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Pedestrian and Bicyclist Safety – Literature Review

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16. Abstract

Pedestrian and bicyclist fatalities in the United States constitute about 20% of traffic fatalities. Pedestrians and bicyclists are far more susceptible to risks in the built environment (i.e., all the physical items in the environment created by people – roads and roadway design, bridges, crosswalks, lighting, buildings, engineering treatments, etc.) than are motor vehicle occupants, and pedestrian fatalities have grown consistently over the past decade. While new data sources and analysis methods are available for measuring safety risks to pedestrians and bicyclists, research is still limited in many ways.

This report collects academic and government research conducted primarily from 2013 to 2020 in the United States; seminal references and important research conducted during the course of completing this report are also cited as is relevant international research. To help readers understand pedestrian and bicyclist safety, the risks to safety, and the countermeasures that can be used to improve safety, this report synthesizes the body of literature on key topics such as crash patterns and trends, the role of human behavior on pedestrian and bicyclist safety, the role of the built environment on pedestrian and bicyclist safety, the role of the vehicle on pedestrian and bicyclist safety, emerging safety concerns, laws and policies, programs for behavior change, engineering countermeasures, technology-based interventions, safety data sources, and analysis methods.

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Executive Summary

Introduction to the Literature Review

In the United States 20.3% of traffic fatalities are pedestrians and bicyclists (National Center for Statistics and Analysis, 2024), despite these modes only constituting an estimated 12.9% of the travel mode share (Buehler et al., 2020). Addressing this disparity is a major goal for the United States Department of Transportation, as emphasized in the National Roadway Safety Strategy (U.S. DOT, 2022), and people supporting Safe System Approach principles and Vision Zero programs, which emphasize the importance of well-connected walking and bicycling networks and that zero is the only acceptable number of serious and fatal injuries on the nation's transportation system.

This report is based on a literature review of topics relevant to the safety of bicyclists and pedestrians in relation to motor vehicle traffic. The report was developed to help readers understand the roadway-related risks pedestrians and bicyclists face so adequate data can be collected and appropriate countermeasures selected. This report builds on both the National Highway Traffic Safety Administration's existing resources about pedestrian and bicyclist safety and on academic and government literature, primarily collected from the years 2013 to 2020 in the United State. Seminal sources prior to that period and important works after that period have been cited as is relevant international research.

This report uses the NHTSA definition of a pedestrian - any person not in or upon a motor vehicle or other vehicle, specifically, any person on foot, walking, jogging, hiking, sitting, or lying down in a public traffic way (NCSA, 2022c), but also uses definitions based on injury surveillance that include non-public traffic ways (e.g., sidewalks, trails) may be referenced (Injury Surveillance Workgroup 8 [ISW8], 2017). A bicyclist is defined as a rider on two-wheel vehicles, tricycles, and unicycles powered primarily by pedals, but may include electric-assist bicycles (e-bikes).

This report has four sections.

1. Introduction to Pedestrian and Bicyclist Safety
2. What Creates and Mitigates Risk for Bicyclists and Pedestrians
3. Effectiveness of Safety Interventions for Pedestrians and Bicyclists
4. Measuring and Monitoring Bicyclist and Pedestrian Safety

The executive summary provides a synthesis of each part of the report to show readers how to identify risks, collect data relevant to those risks, and then prescribe countermeasures relevant to those risks. This includes a broad overview of pedestrian and bicyclist safety problems and a conclusion highlighting emerging safety trends. The focus of this report is safety, so concepts like walkability or bikeability may be referenced, but broad discussion of these topics is beyond the scope of this report. Other determinants of safety, such as pedestrian falls, are also referenced but not central to the report.

Overview of Pedestrian and Bicyclist Safety Problems

NHTSA defines a pedestrian or bicycle crash as an incident involving one or more moving motor vehicles striking a pedestrian or bicyclist (NCSA, 2022c, 2022d). These kinds of crashes produce a spectrum of crash outcomes, including fatalities, injuries that may or may not be fatal, and non-injuries. However, the absence of a crash does not necessarily indicate the presence of safety.

Pedestrians and bicyclists may be dissuaded from using certain roadway facilities due to perceived or actual threats to their safety. Pedestrian and bicyclist safety analysis sometimes involves the use of surrogate safety measures to capture those latent risks where crash data are sparse.

Crash trends for pedestrians and bicyclists vary across geographic and sociodemographic lines, and safety risks may not be consistent for all pedestrians and bicyclists. Nationally, pedestrian fatalities have increased since 2009, with these road users accounting for 20% of all traffic fatalities in 2022 (NCSA, 2024). Key facts regarding pedestrian safety include these.

