, making note of stated safety outcomes, treatment details, study design, sample size, controls, exposure data, and statistical significance of results. 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 across studies. In each case, the range and uncertainties are given as they were presented in the study. In the absence of data required to conduct a full meta-analysis, the authors attempted to find metrics that could be directly compared. In this case, risk ratio was chosen because it is the standard in health and safety research. Although risk ratio has limitations for low-risk events, the ratio does effectively communicate the relative value of treatments.

For bicycle treatments, the research team reviewed 81 papers, of which 19 presented meaningful results on 22 bicycle treatments. These studies show a wide range of variability in design, controls, and depth. Overall, quantitative safety outcomes (i.e., 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.

Analysis of the impacts of these various safety treatments and the development of the associated CMFs is ultimately dependent on observational studies of crash experience. Observational studies can be undertaken using a variety of approaches. Analyses may be longitudinal (i.e., cohort analysis over time) or cross-sectional (i.e., population) in nature. These approaches may, or may not, include additional regression-based analyses (Gross, et al., 2010)[1]. For installation of new treatments, longitudinal (i.e. before–after) analyses are generally preferred to population-based approaches. These longitudinal analyses can range from Naïve (uncontrolled), to basic empirical (controlled), to comprehensive Bayesian probabilistic approaches. In general, it is preferred that control sites and temporal analysis be employed to control for area-wide changes in risk or exposure or correct for regression-to-the-mean and similar biases (FHWA, 2010). Finally, meta-analysis can be used to combine outcomes from various studies. Meta-analysis combines the results from multiple studies to produce a

[1] Case control techniques have also been applied, but less frequently.

combined estimate of a treatment's safety effectiveness. Studies reviewed in this paper used all the methods above except for case-control and cohort analyses. The summary of findings presented in the literature is presented below. However, this section of the report only summarizes the literature; the research team does not present any inferences in this report as to whether the findings presented in these papers are reliable or based on solid statistical inference.

4.1 Summary of Findings Presented in the Literature

The following section summarizes study outcomes found in the literature. Outcomes are divided into corridor treatments, intersection treatments, and other treatments.

4.1.1 Bicycle Corridor Treatments

Bicycle corridor treatments include traditional bike lanes, buffered bike lanes, colored bike lanes, bicycle boulevards, cycle tracks, multi-use trails, shared lane markings, wide shoulders, and wide curb lanes. Descriptions of these facilities and a photo of each are shown in Table 1.

Table 1. Bicycle Corridor Treatments

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. (Image: authors)	

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. (Image: authors)	
Colored bike lanes Use 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. (Image: T. Sando, U North Florida Tech Report)	
Bicycle boulevards 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. (Image: A. Fukushima, pedbikeimages.org)	
Cycle tracks Physically separate exclusive bicycle facilities 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. (Image: authors)	

Multi-use trails Physically separate multi-use or shared-use paths from motorized traffic by either open space or barriers, designed for use by bicyclists, pedestrians, inline skaters, and other non-motorized users. These paths can serve a variety of purposes from transportation to recreation. Their separation from roadways makes conflicts with motor vehicles at non-intersection locations far less probable (Image: Beltline)	
Shared lane marking Use pavement markings to indicate a shared lane environment, often called “sharrows,” for bicycles and automobiles. These markings may be used to reinforce the legitimacy of bicycles using the lane, to recommend bicycle positioning in the lane, or to give cyclists wayfinding guidance. (Image: authors)	
Wide shoulder Provide wide paved highway shoulders (recommended 5 feet minimum), most often on rural roadways. This treatment extends the service life of the road, provides temporary storage space for disabled vehicles, and provides space for bicycles to operate with some separation from higher speed traffic. (Image: FHWA)	
Wide curb lane Design the lane closest to the curb wider than a standard lane, leaving enough room for bicycles and motor vehicles to share the lane. Wide curb lanes may be present on two-lane or multilane roadways. (Image: FHWA)	

The literature indicates that bike lanes appear to be somewhat beneficial for safety; they encourage obedience with traffic laws and reduce conflicts (Hunter, et al., 1999), as well as potentially reduce accidents (Teschke, et al., 2012; MetroPlan Orlando, 2010; Lott and Lott, 1976; Moritz, 1997; Moritz, 1998). Bike lanes were also found to position bikes away from parked cars (Van Houten and Seiderman, 2005; Duthie, et al., 2010). Other studies were not statistically significant or they actually identified a slight increase in crashes (Smith and Walsh, 1988; Jensen, 2008). There were no crash- or injury-specific studies for buffered bike lanes. Findings for colored bike lanes were mixed. Although there were positive perceptions of safety increases for colored bike lanes (Hunter, 2000; Sadek, et al., 2007), some studies of behavior differed (Hunter, et al., 2008; Sadek, et al., 2007; Hunter, et al., 2000; Jensen, 2008). Contraflow bike lanes seem to offer safety benefits when they allow cyclists to circumvent awkward traffic maneuvers (Patterson, 2013), although encouraging wrong-way riding should be minimized (Wachtel and Lewiston, 1994).

Bicycle boulevards appear to offer safety benefits to cyclists by facilitating travel on roads where traffic volumes and vehicle speeds are low (Minikel, 2012). Cycle tracks provide an opportunity to ride separately from vehicular traffic on crowded arterial streets, and studies have shown a reduction in crash rates (Teschke, et al., 2012; Lusk, et al., 2011; Lusk, et al., 2013), or a slight but not statistically significant increase (Jensen, 2008). One-way cycle tracks appear to be safer at intersections than two-way cycle tracks (Thomas and DeRobertis, 2013). Cycle tracks and bike lanes were found to have similar safety implications in at least one study (Nosal and Miranda-Moreno, 2012). Multi-use paths seem to be associated with higher crash rates for cyclists in general, possibly due to constrained space shared with trail users including pets (Aultman-Hall and Kaltenecker, 1999; Moritz, 1998), although other studies were not statistically significant (MetroPlan Orlando, 2010; Teschke, et al., 2012).

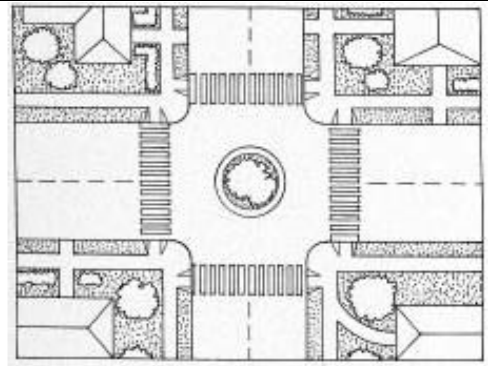
In terms of pavement markings, no studies addressed changes in crashes or conflicts associated with shared lane markings. However, shared lane markings, or sharrows, seem to influence improved cyclist positioning on roadways (Alta, 2004; Brady, 2010; Fitzpatrick, et al., 2011; Pein, et al., 1999; Sando, 2014). Greater shoulder pavement width may have a slight positive impact on cyclist safety (Abdel-Rahim and Sonnen, 2012; MetroPlan Orlando, 2010) because injuries may be less severe (Klop and Khattak, 1999). Wide curb lanes were found to have similar effects as bike lanes and can potentially mitigate crashes caused by drivers overtaking cyclists riding in the street by allowing more space for passing within the lane (MetroPlan Orlando, 2010; Hunter, et al., 1999; Harkey and Stewart, 1996).

4.1.2 Intersection Treatments

Intersection treatments include bike-specific intersection markings, such as bike boxes, two-stage turn queue boxes, and raised bicycle crossings. Intersection treatments also include typical traffic calming treatments, such as neighborhood traffic circles and roundabouts. Descriptions of these facilities and a photo of each are shown in Table 2.

Table 2. Bicycle Intersection Treatments

Bike box Sometimes called an advance stop line, designate areas ahead of the stop bar at signalized intersection for bicyclists to queue in during the red signal phase. Bike boxes are typically marked by white painted borders and/or colored paint.	
Two-stage turn queue box Also known as Copenhagen left turns, offer bicyclists a way to make left turns (or in some cases right turns) at multilane signalized intersections without the need to merge across traffic to enter the left-turn lane. 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 right corner, and waits until the green signal phase for the cross-street to complete the "turn." (Image: authors)	
Raised bicycle crossing Provide 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 the intersecting drivers must traverse when entering or existing the minor street. (Image: authors)	

Neighborhood traffic circle Circulate traffic around a raised island in the middle of an intersection, also known as an intersection island. Islands are often landscaped and usually circular, and the intersection is typically controlled by stop or yield signs. The purpose is to prevent drivers from speeding through intersections by impeding the straight-through movement.	
Roundabout Circulate traffic counter-clockwise through the intersection to complete a movement using "modern roundabouts," which are circular intersections with a center island. Entering traffic must yield to traffic already in the roundabout. Roundabouts may have more than one lane; they may have bicycle-specific facilities such as paths or lanes, or may allow bicycles to operate in mixed traffic. (Image: authors)	

Results for bike boxes showed a reduction in bicycle–motor-vehicle conflicts (Dill, et al., 2012; Loskorn, et al., 2013) or little change (Hunter, 2000). However, the City of Portland reported a doubling of bicycle right-hook crashes with motor vehicles at some intersections where bike boxes had been installed (Burchfield, 2012). No studies were found that examined safety performance of two-stage turn queue boxes. Raised bicycle crossings were found to increase bicycle volumes while simultaneously reducing crashes in Sweden (Gårder, et al., 1998).

Results for neighborhood traffic circles are limited, but Harris, et al., (2013) found a marked increase in risk compared to a signalized intersection with no bicycle controls. 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 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 appear to increase crash risk. Daniels, et al., (2008), found a statistically significant higher risk of injury crashes after conversion to roundabouts; Schoon and van Minnen (1994) found a reduction in bicyclist crash rate for single-lane roundabouts; Brude and Larsson (2000) found multilane roundabouts to be associated with about twice the crash risk and injury risk; Daniels, et al., (2009) found a statistically significant higher risk of bicycle injury crashes after conversion from “conventional” intersections to roundabouts constructed with bicycle lanes; and Brude and Larsson (2000) found roundabouts with separated bicycle facilities to be associated with about half the crash risk as “conventional” intersections.

4.1.3 Other Treatments

Other treatments can include roadway design principles, such as access management, and roadway design elements, such as rumble strips, lighting, and slopes. On-street parking and increased levels of cycling also impact cyclist safety. Table 3 shows descriptions of these facilities.

Though the literature does not specifically support access management as a bicycle safety measure, Hunter, et al., (1996 and 1999) observed that more crashes and conflicts occur at driveways and intersections, therefore minimizing conflict points could impact cyclist safety. No studies were found that attempted to measure the safety effects of bicyclists riding in locations with shoulder rumble strips versus those without. However, the rumble strips appear to be beneficial in warning drivers that they are encroaching on cyclist space (Gårder, 1995) as long as they are properly designed so that cyclists can maneuver around the rumble strips (Moeur, 2000; AASHTO, 2012). In terms of general roadway conditions, roadway lighting appears to have a substantial positive effect on cyclist safety at night (Kim, et al., 2007). At least two studies found significantly more danger to bicyclists on routes with steeper slopes (Klop and Khattak, 1999; Teschke, et al., 2012) and routes crossing train or streetcar tracks (Teschke, et al., 2012).

Table 3. Other Bicycle Treatments

Access management	Use of 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.
Shoulder rumble strip placement that accommodates cyclists	Provide noise and tactile feedback when motorists drive onto shoulder rumble strips, which are raised or indented patterns in the pavement. Rumble strips have been shown to reduce run-off road crashes for drivers on high-speed roadways; however, they can be unpleasant for bicycles to traverse.
Street lighting	Illuminate streets by means of street lights that increase visibility at night for road users.
On-street parking removal	Reduce on-street parking that allows cars to be parked on the edge of a street either during specific times of day or all the time. Although such parking can act as a means of convenient access to businesses (by car) and as a buffer between streets and sidewalks, it often provides a conflict for bike lanes.
Increased bicycling level in community	Measure bicycling levels in a community by mode share (of total trips, commuting trips, etc.), distance, or number of trips to impact individual safety through safety in numbers.

The presence of on-street parking may be an important element in traffic calming schemes (Ewing, 1999; Sisiopiku, 2001); however, on-street parking appears to be a hazard to cyclists due to cars crossing the cyclists' space to enter or leave a parking space and the potential of having a car door open directly in a cyclist's path (Teschke, et al., 2012; Hunter, et al., 1999; Johnson, et al., 2013). Striping a bike lane or properly marking a shared lane may help mitigate some of those dangers by influencing bicyclists' positioning and bringing them farther from the dangerous door zone (Alta, 2004; Brady, et al., 2010; Duthie, et al., 2010; Fitzpatrick, et al., 2011; Pein, et al., 1999; Van Houten and Seiderman, 2005).

Finally, and possibly most importantly, increased levels of bicycling have been associated with improved safety on a per cyclist basis (Jacobsen, 2003; Gårder, et al., 1998; Leden, 2002; Robinson, 2005; Pucher, et al., 2010). Therefore, facilities that appear to offer modest safety increases but attract new cyclists may lead to better-than-expected safety outcomes.

4.2 Synthesis of the Literature

For the next stage of the analysis, the research team evaluated each of the papers presented in the literature review to assess the data and methods employed. The evaluation focused on whether sufficient data and controls were employed to ensure that statistical inferences would lead the team to concur that the treatment effectiveness results flowed from the analyses and remain reasonably transferrable to other locations (as opposed to applying only to the locations studies). This analysis involved some judgment on the part of the research team and, therefore, the team does not expect that all reasonable researchers will necessarily agree completely with the conclusions. In addition, the original authors of the subject studies may be privy to additional information and data that support the reported claims but are not discussed in the papers.

4.2.1 Study Details

For studies that derived safety outcomes for individual bicycle treatments, the researchers tabulated the details of their investigations for comparison in Table 4. The table is organized by treatment type with multiple papers listed for some treatments. Specific details about the treatment as provided in the paper, study controls, and outcome measures are provided, along with the source of the crash rate data, statistical significance of the results according to the original study authors, and a rating of the study's overall strength as evaluated by the authors of this report. Ratings included:

- *Informative but Not Conclusive:* The study presented quantitative and informative background, but did not claim to present a causal relationship
- *Lacking in Sample Size, Study Depth, or Controls:* The study likely failed to control for key factors or had a very small sample size
- *Fairly Robust, but Still Lacking in Depth or Completeness:* 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
- *Excellent:* The study employed sufficient sample sizes, controls, and a strong base rate, to develop transferrable results; none of the studies received an excellent rating

The studies represented in Table 4 show a wide range of variability in design, controls, and depth. Before–after studies accounted for 14 of the outcome measures, while 18 studies used non-intervention study methods. Regression was used for 10 outcome measures; nine used a simple before–after approach (four of which accounted for exposure, while five did not); one study for three outcomes used the empirical Bayes method; one study used other Bayesian methods; eight outcome measures were a result of simply comparing rates from different sites. Of all the approaches, simply comparing sites or results before and after a treatment is the simplest; however, these methods require assumptions about what variables to control for. Without proper controls, simple comparison methods are weak compared to the others.

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. Twenty-seven (27) outcome measures used at least 10 treatment locations in the study, but only half of those used more than 20 treatment sites. The remaining fifteen (15) of the 39 outcome measures used fewer than 10 comparison sites. Twenty-two (22) of the outcome measures mentioned controlling for any kind of exposure, and 14 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, although some included earlier data collected by local governments.

This is an important limitation of all existing bicycle safety studies. Unlike motor vehicle networks for which activity data are systematically collected, bicycle activity is only generally known, with much of this based on user information with little, if any, effort to spatially allocate this overall activity by route. As a consequence, estimates of the effectiveness of bicycle (and pedestrian) safety are relative, point-based measures (i.e., local CMFs) based on the assumption that other exposures along the route are unchanged by the installation of the safety treatment. In other words, while crash modification factors can be estimated, the overall safety performance function (SPF) or base rate cannot. This limitation has significance for long-term safety as changes in infrastructure can impact base rates (e.g., changes in route selection based on the existence of an off-street trail) as well as have local impacts.

The impact of a treatment may also change with time as users become familiar with its presence and usage. 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. Only 14 of the 39 outcome measures had studies reporting statistically significant results at the 0.05 level; most of the rest (16) did not specify statistical significance.

On the authors' 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 lacked key controls, which rendered their outcomes less defensible. Those studies that were well-controlled still lacked treatment details, reproducible exposure data, sample size depth, or some other element that would be needed for transferability of results.

4.2.2 Literature Review Summary of Treatment Effectiveness

Overall, quantitative safety outcomes (i.e., crash reduction, injury crash reduction, injury severity reduction, or conflict reduction) were reported in the literature for 14 of the 22 treatment types examined in the literature review. Figure 1 summarizes quantitative results of studies as they were presented in the articles and reports. The risk ratio on the vertical axis of the figure 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 (i.e., a change at the margin). Risk ratios are much like crash modification factors, but they apply to outcome measures other than 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 the marginal improvement for that cycle track's case. Marginal improvements were either explicitly reported in the literature as risk ratios, or were reported as percentages and converted to risk ratios.

Of the 14 treatments with study outcomes presented in Figure 1, only bike boxes, bike lanes, cycle tracks, and roundabout treatment types had more than one quantitative study that described risk ratios associated with implementation. The bike box studies were all conflict-based studies (as opposed to crash-based or injury-based); hence, any reduction in crashes or injuries must be inferred from the reduction in conflicts. The studies associated with bike lanes, cycle tracks, and roundabouts conflicted as to whether the treatment helped or harmed in terms of safety outcomes. These differences may be 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, and/or possibly even chance.

Table 4. Review of Literature Methods, Controls, and Strengths/Weaknesses

Treatment	Paper	Treatments Assessed	Controls	Outcome Measures	Source of Crash Rates	Stated Signif. >0.05	Overall Strengths and Weaknesses
Access Management	Hunter, et al., 1999	Striped bike lanes of various widths and wide curb lanes 4.0–4.6 m wide; on-street parking, driveways, turn lanes, and other characteristics varied by site	Not Stated	Conflict rate	N/a	Not Stated	Informative but not conclusive
Bicycle Boulevard	Minikel, 2012	Varies	Segment length (between pairs), bicycle counts	Crash rate	California Statewide Integrated Traffic Records System	Yes	Lacking in sample size, study depth, or controls
		Varies		Crash severity		No	Lacking in sample size, study depth, or controls
Bike Box	Dill, Monsere and McNeil, 2012	Advance stop line, green textured thermoplastic marking (all but 3) with a bicycle stencil, intersection striping, regulatory signage (including no-turn-on-red), the words “WAIT HERE”	Bicycle movement counts, motor vehicle movement counts	Conflict rate	N/a	Not Stated	Lacking in sample size, study depth, or controls
				Motor vehicle encroachment into crosswalk (“before”) and into bike box (“after”)	N/a	Yes	Lacking in sample size, study depth, or controls

Treatment	Paper	Treatments Assessed	Controls	Outcome Measures	Source of Crash Rates	Stated Signif. >0.05	Overall Strengths and Weaknesses
		stenciled just before the stop line, and colored bicycle lane markings added in the intersection		Motor vehicles encroaching into bike lane	N/a	Yes	Lacking in sample size, study depth, or controls
				Yield rate	N/a	Not Stated	Lacking in sample size, study depth, or controls
	Hunter, 2000	The bike box accidentally spanned all 3 lanes, including the right-turn-only lane; it was a continuation of a left-side bike lane, and seemingly was not painted green on the inside	Bicycle counts	Conflict rate	N/a	Not Stated	Lacking in sample size, study depth, or controls
Bike Lane	Jensen, 2008	1.5–2 m (4.9–6.6 ft) wide and included BLs behind parking lanes	Bicycle volume, motor vehicle volume, crash trends, examination to prevent regression-to-the-mean	Crash rate	Not Stated	No	Lacking in sample size, study depth, or controls
				Injury rate	Not Stated	No	Lacking in sample size, study depth, or controls

Treatment	Paper	Treatments Assessed	Controls	Outcome Measures	Source of Crash Rates	Stated Signif. >0.05	Overall Strengths and Weaknesses
	Teschke, et al., 2012	Not Stated	Bicycle distance traveled, personal characteristics, route characteristics, exposure to traffic and infrastructure	Injury rate	As this was a case-crossover study, the study participants were the crash source	Mixed	Fairly robust, but still lacking in depth or completeness
Bike Lane, Wide Curb Lane	Hunter, et, al., 1999	Striped BLs of various widths and WCLs 4.0–4.6 m wide; on-street parking, driveways, turn lanes, and other characteristics varied by site	Bicycle counts, motor vehicle counts	Conflict rate	N/a	Yes	Lacking in sample size, study depth, or controls
Cycle Track	Jensen, 2008	2–2.5 m (6.6–8.2 ft) wide, raised, and one-way on each side of the street	Bicycle volume, motor vehicle volume, crash trends, examination to prevent regression-to-the-mean	Crash rate	Not Stated	Mixed	Lacking in sample size, study depth, or controls
				Injury rate	Not Stated	No	Lacking in sample size, study depth, or controls

Treatment	Paper	Treatments Assessed	Controls	Outcome Measures	Source of Crash Rates	Stated Signif. >0.05	Overall Strengths and Weaknesses
	Lusk, et al., 2011	Two-way cycle tracks on one side of the street separated from traffic by parking, planting strips, raised medians/curbs, delineator posts, or a combination of these elements	Bicycle distance traveled, motor vehicle traffic and speed, “vehicular traffic danger”	Crash rate	Police crash data and hospital injury data	Yes	Fairly robust, but still lacking in depth or completeness
	Teschke, et al., 2012	Not Stated	Bicycle distance traveled, personal characteristics, route characteristics, exposure to traffic and infrastructure	Injury rate	As this was a case-crossover study, the study participants were the crash source	Yes	Fairly robust, but still lacking in depth or completeness

Treatment	Paper	Treatments Assessed	Controls	Outcome Measures	Source of Crash Rates	Stated Signif. >0.05	Overall Strengths and Weaknesses
(Multiple)	MetroPlan Orlando, 2010	Varies	None	Crash rate	Local governments in Orange, Seminole, and Osceola Counties, and Florida Department of Highway Safety and Motor Vehicles records	Not Stated	Informative but not conclusive
Multi-use Path	Aultman-Hall and Kaltenecker, 1999	All off-road paths excluding sidewalks	Cyclist experience and other personal characteristics, distance traveled	Crash rate	Surveys	Yes	Fairly robust, but still lacking in depth or completeness
	Aultman-Hall and Kaltenecker, 2000			Injury rate	Surveys	Yes	Fairly robust, but still lacking in depth or completeness

Treatment	Paper	Treatments Assessed	Controls	Outcome Measures	Source of Crash Rates	Stated Signif. >0.05	Overall Strengths and Weaknesses
Neighborhood Traffic Circle	Harris, et al., 2013	Islands 6–8 m in diameter, intersections of local streets	Bicycle distance traveled, personal characteristics, route characteristics, exposure to traffic and infrastructure	Injury rate	As this was a case-crossover study, the study participants were the crash source	Yes	Fairly robust, but still lacking in depth or completeness
On-street Parking	Hunter, et al., 1999	Striped BLs of various widths and WCLs 4.0–4.6 m wide; on-street parking, driveways, turn lanes, and other characteristics varied by site	Not Stated	Conflict rate	N/a	Not Stated	Informative but not conclusive
	Teschke, et al., 2012	Major streets (arterials and collectors) without vs. with on-street parking	Bicycle distance traveled, personal characteristics, route characteristics, exposure to traffic and infrastructure	Injury rate	As this was a case-crossover study, the study participants were the crash source	Yes	Fairly robust, but still lacking in depth or completeness