- Pedestrian injury-only crashes decreased from 2016 (82,752 crashes) to 2020 (52,558 crashes) (NCSA, 2022c).
- In the United States, sunbelt States such as New Mexico, Florida, and Arizona have had the highest population-based pedestrian fatality rates (Schneider, 2020).
- Pedestrian injuries and fatalities are not equitably distributed by race and ethnicity, with Black, Hispanic, and American Indian or Alaska Natives struck by motorists while walking at a disproportionate rate to population (CDC, 2013; Zaccaro, 2019).
- Although pedestrian fatalities among children younger than 15 have decreased over the last few decades, this trend change may be due more to reduced rates of walking by children (Schneider, 2020).
- Men and women have comparable walking rates (Buehler et al., 2020), but men consistently represent about 70% of pedestrian fatalities (Schneider, 2020).
- Pedestrian fatalities are more likely to occur in urban areas (82%) than in rural areas (18%) (NCSA, 2022c).

For bicyclists, fatalities have remained relatively stable at about 2% of all traffic fatalities per year since 2008 (NCSA, 2022b). As with pedestrian injuries and fatalities, bicyclist injuries and fatalities follow some similar annual trends. Key facts regarding bicyclist safety include:

- Bicyclist injury-only crashes decreased from 2016 (63,772 crashes) to 2020 (38,449 crashes) (NCSA, 2022d).
- Although limited to one geographic area, some research indicates that Black bicyclists are involved in the most crashes per person per distance traveled, indicating a potential disparity based on population size (Barajas, 2018).
- The average age of bicyclists killed in traffic crashes has been increasing for the last two decades and was reported as 48-years-old in 2020, with the highest fatality rate occurring between ages 60 and 64 (NCSA, 2022d).
- Men are three times more likely to ride a bicycle than women, but they are about seven times more likely to be involved in fatal bicycle crashes (Buehler et al., 2020; NCSA, 2022d).
- Bicyclist fatalities tend to occur in urban areas more than rural areas, with urban fatalities accounting for approximately 79% of bicyclist fatalities in 2018 (NCSA, 2022d).

Identifying Risks, Collecting Data, and Prescribing Treatments

Crashes occur due to complex interactions between human behavior, the built environment, and all the technologies in them. While it is simple to blame human error for crash occurrence, doing so creates a misunderstanding about how humans make decisions, interpret risks, and ultimately use systems. Decision making (e.g., when, where, and how to cross a road) must occur in a roadway environment in which pedestrians and bicyclists are far more susceptible to crash energies than motor vehicle occupants and where they may have insufficient facilities to keep them safe. Due to this complexity, improving safety requires eliminating risks as often as possible and minimizing the severity of collision when risks cannot be fully removed.

Collecting Data and Identifying Risks

Exposure to risk is a complex topic. Sometimes roadway designs that can reduce the likelihood of a severe crash occurring (e.g., by slowing motor vehicle traffic) may also increase the total likelihood of a crash occurring. This can occur by making the roadway more hospitable to the needs of a pedestrian or bicyclist, thereby increasing the likelihood that a pedestrian or bicyclist will use that roadway. Readers should consider the following key points when reading about potential treatments to pedestrian and bicyclist safety problems:

1. Risk is a complex, nonlinear function of the built environment and the various volumes of different road users in that environment.
2. The risk of a crash can increase while the risk of that crash being severe can decrease (or vice versa) based on the how pedestrians and bicyclists interact with infrastructure.
3. Exposure to risk depends on the number of road users in a space, and while the overall number of expected crashes may increase as road user volume increases, the individual risk per person may decrease.
4. The mechanisms of risk for pedestrians and bicyclists are similar due to the susceptibility of these road users to harmful crash energies, but their risks are not the same, nor are the infrastructure improvements that can protect them the same.

To understand this complexity and appropriately measure safety, researchers and practitioners are encouraged to collect three types of data: safety data, exposure data, and contextual data.

Safety Data

The most common type of road safety data collected are police-reported crash data. A variety of databases for crash data are available, often depending on severity. NCSA has used the crash typing framework Pedestrian and Bicycle Crash Analysis Tool (PBCAT) to describe the events and maneuvers that led up to fatal bicyclist and pedestrian crashes since 2014. States are encouraged to record and report crash data consistent with the Model Minimum Uniform Crash Criteria (MMUCC) (fifth edition at the time of publication of this report), which is intended to lead to increased consistency over time (NHTSA, n.d.-a). Unfortunately, police-reported crash data may be subject to inaccuracy and incompleteness (see Noland et al., 2017, for example), underreporting (de Geus et al., 2012), and bias (Tarko & Azam, 2011). To circumvent these limitations, some researchers and practitioners supplement crash data with hospital and emergency medical services (EMS) data (see, e.g., Cherry et al., 2018).

Other researchers will collect surrogate safety data to identify crash potential (see, e.g., Johnsson et al., 2018). Common surrogate measures—such as time to collision (TTC), post-encroachment time (PET) (a measure of vehicle conflicts), and deceleration (reduction in travel speed)—capture the potential for collisions to occur when conflicting streams of motor vehicle and pedestrian and bicyclist traffic cross. Surrogate data can be helpful due to the sparse nature of pedestrian and bicyclist crash data.

Public surveys may also provide insight into safety problems not easily assessed through crash data or surrogate safety data. See Medury et al. (2017) for an example of how survey data can be used to identify perceived hazards for pedestrians and bicyclists.

Exposure Data

Exposure refers to a quantification of the number of events that could potentially result in a crash, such as the number of pedestrians crossing per year in a given crosswalk or the annual number of bicycle miles traveled throughout a city. Exposure data are critical for understanding the number of events that could potentially result in a crash. Common measures of exposure include distance traveled, time traveled, volume counts, trips made, and population estimates. These metrics are available from many sources including site examinations, travel surveys, counting programs, demand estimation models, and U.S. Census data reports. See Turner et al. (2018) for more information.

Contextual Data

Contextual data (i.e., characteristics of the environment) are critical for understanding how the built environment and exposure interact to produce risks to pedestrians and bicyclists. Readers are encouraged to note the contexts in which treatment effects were analyzed in subsequent sections of this summary. Some treatments may be more appropriate in certain contexts than others, and exposure will vary depending on nearby land use and the types of facilities available to road users.

Analysis Tools and Methods

Some common safety analysis tools and methods used to measure safety include these.

- **Crash heatmaps** – maps with color variations showing magnitude and clustering of pedestrian and bicyclist crashes (see Liggett et al., 2016 for an example)
- **Safety Performance Functions (SPFs)** – statistical equations that express the number of crashes at a given location as a function of traffic volume and roadway characteristics, typically developed by individual agencies to predict where crashes will occur (see Nordback et al., 2014 for an example)
- **Crash Modification Factors (CMFs)** – numbers derived from statistical equations to describe how the presence of safety interventions modify the chance of a crash (see the CMF Clearinghouse for relevant CMFs [Federal Highway Administration, n.d.-a]).
- **Systemic analysis** – a traffic safety management process wherein agencies use crash, exposure, and contextual data (ideally) to screen roadway networks for where pedestrians and bicyclists are at risk of being struck by motor vehicles; (see Thomas et al., 2018 for a thorough review of the systemic method for pedestrian safety)

Eliminating Risks to Pedestrians and Bicyclists

Because the largest threat to pedestrian and bicyclist safety emerges from the interaction of road users in the built environment (all the physical items in the environment created by people – roads and roadway design, bridges, crosswalks, lighting, buildings, engineering treatments, etc.), the most effective way to improve safety for these road users is to eliminate the threat of death or injury by separating pedestrians and bicyclists from exposure to risk. This approach does not mean that pedestrians and bicyclists are removed from the built environment entirely, but rather that the built environment is transformed to mitigate the potential for harmful interactions between motor vehicles and pedestrians and bicyclists.

Engineering countermeasures are commonly used to alter the built environment and mitigate risks. Countermeasures can be evaluated by measuring changes in crash outcomes (i.e., frequencies, rates, injuries, and fatalities), but it can also be measured through surrogate safety metrics, including travel speed, yielding behavior, safe passing distance, signal or crosswalk compliance, and motorist encroachment or interactions with pedestrians and bicyclists.

Broadly, the countermeasures that can be used to reduce risk and, in some cases, separate pedestrians and bicyclists from harm include those that reduce crash impact (speed management), increase visibility (lighting improvements), and reduce conflict (crossing and corridor interventions). Specific interventions exist for both pedestrians and bicyclists, although some treatments will benefit both types of road users.

Speed Management

Pedestrians and bicyclists are significantly more susceptible to the kinetic forces involved in a motor vehicle crash than are motor vehicle occupants because of human physiology. The risk of death or serious injury increases along an S-shaped curve as the impact speed—which is a product of speed limits, the built environment's cues to drivers, and driver behavior—increases. At an impact speed of 24 mph, the risk of pedestrian fatality is 10%, but at an impact speed of 41 mph, the risk of pedestrian fatality is 50% (Tefft, 2013). Speed management programs can seek to limit the impact of speed in a crash by changing the built environment, enforcing speed limits, or both.