Treatment	Paper	Treatments Assessed	Controls	Outcome Measures	Source of Crash Rates	Stated Signif. >0.05	Overall Strengths and Weaknesses
Raised Bicycle Crossing	Gårder, Leden, Pulkkinen, 1998	Red pavement in crossing, 4–12 cm rise above side streets	Bicycle counts, comparison group	Crash rate	Gothenburg, Sweden police- and hospital-reported incidents database	Not Stated	Fairly robust, but still lacking in depth or completeness
Roundabout – Bike Lane	Daniels, et al., 2009	Most BLs were colored red	Comparison group helped control for general traffic trends and possible regression-to-the-mean bias	Injury rate	Flanders, Belgium, Ministry of Mobility and Public Works	Yes	Lacking in sample size, study depth, or controls
	Schoon and van Minnen, 1994	One-lane roundabouts with small diameters (average 30 m outside diameter) and BLs	Corrects for temporal crash and injury rate trends across all intersections in the Netherlands but not exposure at the treatment intersections	Other	Netherlands national crash database	Not Stated	Lacking in sample size, study depth, or controls

Treatment	Paper	Treatments Assessed	Controls	Outcome Measures	Source of Crash Rates	Stated Signif. >0.05	Overall Strengths and Weaknesses
Roundabout – General	Daniels, et al., 2008	Mostly single-lane roundabouts with a few having two lanes; included roundabouts with BLs and separated facilities	Comparison group helped control for general traffic trends and possible regression-to-the-mean bias	Injury rate	Flanders, Belgium, Ministry of Mobility and Public Works	Yes	Lacking in sample size, study depth, or controls
		Same, but only inside built-up areas				Yes	Lacking in sample size, study depth, or controls
	Schoon and van Minnen, 1994	One-lane roundabouts with small diameters (average 30 m outside diameter). Cyclists either rode in BLs, mixed traffic, or on separated paths	Corrects for temporal crash and injury rate trends across all intersections in the Netherlands but not exposure at the treatment intersections	Crash rate	Netherlands national crash database	Not Stated	Lacking in sample size, study depth, or controls
				Injury rate	Netherlands national crash database	Not Stated	Lacking in sample size, study depth, or controls

Treatment	Paper	Treatments Assessed	Controls	Outcome Measures	Source of Crash Rates	Stated Signif. >0.05	Overall Strengths and Weaknesses
Roundabout – Mixed Traffic	Daniels, et al., 2009	Mostly single-lane roundabouts with a few having two lanes	Comparison group helped control for general traffic trends and possible regression-to-the-mean bias	Injury rate	Flanders, Belgium, Ministry of Mobility and Public Works	No	Lacking in sample size, study depth, or controls
	Schoon and van Minnen, 1994	One-lane roundabouts with small diameters (average 30 m outside diameter); no BLs or separated paths	Corrects for temporal crash and injury rate trends across all intersections in the Netherlands but not exposure at the treatment intersections	Crash rate	Netherlands national crash database	Not Stated	Lacking in sample size, study depth, or controls
Roundabout – Multilane	Brüde and Larsson, 2000	Multilane roundabouts	Number of entering motorists, number of entering cyclists	Crash rate	Not Stated	Not Stated	Lacking in sample size, study depth, or controls

Treatment	Paper	Treatments Assessed	Controls	Outcome Measures	Source of Crash Rates	Stated Signif. >0.05	Overall Strengths and Weaknesses
Roundabout – Separated Bike Facility	Brüde and Larsson, 2000	Not Stated	Number of entering motorists, number of entering cyclists	Crash rate	Not Stated	Not Stated	Lacking in sample size, study depth, or controls
	Daniels, et al., 2009	Bike facility was separated from carriageway by at least 1 m	Comparison group helped control for general traffic trends and possible regression-to-the-mean bias	Injury rate	Flanders, Belgium, Ministry of Mobility and Public Works	No	Lacking in sample size, study depth, or controls
	Schoon and van Minnen, 1994	One-lane roundabouts with small diameters (average 30 m outside diameter) and separate paths for cyclists	Corrects for temporal crash and injury rate trends across all intersections in the Netherlands but not exposure at the treatment intersections	Crash rate	Netherlands national crash database	Not Stated	Lacking in sample size, study depth, or controls

Treatment	Paper	Treatments Assessed	Controls	Outcome Measures	Source of Crash Rates	Stated Signif. >0.05	Overall Strengths and Weaknesses
Roundabout – Single-lane	Brüde and Larsson, 2000	One-lane roundabouts with diameters greater than 10 m (33 ft)	Number of entering motorists, number of entering cyclists	Crash rate	Not Stated	Not Stated	Lacking in sample size, study depth, or controls
Shoulder Width	Abdel-Rahim and Sonnen, 2012	Varying right shoulder widths	None	Crash rate	Idaho state database for crashes on state highways	Not Stated	Lacking in sample size, study depth, or controls
Shoulder Width and Speed Limit Interaction	Klop, Khattak, 1999	Varying right shoulder widths and speed limits	Vertical and horizontal curvature, traffic volumes, speed limit, light conditions, and others	Injury severity	North Carolina HSIS (Highway Safety Information System) database 1990–1993	No	Informative but not conclusive
Street Lighting	Kim, et al., 2007	Not Stated	Speeds, helmet use, time, weather, driver/cyclist characteristics, and others	Injury severity	North Carolina state crash database 1997–2002	Yes	Informative but not conclusive

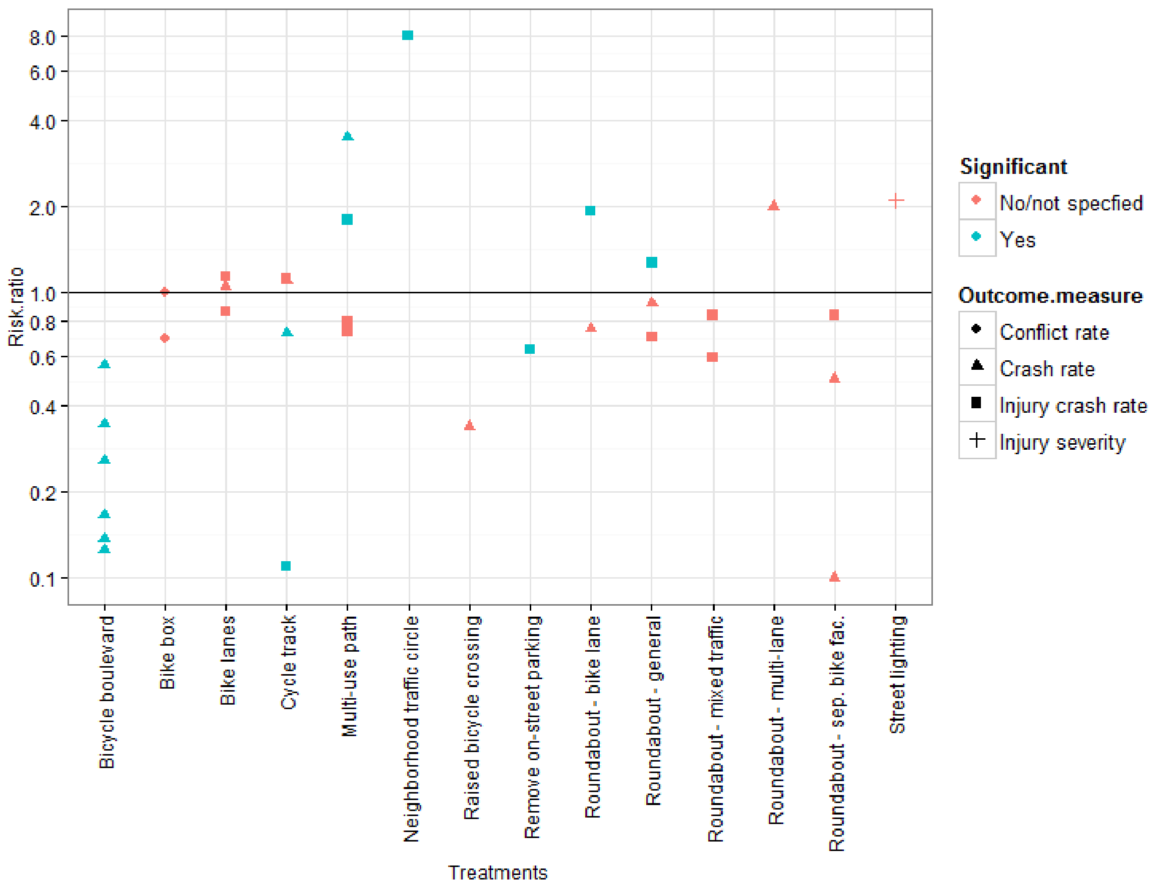


Figure 1. Summary of Risk Ratios in the Literature

Note: Significance stated above is based on the authors' claims in the original studies. In some cases, significance claims were reviewed and assumptions employed in the analyses were called into question. In most cases, significance claims were not reviewed. Hence, the authors do not recommend that these confidence bounds

4.3 Discussion

Although limited research on pedestrian and bicycle design has been conducted since the 1950s, the last decade has shown a substantial upsurge in research activity. Researchers have established several key relationships in understanding propensity to walk and cycle, and related safety implications. Research studies have established that cyclist density has a substantial influence on number and severity of crashes (Jacobsen 2003; Nordback, et al., 2014; Robinson 2005; Shinkle 2012). In addition, numerous studies have quantified the impact of various behavior-influencing laws and programs, such as 3-foot passing laws, helmet laws, and the safe routes to school program (Karsch, et al., 2012; Shinkle, 2012). Less attention has been given to individual countermeasures, such as crosswalk treatments, illumination, rumble strips, and bike lanes, although some useful studies do exist (Bartlett, et al., 2012; Karsch, et al., 2012; Raborn, et al., 2008; Reynolds, et al., 2009; Shinkle, 2012; Zegeer, et al., 2005).

Knowing the number, type, and severity of crashes is a significant problem for understanding the effectiveness of pedestrian and bicycle treatments. While 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 (Cryer, et al., 2001; Elvik and Mysen, 1999; Maas and Harris, 1984), 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 (AASHTO, 2010).

One common theme among the studies in this review was a lack of standardized, transferable exposure data to understand the extent to which users are exposed to risk. Fewer than half of the outcome measures identified in the literature controlled for exposure in any way. Many of the researchers found creative ways to try to control for exposure, such as interviewing cyclists involved in injury crashes about the infrastructure characteristics along their routes (Harris, et al., 2013; Teschke, et al., 2012), or controlling for motor vehicle occupant injuries as a surrogate for traffic danger along the routes studied (Lusk, et al., 2011). However, the reasonableness of such surrogate control measures may be questionable, and certainly should be subjected to further statistical justification. 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. It is imperative that transportation agencies invest in collecting and maintaining non-motorized user counts if bicycle treatments are to receive rigorous and unbiased analysis.

With regard to exposure, several studies have shown an increase in bicyclist safety accompanying local increases in biking, a phenomenon referred to across the literature as "safety in numbers" (Gårder, et al., 1998; Jacobson, 2003; Leden, 2002; Robinson, 2005). 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.

Finally, studies must be of significant statistical rigor, for which substantial work in investigating various treatments remains. Of the studies reviewed, some used very simple methodologies with few controls, while others developed more rigorous methods to control for certain confounding factors. Without multiple sites in varying locations, presenting and controlling for multiple confounding factors, an understanding of the broad safety impacts of a treatment simply cannot be obtained. 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. Additionally, some treatment types had multiple studies that 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.

5 Literature Review of Pedestrian Treatments

Over the past several decades, many studies have been conducted to evaluate the potential safety impacts of pedestrian treatments. In motor vehicle safety analysis, many states are looking to customize the crash modification factors provided in the Highway Safety Manual to suit the local needs. However, data from research have been insufficient to develop CMFs for pedestrian safety designs due to lack of effective crash data and exposure measures. The aim of this paper is to fill these gaps when it comes to the evaluation of safety impacts of pedestrian treatments. This paper reviews literature (e.g., technical reports, journal papers, and conference papers) related to pedestrian safety treatments and the reported potential effectiveness. The research team reviewed the treatment details, research methods, data sources, findings, and research conclusions presented in each of those papers. This paper seeks to identify common inferences in the literature related to treatment effectiveness, and identify gaps in existing pedestrian safety data and methods that currently prevent the generation of statistically significant crash modification factors. Finally, this paper identifies the kinds of data that will be necessary for generating pedestrian intervention CMFs using the HSM method and recommends how data issues could be addressed in the future.

5.1 Methodology of Literature Review

The research team conducted a thorough literature review in transportation planning, engineering, and public health research areas to find studies conducted on actual safety outcomes for specific pedestrian treatments. The authors identified common transportation engineering and planning treatments related to pedestrians and walking through resources such as the NACTO *Urban Streets Design Guide*, and various AASHTO and Federal Highway

Administration (FHWA) resources. For each study, the researchers considered types of experimental design, characteristics being measured, presence of statistical significance, limitations, and overall conclusions. This paper brings together the most informative findings from recent literature and synthesizes results from various research groups into one comprehensive analysis of the studied pedestrian safety treatments.

The literature review focuses on papers from and about the United States, as many standards, regulations, rules, and behavior are US specific. Treatments for which no studies were found are mentioned in the paper to emphasize that they were not left out of the literature search, only that there are no relevant papers to include, which implies a need for further research. Studies are organized by the treatment(s) they focus on, and experiments are compared and contrasted to each other where applicable.

5.2 Summary of Findings Presented in the Literature

The following section summarizes study outcomes found in the literature. Outcomes are divided into controlled intersection treatments; uncontrolled intersection treatments; physically separated treatments; automatic pedestrian detection; other treatments; and enforcement, education, outreach, and training.

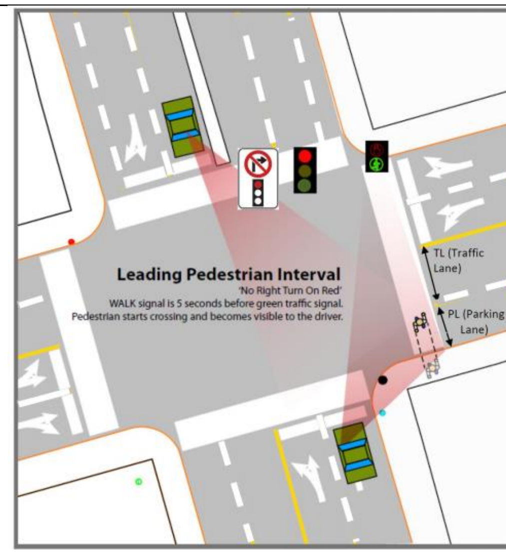
5.2.1 Controlled Intersection Treatments

Controlled crossings manage the interaction between pedestrians and vehicles, and present operational benefits to pedestrians by providing priority over vehicles either at all times or for allocated periods of time. They include traffic control signals, pedestrian signals, STOP or YIELD signs, pedestrian crossovers and flashing beacon or HAWK signals (Ontario Traffic Council, 2010). Descriptions of these facilities and a photo of each are shown in Table 5.

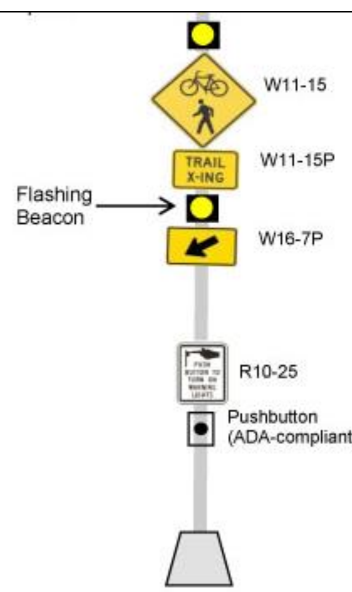
Table 5. Controlled Intersection Treatments

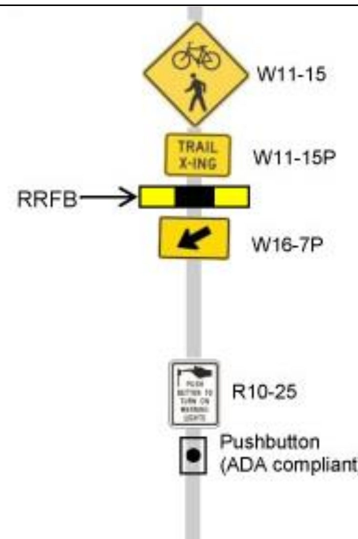
Pedestrian prompting devices Prompting device relates generally to an apparatus used for signaling pedestrian traffic at intersections and, in particular, to an apparatus for prompting pedestrians using crosswalks to look for turning vehicles. It can be a picture message in the form of a pair of scanning eyes/"WALK" indication. It can also be generated by the pedestrian signal display. Sound signaling and optical signaling at a crosswalk both can be activated by a single push button as shown in the U.S. The audio message prompts blind persons as to whether crossing the road is authorized or prohibited. (Image: FHWA)	
Install/upgrade traffic & ped signals Installing/ Upgrading a pedestrian signal includes adding pedestrian lights, pedestrian recall or pedestrian countdown timers that provide pedestrian priority over vehicles at allotted periods of time. Countdown signals have been demonstrated to reduce pedestrian crossings when only a few seconds remain. (Image: Streets MN: All about Ped Signals)	

<table>
<tr>
<td>Leading pedestrian interval (early release)

A Leading Pedestrian Interval (LPI) typically gives pedestrians a few second head start when entering an intersection with a corresponding green signal in the same direction of travel. LPIs enhance the visibility of pedestrians in the intersection and reinforce their right-of-way over turning vehicles, especially in locations with a history of conflict. (Image: Saneinejad, TRB annual meeting 2015)</td>
<td>
</td>
</tr>
<tr>
<td>"Yield to pedestrians" sign

"Stop (or Yield) Here for Pedestrians" are warning signs which are mounted near pedestrian crossing locations to alert drivers to stop to let a pedestrian cross. This improves visibility of pedestrians to motorists, and helps prevent crashes that occur at crosswalks on multilane roadways (Image: City of Prairie Village, Kansas)</td>
<td>
</td>
</tr>
<tr>
<td>Pedestrian-activated flashing beacons (not rapid)

Flashing beacons are warning signs typically placed in advance of a marked crosswalk or on signs located adjacent to the crosswalk entry. Flashing amber beacons can be installed on traffic signal poles and mast arms or post-mounted on the roadside along with signs. Flashing beacons can be programmed to either operate continuously or be pedestrian activated. Pedestrian-activated flashing beacons remain “dark” until activated. (Image: Boston Regional MPO)</td>
<td>
</td>
</tr>
</table>

Pedestrian-activated rapid-flashing beacons Rapid flashing beacons (RRFB) are a type of warning device developed to improve safety at uncontrolled marked crosswalks. They are pedestrian-activated warning systems that alert motorists about pedestrians and bicyclists wanting to enter the crosswalk. RRFBs are extremely cost-effective to install, particularly when solar and wireless technology is used, since grid connections and trenching across the roadway are not required. (Image: Boston Regional MPO)	
High-intensity Activated crossWalK (HAWK) signal A HAWK is a pedestrian-activated warning device located on the roadside or on mast arms over midblock pedestrian crossings. The beacon head consists of two red lenses above a single yellow lens. Once the pedestrian pushes the button to activate the signal, it displays brief flashing and steady yellow intervals. The device then displays a steady red indication to drivers and a "WALK" indication to pedestrians, allowing them to cross a major roadway while traffic is stopped. After the pedestrian phase ends, the "WALK" indication changes to a flashing orange hand to notify pedestrians that their clearance time is ending. The hybrid beacon displays alternating flashing red lights to drivers while pedestrians finish their crossings before again going dark at the end of the cycle. (Image: FHWA)	
Include ped only phase A pedestrian only phase is often called a ped scramble. It consists of a phase dedicated to pedestrians in which no other traffic has a green signal. (Image: Wikipedia)	

5.2.1.1 Signals

There were many different signal treatments studied in the literature. These included adding pedestrian lights, pedestrian recall, pedestrian countdown timers, split phasing, pedestrian-only phasing, and changing the type of left-turn signal for vehicles. The results varied for each treatment.

The literature indicated that installation of signals seems to reduce total crashes (Chen, et al., 2012; Gan, et al., 2005), although there were no significant effects on pedestrian crashes (Chen, et al., 2012). Adding a protected-permissive left-turn signal or a pedestrian recall cycle decreased conflicts to a large extent (Pratt, et al., 2012). Left-turn signal phases were further observed to reduce crashes significantly at the locations in other studies (Pratt, et al., 2013; Chen, et al., 2012; Gan, et al., 2005). In their study of split-phasing, Chen, et al., (2012) found no significant reduction in any kind of crashes. Literature also includes studies that have been conducted to analyze pedestrian behavior after installing pedestrian countdown timers (Huitema, et al., 2014; Vasudevan, et al., 2011; Markowitz, et al., 2006; Eccles, et al., 2004). All the studies indicated countdown timers to be beneficial in reducing pedestrian injury crashes (Markowitz, et al., 2006; Huitema, et al., 2014) and pedestrian–vehicle conflicts (Eccles, et al., 2004).

Studies that evaluated the effects of installation of a scramble signal were included in the literature. In the study conducted by Bechtel, et al., (2004), the scramble signal allowed pedestrians to move in any direction, including diagonally through the intersection. It reported up to 50% reduction in conflict rates; however, they found a slight increase in pedestrian crossing violations. The authors recommended more pedestrian education and enforcement at this site to reduce the crossing violations. Another study conducted in New York City analyzed 20 years of crash data and found that a pedestrian-only phase reduced crashes significantly (Chen, et al., 2012).

Leading pedestrian intervals give pedestrians a head start at signalized intersections so that pedestrians may avoid turning vehicles. LPIs appear to have a mostly positive impact on pedestrian safety at intersections. Studies have reported significant reduction in crash rates (Fayish and Gross, 2010) and pedestrian-vehicle conflicts (Van Houten, et al., 2000) at the treatment sites. However, another study conducted in California near Disneyland found that the LPI moderately decreased pedestrian-vehicle conflicts when there were high right-turn volumes, but did not help when there were low right-turn volumes. The study also found that the LPI actually increased the amount of pedestrians trapped on the curb due to right-turning vehicles.

5.2.1.2 Signage

Signs alerting drivers to the possible or actual presence of pedestrians, as well as signs to alert drivers to stop or slow down, are treatments that may affect interactions with pedestrians and vehicles. In-street, impact-resistant signage provides warning for drivers that a crosswalk is approaching and reminds them that they are required to stop for crossing pedestrians. Studies seem to indicate that this type of sign provides positive benefits for pedestrian safety.

Only one study that was found looked at the effects of changing a signalized intersection to an all-way stop intersection. Persaud, et al., (1997) found that after removal of the signals and installation of the stop signs, there was a significant decrease in severe crashes and a smaller but still significant decrease in minor crashes. Although this appears to be beneficial to pedestrian safety, this method may only work for specific intersections. Another study that looked at driver behavior and conflicts after the installation of signs and pedestrian markings observed that there was a great reduction in conflicts and also increased pedestrian scanning for potential threats (Retting, et al., 1996).

Gedafa, et al., (2014), Hunter, et al., (2012), City of Madison, et al., (1999), and Ellis, et al., (2007) examined the effectiveness of in-street, impact-resistant signs at several distances from the crosswalk. Gedafa, et al., (2014) found that the sign was most effective 0 feet from the crosswalk (i.e., directly at the crosswalk), whereas Ellis, et al., (2007) found that the location of the sign did not significantly improve yield rates, but the authors recommend that the location be at the crosswalk. The studies also found that the treatment significantly increases motorist yield rates (Hunter, et al., 2012; City of Madison, 1999; Ellis, et al., 2007). Bennett, et al., (2014) studied the effectiveness of several configurations of the signs and compared their effect on driver yield rates to the Pedestrian Hybrid Beacon (PHB) and Rectangular Rapid Flash Beacon (RRFB) treatments. They found that the gateway treatment where there are two signs on each side of the road and one splitting travel lanes was the most effective configuration for the sign. Van Houten, et al., (2013) also found favorable safety results from the gateway treatment. Both studies concluded that the gateway treatment was more effective than one sign alone.

Strong and Ye (2010) studied the spillover effects of in-street signs looking at sites near intersections with the treatment. They found that there were significantly positive effects in terms of yielding to pedestrians and usage of crosswalk at both treatment locations and at spillover intersections, but negative effects at spillover midblock locations. Abdulsatter, et al., (1996), reported positive effects for pedestrian safety when a "turning traffic must yield to pedestrian" sign was present, and the observations suggested that the larger the pedestrian crossing group, the fewer conflicts.

5.2.1.3 Flashing Beacon and HAWK Signal

Two types of flashing beacons were found in the literature: pedestrian-activated flashing beacons or pedestrian hybrid beacons, and pedestrian-activated rapid flashing beacons or rectangular rapid flashing beacons. There were many more studies on rapid flashing beacons, and those were mostly comparative studies. Most studies reported positive pedestrian safety impacts for both types of beacons.

Studies have found a significant increase in yield distance (Vasudevan, et al., 2011) and yield rates after the installation of PHBs (Fitzpatrick, et al., 2014; Brewer, et al., 2015). Similarly, studies also showed significant increase in yield rates after the installation of RRFBs (Shurbutt and Van Houten, 2010; Van Houten, et al., 2008; Fitzpatrick, et al., 2014; Van Houten and Malenfant, 2011). However, when RRFBs were compared with traffic signals and PFBs, traffic signals had the highest driver yielding rates, followed by PHBs and then RRFBs (Brewer, et al., 2015; Fitzpatrick, et al., 2014). Only one study in the United States studied high-intensity activated crossWalK signals. Fitzpatrick and Park (2009) studied 21 HAWK locations and 102 comparison locations in Tucson, Arizona. They found a significant reduction in pedestrian crashes and total crashes, implying that HAWK signals are an effective method to increase pedestrian safety.

5.2.2 Uncontrolled Intersection Treatments

Uncontrolled intersection treatments are usually mid-block treatments where the vehicle traffic is not controlled by signals or signs to stop for pedestrians. They usually include enhanced crosswalks, raised crosswalks, and crosswalk markings to provide better visibility of pedestrians. Descriptions of these facilities and a photo of each are shown in Table 6.

Table 6. Uncontrolled Intersection Treatments

Marked crosswalks at uncontrolled locations Marked crosswalks indicate optimal or preferred locations for pedestrians to cross and help designate right-of-way for motorists to yield to pedestrians. They are desirable at some high pedestrian volume locations (often in conjunction with other measures) to guide pedestrians along a preferred walking path. (Image: pedbikeimages.org)	
Crosswalk enhancements Crosswalk enhancements include enhanced marking and paving on crosswalks to increase pedestrian visibility to oncoming traffic. These markings make it easy for drivers to notice the pedestrians while they cross. (Image: City of Redmond, WA)	

In-pavement flashing lights to warn drivers The experimental embedded pavement light system utilizes a series of light emitting diodes (LEDs) in a housing embedded in the roadway which flashes to warn approaching motorists that a pedestrian is entering or is in the crosswalk. The lights shine out toward the oncoming traffic to warn drivers and flash for a set period of time before automatically turning off. (Image: Legal Examiner, 2009)	
Raised intersections Raised intersections are alternatively called raised junctions, intersection humps, or plateaus. They create a safe, slow-speed crossing and public space at minor intersections. Similar to speed humps and other vertical speed control elements, they reinforce slow speeds and encourage motorists to yield to pedestrians at the crosswalk. (Image: Yarger Engineering)	

5.2.2.1 Marked Crosswalks, In-pavement flashing lights, Enhanced Crosswalks

According to the papers reviewed, marking crosswalks appears to increase crashes for pedestrians, which seems to decrease safety. However, much of the literature points out that marking crosswalks increases pedestrian traffic at that area, which could possibly explain the increase in crashes at those locations. High-visibility treatments to crosswalks appear to decrease crashes by providing more visibility to crosswalks and pedestrians. Many researchers studied the results of in-pavement flashing lights, but only one study included conflict data and none included crash data. There were mixed results with the installation of flashing lights. Advance pavement markings in the road for drivers approaching pedestrian crossing locations appear to be helpful to pedestrian safety as they alert motorists of crosswalks ahead.

Zegeer, et al., (2005) compared marked and unmarked crosswalks in the United States and found that the influence of marked crosswalks depended on the number of lanes, as well as the average daily traffic count of the road. On multilane roads with AADT greater than 12,000, there were significantly higher pedestrian crashes, as multilane roads are more difficult to cross. With more cars, it is more difficult to find a gap in which to cross. The study also examined pedestrian traffic at marked versus unmarked crosswalks and found that more pedestrians tend to cross at marked crosswalks than unmarked crosswalks, thus resulting in more crashes at those locations, specifically. A similar study conducted by Jones and Tomcheck (2000) found that there were significant reductions in crashes after a crosswalk was removed.

Multiple studies (Knoblauch, et al., 2001; Knoblauch and Raymond, 2000; Mitman, et al., 2010) observed pedestrian and driver behavior at marked crosswalks to draw conclusions on the safety of crosswalks for pedestrians. Knoblauch, et al., (2001) found a slight decrease in driver speed when pedestrians were present. Knoblauch and Raymond (2000) found a significant decrease in speeds both when pedestrians were present and not present, implying that crosswalks increase driver awareness of pedestrians. Knoblauch, et al., (2001) found no significant change in driver yield rates with the installation of crosswalk markings. However, Mitman, et al., (2010) found that vehicles are significantly more likely to yield to pedestrians at a marked crosswalk than an unmarked one. Knoblauch, et al., (2001) also found that pedestrian volumes increase significantly with the addition of a crosswalk, contributing to the theory that marking crosswalks leads to more crossing pedestrians, which leads to more crashes and conflicts. Studies conducted on school crosswalks (Feldman, et al., 2010) and uncontrolled crossings (Chen, et al., 2012; Pulugurtha, et al., 2012) that were given a high-visibility treatment, found that pedestrian crashes reduced to about half (Chen, et al., 2012) and also driver yielding increased (Pulugurtha, et al., 2012; Nitzburg and Knoblauch, 2001).

Flashing lights appear to be beneficial with respect to changing driver behavior. Multiple studies reported significant increases in driver yielding rates (Karkee, et al., 2010; Kannel and Jansen, 2004; Gadiel, et al., 2007; Huang and Cynecki, 2000; Van Derlofske, et al., 2003; Prevedouros, 2001; Godfrey and Mazzella, 1999). Godfrey and Mazzella (1999) and Karkee, et al. (2010) reported significant increases in driver yielding distance. Karkee, et al. (2010) and Kannel and Jansen (2004) reported significant decreases in motorist speeds. However, the only study that observed conflict rates did not find a significant change (Van Derlofske, et al., 2003). In addition, Huang and Cynecki (2000) did not find a significant decrease in speed. Several studies also found problems with the automatic detectors installed with the flashing lights due to false activation rates (Van Derlofske, et al., 2003). A study by Whitlock & Weinberger Transportation (1998) found that a bollard gateway system for automatic activation had the lowest false activation rate out of several automated systems. They also found that an automatic detection system is generally better than a push button system. Malek (2001) compared the in-pavement flashing lights to a standard overhead beacon. He found that the in-pavement system appeared to have higher yield rates than the overhead beacon and increased visibility of pedestrians better.

Retting and Van Houten (2000) found that driver behavior positively increased when stop bars were moved from 4 feet to 20 feet in advance of the crosswalk. They found a significant increase in vehicles that stopped at least four feet from the crosswalk, a significant decrease in vehicles that stopped in the crosswalk, and a significant increase in the average time the lead vehicle took to enter the intersection. The authors argue that these behavioral changes positively impact pedestrian safety.

Gomez, et al., (2011) compared the crash rates of crosswalks with advance pavement markings to those with standard markings, and Fisher and Garay-Vega (2010) studied the effects of advance pavement markings using a simulator equipped with an eye-tracker. They found that drivers scanned for pedestrians more when advance markings were installed, potentially increasing safety by increasing their awareness of pedestrians waiting to cross. Samuel, et al., (2013) used eye trackers in the field to track driver scanning behavior. They found that with advance pavement markings, drivers were more likely to scan the side of the road for pedestrians. They also found that more drivers yielded to pedestrians with the advance markings.

5.2.2.2 Raised Intersections, Crosswalks, and Speed Humps

No studies looked at raised intersections or crosswalks. While no research was found on the safety of raised crosswalks on their own, this treatment is very similar to a speed hump in design, the difference being that it is also a marked location for pedestrian crossings. Speed humps may be an effective way to decrease speed and, therefore, crash rates, but there is not enough substantial evidence to say this with confidence.

In a study of 244 treatment sites and 915 comparison sites in New York City, Chen, et al., (2012) did not find any significant decrease in crash rates with the use of speed humps. Chicago DOT (2005) studied a school route improvement program and concluded that speed humps may be beneficial, but no significant changes in vehicle and pedestrian safety behavior could be found. Tester, et al., (2004) conducted an examination of emergency room records of children struck by cars to determine if there were any trends associated with injuries and speed humps. They found that children who lived in neighborhoods with speed humps had significantly lower odds of being injured.

5.2.3 Physically Separated Treatments

Safety treatments that prevent vehicles from entering the right of way (ROW) provided for pedestrians are included in this section. Physically separating the two ROWs tends to improve safety. They include the presence of sidewalks, pedestrian channelization, medians, refuge islands, and curb extensions. Descriptions of these facilities and a photo of each are shown in Table 7.

Table 7. Physically Separated Treatments

Sidewalks Sidewalks are paths along the side of a road that are constructed to accommodate pedestrians using the roadway. Sidewalks are an essential component of the urban environment and serve as key corridors for people, goods, and commerce. Safe, accessible, and well-maintained sidewalks are a fundamental and necessary investment for cities, and have been found to enhance general public health and maximize social capital. (Image: City of New Brighton)	

Pedestrian channelization Pedestrian channelization barriers are used along medians and roadsides to help guide pedestrians to crosswalk locations. The Pedestrian channelization barriers are not designed to withstand vehicular impact and are intended to yield in this condition. They can also be used in a variety of applications including airports, work zones, vertical construction and more. (Image: FHWA)	
Medians A median is a grass or concrete strip in the middle of the roadway separating the two directions of traffic. It can provide a location for pedestrians to wait to make a crossing in two stages and calm traffic by having a visually smaller expanse of pavement. (Image: Tiffany Robinson, pedbikeimages.org)	
Refuge Islands Refuge islands provide a location for pedestrians to stop part way as they are crossing a street, thus reducing the burden of looking multiple directions at the same time and having a safe place to stand to cross in stages. (Image: Dan Burden, pedbikeimages.org)	
Curb Extensions By extending the curb out from the sidewalk, the distance that must be crossed by a pedestrian is reduced. The narrowing of the roadway also slows vehicles on the intersection approach, which is critical as that is where pedestrians and vehicles will interact. (Image: Mitchell Austin, pedbikeimages.org)	

5.2.3.1 Sidewalk Presence and Widths

Sidewalks appear to be beneficial to pedestrians by providing a separated right-of-way from moving vehicles. In Wake County, North Carolina, McMahon, et al., (2002) compared reported pedestrian crash sites to non-crash sites. They found that sites with sidewalks had an 88.2% lower chance of being a crash site than sites without sidewalks, implying that sites with sidewalks are safer for pedestrians. Gan, et al., (2005) surveyed several states and averaged their reported crash reduction factors of many different treatments. They found a 74% crash reduction after the installation of sidewalks.

Although the Americans with Disabilities Act (ADA) requires sidewalks to have specific minimum widths for accessibility purposes (Americans with Disabilities Act, 2010), no studies were found looking at the potential safety implications of sidewalk width. However, Gan, et al., (2005) conducted a study using crash reduction factors provided by Arizona, and found that widening the shoulder pavement resulted in a 71% crash reduction. Thus shoulder widening appears that it may be beneficial for pedestrian safety, but more studies and information are needed to draw any definite conclusions.

5.2.3.2 Medians, Refuge Islands, and Curb Extensions

There were not many studies on medians or pedestrian refuge islands. The few studies on medians seemed to show an improvement in pedestrian safety, while those on refuge islands were mixed. Although both temporary and permanent curb extensions can be found in many cities in the United States, few studies were found on safety implications related to curb extensions. The same is true for widening medians. There were no conflict or crash data found in locations where curb extensions were studied; the literature found focused on vehicle and pedestrian behavior in those instances.

Both studies on medians compared the crash rates of raised-median cross-sections to other kinds of cross sections. Parsonson, et al. (2000), compared raised-median facilities with two-way left-turn lanes. They studied multilane state highways in both urban and rural locations in Georgia. They found that pedestrian fatalities were 78% lower for raised-median locations. Bowman and Vecellio (1994) compared raised-median cross sections with two-way left-turn lanes and undivided roads. They found that pedestrian accidents at raised medians were significantly lower than both other kinds of cross-sections. However, they found no significant change in pedestrian-vehicle conflict rates at raised-median sites.

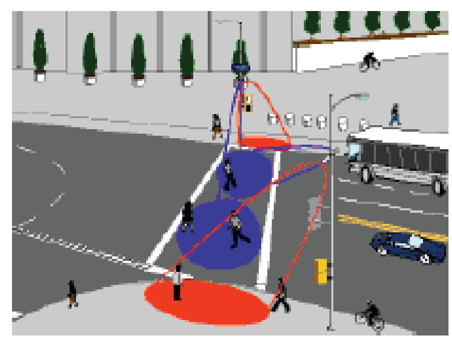
Pulugurtha, et al., (2012) studied refuge islands in Las Vegas at three sites. They found a significant increase in pedestrians looking for vehicles and a significant increase in driver yielding rate and driving yielding distance. Huang and Cynecki (2000) studied five crossings in two cities. They found the only significant result to be the increase in pedestrians crossing in the crosswalk. However, they noted that their small sample size might have affected their data. It is hard to say with confidence whether this treatment is effective or not with the small amount of data available. Pulugurtha, et al., (2012) was also the only study found that looked at Danish offsets. They found a significant increase in percent of drivers yielding and driver yielding distance. They also found a significant decrease in the number of pedestrians trapped in the street.

There were mixed findings in regard to curb extensions. Johnson (2005) found that there was a significant decrease in the number of cars that passed through the crosswalk before stopping for a pedestrian. However, he also found no significant change in vehicles yielding to pedestrians or stopping at the stop bar. Huang and Cynecki (2000) found that fewer pedestrians crossed in the crosswalk after the installation of the curb extensions and the average pedestrian wait time to cross increased. They also found no significant increase in vehicle yield rates.

5.2.4 Automatic Pedestrian Detection

A description of automatic pedestrian detection and an illustration are shown in Table 8.

Table 8. Automatic Pedestrian Detection

Automatic pedestrian detection Automated pedestrian detection systems can detect the presence of pedestrians and call the Walk signal without any required action by the pedestrian. Infrared or microwave devices are used to detect pedestrians. This is useful for visually impaired pedestrians who cannot press the push button to activate the Walk signal. It also eliminates the delay between the time the push button is pressed and the Walk signal appears. (Image: FHWA)	

Automated pedestrian detection treatments seem to be effective for increasing pedestrian safety. There are several ways to implement this type of device. One study focused on the use in controlling walk signals. Another study focused on automatic crosswalk illumination. Hughes, et al., (2000) studied the results of both microwave and infrared detection. The device was used in conjunction with pre-existing push buttons and detected pedestrians waiting to cross and pedestrians in the crosswalk. They found a significant decrease in pedestrian-vehicle conflicts during pedestrian crossing. They also found a significant reduction in pedestrians who began crossing during the “don’t walk” phase. The effectiveness of each type of detector was found to be roughly the same. Nambisan, et al., (2009) used microwave and infrared automatic detection to implement a smart lighting treatment to a midblock crosswalk. When pedestrians were detected in the crosswalk, the lighting would brighten, alerting drivers of crossing pedestrians. They measured an increase in motorist yielding from 22% before the treatment to 35% after installation. This was statistically significant. In addition, the percentage of pedestrians that became trapped in the roadway after beginning to cross decreased from 30% to 14%, a statistically significant result. This implies that the treatment made drivers more aware of crossing pedestrians and allowed them to cross the street in one motion.

5.2.5 Other Treatments

Some of the other treatments included are removal of on-street parking near intersections, road diets, and installation of overpasses and underpasses. Descriptions of these treatments and a photo of each are shown in Table 9.

Table 9. Other Treatments

Road diet A roadway reconfiguration known as a road diet is a low cost improvement usually applied to traditional four-lane undivided highways. In addition to low cost, the primary benefits of a road diet include enhanced safety, mobility and access for all road users, and a "complete streets" environment to accommodate a variety of transportation modes. The key feature of a road diet is that it allows reclaimed space to be allocated for other uses, such as turn lanes, bus lanes, pedestrian refuge islands, bike lanes, sidewalks, bus shelters, parking, or landscaping. (Image: FHWA)	

Removal of on-street parking near intersections 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. However, close to intersections, it can create conflicts with pedestrians trying to cross. (Image: NACTO)	
Overpass or Underpass An overpass is a bridge, road, railway or similar structure that crosses over another road or railway. An underpass is a tunnel-like structure created to allow pedestrians to cross the road. A pedestrian overpass and underpass provide grade separation from a motorized roadway. They typically span the transportation right of way to provide connection between destinations that have high pedestrian volumes. (Image: pedbikeimages.org)	

There were very little data on the topic of removing on-street parking. Samuel, et al., (2013) studied the effects of removing parking spaces adjacent to crosswalks that were treated with advance yield markings and signage. They found with the markings alone there was an increase in yielding of 8.2%. When the nearest parking spot was empty, there was an improvement in yielding of 35.1%. After they eliminated two of the closest parking spots, yielding improved by 56.1%. This implies that eliminating on-street parking adjacent to crosswalks increases visibility of pedestrians waiting to cross and, therefore, allows pedestrians to cross sooner. In a survey of state crash reduction factors, Gan, et al., (2005) found that Missouri was the only state that reported a crash reduction factor for this treatment. They reported a 30% crash reduction factor.

Chen, et al., (2012) studied a road diet in which the number of travel lanes was decreased from four to three and left-hand turn lanes were added. They found that the total number of crashes was decreased by 67% and injury/fatal crashes were decreased by 79%. They did not find a change in pedestrian crashes. Therefore, this treatment may not be effective for pedestrian safety.

Overpasses and underpasses as a pedestrian safety treatment were studied by Gan, et al., (2005) as a compiled survey taken of several states. The average of the three states' crash reduction factors was 86% pedestrian crash reduction with the use of an overpass or underpass. This implies that the use of this treatment is beneficial to pedestrian safety, but more research is needed on this treatment to say this with confidence.

5.2.6 Enforcement, Education, Outreach, and Training

Although there were no crash or conflict data for the use of enforcement campaigns, there have been studies that examine driver yield rates and speeds. Enforcement campaigns appear to be beneficial as they generally increase driver yield rates and decrease driving speed. The enforcement campaign studied by Van Houten, et al. (2013), included the issuing of citations and warnings, along with flyers, outreach and education, sandwich board signs, feedback signs, newspaper articles, and paid radio ads. They found the number of citations issued for failure to yield to pedestrians dropped from 182 to 66 over the course of a year. Driver yielding increased from 45.4% to 82.7%. The study also determined that the benefits to non-enforcement sites were inversely proportional to the distance from the enforcement locations.

O'Brian and Simpson (2012) studied the impacts of a "Your Speed" message sign posted in school zones that lit up during school hours. There was also an enforcement program and several outreach activities such as brochures and newsletters. Twelve months after installation, the authors measured a 12% decrease in speeds during times the signs were lit. Lower speeds potentially equate to lower crash rates and decreased severity of injury during crashes. During non-school times while the signs were not lit, there was a slight increase in driving speed. The number of citations for speeding issued per day in this location decreased from an average of two per day to one every two days.

Boyce and Geller (2000) studied an outreach campaign undertaken at Virginia Tech. It involved the use of promise cards, trifold brochures, buttons and t-shirts, posters, and prizes. They found an increase in crosswalk usage during the time of the outreach program, then a decrease during withdrawal. Eventually the usage went back to baseline levels. Driver yielding increased during all periods. It started at 23% and ended at 53% one year later. However, this increase was only significant in the first period of the study. Nasar (2003) studied how social cues could impact driver behavior. They had pedestrians hold signs that either thanked drivers for yielding or encouraged them to do so next time. There was a significant increase in yielding.

5.3 Synthesis of the Literature

For the next stage of the analysis, the research team evaluated each of the papers presented in the literature review in more detail, to assess the data and methods employed. The evaluation focused on whether sufficient data and controls were employed to ensure that statistical inferences would lead the team to concur that the treatment effectiveness results flowed from the analyses and remained reasonably transferrable to other locations (as opposed to applying only to the locations studies).

5.3.1 Study Details

For studies that derived safety outcomes for individual bicycle treatments, the details of their investigations are tabulated in Table 10 for comparison. The table 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 authors of this paper. Ratings included:

- *Informative but Not Conclusive:* The study presented quantitative and informative background, but did not claim to present a causal relationship
- *Lacking in Sample Size, Study Depth, or Controls:* The study likely failed to control for key factors or had a very small sample size
- *Fairly Robust, but Still Lacking in Depth or Completeness:* 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
- *Excellent:* The study employed sufficient sample sizes, controls, and a strong base rate, to develop transferrable results.

The studies represented in Table 10 show a wide range of variability in design, controls, and depth. Before-and-after studies accounted for 20 of the outcome measures, while 18 used non-intervention study methods. Regression was used for 14 outcome measures, and one study used non-regression measures; three studies used the empirical Bayes method; five outcome measures were a result of simply comparing rates from different sites. Of all the approaches, simply comparing sites or results before and after a treatment is the simplest; however, these methods require that assumptions be made about what variables to control for. Without proper controls, simple comparison methods are weak compared to the others.