Research has shown that roadway designs that increase a driver's feeling of being hemmed in—such as sidewalks, commercial development, or on-street parking—tend to induce lower average operating speeds on roadways (Ivan et al., 2009). Therefore, some engineering treatments (i.e., roadway designs) or development practices can be used to decrease available travel width for motor vehicles to induce lower speeds. Road diets (street reconfigurations), for example, have been used effectively to reduce motorist speeds while potentially creating more space for pedestrians and bicyclists (Sanders et al., 2019). Traffic calming devices that cause either vertical deflection (e.g., speed humps, speed cushions, and raised crossings) or horizontal deflection (e.g., chicanes, neckdown, and mini-traffic circles) can also be used to slow motor vehicles by forcing them to navigate over changes in alignment, significantly decreasing average vehicle speeds and 85th percentile speeds (i.e., a method used by some engineers to set speed limits based on the speed at which the majority, 85%, of drivers are traveling at or below).

Lighting

Installing lighting along road segments, at intersections, and at crossings may be one way to improve safety for pedestrians and bicyclists by increasing visibility for all road users (DiGioia et al., 2017). In 2020 some 77% of pedestrian fatalities and 45% of bicyclist fatalities occurred in dark conditions (NCSA, 2022c, 2022d). Placement of lighting facilities to improve visibility is critical, with research indicating that high illuminance ratings at urban, signalized intersections reduce the risk of fatal and severe injuries for pedestrians and bicyclists (Wei et al., 2016). Furthermore, streetlights may be more effective in advance of a crosswalk rather than directly over a crosswalk (Bullough et al., 2012).

Crossing Treatments

Where pedestrians and bicyclists must interact with motor vehicles (or where demand exists for crossing facilities based on nearby land uses), it is critical to provide crossing treatments to slow motor vehicle traffic, induce yielding behaviors, and ultimately separate pedestrians and bicyclists from conflicts with motor vehicles. For pedestrians, crossing treatments that have been demonstrably effective at reducing crashes, improving motorist yielding rates, and reducing exposure include crosswalk markings (Chen et al., 2013), advance stop/yield markings and signs (Zegeer et al., 2017), and curb extensions (Kang, 2019), respectively. For bicyclists, bike boxes (Loskorn et al., 2013) and protected intersections (Madsen & Lahrmann, 2017) may improve safety, especially when used alongside turning restrictions. Other engineering treatments, such as pedestrian hybrid beacons (PHBs) and conflict area/intersection pavement markings, may provide some benefits but need more research.

Traffic signalization countermeasures may all provide benefits to pedestrians and bicyclists by separating these users in time from motor vehicles. These include:

- green waves (traffic control strategies that synchronize the green phase of a series of traffic signals),
- leading pedestrian intervals (LPIs) (Fayish & Gross, 2010),
- leading bicycle intervals (LBIs) (Kothuri et al., 2018),
- protected or exclusive phasing for pedestrians and bicyclists (Brunson et al., 2017),
- split phasing (Chen et al., 2014),
- pedestrian countdown timers (Boateng et al., 2018),
- bicyclist detection devices (Boudart et al., 2016), and
- No Turn on Red signs (Lin et al., 2015).

Corridor Interventions

Treatments on corridors can be implemented to physically separate pedestrians and bicyclists from motor vehicles, thereby reducing the potential for crashes to occur. Some corridor treatments with safety effects attested in the literature include:

- Road diets/channelization (Sanders et al., 2019),
- Sidewalks and paved shoulders (Gan et al., 2005; Akar & Wang, 2018), and
- Separated bike lanes (Dill & McNeil, 2012).

Separated bike lanes (separated from travel or parking lanes by space and physical barriers such as curbs, bollards, and planters) are generally agreed to be the safest on-street corridor treatments for bicyclists when compared to standard bike lanes (marked lanes directly adjacent to travel lanes) and buffered (separated from travel or parking lanes by some space and pavement markings) bike lanes (Marshall & Ferenchak, 2019). However, when severe crashes are likely, providing bicyclists viable shared use paths is beneficial. Regardless of the corridor treatment selected, pavement and surface quality should be maintained to avoid unintended falls or unnecessary conflicts with motor vehicles.