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. Twenty-six (26) outcome measures used at least 10 treatment locations in the study, out of which 21 of them used more than 20 treatment sites. Twenty (20) of the 52 outcome measures used more than 10 comparison sites, with the rest of them using zero or less than 10. Twenty-nine (29) of the outcome measures mentioned controlling for any kind of exposure in the study, and all of these controlled for more than one type of exposure. Most of the exposure types were pedestrian 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. Only 24 of the 52 outcome measures had studies reporting statistically significant results at the 0.05 level; most of the rest (28) did not specify statistical significance.

On the authors' scale of study robustness, two papers were excellent; six were fairly robust; 22 were lacking in sample size, study depth, or controls; and four were informative but not conclusive. Overall, many of the studies examined lacked key controls, which rendered their outcomes less defensible. Those studies that were well-controlled still lacked treatment details, reproducible exposure data, sample size depth, or some other element that would be needed for transferability of results.

5.3.2 Literature Review Summary of Treatment Effectiveness

Overall, quantitative safety outcomes (i.e., crash reduction, injury crash reduction, or yield rate) were reported in the literature for all 29 treatment types examined in this literature review. Table 10 summarizes the results of studies as they were presented in the articles and reports. Figure 2 summarizes quantitative results of studies as they were presented in the articles and reports. The risk ratio on the vertical axis of the figure 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 (i.e., a change at the margin). Risk ratios are much like crash modification factors, but they apply to other outcome measures besides crashes. For example, if presence of sidewalk versus without sidewalk has a risk ratio of 0.15, that means that the risk of having an injury crash on the sidewalk is 0.15 times that of having an injury crash on the comparison scenario; this represents the marginal improvement for that sidewalk's case. Marginal improvements were either explicitly reported in the literature as risk ratios, or were reported as percentages and converted to risk ratios.

Of the 18 treatments with study outcomes presented in Figure 2, only adding or improving crosswalk treatments, installing/upgrading signals, and providing sidewalks treatment types had more than one quantitative study that described risk ratios associated with implementation. Most of the installing/upgrading signal studies were conflict-based studies (as opposed to crash-based or injury-based); hence, any reduction in crashes or injuries must be inferred from the reduction in conflicts. The studies associated with installing overpass/underpass, left-turn bays, modern roundabouts, and pedestrian prompting device had outcomes that showed no change in the risk ratios. Also, some of the treatments (e.g., installing/improving a signal and adding/improving sidewalks) had a varied range of effectiveness, with one treatment showing an increase in crashes. These differences may be 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, and/or possibly even chance.

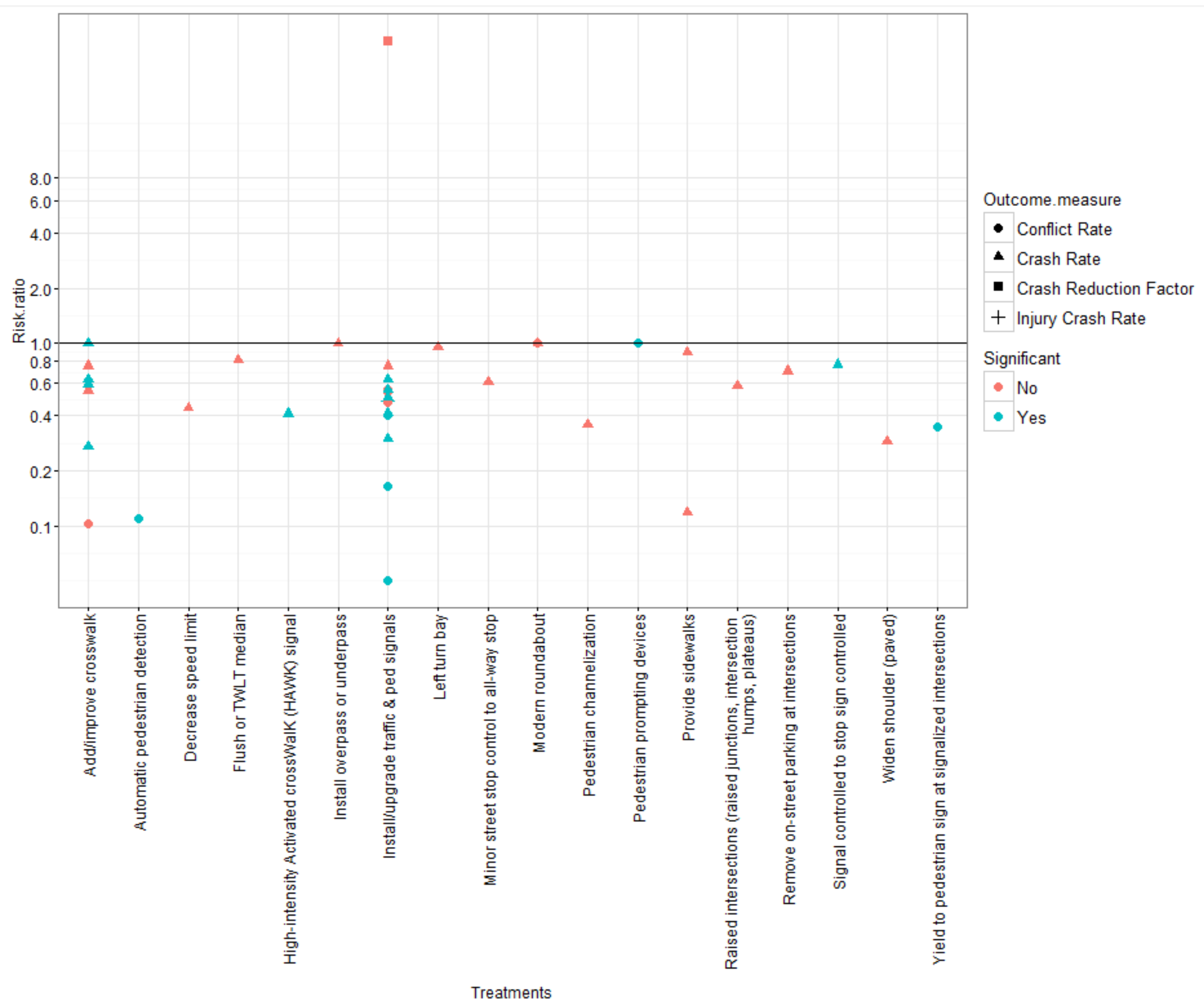


Figure 2. Risk Ratios of Various Treatments

Table 10. Review of Literature Methods, Controls, and Strengths/Weaknesses

Treatment	Paper	Treatments Assessed	Controls	Outcome Measures	Source of Crash Rates	Significant at 0.05 Level?	Overall Strengths and Weaknesses
Provide sidewalks	Gan, et al., 2005	Survey of crash rate reduction statistics due to addition of sidewalks from several states	None	Crash Rate	State Data	Not Specified	Lacking in sample size, study depth, or controls
	McMahon, et al., 2002	Compared crash sites to near and far-away sites to determine significant factors relating to crashes	Vehicle speed, pedestrian and traffic volume	Crash Rate	State Data	Presence of sidewalks – No; Speed limit – Yes	Informative but not conclusive
Pedestrian prompting devices	Retting, et al., 1996	Painted markings and signs to warn pedestrians to look for turning cars	None	Conflict Rate	N/a	Not Specified	Lacking in sample size, study depth, or controls
	Van Houten, et al., 1999	Upgraded walk indicators to LED lights and added 'scanning eyes' on the signal to prompt pedestrians to look for cars	None	Conflict Rate	N/a	Not Specified	Lacking in sample size, study depth, or controls
Automatic pedestrian detection	Hughes, et al., 2000	Automated detectors (microwave or infrared) were placed at signaled crossings in urban areas; they were used in conjunction with pre-existing push buttons	None	Conflict Rate	N/a	Yes	Lacking in sample size, study depth, or controls
Install/upgrade traffic and ped signals	Pratt, et al., 2013	Compared conflict rates of 20 sites in Austin, TX, to measure the effects of the type of signalization and pedestrian compliance	None	Conflict Rate	N/a	Not Specified	Lacking in sample size, study depth, or controls
	Pratt, et al., 2012	Implemented a pedestrian recall (required a vehicular cycle to be served that had enough time for a full pedestrian cycle)	Left-turn movement direction, speed limit, left-turn phasing, push button presence, special treatments used	Conflict Rate	N/a	Yes	Lacking in sample size, study depth, or controls

Treatment	Paper	Treatments Assessed	Controls	Outcome Measures	Source of Crash Rates	Significant at 0.05 Level?	Overall Strengths and Weaknesses
	Pratt, et al., 2012	Implemented split phasing in place of leading protected permissive	None	Conflict Rate	N/a	Yes	Lacking in sample size, study depth, or controls
	Pratt, et al., 2012	Added a leading protected-permissive left-turn phase	None	Conflict Rate	N/a	No	Lacking in sample size, study depth, or controls
	Huitema, et al., 2014	Included a pedestrian countdown timer	Within-site, between-site	Crash Rate	City Database	Yes	Fairly robust, but still lacking in depth or completeness
	Eccles, et al., 2004	Implemented a pedestrian countdown timer	None	Conflict Rate	N/a	Yes	Lacking in sample size, study depth, or controls
	Chen, et al., 2012	Installed signals at previously unmarked intersections	Site characteristics, geographical distribution	Crash Rate	City Database	All crashes – Yes; Pedestrian crashes – No; Injurious/fatal crashes – Yes	Excellent
	Chen, et al., 2012	Left-turn-only phase for vehicles	Site characteristics, geographical distribution	Crash Rate	City Database	Yes	Excellent
	Chen, et al., 2012	Implemented split phasing: protected phase for pedestrians and a protected phase for vehicles	Site characteristics, geographical distribution	Crash Rate	City Database	No	Excellent
	Markowitz, et al., 2006	Installed a pedestrian countdown timer at signalized intersections	Temporal and regional factors, traffic volume	Crash Rate	City Database	Yes	Fairly robust, but still lacking in depth or completeness
	Gan, et al., 2005	Installed or upgraded pedestrian signals at controlled intersections	None	Crash Rate	State Database	Not Specified	Lacking in sample size, study depth, or controls
Include ped only phase	Bechtel, et al., 2004	Implemented a scramble signal in which pedestrians and vehicles each have their own phases (allows diagonal pedestrian crossings)	Time of day, pedestrian volume	Conflict Rate	State Database	Yes	Lacking in sample size, study depth, or controls

Treatment	Paper	Treatments Assessed	Controls	Outcome Measures	Source of Crash Rates	Significant at 0.05 Level?	Overall Strengths and Weaknesses
	Chen, et al., 2012	Added a pedestrian-only phase during which all traffic is stopped (does not allow diagonal pedestrian crossing)	Site characteristics, geographical distribution	Crash Rate	City Database	Yes	Excellent
Leading pedestrian interval (early release)	Van Houten, et al., 2000	3-second LPI	Time, site location, pedestrian age	Conflict Rate	N/a	Yes	Lacking in sample size, study depth, or controls
	Fayish and Gross, 2010	Implemented a 3-second LPI on low-speed multilane intersections	Temporal and regional factors, traffic volume	Crash Rate	Not Specified	Yes	Fairly robust, but still lacking in depth or completeness
	Hubbard, et al., 2008	3-second LPI in a multilane suburban setting; allowed right turn on red during the LPI	None	Conflict Rate	N/a	Yes (with high right turn on red volume)	Lacking in sample size, study depth, or controls
Change interval timing	Pratt, et al., 2012	Increased walk interval by 5 seconds	None	Conflict Rate	N/a	No	Lacking in sample size, study depth, or controls
	Chen, et al., 2012	Increased walk interval by a varied number of seconds	Site characteristics, geographical distribution	Crash Rate	City Database	Yes	Excellent
	Retting, et al., 2002	Re-timed yellow signal phase based on ITE guidelines for determining duration	General site characteristics, crash data trends	Crash Rate	State Database	Total crashes – No; Pedestrian and bicycle crashes – Yes; Crashes with injuries – Yes	Fairly robust, but still lacking in depth or completeness
Pedestrian channelization	Chen, et al., 2012	Added fencing along sidewalks to prevent pedestrians from crossing midblock at unmarked locations	Site characteristics, geographical distribution	Crash Rate	City Database	No	Excellent

Treatment	Paper	Treatments Assessed	Controls	Outcome Measures	Source of Crash Rates	Significant at 0.05 Level?	Overall Strengths and Weaknesses
Mark crosswalks at uncontrolled locations	Zegeer, et al., 2005	Studied marked and unmarked crosswalks to determine if there was a significant difference between the crash rates	Traffic volume, pedestrian volume, number of lanes, median type	Crash Rate	City Database	Yes (marked crosswalks increase crash rates)	Informative but not conclusive
	Jones and Tomcheck, 2000	Intersections previously had a mix of marked and unmarked crosswalks; crosswalks were removed from one street in the intersection	General site characteristics, crash data trends	Crash Rate	City Database	Yes (unmarked crosswalks decrease crash rates)	Fairly robust, but still lacking in depth or completeness
Crosswalk enhancements	Huybers, et al., 2004	Added advance markings on the pavement	None	Conflict Rate	N/a	Not Specified	Lacking in sample size, study depth, or controls
	Gomez, et al., 2011	Compared crash rates of crosswalks with advance pavement markings to crosswalks with standard markings	Simulator	Crash Rate	Other	Not Specified	Lacking in sample size, study depth, or controls
	Feldman, et al., 2010	School crosswalks that were given high visibility treatments (yellow, continental style)	Traffic counts, street width, signal type	Crash Rate	City Database	Yes	Informative but not conclusive
	Chen, et al., 2012	Added high visibility markings: a series of longitudinal white stripes that are constructed from thermoplastic materials	Site characteristics, geographical distribution	Crash Rate	City Database	Yes	Excellent
	Van Houten, et al., 2001	Added advance markings on the pavement and a symbol sign at uncontrolled multilane crossings that already had pedestrian-activated flashing beacons	None	Conflict Rate	N/a	Not Specified	Lacking in sample size, study depth, or controls

Treatment	Paper	Treatments Assessed	Controls	Outcome Measures	Source of Crash Rates	Significant at 0.05 Level?	Overall Strengths and Weaknesses
In-street impact-resistant "yield to peds" sign	Gedafa, et al., 2014	Placed "yield to pedestrian" signs at crosswalks on multilane, uncontrolled crosswalks; collected data when there was no sign present and when the sign was in 5 different locations	None	Conflict Rate	N/a	YR – Yes; cR – Not calculated; Traffic speeds – Yes	Lacking in sample size, study depth, or controls
In-pavement flashing lights to warn drivers	Van Derlofske, et al., 2003	Flashing in-pavement lights activated by automatic microwave detectors, paired with high visibility crosswalk markings	None	Conflict Rate	N/a	Yes – visibility only (others not calculated)	Lacking in sample size, study depth, or controls
Pedestrian-activated flashing beacons (not rapid)	Huybers, et al., 2004	Measured effectiveness of a sign with pedestrian-activated flashing beacon in 2 arrangements: sign alone and sign with advance pavement markings	None	Conflict Rate	N/a	Not Specified	Lacking in sample size, study depth, or controls
Pedestrian-activated rapid-flashing beacons	Van Houten, et al., 2008	RRFB with stutter pattern	None	Conflict Rate	N/a	Yes	Lacking in sample size, study depth, or controls
	Van Houten, et al., 2008	RRFB with stutter pattern paired with a dynamic lighting pad (lighting the crosswalk)	None	Conflict Rate	N/a	No	Lacking in sample size, study depth, or controls
	Ross, et al., 2011	Installed an RRFB at uncontrolled, marked crosswalks on roads with speed limits above 35 mph	None	Conflict Rate	N/a	Not Specified	Lacking in sample size, study depth, or controls
High-intensity Activated crossWalK (HAWK) signal	Fitzpatrick and Park, 2009	HAWK treatment to uncontrolled multilane crossings	Used staged crossings to control for differences in pedestrian behavior	Crash Rate	City Database	Total crashes – Yes; Pedestrian crashes – Yes; Severe crashes – No	Excellent

Treatment	Paper	Treatments Assessed	Controls	Outcome Measures	Source of Crash Rates	Significant at 0.05 Level?	Overall Strengths and Weaknesses
Raised intersections (raised junctions, intersection humps, plateaus)	Chen, et al., 2012	Added speed humps midblock and at intersections	Site characteristics, geographical distribution	Crash Rate	City Database	No	Excellent
Decrease speed limit	Chen. et al., 2012	Decreased speed limit by a varied number of miles per hour	Site characteristics, geographical distribution	Crash Rate	City Database	No	Excellent
Road diet	Chen. et al., 2012	Decreased the number of travel lanes and increased the number of left-turn lanes	Site characteristics, geographical distribution	Crash Rate	City Database	All crashes – Yes; Pedestrian crashes – No; Injurious/fatal crashes – Yes	Excellent
Left-turn bay	Chen. et al., 2012	A storage area of some length for left-turning vehicles at an intersection	Site characteristics, geographical distribution	Crash Rate	City Database	No	Excellent
Convert intersections from signal controlled to stop sign controlled	Persaud, et al., 1997	Converted signalized intersections to multi-way stop sign controlled intersections	Traffic volume, pedestrian volume, geographic factors	Crash Rate	City Database	Yes	Informative but not conclusive
"Yield to pedestrian" sign at signalized intersections	Abdulsattar, et al., 1996	"Turning Traffic Must Yield to Pedestrians" sign installed at marked crosswalks at signalized intersections	None	Conflict Rate	N/a	Yes	Lacking in sample size, study depth, or controls

Treatment	Paper	Treatments Assessed	Controls	Outcome Measures	Source of Crash Rates	Significant at 0.05 Level?	Overall Strengths and Weaknesses
Raised medians compared to two-way left-turn lanes	Parsonson, et al., 2000	Compared pedestrian fatalities per 100 miles of raised medians to those of two-way left-turn lanes on divided highways in the State Highway System of Georgia	None	Fatality Rate	State Database	Yes	Fairly robust, but still lacking in depth or completeness
Raised medians compared with two-way left-turn lanes and undivided roads	Bowman, et al., 1994	Compared pedestrian accidents of raised medians to those of two-way left-turn lanes and undivided arterials	None	Conflict Rate and Crash Rate	Not Specified	Crash rates-yes; conflict rates-no	Lacking in sample size, study depth, or controls
Flush or TWLT median	Gan, et al., 2005	Installed flush or two-way left-turn lane medians	None	Crash Rate	State Database	Not Specified	Lacking in sample size, study depth, or controls
Convert minor street stop control to all-way stop	Gan, et al., 2005	Converted a 2-way stop sign controlled intersection to an all-way stop	None	Crash Rate	State Database	Not Specified	Lacking in sample size, study depth, or controls
Widen shoulder (paved)	Gan, et al., 2005	Widened a paved shoulder of a roadway	None	Crash Rate	State Database	Not Specified	Lacking in sample size, study depth, or controls
Remove on-street parking	Gan, et al., 2005	Removed the parking on the roadway	None	Crash Rate	State Database	Not Specified	Lacking in sample size, study depth, or controls
Install overpass or underpass	Gan, et al., 2005	Installed an overpass or underpass for pedestrian use	None	Crash Rate	State Database	Not Specified	Lacking in sample size, study depth, or controls
Modern roundabout	Harkey and Carter, 2006	Modern roundabout	None	Conflict Rate	Other	Not Specified	Lacking in sample size, study depth, or controls
	Harkey and Carter 2006	Modern roundabout	None	Crash Rate	State Database	Not Specified	Lacking in sample size, study depth, or controls

5.4 Discussion

In addition to the existing literature, several research studies pivotal to developing a greater understanding of pedestrian safety have just begun. As an example, National Cooperative Highway Research Program 17-56 is already in progress to identify crash reduction factors for uncontrolled pedestrian crossing treatments. The objectives of this research are to quantify the relationships between pedestrian safety and crossing treatments at uncontrolled locations, and develop crash modification factors by crash type and severity for unsignalized pedestrian crosswalk signs and pavement markings, high-intensity activated crosswalk signals, rectangular rapid flashing beacons, pedestrian refuge areas, curb extensions, in-pavement warning lights, and high-visibility crosswalk marking patterns.

The Georgia Tech team reviewed 62 papers on pedestrian treatments, and 52 of those studies had meaningful results on 35 types of pedestrian treatments. Some of these treatment types are easily categorized together and those studies were looked at as evaluating similar treatments. Quantitative safety outcomes (i.e., crash reduction, injury crash reduction, injury severity reduction, or conflict reduction) were reported in the literature for all 35 of the treatment types covered here. Statistically significant results are available for pedestrian crash or conflicts in the context of 25 treatment types and an additional 1 study and treatment with statistically significant results for bicycle and pedestrian crashes combined, 2 studies with statistically significant overall crash rates (not specific to pedestrians), and 1 study with statistically significant changes in yield rates. Literature searches turned up empty for evaluations of chicanes, raised crosswalks, and shared streets. Additionally, many of the treatments were only studied by one or two research groups and only in a few specific locations in the United States. In order to draw broad conclusions on the actual effects of the treatments, further and more diverse research is necessary.

Similar to the bicycle studies in the previous chapter, knowing the number, type, and severity of crashes is a significant problem for understanding the effectiveness of pedestrian treatments. While most studies were able to obtain some kind of crash data, the quality of that data is often lacking due to problems of underreporting and reporting bias, 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 (AASHTO, 2010).

Again, one common theme among the studies in this review was a lack of standardized, transferable exposure data to understand the extent to which users are exposed to risk. 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. It is imperative that transportation agencies invest in collecting and maintaining non-motorized user counts if pedestrian treatments are to receive rigorous and unbiased analysis.

Finally, studies must be of significant statistical rigor, for which substantial work in investigating various treatments remains. Of the studies reviewed, some used very simple methodologies with few controls, while others developed more rigorous methods to control for certain confounding factors. Without multiple sites in varying locations, presenting and controlling for multiple confounding factors, an understanding of the broad safety impacts of a treatment simply cannot be obtained. 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.

6 Survey of DOTs and MPOs for Bicycle and Pedestrian Design Policies

The research team developed an online survey about bicycle and pedestrian treatments. The purpose of the survey is to better understand the process that agencies use to determine which bicycle and pedestrian treatments to install in their region. The researchers goal is to be able to examine how state DOTs, MPOs, consulting agencies, and cities and counties conduct bicycle and pedestrian transportation planning and engineering. In evaluating safety for non-motorized modes, many methods require an exposure rate and crash, incident, or near miss rates. A major barrier that has been identified in the literature to these studies and analyses is the lack of bicycle and pedestrian counts to combine with vehicle counts to provide exposure information. Looking at how safety has or has not been studied, and how important safety is to different types of agencies in their choices for treatment sites and treatment types, can help inform further research on bicycle and pedestrian safety.

6.1 Survey Development

6.1.1 Development Tools and Process

The research team used the online survey platform Survey Gizmo to develop and deploy the survey. The platform allowed for the development of various question types, including the use of logical flow to display follow-up questions when appropriate. Question types include single answer, multiple answer, Likert scale, fill in the blank, drop down menu options, and open answer. The survey was pretested by the research team and colleagues, and then by former bicycle and pedestrian coordinators for the Atlanta Regional Commission (ARC), who were instructed to answer the survey as if they still held their former position of bike/ped coordinator. Feedback on question wording and content from the pretests was incorporated before finalizing the survey. Pretesting also confirmed that completing the survey should take respondents less than 10 minutes. The Survey Gizmo platform allows users to complete the survey on a laptop or desktop computer or mobile device. Results can be downloaded from the platform in comma-separated values (.csv) form for analysis with any preferred statistical package.

6.1.2 Survey Instrument

The online survey instrument contains five consecutive pages, including a first page for the introduction and consent, and a closing thank you page. Figure 3 shows the progressive flow of the survey by page.

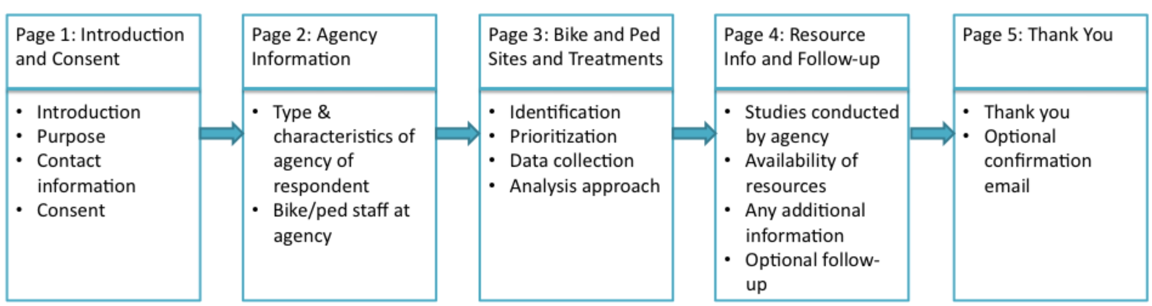


Figure 3. Survey Flow

The first page welcomes the user, states the purpose of the survey, gives a contact for questions or concerns, and states the agreement of consent in continuing with the survey. The purpose of the second page is to collect information about the type of agency the survey respondent represents. The second page asks information about the agency, such as if it is private or public; in what type of jurisdiction the agency operates; characteristics of the agency, such as size and the existence and number of staff who focus on bicycle and pedestrian issues; and the presence of complete streets policies. The third page asks questions about how the respondent's agency identifies and prioritizes sites for bicycle and pedestrian treatments, as well as how they identify and prioritize which treatments to implement. The questions on page three include what types of analyses the agency employs and data they collect. Page four covers whether the agency has conducted before and after, or other types of studies, relating to new bicycles or pedestrian treatments, and where to find information on the studies and projects relating to bicycles and pedestrians, and it provides an opportunity for the respondent to add any additional information. The fourth page ends with a section that allows the respondents to provide contact information if they are willing to be contacted with follow-up questions. Once the respondent completes the fourth page, he/she is brought to page five, which thanks them for completing the survey and marks the response as a complete response.

6.1.3 Survey Deployment

As the purpose of the survey is to gather information about bicycle and pedestrian aspects of transportation planning, the researchers deployed the survey to people at state and regional agencies. Those individuals were likely to specialize in bicycle and pedestrian issues, or know to whom they could pass the survey to answer the questions knowledgably (whether another person at the same agency or a person at a contracted agency). The research team deployed the survey via email. A personal email from one of the researchers, deployed in small batches, went out to each targeted respondent. Additionally, the National Association of Regional Councils (NARC) included the survey in their weekly newsletter one week. Given the temporal space between personal email deployments and the newsletter deployment, and the tracking of incoming responses by date, the research team estimates that only zero to two full responses were recorded as a result of the newsletter deployment. Researchers gathered email addresses to deploy the survey, developing comprehensive lists of bicycle and pedestrian coordinators and similar positions for each state using the Federal Highway Administration database of contact information (http://www.pedbikeinfo.org/data/state_contacts.cfm). This resulted in 100 target users who were initially contacted on Monday, October 26, 2015. Of those 100 potential users, 96 of the email invitations to participate went through successfully. One reminder email was sent to the State DOT portion of the sample on Friday, November 13, 2015.

Perhaps due to the fact that MPOs and councils of government (COGs) are not required by federal law to identify a person responsible for bicycle and pedestrian coordination, a complete list of people in that role for regional councils was not identified by the researchers. To contact MPOs and COGs, the research team developed a list of all MPOs and COGs in the country and identified contacts at these agencies by looking at agency websites. In some cases, researchers called state bike/ped coordinators and asked who they contacted at the regions in that state for regional bike/ped coordination. The follow-up calls also served as a reminder to the state coordinator to complete the survey. Contacts, including general transportation planners and in some cases agency directors when no bicycle or pedestrian staff member existed, were compiled for all identified MPOs and COGs. The resulting list of 683 target invitations (with 80 non-deliverable invitations) were sent on Tuesday, December 15, 2015, in addition to the 96 users from state DOTs. This gave a recipient list of 699 potential users, assuming the newsletter recruitment (which was sent on Thursday, October 29, 2015, to 379 recipients) was negligible.

6.2 Results

6.2.1 Respondents

A total of 238 responses were recorded at the close of the survey. Of these, 133 responses were complete with the user ending on the closing page of the survey. Only complete answers are used in the statistical analysis of the survey responses for consistency purposes with a known sample size. The 133 responses from a potential sample of 699 people gives a 19% response rate. Figure 4 shows the locations from which responses came in on a map of the US. Responses were also recorded from the states of Alaska and Hawaii (not pictured).

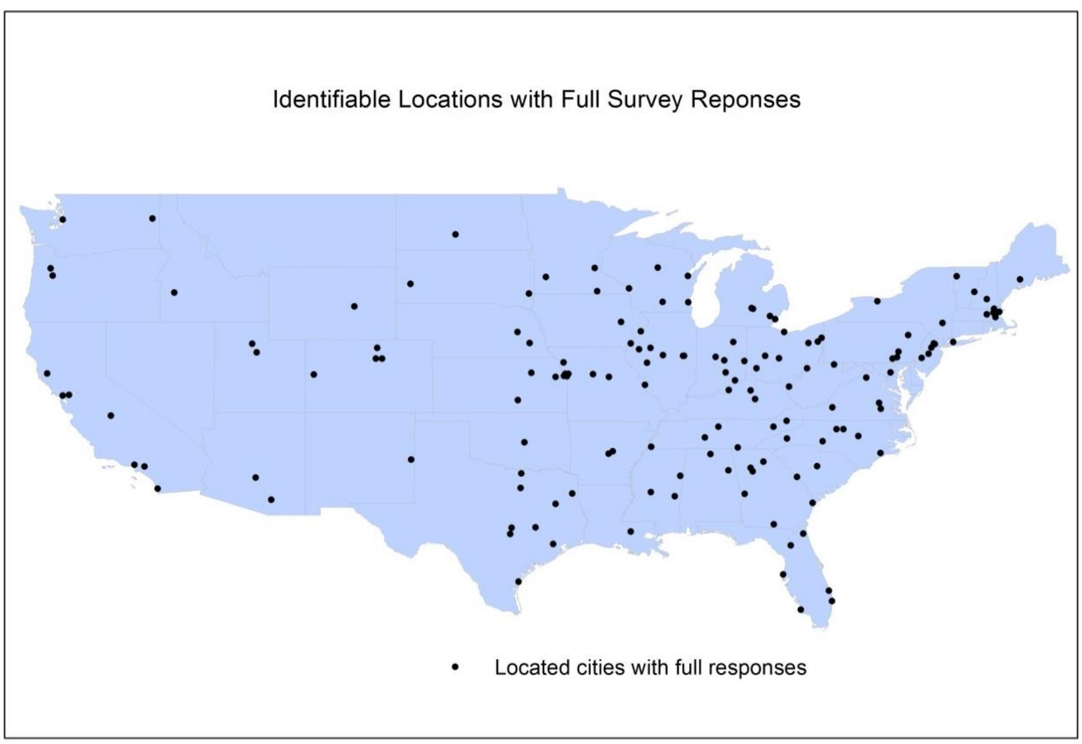


Figure 4. Geospatial Spread of Complete Responses (Responses from State DOTs are shown in location of the office where the survey was completed.)

Of the agencies reporting, 34% have at least one full-time person in charge of bicycle and pedestrian issues, 47% have at least one part-time person in charge of bicycle and pedestrian issues, 8% contract out bicycle and pedestrian work, and 21% do not have anyone to handle bicycle and pedestrian issues (note that some agencies have a combination of part-time, full-time, or contracted staff). The low number of agencies reporting staff who specialize in bicycle and pedestrian issues, along with 21% specifying that there is no specific person in charge of these modes, suggests a general lack of expertise and dedicated time for bicycle and pedestrian issues among transportation agencies.

6.2.2 Treatment Site Identification and Prioritization

The first step agencies often take when deciding to install a bicycle or pedestrian safety treatment is to identify a site where they believe a treatment would be beneficial. Respondents were asked to check all that applied of the variables in Table 11 when thinking about what they take into account when deciding where to place bicycle and pedestrian safety treatments. Table 11 shows the percent of respondents who identified each variable as one that they consider. Only one respondent answered that they do not know what variables are taken into account for these decisions.

Table 11. Variables used in Identifying Sites for Bicycle and Pedestrian Treatments

	Safety	Vehicle Volumes	Bicycle Volumes	Pedestrian Volumes	Connectivity	Cost–Benefit Analysis	Public or Advocacy Group Input	Coincidence with Other Projects	Monetary Cost	Economic Development	Equity	ADA
% use this metric	77%	41%	38%	43%	69%	27%	65%	76%	32%	33%	35%	45%

Safety considerations are common to take into account when identifying sites for bicycle and pedestrian safety treatments. The second-most common variable used for site identification is whether or not the project has an opportunity to link to other, already planned projects. The high level of use of coincidence with other projects for site selection suggests that bicycle and pedestrian safety treatments may often be a tag-on to other projects instead of a project that is selected with the goals of non-motorized safety in mind. This, combined with the fact that cost–benefit analyses are not very common, shows that while coincidence with other projects could keep the cost down, whether or not the treatment at the site provides a high benefit is not necessarily taken into account.

Responses to this question also show the high amount of influence that the members of the public and advocacy groups can potentially play in identifying sites for treatments. Of agencies in the sample, 65% reported that they take this type of input into account. Examining what the public and advocacy groups see as important for site identification would, therefore, be a useful next step to see what may influence the opinions that they share with decision-making agencies.

Since not all projects can be completed at the same time, or may not even be able to be completed at all due to funding, political, time, or other constraints, agencies must set priorities. The survey asked respondents to identify whether the variables in Table 12 below were "very important," "somewhat important," "not very important," or "not considered" when prioritizing sites for bicycle and pedestrian safety treatments.

Table 12. Types of Analyses Agencies Think are "Very Important" when Prioritizing Sites for Bicycle and Pedestrian Safety Treatments

	Safety	Vehicle Volumes	Bicycle/Pedestrian Volumes	Connectivity	Cost–Benefit Analysis	Public Input	Usage Analysis	Equity
% say this metric is "very important"	74%	32%	28%	59%	20%	44%	26%	25%
% say this metric is "somewhat important"	20%	53%	41%	32%	35%	49%	39%	48%
% say this metric is "not very important"	2%	8%	17%	5%	25%	3%	17%	14%
% say this metric is "not considered"	1%	3%	9%	1%	12%	2%	10%	8%

As with site identification, it is not surprising to see safety as being widely considered to be very important. In prioritizing sites, public input seems to be less important than in identifying possible sites to begin with, and connectivity remains an important element.

6.2.3 Treatment Type Identification

The survey asked respondents how their agency identified which bicycle or pedestrian safety treatments to use. Table 13 shows the percent of agencies who responded that they use each variable listed.

Safety, connectivity, and the coincidence of the ability to combine with other, already planned projects are the most common elements in choosing pedestrian and bicycle safety treatments. This is not particularly surprising since these variables also showed as important in identifying sites for treatments. Public input was seen to have an impact on site selection for the majority of agencies; however, while a popular method to help choose treatments, it was not for as many agencies as during the site selection process.

Table 13. Elements of Treatment Selection

	Safety	Vehicle Volumes	Bicycle Volumes	Pedestrian Volumes	Connectivity	Cost–Benefit Analysis	Public or Advocacy Input	Coincidence with Other Projects	Monetary Cost	Economic Development	Equity	ADA
% use this variable	55%	39%	36%	38%	51%	25%	45%	53%	31%	23%	25%	34%

Local, state and federal agencies have developed documents to try to assist agencies in bicycle and pedestrian transportation planning. Table 14 shows the most commonly used documents according to respondents.

Table 14. Most Common Reported Guidance Documents Used in Treatment Selection

Document	Number of answers including each document
AASHTO	43
NACTO	30
State DOT Guide	29
MUTCD	16
ITE	9
HSM	9

The American Association of Highway and Transportation Officials guide appears to be the most commonly used document in bicycle and pedestrian planning, with the NACTO guide and different state DOT guides also used a large amount.

6.2.4 Data and Research

Given the many avenues and strategies an agency can adopt to work on bicycle and pedestrian safety, such as collecting crash data, using guidance documents, conducting before and after studies for counts and safety, etc., there may be correlations or trends in what agencies are doing. The adoption of complete streets policies among agencies, breaking them into groups of agencies that have done before–after safety or count studies compared with those that have not done any such study give the results as seen in Figure 5.

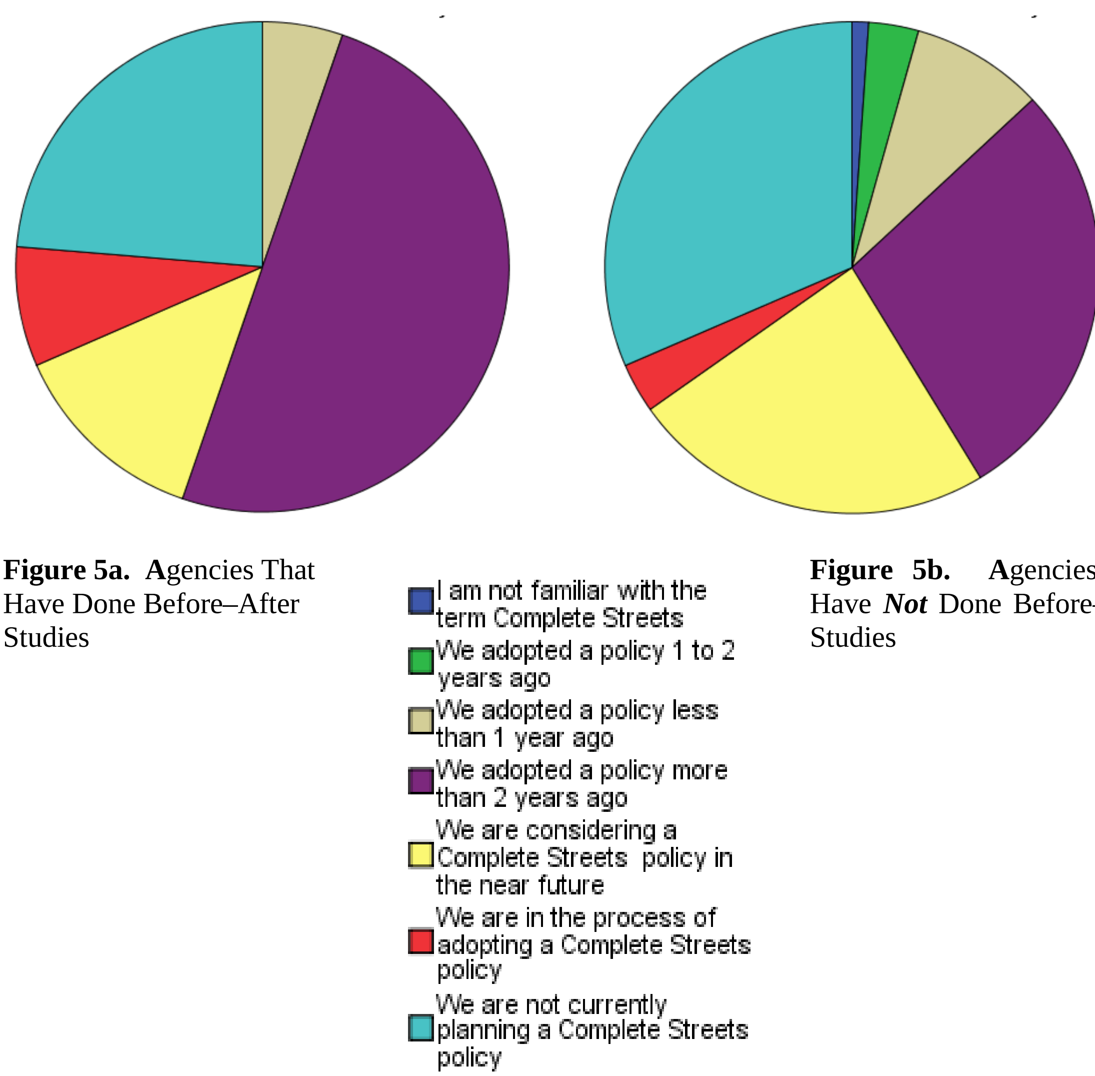


Figure 5a. Agencies That Have Done Before–After Studies

Figure 5b. Agencies That Have ***Not*** Done Before–After Studies

Figure 5. Adoptions of Complete Streets Policies by Agencies that Have and Have *Not* Done Before–After Studies

The agencies that have done studies have a higher probability of having adopted a complete streets policy two or more years ago or being in the process of adopting one. Agencies that have not conducted any studies are more likely to be planning to adopt a complete streets policy in the future or not at all.

About one-third (43 out of the 133) of the responding agencies stated that they did not collect any type of permanent or temporary bicycle or pedestrian counts. Table 15 shows the regions and states with the highest reported number of both temporary and permanent bicycle and pedestrian counting locations.

Table 15. Aggregated, Annual, Reported Bicycle and Pedestrian Count Locations

Metro Region	State	Number of reported bike/ped count locations (annual, aggregated permanent, and temporary)
Greensboro	NC	465
Wilmington	NC	390
Hingham	MA	215
Louisville	KY	210
Milwaukee	WI	190

Regions in North Carolina report the highest number of annual count locations, both also reporting on a high level of support and data from the State DOT. All of the agencies listed above also reported that they use counts collected from other regional, state, and/or private agencies.

Types of volume data collection vary greatly. Milwaukee uses mostly temporary count sites that count bicycles and pedestrians combined (150 sites), and Hingham does not collect any disaggregated counts for bicycles and pedestrians; all counts are combined. Greensboro, Wilmington, and Louisville all have more evenly distributed types of counts for bike only, pedestrian only, and combined bike and pedestrian counts, and the agencies have both temporary and permanent count sites. Both the Atlanta and Kansas City regions are examples of MPOs that assist local jurisdictions with temporary counts by loaning out counter equipment for months at a time. Both MPOs have tube and infrared counters that any local jurisdiction in their region can ask to borrow and receive assistance with setup and data acquisition.

The overall spread of the number of count sites different agencies in the sample have can be seen in Figure 6. The figure also separates responses grouped by whether or not they use counts from outside their agency. The 43 agencies that reported not having any permanent or temporary bicycle, pedestrian, or bicycle and pedestrian count sites do not appear in the figure.

Figure 6 distinctly shows two North Carolina cities spiking in counts in the 'yes' category in light blue (Wilmington) and red (Greensboro). The figure also demonstrates the correlation between agencies who have their own data collection sites and use data from elsewhere.

Of the agencies in the sample, 29% reported that they have completed some sort of before and after study. The majority of these studies reported measuring only once before and once after. Agencies that indicated conducting studies with multiple data collection instances after implementation reported: four studies that measured crashes involving bikes and pedestrians, zero studies measuring near misses, six studies measuring bicycle and pedestrian volumes, and seven studies measuring vehicle volumes. These numbers are very low to comprise even a sample of the literature on robust studies with multiple measurements after implementation by agencies. It is important to collect data multiple times after a safety treatment is implemented because the novelty of a new element to a driving/biking/walking environment can have an effect for a limited amount of time until users are accustomed to the treatment being there. Additionally, new infrastructure can affect risk exposure by encouraging or discouraging travel via certain modes. For example, replacing a vehicle lane with a two-way cycle track may encourage more cyclists and discourage more vehicles. Hopefully, the treatment will still be effective after this novelty wears off and once travel volumes change.

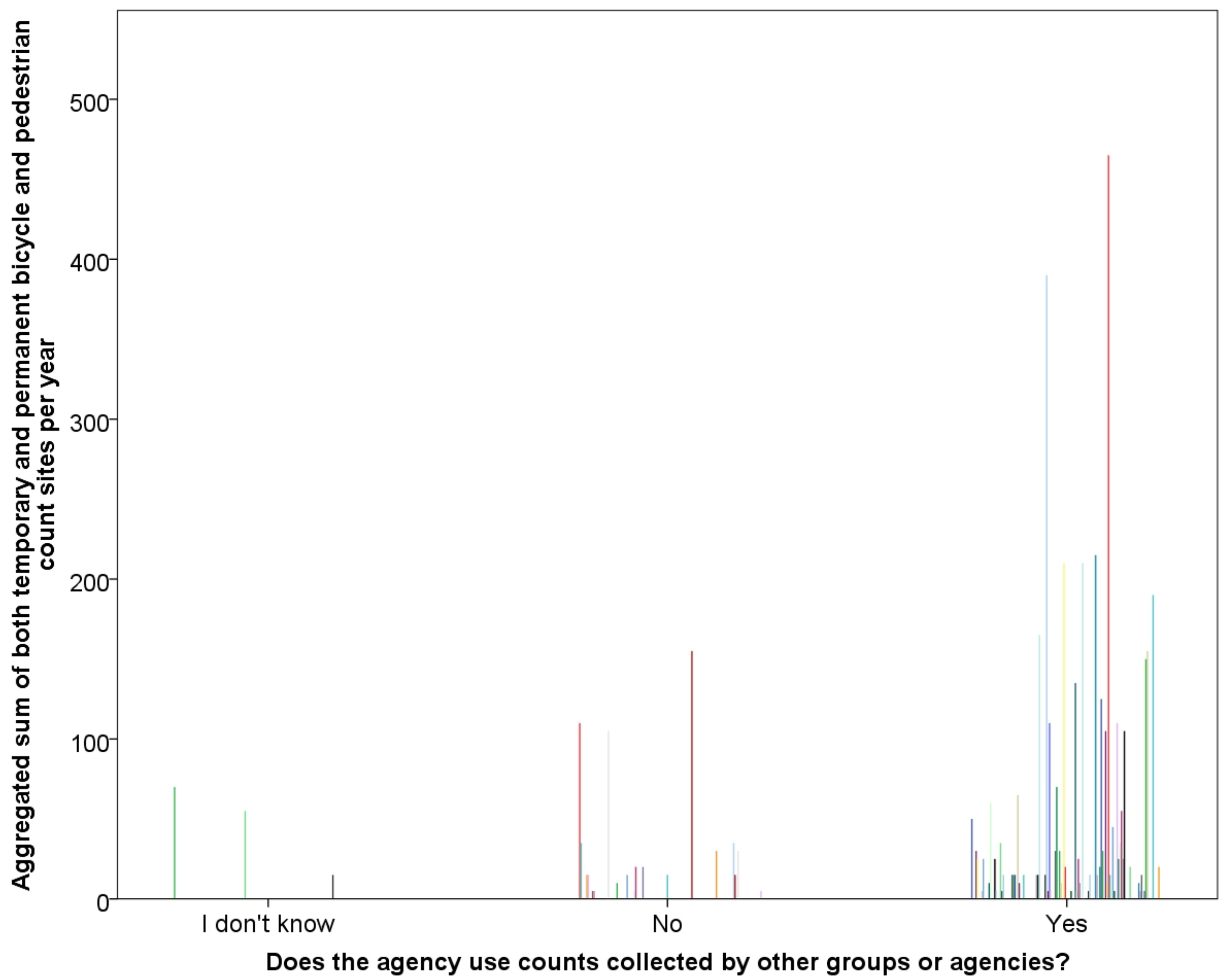


Figure 6. Number of Bicycle and Pedestrian Count Locations by Agency

An attempt at finding a linear relationship between collecting volume data and stating the bicycle and pedestrian counts are "very important" in prioritizing sites at which to consider treatments yielded little to no relationship between respondents' answers to these questions.