Minimizing Risks to Pedestrians and Bicyclists

When it is not possible to remove the risk of crashes occurring to pedestrians and bicyclists, safety may be improved by minimizing the harm that can occur (i.e., the severity of crashes) by targeting human behavior. Human behavior is complex, and not all roadway behaviors (e.g., impairment, distraction, helmet non-use, dart-outs) are made rationally. It may be possible to minimize harmful behaviors through population-level interventions, such as laws, policies, and behavioral programs.

Laws and Policies

In addition to engineering treatments, laws, and policies—like speed limits—that limit speeding behaviors are critical to reducing the severity of crashes when they do occur. Some research shows reduced risk of crash severity for pedestrians when urban speed limits are low (e.g., 20 mph) (Li & Graham, 2016), while other studies show that the risk of fatality increases along with travel speeds when speed limits are raised on high-speed roadways (see Richard et al., 2018, for a brief overview). Research also shows that lowering speed limits produces statistically significant reductions in the odds of motorists exceeding posted limits (Hu & Cicchino, 2019), but speed limit reductions may not affect excessive speeding behaviors (Heydari et al., 2014). Therefore, speed limit reductions should be considered alongside other countermeasures.

Another concern for bicyclists is passing behavior by adjacent motorists. Passing closely can increase the risk of a crash and reduce bicyclist feelings of security. Some States have adopted motorist-passing legislation since the mid-2000s in an effort to reduce the frequency of this severe crash type involving bicyclists (McLeod, 2016). At least 35 States have legislation dictating a passing distance of at least 3 feet when passing a bicycle (NCSL, 2023), but the efficacy of this legislation is still widely unproven (Nehiba, 2018).

Several States have implemented the "Idaho Stop" rule, which allows people on bicycles to treat stop signs as yield signs. The intention of this law is to adapt a traffic control device devised for motor vehicles to the needs of bicyclists. The person on a bicycle must slow and yield to oncoming traffic but is not required to come to a full stop. Rigorous research on the safety implications of Idaho Stop has not been conducted, but an analysis of crashes in States where the law is in place there showed no adverse safety implications (Bike Delaware, n.d.; Meggs, 2010).

Additional laws have been introduced to mitigate other harmful road use behaviors that may increase the severity of crashes between motor vehicles and pedestrians or bicyclists, including impairment and distraction, but little research exists to demonstrate the efficacy of these measures. The most effective countermeasure for distracted driving may be the enactment of Graduated Driver Licensing (GDL) requirements, including passenger, hour, and cell phone restrictions, that limit distractors for novice drivers and reduce exposure (restricted hours) and interactions with pedestrians and bicyclists (Richard et al., 2018).

Programmatic Interventions

A variety of comprehensive programs that combine several intervention types (typically enforcement, education, and engineering) to improve pedestrian safety have been enacted in different jurisdictions across the United States, but the efficacy of these programs is not clear. The most robust evaluation of a comprehensive program, conducted in Miami-Dade, Florida, analyzed pedestrian crashes corresponding to the implementation of pedestrian safety zones that integrated sixteen educational, enforcement, and engineering countermeasures. This study showed an estimated reduction in pedestrian crash rates ranging from 8.5% to 13.3% during the three-year period after implementation (Zegeer et al., 2008). Other comprehensive programs have shown improved yielding behaviors or driver compliance with crosswalks (Van Houten, Malenfont, & Blomberg et al., 2017; Morris et al., 2019), although it is unclear, based on other studies (Dunckel et al., 2014), to what extent comprehensive programs can reduce crashes in comparison to engineering treatments alone. Further research and evaluation are needed of comprehensive programs like Safe Routes to School to disentangle the effects of built environment improvements from other interventions, even though some evidence does indicate improved pedestrian safety (Dimaggio & Li, 2013).

Comprehensive programs are difficult to evaluate, and often an inadequate measure of effectiveness is applied. Many comprehensive programs seek to improve population knowledge, but measures of knowledge change may only reflect short-term memory capacity rather than genuine behavior changes or skill development (Assailly, 2017). Therefore, comprehensive programs should be designed to focus primarily on mitigating crash severity or likelihood and should be evaluated by corresponding reductions in crashes.

Educational Interventions

There is little research indicating the efficacy of educational only programs on improved safety outcomes for child pedestrians and bicyclists (Schwebel et al., 2014). Evaluations of educational programs tend not to use crashes or injuries as measures of effectiveness, so the safety benefits of these interventions are not well established. Moreover, bicycling is a complex skill that requires access and practice, so the evaluations of child bicycle education that do exist tend only to reflect knowledge gains or limited behavior improvements (Ellis, 2014; Pomares et al., 2018). Educational interventions may lack efficacy if not implemented alongside other interventions.