This suggests that other impediments to being able to collect bicycle and pedestrian volumes data exist, because, even if staff at an agency think it is important to consider volumes, that does not make the agency any more likely to collect volume data.

6.2.5 Best Practices

There are 33 agencies in the sample (about 25%) that (1) adopted a complete streets manual at least 2 years ago; (2) have at least one either part- or full-time person in charge of bicycle and pedestrian issues; and (3) collected some type of bicycle and/or pedestrian volume data. Of these 33 agencies, only 16 have actually conducted any sort of before–after study relating to bicycle and pedestrian safety treatments. Especially in cases where an agency has exposure (count) data, conducting these types of studies can give an idea of risk ratios and possible effectiveness of specific types of treatments under specific circumstances.

6.2.6 Separation of Pedestrian and Bicycle Issues

One common limitation in bicycle and pedestrian research is grouping the two modes together. Bicyclists and pedestrians have different needs and preferences for transportation facilities. This study asked agencies about safety treatments for both modes, and generally the person at an agency in charge of one is also in charge of the other. However, it is evident that the two modes are not always planned for in the same way, and some agencies prioritize cycling infrastructure or pedestrian infrastructure over the other or merely focus more on one. For example, the City of Savannah, Georgia and the MPO for the surrounding Chatham County discussed many projects involving bike lanes, multi-use paths, and road diets and performed an in-depth study with bicycle counts when they put in a new bicycle lane to track usage, route choice, and overall ridership in two directions. This focus on bicycle infrastructure may be related to the large share of cyclists and pedicabs in Savannah, as well as the existence of a bike share program in the area.

The metropolitan region of Trenton, New Jersey, on the other hand, focuses on pedestrian safety treatments more than bicycle safety treatments. The State of New Jersey has declared pedestrian safety a top priority and has clearly communicated this to MPOs. In recent years, the Trenton area has installed many pedestrian safety treatments for road crossings, such as HAWK signals, RRFBs, and high visibility crosswalk striping.

6.3 Conclusions

There is a very wide range of data availability and preferences and planning techniques among regional and state bicycle and pedestrian transportation professionals relating to bicycle and pedestrian safety. While the majority of agencies do not have a robust bicycle and pedestrian safety program with consistent and good exposure data and safety data limited to police reports of crashes, there are agencies with large amounts of data, and agencies doing a lot of good work with the data available to them. Comparing the states' responses from this survey with actual safety data would be a good next step to examine how different strategies and practices correlate safety outcomes for non-motorized users.

7 Development of a Method for Determining Crash Modification Factors

7.1 Site-Specific Case Study Approaches

As discussed in the literature review, numerous safety countermeasures have been proposed for bicycle and pedestrian facilities to promote pedestrian safety. While most planners and engineers agree that safety improvements along pedestrian and bicycle facilities are a critical need, the relative effectiveness of countermeasures is largely unknown and some of those that may be effective in reducing pedestrian crashes may even be at odds with motorist safety (Chen, 2012). Assessing the benefits and effectiveness of crash mitigation strategies requires the collection and analysis of sufficient, relevant, and appropriate observational data. As discussed in the literature review, crash frequency and exposure data (i.e., crash statistics) collected in Georgia are insufficient for assessing the direct benefits or even the relative safety benefits of control measures.

Given the lack of adequate crash data and exposure data for use in assessing the safety benefits of safety countermeasures at the aggregate level, alternative means of evaluating benefits may be needed. The site-specific case-study approach may be an assessment method that could prove viable in Georgia, where a significant number of projects that include pedestrian infrastructure improvements are planned and implemented every year. The goal of the site-specific study is to use direct observation before and after an improvement to identify whether changes in motorist, pedestrian, and bicycle behavior and interaction are likely to achieve a reduction in crash events and/or severity. With proper advance planning, analysts can collect design and environment data, motorist and cyclist and pedestrian activity data, and observed agent interactions before and after a planned improvement is made.

In site-specific case-study analysis, it is important to tightly control or specifically account for other conditions that could affect before–after condition assessment. It is important that nothing else that could significantly impact agent behavior or exposure changes through the influence of some outside independent factor (e.g., a new truck route implemented independently of the treatment diverts heavy-duty vehicle traffic around the treated location). Even when external factors are tightly controlled, it is important to note that bicycle and pedestrian crashes are rare events. Site-specific case studies suffer from the high probability that no incidents will be observed during the baseline data collection period and post-implementation study periods. Furthermore, zero observed events in the baseline followed by two observed events in a post-evaluation period may not mean that the modified facility has been made less safe. The observed changes may not be able to be differentiated from random events. As such, site-specific case studies may rely on less perfect data, such as perceived safety, assessment of changes in agent behavior analysis, or other aspects of vehicle–pedestrian/bike interactions (such as quantification of near-collision events). To this end, video data analysis can be employed in site-specific case study analysis. By way of example, a site-specific case study (video-based traffic conflict assessment) was conducted as part of this research effort.

7.2 Video-Based Traffic Conflict Assessment

The ability to analyze bike/pedestrian–vehicle conflicts through automated video detection could reduce the cost of conflict surveys and improve the quality and quantity of safety-related data. However, monitoring intersections can prove to be tricky, due to the presence of multiple flows of the vehicles with turning movements and the mixed traffic that stops at the intersection. Interpreting the video for traffic conflict detection requires a high level of understanding of the intersection.

Researchers often assume that all interactions can be ranked in a safety hierarchy, with collisions at the top (Hyden, 1987; Svensson, 1998). The interactions located next to collisions in the safety hierarchy are often called quasi-collisions, or collisions that might have occurred under slightly different circumstances. To operationalize the concept of quasi-collisions, the safety hierarchy must be transferred into measurable parameters using a set of assumptions. For each interaction in the hierarchy, a quasi-collision severity can also be estimated, based upon its place within the hierarchy. For example, the time separating vehicles from the location where a potential collision would occur in the absence of a driver reaction is presumably related to the probability of collision. A variety of severity indicators for quasi-collisions have been developed (Svensson, 1998; Van Der Horst, 1990), but are most commonly defined for two road users on a collision course as the extrapolated time for the collision to occur. Analysts have concluded that the similarity between collisions and quasi-collisions is significant enough (Van der Horst, 1990) to allow their use in safety diagnosis (Sayed and Zein, 1999). Currently, traffic conflicts and near misses are used as quasi-collisions to quantify safety effectively.

In bicycle and pedestrian safety analysis, a “near miss” would constitute a situation where an imminent collision is avoided by the attention and braking of a driver or the reaction and movement of the pedestrian or cyclist. That is, if one of the agents had failed to identify the danger and react in time, the collision would have occurred. Near-miss incidents occur much more frequently than crash events because agents are generally paying attention and reacting to dangers along their paths. Near-miss observations have been used as an effective substitute for crashes in various studies.

A study from Japan (Matsui, 2012) used time to collision as a quantifiable variable in near-miss incident data analysis. Time to collision was calculated from the velocity of a car with an installed data recorder, where the distance between the car and pedestrian at the moment a pedestrian appeared was captured by a video camera installed in the car. The time to collision was estimated from the near-miss data, considering the worst case that a car moving toward a pedestrian would result in an accident without the car driver's braking. Time to collision is probably a much better surrogate than distance to collision, as it accounts for reaction time, velocity, and braking distance. However, estimating time to collision requires trajectory data for both agents, which is typically difficult to obtain in case-study analysis.

7.2.1 Perceived Safety Analysis

Some studies that have analyzed near misses have included such factors as severity of evasive action, complexity of evasive action, distance to collision, and perceived safety. A study in the San Francisco Bay Area (Sanders, 2015) found 86% of those who cycled at least annually had experienced a near miss, with 20% having been hit. Another study in the UK (Aldred and Crossweller, 2015) investigated the occurrence of near misses among cyclists by collecting data from online surveys and analyzing the incidents and exposure by time of day, gender, and age, and observed that incident rate is positively associated with exposure.

Perceived-risk factors that have been categorized as near-miss incidents in pedestrian and cyclist behavioral studies have included:

1. Cyclist's way is blocked
2. Problematic passing maneuver
3. Vehicle pulls into or across pedestrian's or cyclist's path
4. Near left or right hook
5. Tailgating of cyclist without passing
6. Person opened a car door in cyclist's way
7. Driving too close (side or rear)
8. Speeding or aggressive driver

7.2.2 Traffic Conflict Techniques

The concept of traffic conflicts was first proposed by Perkins and Harris (1967) as an alternative to collision data. The traffic conflict technique involves observing and evaluating the frequency and severity of traffic conflicts at an intersection. Traffic conflicts are more frequent than collisions, and their study can give detailed information about safety. A traffic conflict between two road users includes two components: (1) identification that agents are on a collision course, and (2) observation of some kind of an emergency evasive action. Deciding if two road users are on a collision course depends on the extrapolation hypotheses. Common hypotheses are extrapolation with constant direction and speed. A traffic conflict is then defined as an observed interaction wherein two or more vehicles are close enough in space and time to meet a pre-defined conflict definition. The technique therefore provides a means for the analysts to immediately observe and evaluate unsafe driving maneuvers at an intersection.

Traffic conflict detection based on video sensors can be achieved with various methods. The approach described by Atev, et al., (2005) detects pairs of vehicles that would collide if they maintain their current speeds and directions. To decide if two vehicles are on a collision course, their positions, speeds and movement directions are required. This follows the same technique as mentioned in "near misses" by tracking the vehicle and pedestrians/bikes and calculating the time to collision.

Traffic conflict techniques have been used in research to form a qualitative framework that describes the mindset and rationale of road users. Kaparis, et al., (2013) uses video data from before and after periods at a conventional road treated with some elements of shared space. In this study, pedestrian confidence and vehicle tolerance were related to instantaneous characteristics of vehicle flow (vehicle approach speed and density). The interactions are categorized based on their severity, which is based on the change in pace, change in direction, and subsequent acceleration. The frequency and the severity of interactions are being used to develop a new qualitative behavioral analysis.

7.2.3 Naturalistic Driving Studies

Naturalistic driving has been developed as a result of advancing techniques enabling the collection, storage, and analysis of increasing amounts of data with increasingly efficient instrumentation. Studies in the United States (Du, et al., 2013; Lin, et al., 2015; Tian, et al., 2014) and Europe (Dozza, et al., 2012; Gustafsson and Archer, 2013) have applied naturalistic driving data in the analysis of motor vehicle/pedestrian and motor vehicle/bicycle interactions. Naturalistic driving data can also be employed in near-miss analysis (SWOV 2012). It also helps to understand pre-crash causal and contributing factors. The information regarding what is happening inside the vehicle just seconds before a crash can suggest countermeasures such as education, training, or advanced safety technologies that might mitigate certain types of crashes. In-vehicle event recorders (IVERs) have become a widely accepted means of gathering crash data both in research and real-world applications. The data allow researchers to examine behaviors and potential contributing factors in the seconds leading up to the collision, and provide information not available in police reports (Carney, et al., 2015).

Vulnerable road users (pedestrians and cyclists) have always been topics of interest when it comes to naturalistic driving studies. In-depth analysis of pedestrian and cyclist behavior in regular and near-miss scenarios have been conducted using the naturalistic data available. The data are used to observe pedestrian/cyclist and vehicle interaction from videos and study what scenarios might be more dangerous and could more likely result in potential conflicts. The data are then extracted effectively and analysis tools are used to identify factors that affect these interactions.

In 2002, with support from the National Highway Traffic Safety Administration (NHTSA), Virginia Tech Transportation Institute (VTTI) performed 100-car naturalistic driving data collection (Dingus, et al., 2006). The focus of VTTI's 100-car study was to obtain data on driver performance and behavior in the moments leading up to a crash. This database is available for public use on the Virginia Tech Transportation Institute website. These data have been used for various behavior analysis and safety-related studies. It would be worth considering implementing research that examines the applicability of the naturalistic driving data for use in vehicle, pedestrian, and cyclist interactions and near-miss analysis. Even if there are too few events observed in the naturalistic driving study video data, the detailed assessment of the data could be used to help quantify the amount of IVER data that would need to be collected to begin to use the data for identifying causal relationships and developing crash modification factors.

Recently, the National Academies of Science Strategic Highway Research Program 2 sponsored the SHRP 2 Naturalistic Driving Study (Antin, et al., 2011). The objective of SHRP 2 is to address the role of driver performance and behavior in traffic safety. The study recorded the driving behavior of a large sample of drivers (3400+ participants; 5,400,000+ trip summary records; and 36,000+ crash, near crash, and baseline driving events) in their personal vehicles, offering project researchers comprehensive naturalistic driving behavioral data for researching the interactions between drivers and various pedestrian features at selected signalized intersections through which they drove. For example, this approach was used effectively by the Florida Department of Transportation to understand the interactions between drivers and pedestrian features at signalized intersections to increase pedestrian safety (CUTR, 2015).

Overall, naturalistic driving observation as a method is recognized to be able to substantially improve understanding of a wide range of road safety issues. A large data set is required to verify, complement, and extend the results of the small-scale studies. Therefore, this analysis is not currently feasible with the available video data. However, if large-scale naturalistic driving data could be obtained from the intersection, it would be highly effective to perform this kind of analysis. Data collection of this type is very expensive. However, before-and-after naturalistic driving data may be worth collecting from volunteer fleets in specific areas where crash rates appear elevated and significant treatments are planned (such as the Buford Highway corridor in Atlanta).

7.3 Case Study Site and Data Collection

For this case study, the research team selected the intersection at 10th Street and Myrtle Avenue adjacent to the Piedmont Park where a high-intensity flasher would be installed to support pedestrian crossings in an area where commercial properties attract dining and shopping trips, and to simultaneously support cyclists who need to move from the south side of 10th Street into the 10th Street Cycle Track on the north side of 10th Street. Before the high-intensity flashers were installed, the site did not have any bike lanes for the cyclists to cross the street and no signal was provided to support pedestrian crossings. The installation of the high-intensity flasher crossing and crosswalk markings was based upon the premise that installation should have a notable impact on pedestrian safety. Video data were collected for the "before" and "after" analysis. As mentioned before, due to the lack of crash data, the research team explored the potential implementation of reasonable surrogates for crash risk. The goal of the study was to collect and analyze pedestrian, cyclist, and motorist activity before and after the installation of the beacon crossing and assess whether notable changes in operating conditions could be observed.

7.4 Analysis of Case-Study Video Data

Researchers at the Georgia Tech Research Institute (GTRI) have developed and deployed an automated video system that can be rapidly deployed for data collection to support the analysis of pedestrian behavior at intersections and midblock crossings, with and without traffic signals. This system is used to analyze the collected video data and automatically identify and characterize the number of pedestrians and their behavior. It consists of a mobile trailer with four high-definition pan-tilt cameras for data collection. The software is custom designed and uses state of the art commercial pedestrian detection algorithms (Usher and Daley, 2015). *T*he software could be further modified to identify vehicles and also calculate the time to collision. Thus, the "before" and "after" videos were analyzed manually to determine how effectively the software could be used.

Because vehicle trajectories are not available from the video data (a long field of view is required to obtain such data), time to collision could not be employed as a variable in the 10th Street case-study analysis. Instead, the before and after video for the intersection at 10th Street was manually reviewed to obtain estimates of near misses, based on the perceived risks presented earlier. The process was time consuming and results were subject to the observer's perception of risk.

7.4.1 Before-Treatment Video Analysis

Two cameras (Camera 1 and Camera 2) were used to record the "before treatment" videos. Camera 1 was mounted on the trailer and video was collected on November 10, 2014. Due to various technical issues with Camera 1, only 3 hours of video were recorded in total for the "before" analysis. The view from Camera 1 for the "before treatment" analysis is shown in Figure 7. Due to the lack of sufficient data from Camera 1, a hand-camera (Camera 2) was placed in an apartment window with a direct view of the intersection. Camera 2 was used to record video for four days (Nov 25, Nov 26, Nov 28, and Nov 29). The two views from Camera 2 are shown in Figures 8 and 9.

These video data were used to quantify the number of near-misses by observing pedestrian, bike, and vehicle behavior at the intersection. Near misses were identified as sudden changes in speeds of the vehicle, sudden changes in direction of the vehicle to avoid collision, and driving too close. Figures 8 and 9 provide the fields of view. View 1 makes it easy to observe near misses. However, it is not possible to calculate the approach speed of the vehicle as the field of view is too narrow. This eliminates the possibility of calculating time to collision in the before-treatment videos.

View 1 included 48 hours of video that were manually analyzed to obtain the number of near misses. The videos did not record any crashes. An average of one near-miss for every two hours was observed. Peak hours included more near-misses than off-peak hours. Vehicles usually slowed down or stopped to let the pedestrians cross the road, and the cyclists were comfortable riding on the road with the vehicle traffic. Two near misses were observed for cyclists when they rode too close to the vehicle traffic. Even on this heavily-traveled cycle-path and active pedestrian crossing the data collected for 48 hours were insufficient to identify any significant issues or trends or come to any significant conclusions.

Figure 7. View from Camera 1 (Before Treatment)

Figure 8. View 1 from Camera 2 (Before Treatment)

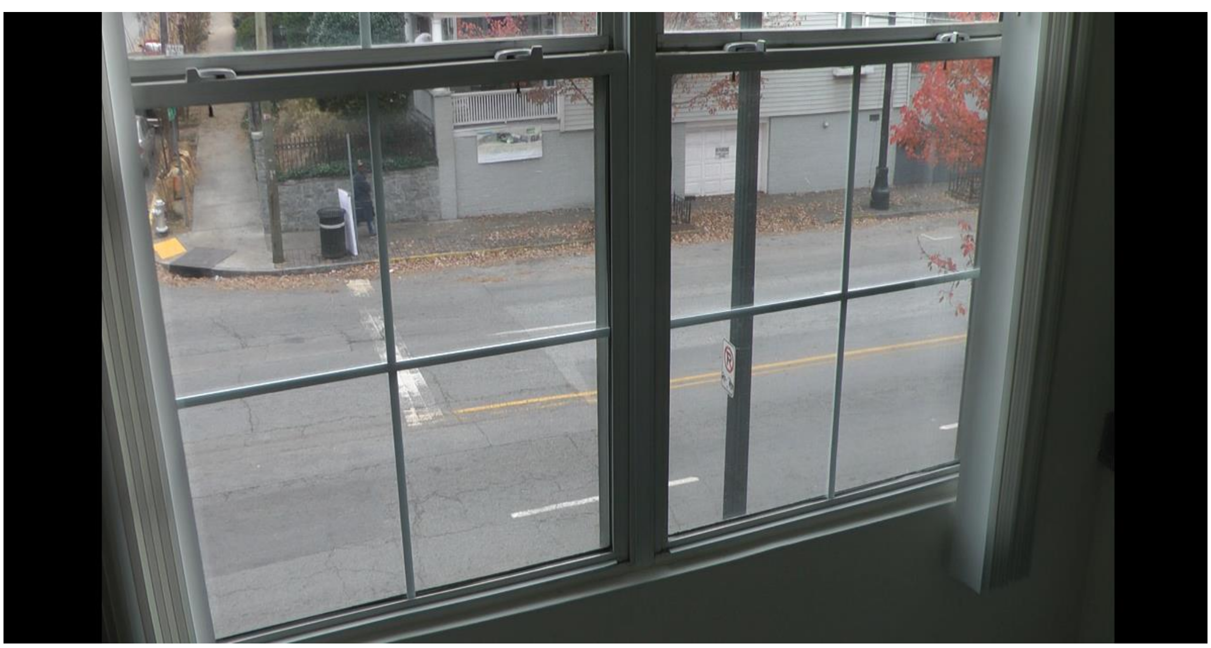


Figure 9. View 2 from Camera 2 (Before Treatment)

7.4.2 After-Treatment Video Analysis

For the after-treatment analysis, Camera 1 was used to record the data for a period of five days (Oct 8 to Oct 12, 2015). Care was taken to mount the camera at the proper angle to obtain the required field of view for calculating time to collision. The view from Camera 1 for the "after treatment" videos is shown in Figure 10. Initially, the camera was supposed to record data from Wednesday through Sunday. However, due to technical issues, videos were available only for Thursday and Friday (Oct 8 and Oct 9). Due to rain and battery issues, weekend data could not be collected.

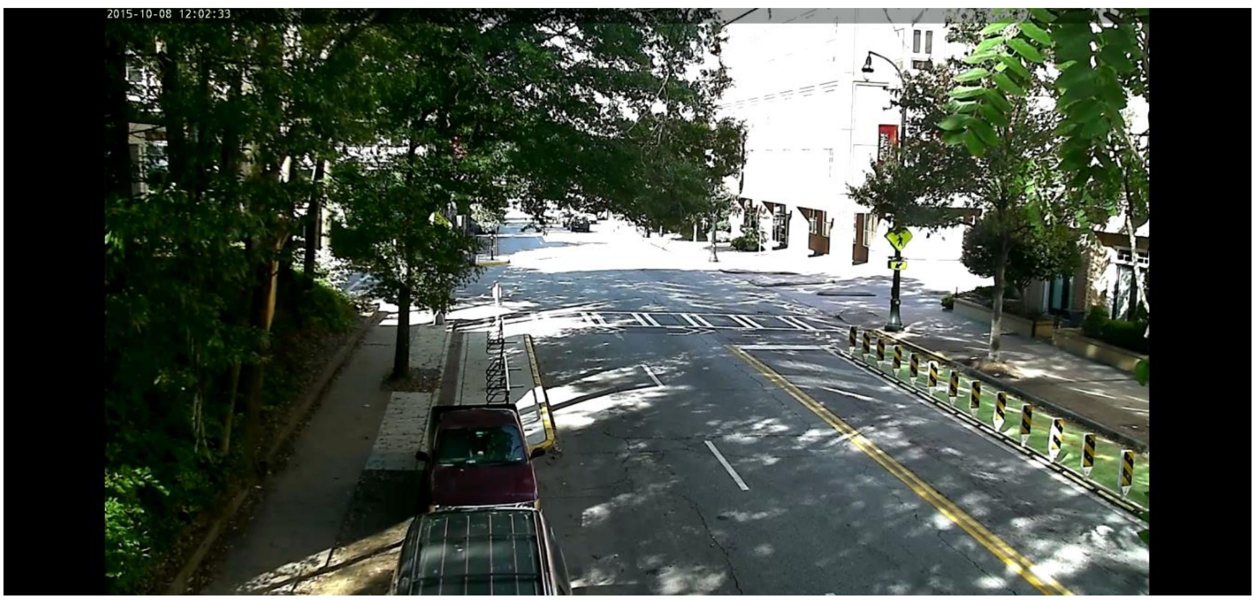


Figure 10. View from Camera 1 (After Treatment)

Figure 11 includes a long field of view, which allows the approach speed of the vehicle to be calculated using the known skip line lengths. However, the time-to-collision data were not useful because barricades were placed along the sidewalks at the commencement of the "Pride Parade," and no conflict was available for the weekend. A second recording setup was arranged such that there would not be any problems with the weather or conflicts with parades. Camera 2 and Camera 4 were used to record the data for a period of four days (March 3 to March 6, 2016). However, during recording, it did rain on March 10, resulting in fewer-than-expected pedestrians and cyclists. Care was taken to mount the camera at the proper angle to obtain the required field of view for calculating the time to collision. The view from Camera 2 and 4 for this after-treatment video is shown in Figures 11 and 12, respectively. Initially, the camera was supposed to record data from Wednesday through Sunday. However, due to battery issues, videos were available only for Thursday and Friday (Mar 3 and Mar 4). These videos provided a much clearer view than previously recorded videos and, hence, can be used effectively to count the number of pedestrians crossing the road and also to calculate time to collision.