Improving Personal Protection

Finally, when it is not possible to separate pedestrians and bicyclists from risk nor to minimize the severity of crashes that occur from population and roadway-specific interventions, personal protective equipment has some potential to improve crash outcomes. However, these types of interventions are generally unable to prevent crashes from occurring and should be considered as part of broader safety interventions, rather than the first reaction to safety problems.

A substantial amount of research has examined the efficacy of helmets for minimizing head injuries for bicyclists, and these studies have generally concluded that helmets do reduce head injuries when they occur due to crashes or falls (see Olivier & Creighton, 2017). The most recent estimate at the time of reporting is that helmets reduce head injuries by 48% (Høye, 2018). However, it should be noted that helmets do not prevent crashes from occurring, nor are they always worn by older bicyclists. In fact, helmet use has been shown to decrease with age and that children who are minorities or are from lower income households may be less likely to wear helmets (Gulack et al., 2015; McAdams et al., 2018; Sullins et al., 2014). Laws requiring mandatory helmet use may have some potential to reduce the severity of head injuries when crashes occur, as shown by a study in Seattle, Washington, that analyzed hospital records in relation to an all-ages helmet law (Kett et al., 2016). There is some debate about whether helmet laws suppress bicycle ridership, but no studies based in the United States have shown that mandatory helmet laws suppress bicycling (Kett et al., 2016). The topic is a difficult one to study, and even more so when considering inequitable enforcement and ticketing that may have an adverse effect on helmet use and ridership.

Other research has examined the benefit of increased conspicuity (or the ability of an object to be attention-getting) for pedestrians and bicyclists (Brookshire et al., 2016). Motorists are often guilty of underestimating their visual limitations and not adjusting their own speeds appropriately. Changes in vision during twilight hours and at night, headlamp glare, and age-related decline in visual function are among the challenges to pedestrian detection faced by motorists (Tyrrell et al., 2016; J. M. Wood et al., 2014). While it is possible that improvements in conspicuity may improve safety, conspicuity enhancement is unlikely to overcome risky behaviors like motorist distraction (Szubski et al., 2019).

Emergent Transportation Modes

Although measures to improve safety for vulnerable road users tend to focus on pedestrians, bicyclists, and motorcyclists, new modes and adaptations of existing modes are changing the nature of road safety for people traveling outside the confines of a vehicle. Electric-assist bicycles (e-bikes) have dominated bicycling in many countries, and bikeshare systems can facilitate the first and last mile of trips where another mode may have been selected previously. Electric sitting or standing scooters (e-scooters), too, are transforming first- and last-mile trips, but their impact on pedestrian and bicyclist safety is not yet well understood. Risk and safety concerns for e-scooter, e-bike, bikeshare, and other micromobility mode users also extend to the greater transportation system. These newer modes are beyond the scope of this review but are briefly discussed.

Conclusions

Substantial research has been dedicated to understanding the safety concerns of pedestrians and bicyclists, but more research is needed. Crash data remains limited and often inaccurate, and the relationship between exposure and crashes remains complex. Agencies are adopting new methods and countermeasures, such as the systemic approach or Safe System Approach, to proactively address the many risks pedestrians and bicyclists face in the complex roadway environment, but the emergence of new technologies will add additional complexity to the transportation system. Complicating the risks in the existing transportation system are changes in motorized traffic, non-vehicle technologies, and emergent modes. Readers are encouraged to explore this report as a guide for future research while considering the most fundamental methods for improving pedestrian and bicyclist safety, namely eliminating risks before they emerge by providing high quality facilities for humans who want to walk or bicycle to their destinations. The troubling high incidence of pedestrian and bicyclist fatalities in the United States requires this level of consideration and demands more research.

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Part 1. Introduction to Pedestrian and Bicyclist Safety

In the United States our best national estimate of travel mode share shows that 12.9% of trips are made by foot or by bicycle, yet pedestrians and bicyclists continue to account for a disproportionate share of traffic fatalities—20.3% in 2022 (Buehler et al., 2020; National Center for Statistics and Analysis [NCSA], 2022c, 2022d). Addressing this disparity is a major goal for the United States Department of Transportation, as emphasized in the National Roadway Safety Strategy (U.S. DOT, 2022), and people supporting Safe System Approach principles and Vision Zero programs, which emphasize the importance of well-connected walking and bicycling networks and that zero is the only acceptable number of serious and fatal injuries on the nation's transportation system.

The National Highway Traffic Safety Administration (NHTSA) continually updates *Countermeasures That Work*, which documents behavioral focused strategies that have varying levels of effectiveness in improving safety for bicyclists and pedestrians, among other road users. However, addressing the full scope of pedestrian and bicyclist safety requires a broader understanding of the transportation system. Therefore, this report was developed to build on NHTSA's existing resources while offering a more comprehensive examination of transportation topics relevant to the safety of people walking and bicycling. The report will improve the reader's understanding of:

- The behavioral and environmental factors that affect the safety of people walking and bicycling;
- What is known (and unknown) about the effectiveness of interventions (i.e., countermeasures) to improve safety; and
- The underlying sources of data and how these can be used or improved to better understand exposure, risk, and countermeasure effectiveness.

The intended audiences for this report are transportation practitioners, researchers, and policymakers alike. This report could serve as a reference for anyone experienced with pedestrian and/or bicycle transportation or it could warrant a deeper read by someone with a new interest or work assignment related to active transportation and/or transportation safety.

This introduction documents the scope of the report and key definitions used throughout before presenting statistics and research findings about trends in crashes that involve people walking or bicycling. Part 1 also introduces a handful of topics that the reader could consider while reading subsequent sections: the relationship between crashes and exposure, a Safe System approach to traffic safety management, the role of media coverage, and different theoretical frameworks for understanding behaviors and interventions. An outline of subsequent sections of the report is included at the end of this introduction.

Scope

This report is based on a literature review of topics relevant to the safety of bicyclists and pedestrians in relation to motor vehicle traffic. This included literature that analyzes and describes the factors that contribute to fatal and non-fatal outcomes of pedestrian- and bicycle-motor vehicle crashes and the effectiveness of interventions targeted at those safety concerns. The literature search and review also covered literature on traffic safety data sources and methods for monitoring and evaluating traffic safety. The literature search was focused on peer-reviewed, scholarly literature and government publications, but in some instances, a topic warranted the inclusion of conference proceedings, news articles, white papers, or other "grey" literature. There were no-time based limits on the search conducted for the literature review. The time frame for each subject was dependent upon the availability of prior reviews or syntheses. Foundational research was included regardless of when it was published, but the research team conducted a comprehensive search for references related to bicycle and pedestrian traffic safety published in 2013-2020. References published after 2020 are included because research team members had specific knowledge of their publication, or they were identified as "research in progress" during the initial search. While most research cited is based on U.S. studies, relevant international research is included.

The focus on *traffic safety* for this report means that many, but not all, references focused more broadly on walkability, bikeability, and mode share or mode shift, which may indirectly affect safety, were excluded if they did not specifically address safety issues. Select references that are not explicitly safety-related but that provide greater insight into various topics, such as the role of the built environment or theories of behavior change are included in some sections, including this section. The report authors acknowledge that there are limitations to defining pedestrian and bicyclist safety based on motor vehicle crashes such as the exclusion of injuries and fatalities resulting from a bicyclist colliding with another bicyclist or pedestrian, incidents on trails and sidewalks, and slips and falls. In addition, factors that influence what makes people feel safe (when walking/biking) can be much broader than the factors that cause motor vehicle crashes and related injuries, which are the focus of this report.

The report is an overview and starting point for readers to become familiar with pedestrian and bicyclist safety and the many factors that influence safety. Some topics are covered in more depth than others due to availability of published research. The difference in the availability of published research findings is partial due to the availability of reliable data on frequency and characteristics of some safety variables and the challenge of conducting scientifically valid studies. Research results and trends can vary immensely from State to State or community to community or United States to another country. When reading the guide, it is important to keep in mind where the research was conducted, the population studied, and geographic, legislative, regional, and cultural differences as well as other factors that may affect outcomes and conclusions. For instance, for international studies, although some results may not reflect the reality of safety in the United States, they do indicate that safety is dependent on a variety of factors. This literature review synthesizes research that may not be generalizable in all cases, but knowledge of current trends and findings are helpful when trying to understand the complexity of pedestrian and bicyclist safety.

Definitions of Pedestrian, Bicyclist, and Crashes

In terms of crash reporting, NHTSA uses this definition for a pedestrian involved in a motor vehicle crash: any person not in or upon a motor vehicle or other vehicle, specifically, any person on foot, walking, jogging, hiking, sitting, or lying down in a public traffic way. Pedestrians are defined this way based on NHTSA's mission statement focused on road traffic crashes. Notably, this excludes people using personal conveyances like motorized and nonmotorized wheelchairs, mobility scooters, baby strollers, skateboards, and more (NCSA, 2022c). In comparison, a multidisciplinary group of experts in public health injury surveillance recommend a broader definition of pedestrian in the context of injury surveillance that includes people in manually or mechanically propelled wheelchairs (Injury Surveillance Workgroup 8, 2017). A bicyclist is defined as a rider of two-wheel vehicles, tricycles, and unicycles powered primarily by pedals, but may include electric-assist bicycles commonly referred to as e-bikes. Micromobility users are briefly addressed in Part 2 under Emerging Safety Concerns.