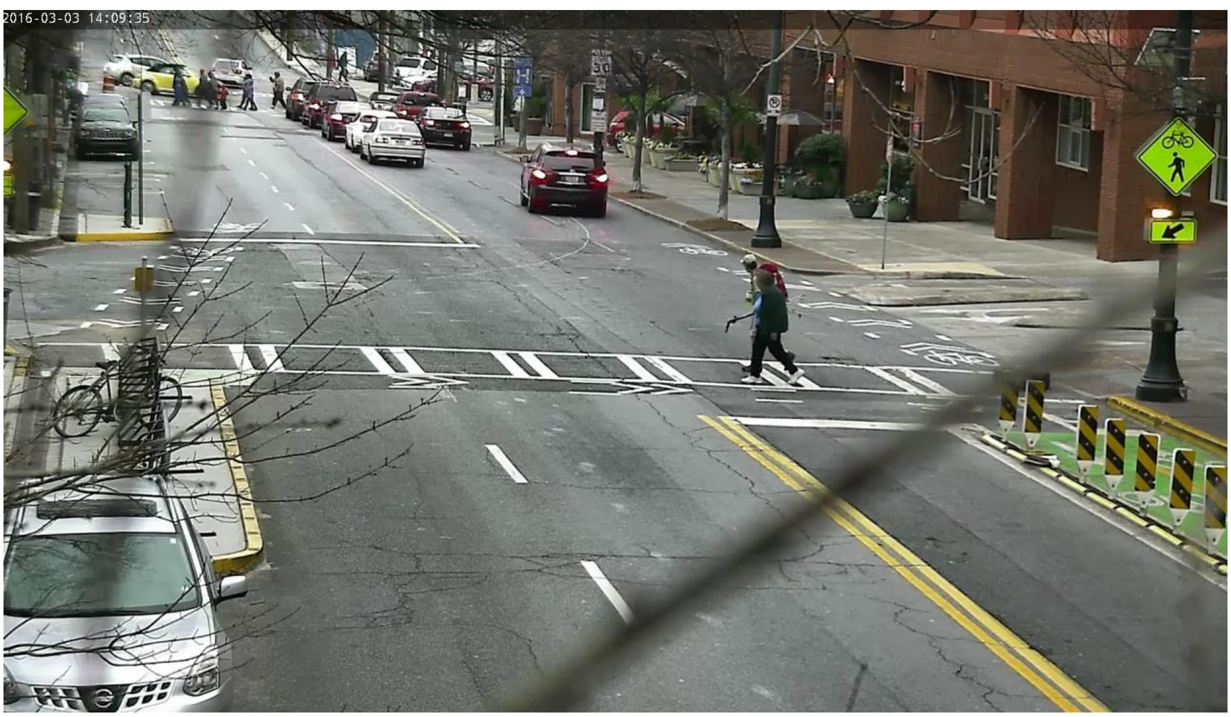


Figure 11. View from Camera 2 (After Treatment)

Figure 12. View from Camera 4 (After Treatment)

After manually analyzing the videos from March 3 and March 4, 2016, it was observed that most of the pedestrians tend to use the HAWK signal before they cross. However, vehicles do not yield every time the signal is flashing. A thorough analysis could be done with better software and better data, which could lead to much better conclusions.

7.5 Site-specific Case Study Challenges

The research reported in this chapter is a demonstration of site-specific case-study analysis; a before-and-after assessment associated with the implementation of a pedestrian and bicycle treatment on 10th Street in Atlanta. Video data were collected and analyzed to provide a qualitative data assessment of agent interactions (vehicle-bicycle and vehicle-pedestrian) using traditional, subjective near-miss criteria.

The final goal of case-study field research is to collect sufficient applicable data to identify factors affecting mode safety and to develop design guidance for the construction of new bicycle and pedestrian facilities and/or implementation of safety interventions. Site-specific case studies can be used to try to assess the impacts of bicycle and pedestrian treatments on bicycle and pedestrian volumes, crash frequency, crash severity, and other factors associated with these modes. However, site-specific case studies are difficult to implement, subjective in nature (unless time to collision can be objectively quantified for the case), and expensive to implement to obtain useful data. Furthermore, the number of days and number of sites that need to be implemented to obtain useful and sufficient data are likely to be impractical.

The manual method of observation and counting used in this project is not a viable option for multiple intersections. Also, the lack of sufficient data for this particular intersection poses a challenge for the before-after analysis. Quantitative analysis could not be performed effectively. Even if better video data were obtained, the software developed by GTRI should be tested and calibrated for the intersection and applied effectively. The software should also be further modified to collect speed and trajectory of vehicles and pedestrians to calculate time to collision. Video detection and spatial tracking of pedestrians is difficult. Therefore, miscounting issues also need to be addressed.

A qualitative or quantitative analysis can be performed using "before" and "after" site-specific case study video data. However, the technical challenges and costs are significant, and very limited data are returned per dollar expended. Other intersections could be selected for study using the video data collection and the software analysis platform system developed by GTRI to calculate time to collision. The research team would not recommend implementation of video case-studies without including time-to-collision as a quantifiable variable in quasi-collision near-miss analyses. Site-specific case study analyses need to be carefully planned to ensure that adequate representative data are obtained over sufficient duration.

8 Project Planning Level Tool for Assessing Facility Effectiveness

CESTAT, the Cost Estimator for Safety Treatments in Active Transportation, is a practical tool to assist GDOT in analyzing costs and benefits of common safety treatments for pedestrian and bicycle modes. The purpose of the tool is to provide a high-level estimate for the planning of pedestrian and bicycle treatments.

8.1 Scope

CESTAT includes 66 pedestrian and bicycle treatments. These treatments are generally categorized as linear, crossing locations, signals/signs, and traffic calming/traffic management. Cost components include capital, operations, and maintenance over the life span of a treatment. All costs are presented as net present value in 2016 dollars. Benefits are estimated as monetized value of avoided injury and fatal crashes over the life span of the treatment. As with costs, benefits are also presented as net present value in 2016 dollars. The default discount rate is 3% and users can customize this number. The resultant benefit–cost (BC) ratio is calculated as

$$BC\ Ratio = \frac{Total\ Injury\ and\ Life\ Savings\ over\ Life\ Span\ (2016\ \$)}{Total\ Costs\ over\ Life\ Span\ (2016\ \$)}$$

8.2 Key Assumptions and Data Sources

8.2.1 Costs

CESTAT includes a comprehensive list of pedestrian and bicycle treatment costs from multiple sources, including GDOT; FHWA; Alameda County, CA; and the Pedestrian and Bicycle

Information Center. To reflect the variable nature of costs, CESTAT includes the low, high, median, and average costs from the different sources. For BC ratio calculation, the median cost is used.

8.2.2 Savings

To estimate the benefits of pedestrian and bicycle treatments, CESTAT requires three main components—number of crashes before the treatment, crash modification factors, and cost per crash. CESTAT has built-in estimates for crash modification factors for each treatment, based on the aforementioned literature review, and cost per crash data based on Miller, et al., (2004). The cost for each crash is for injury and fatal crashes only, and includes medical cost, work loss, and quality of life loss.

Users will need to supply the total number of crashes per year for the treatment of interest. Out of the total crashes, CESTAT assumes that 83% are injury or fatal crashes. This ratio was estimated based on an analysis of pedestrian crashes in Georgia in 2015 as extracted from the GEARS safety database.

8.3 Future Work

CESTAT establishes a framework in which pedestrian and bicycle treatments can be analyzed in a consistent manner. However, the tool currently suffers from lack of data for both costs and savings. In terms of costs, two types of improvements are needed as data become available. First, many of the costs currently embedded in the tool are from jurisdictions outside of Georgia. GDOT can customize the tool by supplying the tool with Georgia-specific cost information. Second, while most sources have information regarding construction costs, operations and maintenance (O&M) costs have not been well tracked. Because many treatments feature long life spans during which O&M costs can accumulate, having accurate O&M costs is very important for making informed decisions regarding safety treatments.

The lack of data with regard to savings from avoided crashes, however, is a more acute issue that affects the accuracy of CESTAT results. The crash modification factors included in CESTAT are based on a limited number of studies, and may not necessarily suit local conditions. These CMFs are also not controlled for functional class, vehicular volume, vehicular speed, pedestrian and bicycle volume, or the surrounding land use. As data become available, the tool can be refined to reflect such strata.

9 Highway Safety Manual Analysis as Compared to Case-Control Strategies

The Highway Safety Manual provides users with guidance on use of a variety of robust statistical methods to assess transportation safety. Foremost among these is the HSM predictive method that is based on the development of *safety performance functions* to predict crash rates for specified conditions and *crash modification factors* to assess the impact of particular treatments or conditions on these predicted rates.

As discussed by Rodgers, et al., (2015), these SPFs belong to the broad class of Risk/Exposure models. In Risk/Exposure models, the expected number of crashes or other events (e.g., fatalities or serious injuries) is given as the product of a "risk factor" and an "exposure factor." The "risk factor" represents the probability that the particular adverse event will occur during a single "activity." In this case, activity can be described in a number of different ways. For example, an activity could be defined as crossing a busy street, walking a mile along the sidewalk, or bicycling along a trail for a minute for the purposes of a particular analysis. The associated exposure factor represents the total number of times that the activity is performed in a specified time period (e.g., a day or a year).

SPFs are simply models of risk factors and how they change with levels of activity for a standard set of conditions (e.g., a rural highway or a freeway ramp). For highway safety, the most common activity used is VMT to take advantage of the data collected by the Highway Performance Monitoring System (HPMS) and other traffic monitoring programs. CMFs associated with safety treatments, thus, tell how the associated risk factor is modified by the presence of the treatment.

Successful application of the HSM predictive method to the case of bicycle and pedestrian safety, thus, requires four separate activities:

1. Defining a "standard" set of conditions and activity factors that will be used for assessing bicycle and pedestrian safety
2. Assessing the risk of crashes, injuries, or fatalities (adverse events) to bicyclists and pedestrians under these "standard" conditions (i.e., developing an SPF)
3. Measuring the activity of bicyclists and pedestrians
4. Understanding how departures from "standard" conditions, including safety treatments, influence the risk of an adverse event

Unfortunately, all four of these activities are more difficult for bicycle/pedestrian safety than for highways. Because both bicycles and pedestrians operate under a broader range of conditions than do motor vehicles, which are largely limited to roadways, defining reasonable "standard" conditions is more difficult. Likewise, activity data are very much more limited. With sufficient time and resources, both of these problems could potentially be addressed.

9.1 Required Data for Highway Safety Manual Analysis

To achieve the activities above, three categories of data are required for a quantitative HSM-type analysis:

1. *Exposure data*; e.g., traffic (vehicular, pedestrian, and bicycle) volume, miles or hours traveled.
2. *Roadway characteristic data*; in this case, pedestrian and bicycle facility characteristics in addition to the standard roadway characteristics

3. *Crash data*, or other surrogate measures

The following section describes the availability and quality of existing sources for each of the three data categories.

9.1.1 Exposure Data

A naïve before–after study for a safety treatment may find an increase in crashes or no change at all, and conclude that the treatment was ineffective. But without knowledge of cyclist exposure, there is no way of assessing the change in risk. For example, if total bicycle crashes increase after a treatment is installed, an actual decrease in risk on a per-cyclist basis might be more than offset by an increase in cyclist activity (i.e., bicycle-miles-of-travel). Similarly, if bicycle crashes decrease after a treatment, an increase in risk on a per cyclist basis may be more than offset by a decrease in vehicle traffic volumes if automobiles divert to alternative routes around the treatment (potentially increasing cyclist risk on those alternative routes).

With regard to pedestrian/bicyclist safety, exposure is defined as pedestrian/bicyclist proximity to potentially harmful situations involving motor vehicles (i.e., crossing an intersection). Exposure is related to the opportunity to have a crash and represents a precondition that must be present in order to have a crash. Pedestrian/bicyclist risk is defined as the probability that a pedestrian/bicyclist crash with a vehicle will occur based on the exposure. Firth (1982) identifies exposure as one of the vital factors contributing to an accident and argues that combining accident and exposure data will provide a better insight into the possible causal factors. There is no single best measure of pedestrian exposure, but some measures are better adapted to specific needs and purposes. The major types of exposure data include the following:

- *Population measures* have been proposed as an estimator for motor vehicle and pedestrian/bicyclist exposure to risk. The data are easy and cheap to obtain and are available for most geographies and time periods. However, such population-based exposure metrics are not sensitive to the amount of time or distance that a pedestrian/bicyclist is exposed to motor traffic, change in behavior of pedestrians/bicyclists, and location factors (Molino, et al., 2012).
- *Pedestrian/motor vehicle volumes* have been used as another exposure metric, which consists of multiplying pedestrian volumes by motor vehicle volumes (P × V) (Cameron and Milne, 1978; Davis, et al., 1987; Tobey, et al., 1983). This is useful to investigate the relationship between pedestrian/motor vehicle conflicts and crashes. The problem with this method is that it does not account for the time and distance separation between the pedestrian and the motorist, and these data cannot be adapted at a macro level.
- *Walking/biking trip* numbers taken by an individual can also be used to measure exposure, regardless of the distance or time the journey takes. The data are useful to assess exposure over wide areas. Number of trips may not be the most useful metric for risk analysis purposes, but it is commonly used for assessing pedestrian/cyclist behavior and activity, for making comparisons between large jurisdictions, and for examining changes over time (Green-Roesel, et al., 2007).
- *Amount of time* that a pedestrian or bicyclist engages in certain activities is a common measure of exposure in Europe. It can be used to measure exposure at both macro and micro levels. However, it is not sensitive to the location of the person.
- *Total aggregate distance* travelled by a pedestrian across an intersection or on a sidewalk is another exposure measure. The FHWA developed a report in 2012 that

presents a methodology for measuring a region's pedestrian and bicyclist exposure: it is defined as 100 million pedestrian/bicyclist mi (161 million pedestrian/bicyclist km) of roadway (or other motor vehicle shared facility) traveled. This measure includes both volume and distance travelled (Molino, et al., 2012). Although this measure is more detailed than others, it does not take into account the speed of travel and, thus, cannot be reliably used to compare risk between different modes.

One common theme among the literature was a lack of standardized, transferable exposure data to understand the extent to which users are exposed to risk. 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.

9.1.2 Infrastructure Characteristics Data

Infrastructure characteristics data are needed for developing facility-specific SPFs and CMFs, to select treatment and control locations, and to implement systematic data collection and monitoring plans. In terms of infrastructure characteristics, pedestrian and bicycle studies face different challenges. For bicycle infrastructure, the standard roadway characteristic (RC) link databases can serve as the base data platform. The task at hand is to identify attributes to be incorporated into the RC link database that are essential for tracking bicycle infrastructure based on the level of stress associated with cycling on that infrastructure. Georgia Tech research is ongoing to better understand the stress associated with certain levels of facilities and which factors have a substantial impact on that level of stress.

For pedestrian infrastructure, there is an additional challenge. Most jurisdictions that track pedestrian infrastructure assets typically record pedestrian infrastructure data in connection with a simple linkage to an established roadway network. That is, pedestrian infrastructure data are tagged to roadway links; independent pedestrian infrastructure networks are generally not generated and used in asset management due to the resource commitment required to generate an independent pedestrian infrastructure network. However, the roadway database is inadequate for effective pedestrian infrastructure management. For each roadway link, there are two sides of the road where a sidewalk could exist; therefore, two sidewalk links are needed for each roadway link. Furthermore, an intersection is typically represented by one node in the roadway database. However, a typical four-way intersection can have four crosswalks and eight curb ramps. It is very difficult to record the condition of each of these elements using a single node in the roadway database. On the other hand, with an independent pedestrian infrastructure network, a four-way intersection would include four nodes, rather than the single intersection node, and links would represent the four crosswalks that connect the pedestrian infrastructure nodes at the four corners where the streets intersect. Therefore, for any metropolitan area that is concerned about the state of good repair of their pedestrian infrastructure, an asset management system specifically designed for sidewalk infrastructure could prove very helpful.

Pedestrian infrastructure network generation (Eggermond and Erath, 2013) has been conducted mainly within geographic information systems (GIS). Karimi and Kasemsuppakorn (2013) present an extensive review of sidewalk network map generation approaches. A distinction can be made between three main approaches: network buffering, collaborative mapping with global positioning system (GPS) traces, and image processing. Of these approaches, network buffering requires the least computation effort, and image processing requires the most. The outcome of all three approaches depends on the completeness and quality of the input data. Ballester, et al., (2011) present a method based on images to generate sidewalks and walkable plains (i.e., squares). Kim, et al., (2009) made a distinction between roads and crossings and point out that the accuracy of the pedestrian infrastructure network is strongly based on the sophistication of the spatial datasets. Parker and Vanderslice (2011) proposed a tool to create sidewalks from road centerlines and create crossings based on road intersections. Compared to GPS traces and image processing approaches that require either extensive data collection or complicated algorithms, network buffering is the least expensive and time-consuming approach, relying on existing spatial data. However, the quality of the previously developed network buffering methods relying on existing spatial data and are dependent on the quality and availability of input data.

The GT team has developed a pedestrian infrastructure asset management database and the supporting pedestrian infrastructure network generation methodology that uses parcel data as the main input data (Khoeini, et al., 2015). The advantage of this methodological approach is that parcel data have high spatial and temporal quality. They are publicly available and free across most of the states. The high quality of parcel data is due to legal applications in disputes and lawsuits. The management database is being used in an existing Atlanta Regional Commission project and will be used in a forthcoming Department of Energy project.

Understanding exposure and risk is more complicated than simply estimating total activity, crash rates, and severity. The ultimate goal of developing crash modification factors is to facilitate the selection of treatments that reduce crash rates or severity. For every potential intervention, the change in on-road operating conditions that affect crash or rates or severity must be understood. That is, the cause-effect relationships at work must be identified and quantified through data collection and analysis before crash modification factors can be developed. For example, widening bicycle lanes is thought to reduce cycling risk by providing a wider separation between bicycle and automobile traffic and improving lines of sight and cyclist visibility. To assess whether such an intervention reduces crash rates, the activity on 3-foot bicycle lanes and 5-foot bicycle lanes must be tracked separately, as well as the number and severity of crashes occurring on the different facility types. Further complicating the analysis, any other factors that may impact these crash rates must be controlled in the data set. For example, if the presence of heavy-duty truck activity impacts crash rates or severity, tracking of truck activity on both facilities is needed to ensure that the impacts of bicycle lane widening can be isolated from the impacts of truck activity. Identification of all of the cause-effect relationships potentially involved in risk assessment is critical, and field studies need to ensure that the differences in all of these variables across treatment alternatives are quantified. These variables will serve as independent variables in statistical analyses. The larger the number of potential variables that need to be controlled in statistical analyses, the larger the number of sites that need to be monitored, and the longer the duration of monitoring that must be conducted. Furthermore, the HSM assumes that countermeasure CMFs have independently additive benefits (FHWA, 2013). However, for bicycle infrastructure in particular, benefits may not be multiplicative for combinations of treatments.

9.1.3 Crash Data

To meet federal reporting requirements, state DOTs maintain a crash information database containing basic information (e.g., time, location, number of vehicles, type of crash, injuries) regarding crashes and often maintain an archive with images of the police reports from which these data were drawn. Crash databases serve as a standard database in safety analysis.

Knowing what types of activities even expose pedestrians and cyclists to risk is a major issue. 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. For example, knowing that a large number of accidents involve an impact in the left rear quarter panel of a turning vehicle helps researchers understand causality and design appropriate safety treatments. Much of the causation data found in crash reports is less relevant for non-motorized users, leaving critical gaps in information (Karsch, et al. 2012). Karsch, et al., (2012) suggest that better data on crash causation for pedestrians and cyclists could be captured by using standardized, automated crash reports specific to non-motorized modes. If the report were electronic, the level of detail could be enhanced and the system could provide automated instructions to officers on how to complete specific data entry fields. Enhanced crash details would likely help answer questions about crash causation, which could contribute to better exposure data and treatment designs. Research is needed in this area to determine what data would be best to include in non-motorized crash reports.

One significant issue in the understanding of the safety attributed to bicycling and walking is the substantial underreporting of bicycle and pedestrian crashes in official crash records. Bicyclists and pedestrians in particular are less likely than other users to report crashes (Cryer, et al., 2001; Maas and Harris, 1984). Elvik and Mysen (1999) 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 because cyclists in particular are less likely than other users to report crashes (Cryer, et al., 2001; Maas and Harris, 1984).

Multiple studies have been done using emergency room data by matching crashes reported at the emergency room to police crash reports. One older paper drew attention to this problem, finding that only 55% of patients treated for injuries were found in a motor vehicle crash report (Barancik and Fife, 1985). Studies focused on non-motorized travelers have found 44% of pedestrian crashes and 52% of bike crashes went unreported in the crash database using data in California, New York, and North Carolina (Stutts and Hunter, 1998) and 21% using data in San Francisco (Sciortino, et al., 2005). A comparison of National Center for Health Statistics (NCHS) and National Highway Traffic Safety Administration databases indicated a discrepancy of about 8% to 10% because NHTSA only includes fatalities that involve a motor vehicle and occur on a public roadway (Rodgers, 1991).

This method of tying hospital records to crash data to assess underreporting means that only crashes that involved a serious injury or fatality would be included in the analysis. One study that used a survey on college campuses found that less than 10% of crashes were reported, predominantly because students thought the crash was too minor (Loukaitou-Sideris, et al., 2014). Clearly, underreporting of crashes, especially for pedestrians and cyclists is a substantial issue. Therefore, using from one database versus another can impact the actual crash rates and the change in crash rates. Furthermore, if low-severity crashes go unreported, treatments that improve such crashes will not show results in improving crashes.

Perhaps most critical in using crash records for pedestrian and bicycle safety research is that crashes are rare events, especially in places where pedestrian and bicycle activity levels are low. Therefore, a more fundamental problem for applying the HSM predictive method to bicycle and pedestrian safety is obtaining the data necessary to quantitatively estimate both the SPF and the associated CMFs necessary to evaluate the effectiveness of safety treatments.

9.2 The HSM Predictive Method applied to Bicycle and Pedestrian Crashes

To understand why data are the key to applying the HSM method to bicycle and pedestrian safety, consider a particular example. From 2003 to 2013, approximately 155 pedestrians and 20 bicyclists were killed in Georgia each year in reported crashes. The number of serious injuries is more difficult to determine as actual values tend to be underrepresented in crash reports. However, studies from New York City indicate that there are perhaps 50 serious injuries for every fatality (the exact ratio is not important) (New York City Department of Health, et al., 2006). Thus, for bicyclists there are perhaps 1000 serious injuries/fatalities per year statewide. Estimates of the ratio of total crashes to serious injuries for bicyclists vary, but with an assumed ratio of 10:1 (i.e., 10% of bicycle crashes involve serious injury) the estimate may be 10,000 bicycle crashes per year in Georgia.

While 10,000 bicycle crashes, 1000 serious injuries, and 20 deaths carry a very high social cost, thus justifying a significant investment in safety, it does create problems for the application of the HSM predictive method. To see why this is the case, consider motor vehicle crashes. Each year there are approximately 360,000 motor vehicle crashes in Georgia of which the highest locations (a few intersections and some freeway ramps) account for about 0.1% or about one crash per day. Applying that factor to bicycle crashes (again the exact factor is not important) would imply that the top locations for bicycle crashes are unlikely to experience more than 1 crash per month. Typical locations would be much lower, with one crash per year or less.

While SPFs could be developed by looking at numerous sites, evaluation of quantitative CMFs for safety treatments is likely impractical. For example, at this hypothetical “top site” collecting the approximately 350 or so incidents necessary to determine a CMF value to a 10% uncertainty would require the better part of a decade.

For this reason, it is imperative that data collection practices improve immediately. However, in the interim, a different approach is required to understand bicycle and pedestrian safety in Georgia; specifically, the use of case control strategies.

9.3 Case Control Strategies

Representative data for activity, prevailing conditions, and crash rates are not likely to be generated from region-wide sampling efforts for a reasonable cost for over a decade. Given the impractical nature of ubiquitous monitoring, alternative means for assessment need to be developed and implemented to supplement ongoing efforts to improve exposure and risk data collection.

Given the infrequent nature of bicycle and pedestrian crash events, and the lack of current knowledge associated with treatment benefits and effectiveness discussed in the literature review, site-specific case-study analysis serves as a more practical immediate option. That is not to say that larger-scale counting programs should not be implemented, but given the example above, such counting programs will not be enough to probabilistically monitor safety. With proper planning, before-and-after studies can be implemented to assess changes in agent activity, agent interactions, crash rates, prevailing conditions, and perhaps, ultimately, risk-exposure and risk-mitigation. However, as discussed in the previous chapter, site-specific case-study monitoring and analysis requires a significant effort to ensure that comprehensive and representative data are collected both before and after the treatment is installed, and to ensure that all competing factors that could affect risk within the case study are properly controlled for the duration of the study.

There is also some inherent risk associated with implementing only a site-specific case-study approach, in that safety treatments are implemented without a priori knowledge or insight into whether the treatments will reduce risk to cyclists and pedestrians. This approach is tantamount to conducting controlled experiments to assess:

1. whether the interventions appear to have provided a benefit (reduced crash risk and severity);
2. whether the imposed costs of the treatment (capital costs, maintenance costs, imposed congestion costs, imposed fuel consumption costs, etc.); and
3. ultimately, whether the treatments are cost-effective.

While this may initially sound questionable from a public policy perspective, transportation planners and traffic engineers employ the same approach in developing design treatments for motor vehicles. As long as selection and implementation of treatments employ the rule of reason, and the public record indicates why the treatment is being implemented (i.e., based upon expected benefits derived from a rational analysis of the literature), treatment implementation generally moves forward. However, it is also important that public entities conduct before-and-after analyses for these efforts, to ensure that the treatments achieve their desired effects, and that treatments are re-engineered when they do not. Site-specific case-study analyses will likely be the most effective along high-traffic corridors, over extended time periods, where agent activity can be adequately monitored and agent interactions can be assessed.

With respect to overall assessment of pedestrian and cyclist risk, even the site-specific case study approach will be costly and will only provide data for those sites and conditions that are selected. Given that ubiquitous data collection is impractical, the bigger picture aspects of risk assessment will remain unexplored without the implementation of additional strategies. Given these findings, the research team has concluded that case-control studies may be the most practical approach to identifying and assessing bicycle and pedestrian risk factors. Case-control approaches are employed in safety assessment for aviation and rail travel, where infrequent events preclude aggregate, top-down data assessment approaches. In case-control analysis, research teams focus on the individual events to identify the most-likely cause of the event and factors that contributed to the causality. Case-control analysis focuses on identifying and implementing treatments designed to ensure the event is not repeated.

With respect to bicycle crashes, the research team believes that the case-control approach will be much more likely to yield insight that can be used to design treatments that will improve safety, especially with respect to preventing fatalities. Given the relatively low numbers of crash events that involve pedestrians (those that were actively traveling) and cyclists, the research team believes that a case-control study could be implemented, such that every bicycle and pedestrian crash that occurs in the state of Georgia is further investigated for causality (see Table 16). Clearly, every fatal event could be investigated in detail. While the number of injury collisions and total collisions are not small, the research team believes that a bicycle safety assessment program could be implemented at reasonable cost to fully investigate 750+ annual events and to assess the most likely causes. Such a program could likely be staffed and implemented by state and/or local agencies.

Table 16. GEARS-reported Bicycle Collisions, Injury Collisions, and Fatal Collisions[2] for 2012-2015

GEARS Reporting Year	Bicycle Collisions	Bicycle Injury Collisions	Bicycle Fatal Collisions
2015	743	546	10
2014	707	519	5
2013	668	488	15
2012	675	511	6

Case-control implementation for pedestrian collisions will be more difficult and costly to implement. As seen in Table 17, the number of pedestrian events is about 5.5 times the number of bicycle events. The cost to implement the pedestrian program will greatly depend upon how many of the pedestrian injuries involved actual travel by pedestrian mode, versus the number of injuries of non-drivers and non-cyclists represented in the data. This is because the pedestrian crash count includes construction workers, bystanders struck by vehicles leaving the roadway, and other events. In any case, a much larger investigatory program would be required for pedestrian case-control analysis than would be required for bicycles. Given the need for a larger program, contracting of services may be required, or case-study sampling could be implemented (e.g., random stratified sampling of a subset of events, and/or the level of detail associated with individual pedestrian crash investigations could be reduced to match the program to available resources).

2 The FARS database contained a different number of fatalities for 2013 (28 vs. 15) and 2012 (17 vs. 6), indicating that further review of GEARS data may be warranted.

Table 17. GEARS-reported Pedestrian Collisions, Injury Collisions, and Fatal Collisions[3] for 2012–2015

GEARS Reporting Year	Pedestrian Collisions	Pedestrian Injury Collisions	Pedestrian Fatal Collisions
2015	4154	2825	199
2014	3762	2608	157
2013	3601	2452	175
2012	3490	2319	145

3 The FARS database contained a different number of fatalities for 2013 (176 vs. 175) and 2012 (167 vs. 145), indicating that further review of GEARS data may be warranted.

10 A Plan of Action for Georgia Department of Transportation regarding Bicycle and Pedestrian Infrastructure

Georgia DOT would like a process of bicycle and pedestrian treatment selection that is grounded in safety analysis. Similarly, the expert survey the GT team conducted showed a wide gap between what agencies would like to achieve and what they are currently practicing when it comes to the evaluation of safety impacts of pedestrian and bicycle treatments. Safety is considered the most prominent variable in identifying sites for bicycle and pedestrian treatments and the most prominent variable in treatment selection. Yet, only 29% of the agencies in the sample reported that they have completed some sort of before-and-after study; and the majority of these studies reported measuring only once before and after. Exposure is a fundamental variable necessary to understand crash rates; yet, only four agencies had more than 200 count locations per year.

This discrepancy reveals the paramount need for guidance on how to incorporate safety analysis into agency practice. As the researchers propose the guidance, they place a premium on defining the process, rather than providing outcome measures of specific treatments. This emphasis on process is grounded in the fact that base rates and CMFs are intrinsically sensitive to local conditions, and, therefore, customization is key to proper selection of treatments. In the case of motor vehicle safety analysis, many states are looking to customize the CMFs provided in the HSM to suit the local needs (Rodgers, et al., 2015).

Agencies have limited resources such that they are not able to carry out detailed safety analysis for every treatment at every site; nor can they afford to acquire all the required data at once. As such, the research team presents a tiered approach to treatment adoption, and a phased implementation plan for data acquisition.

10.1 Tiered Approach

In considering implementation of HSM-type analysis into the adoption process of pedestrian and bicycle treatments at intersections, it is important to recognize that such an implementation is not a binary "yes/no" type decision, but rather is a range of discrete choices where an agency can choose to implement certain elements while deferring or declining to implement others. As an aid in guiding subsequent discussions, it is useful to define an approach that illustrates these implementation levels. Figure 13 illustrates such an approach with three levels:

1. *Minimum accommodation:* This level applies to situations where pedestrian and bicycle activities are extremely unlikely, such as on a freight corridor, or a major arterial to which a parallel multi-use trail is adjacent.
2. *Standard accommodation*: This level applies to situations where low to medium pedestrian and bicycle activities are to be expected and no significantly high risks are identified. This will be the most common situation in agency practice. In this case, treatments and their safety impacts will be classified by roadway classification, and a standard operating procedure should be established in selecting treatments.
3. *Special accommodation*: This level applies to situations with significant pedestrian and bicycle demand and/or high crash risk. In this case, agencies should conduct quantitative HSM-type analysis to develop localized CMFs, as well as cost-benefit analysis in selecting treatments.

In the short term, when CMFs for pedestrian and bicycle treatments are lacking, most new analyses will fall under Level 3 (special accommodation). Over time, however, as CMFs become available for more and more treatments, agencies can focus more on developing the procedures for Level 2 (standard accommodation). To enable such a transition in the long term, the research team presents a phased implementation plan as described below.

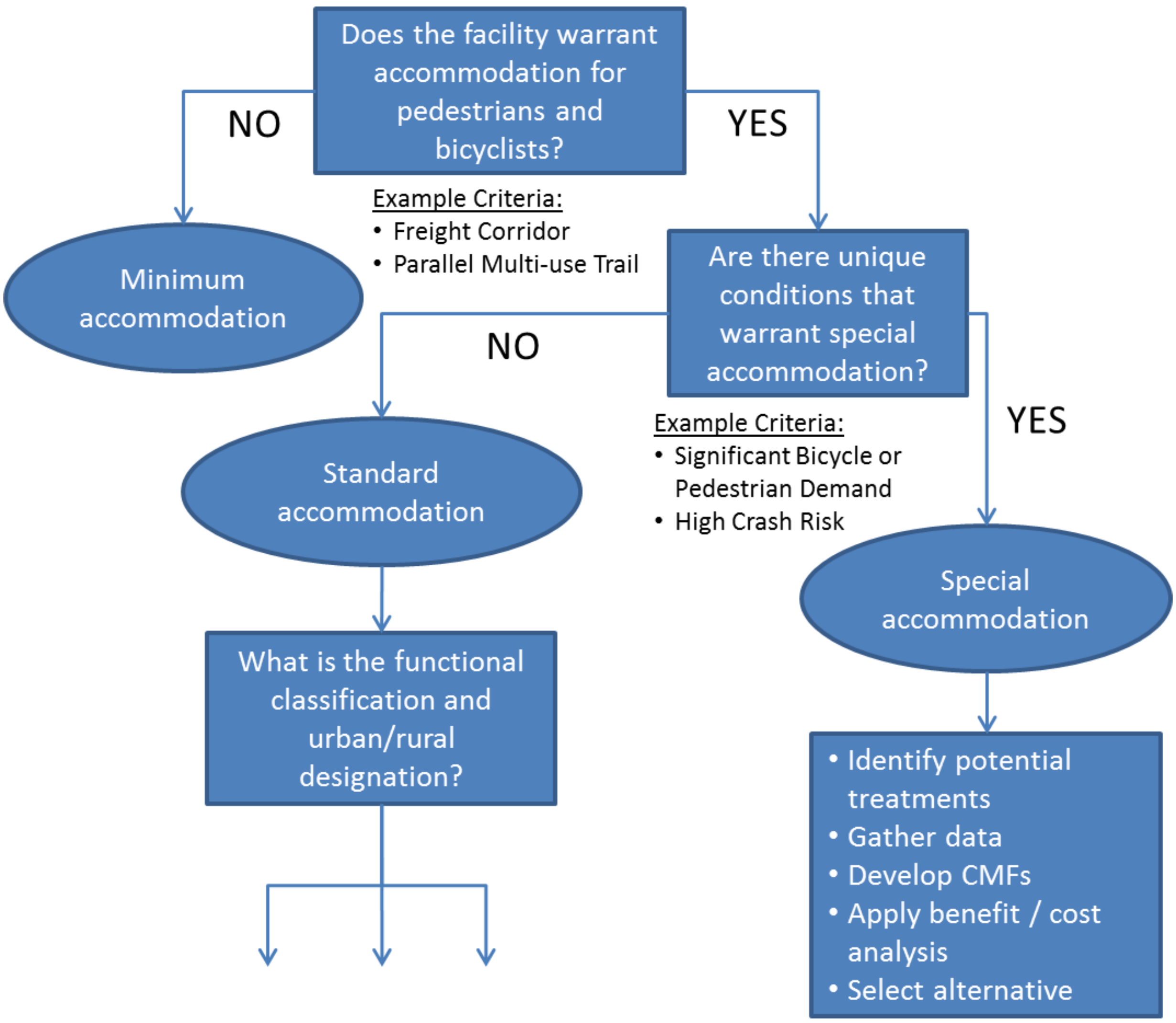


Figure 13. Tiered Approach to the Adoption of Pedestrian and Bicycle Treatments at Intersections

10.2 Phased Implementation

As described previously, agencies need exposure data, crash or surrogate data, and infrastructure characteristic data for rigorous safety analysis for pedestrian and bicycle treatments at intersections. Currently, data are lacking or unreliable in all three data categories. Accordingly, the researcher team envisions a process that focuses on different aspects of safety analysis in the short, medium, and long term.

In the short term, given the data constraints, agencies will have to conduct localized studies to evaluate individual treatments, following the procedures for Level 3 (special accommodation), as described above. Such studies will likely use temporary camera setups, or tap into the rich information offered by the increasing ubiquitous security and/or traffic camera systems in many areas.

In the medium term, as the number of localized safety studies increases, and the exposure and crash data accumulate, it is necessary to put in place an infrastructure characteristic database for systematic analysis based on which procedures for Level 2 (standard accommodation) can be developed. The infrastructure characteristic database needs to reflect the unique features of pedestrian and bicycle facilities, and the standard RC link database is unlikely to fulfill the needs, especially for pedestrian facilities.

In the long term, as agencies mature in collecting all three categories of data, HSM-type evaluation techniques need to be refined for pedestrian and bicycle studies.

10.3 Case-control Strategies

Case-control approaches discussed in Chapter 9 are employed in safety assessment for aviation and rail travel, where infrequent events preclude aggregate, top-down data assessment approaches. In case-control analysis, research teams focus on the individual events to identify the most-likely cause of the event and factors that contributed to the causality. Case-control analysis focuses on identifying and implementing treatments designed to ensure the event is not repeated. Such analysis provides a better understanding of the conditions of the crash and insight into potential interventions that might have prevented the crash. The level of detail associated with the individual event investigation could also vary as a function of factors that likely contributed to the cause. Implementing a case-control approach for bicycle and pedestrian crashes in the state of Georgia would require significant changes in current data collection efforts to improve the amount and quality of data available for case-control analysis. Implementation of a case-control approach would also likely require allocation of significant resources to establish the expertise necessary to implement an investigatory program and enhanced investigator training that goes beyond current professional and legal standards. The research team recommends that GDOT conduct a detailed study to assess the feasibility of implementing case-control analysis for fatal bicycle and pedestrian collisions at a minimum, but preferably for all crashes that would currently be reported.

10.4 Collection of Unreported Crash Data

In the absence of death or significant physical injury, bicycle and pedestrian crashes typically go unreported to the police (Cryer, et al., 2001; Maas and Harris, 1984; Elvik and Mysen, 1999). A quick glance at Tables 16 and 17 clearly illustrates this point. If all bicycle and pedestrian crash events were reported, the data for 2015 indicate that 74% of all bicycle incidents and 68% of all pedestrian incidents result in injuries. Common sense dictates that this is simply not the case, and that many more incidents with or without reportable injuries go unreported. Even in the Georgia Tech transportation research lab, none of three incidents involving laboratory staff (two of which were documented on video) ended up being reported in the Georgia crash database. All three of these incidents were serious, and could have resulted in a fatality had conditions been slightly different. The research team believes that if data were available for incidents that currently go unreported, significant additional insight into causality could be obtained.

The study team proposes a pilot study to assess two possible means to collect improved crash data, via bicycle shops and the Cycle Atlanta app. Surveys will serve as the primary means for identifying unreported events. A survey would be designed to identify recent crash events (including date, time, and location), and to identify near-miss event locations that might help to identify trouble spots in the system.

10.4.1 Near-miss and Crash Location Crowdsourcing

In 2012, Georgia Tech extended the open-source mobile application CycleTracks as part of the Cycle Atlanta project to address specific issues and planning goals in Atlanta. Cycle Atlanta (http://cycleatlanta.org/) is a mobile application that uses a smartphone's geolocation capabilities to record a cyclist's bike route as she travels to her destination. The Georgia Tech version, available on iOS and Android platforms, includes the ability to record cyclists' trips, obtain socio-economic information about the user, and crowdsource issues and amenities found en route (e.g., potholes, storm grates, bike racks, water fountains). The goal of the Cycle

Atlanta project is to connect citizens to local government through the app and the data they collect, allowing citizens to participate in the planning process without being inhibited by spatial or temporal limitations in existing participatory planning practices, and by providing a rich and much-needed source of cyclist route data for city planners developing new infrastructure and cycling facilities. The initial experiment of Cycle Atlanta has been a success. To date, over 1600 cyclists have contributed 20,000 trips and, over time, these cyclists continue to contribute data about their rides with the app. Building on the original success, the Cycle Atlanta code base has been adopted by several other U.S. cities (e.g., Pittsburgh, Austin, Chattanooga, Minneapolis, Auburn, Tampa, Philadelphia, Boulder, and Portland).

One significant component that the current Cycle Atlanta application does not allow is the pin-pointing of "near miss" or incident locations for cyclists to designate locations they feel are less than safe based on their own experience cycling. This functionality would be added to the smartphone application to allow cyclists to pinpoint the intersections and roadway segments that are of concern. The benefit of allowing this on the smartphone application is that locations designated while traveling can be geolocated to avoid having to find the correct location on a map.

10.4.2 Bike Shop-based Crash Database

One characteristic of bicycle crashes that differs from pedestrian crashes is the potential for property damage that could be objectively monitored. Even minor incidents between bicycles and motor vehicles can result in bicycle damage due to the fragility of the mode (i.e., bent rims, brakes, pedals, or forks may need replacing after even a minor low speed collision). Because bicycles generally need to be professionally repaired before the bicycle can be put back into service, an opportunity to collect objective data exists for unreported crashes. The research team has concluded that unreported bicycle crashes might be identified by monitoring repair shop activity and parts sales throughout the metropolitan area. This program would be very manageable at reasonable cost, given that there are only 70 to 80 repair shops in the entire metropolitan area. Bicycle repair technicians would be given a form for patrons to fill out as they are having their bicycle repaired to report any incident with a vehicle that led to the need for the repair. The survey would allow users to self-report the map location and details associated with the incident, and researchers could use the data to supplement information available in the FARS and GEARS databases.

10.5 Enhanced Collection of Bicycle and Pedestrian Activity Data

Even in well-controlled, statistically rigorous studies, the common denominator in data need is quantifiable exposure data. A variety of continuous and rotating monitoring efforts are employed to quantify motor vehicle activity data, generally as part of planning efforts designed to ensure that transportation plans and programs are achieving mobility, congestion mitigation, and safety goals. One option for the development of cycling and pedestrian activity and risk exposure would be to deploy monitoring systems and data collection plans similar to those employed in the motor vehicle sector. About halfway through this study, the research team concluded that analyzing individual intersections and corridors would simply not provide high-quality transferrable risk assessment results and that a new, comprehensive data collection program would be needed to obtain the data necessary for developing crash modification factors. Permanent count stations and monitoring systems for traffic volumes, speeds, and prevailing cycling and walking conditions would be deployed along high traffic routes. Rotating sampling stations (akin to those employed in HPMS monitoring) would be deployed to sample from low-volume locations.

A good database would likely include more than 500 critical segments for ongoing analysis. Knowing how many people are walking and biking on individual routes and facilities, how they are using the facilities, and how many people are expected to benefit from a safety treatment would be necessary to support strong infrastructure decision making. 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 be most effective, 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. Work is already being done in some places to develop methods of collecting and processing bicycle exposure data on a large scale (Greene-Roesel, et al., 2007). This comprehensive data collection program cannot be achieved in a timeframe that would be reasonable for the immediate analysis of bicycle and pedestrian safety. However, without it, GDOT will not progress toward eventual measurement of safety improvements along the lines of the Highway Safety Manual procedures.

10.6 Before-and-After Analysis

Local governments and transportation agencies are constantly making decisions about how best to achieve their goals with limited available resources. When faced with a decision about 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 prioritize their projects effectively. In the absence of data or past research to evaluate a treatment, jurisdictions may decide to implement a treatment experimentally in hopes that it will address a specific safety concern. Although the research team cannot advocate making design and treatment decisions in the absence of quantifiable evidence to support the benefit of a treatment, when such decisions are made, the research team does recommend that site-specific before-and-after data collection and analysis be considered to help gather data that will be useful in future decisions. Therefore, research team recommends that GDOT employ thorough before-and-after analysis in locations where bicycle and pedestrian treatments are being implemented.

10.7 Conclusion

The HSM presents a methodical way of quantifying and transferring the safety benefits associated with infrastructure countermeasures in the form of CMFs. However, the kinds of data necessary for developing HSM-style CMFs for bicycle treatments are not yet readily available. The development of accurate, reliable, statistically-based crash modification factors for bicycle and pedestrian treatments will require the collection and analysis of sufficient data to assess how modifications of infrastructure and implementation of safety treatments affect collision, injury, and fatality rates. The number of incidents per unit of bicycle or pedestrian activity must be quantified, which requires objective observation of mode activity (bicycle-miles-of-travel and pedestrian-miles-of-travel), as well as number and severity of crashes or near misses that occur during the conduct of that activity. Unfortunately, as noted throughout this report, the amount of bicycle and pedestrian activity is not well quantified. Incidents are also poorly quantified. Many incidents go unreported, and those that are reported lack documentation specificity needed to assess causation. The large uncertainties in both the numerator and the denominator prevent accurate quantification of crash rates under both baseline conditions and when treatments are implemented.

Given the state of data currently available for bicycle and pedestrian activity and crash events, the research team has concluded that accurate and reliable crash modification factors cannot be developed without significantly improving current data collection programs. The wide variety of causal factors that likely contribute to individual crash events (per the literature review) must be controlled in each analysis. New data collection programs would necessarily include the enhancement of existing crash event data, collection of incident data that currently go unreported, and collection of enhanced bicycle and pedestrian activity data. In addition, to begin to assess safety implications within the state in the immediate term, case-control analysis, where individual crash events and sites are investigated in detail, is recommended.

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