A pedestrian or bicycle crash is defined by NHTSA as an incident involving one or more moving motor vehicles striking a pedestrian or bicyclist. Part 4 of this report describes police-reported crash data and some of the cons for using those data to assess safety, including discussion about the challenges associated with underreporting of pedestrian and bicyclist crashes. While this introduction includes a brief section on solo bicycle crashes and pedestrian falls, the full report does not focus on these crashes and falls or crashes that occur between bicyclists or pedestrians without the involvement of motor vehicles. Methorst et al. (2017) point out that most other countries report single-bicycle crashes as traffic crashes and that all countries would be better served by considering traffic crashes and pedestrian falls together so that risks inherent to the transportation system and the built environment can be better identified and proactively addressed.

Injuries sustained during a crash can range from minor to fatal, but in this report the term injury is not always inclusive of fatal injuries and the two crash outcomes are often discussed separately. In most instances, discussion of pedestrian or bicyclist crashes in this report are based on studies examining police-reported crash data unless it is clearly stated that study findings are based on data from the medical profession (e.g., hospital, emergency medical services) or in very few instances, self-report. Most studies included in this report use pedestrian crash data that relies on NHTSA's definition of "pedestrian" mentioned above, but there may be instances where studies analyzed pedestrian crash data that included people using personal conveyance devices as pedestrians.

Bicycle and Pedestrian Crash Patterns and Trends

Because of the relationship between latent risks in the environment and our measures of safety, it is critical to this report that the absence of crashes and fatalities cannot be interpreted as the presence of safety. Low crash figures in an area may be a result of actual or perceived danger that dissuades people from walking or bicycling (see Part 2 for a discussion about spatial correlates like connectivity, accessibility, and stress). In some cases, the only measure we may have is crash data, but in a small area (or short duration of time) there may not be enough to paint a true picture. Observing interactions and near misses on local streets may be an effective means of understanding where interventions are needed (Cloutier et al., 2017). Research has linked walking and bicycling behavior to perception of safety and, if certain locations feel unsafe, there may simply be no bicyclist or pedestrian traffic in that spot. Thus, working to measure suppressed trips is also important if we are to gain a more complete understanding of safety problems (Ferenchak & Marshall, 2019b).

Crash trends vary depending on the source and type of data analyzed. The most common sources of pedestrian and bicycle crash data are police reports. Bicyclist and pedestrian crashes can be studied by examining the documented conditions at the time of the crash (e.g., light condition, weather, time of day), characteristics of the persons involved in the crash (e.g., race, age, gender) and the characteristics of the roadway environment (e.g., lighting, number of lanes, posted speed limit). The pre-crash events and built environment surrounding a crash can also be helpful for identifying risk factors and predicting where future crashes are likely to occur for a more proactive approach to addressing safety. Crash types can be used to organize groupings of similar variables that describe the events and maneuvers of the involved parties in the moments preceding the crashes organized around a predominate action or movement. Part 4 of this report includes background information on crash typing and methods for identifying risk factors and predicting future crashes. While crash types are informative, keep in mind that crash type studies do not capture all the conditions that can lead to injury or death for people walking or bicycling.

The following discussion is based on reported crashes, which are the most readily available form of safety data. These data are sometimes complemented by exposure data that describes the amount of activity in a place or by mode and contextual data that describe the environment in which travel occurs. The trends and studies summarized below do not always refer to the same range of years, but report authors chose to focus on references that reported on several years, not just the single most-recent year. The same types of analyses were not always available for bicycle and pedestrian travel.

Overall Trends

The number of pedestrian fatalities has generally been rising since 2009, and in 2020 accounted for 17% of all fatalities in traffic crashes (NCSA, 2022c). Bicyclist fatalities have consistently represented about 2% of all traffic fatalities nationally since 2008 (NCSA, 2022d). The frequency of crashes (i.e., the number of crashes occurring per unit of time) is just one common metric for understanding crashes. Many studies also report a rate, which is the number of crashes normalized by a population or metric of exposure. Looking at crash outcomes can also be informative. For example, this type of analysis shows that the number of pedestrian fatalities is rising at a disproportionate degree compared to the total estimated injury-only pedestrian crashes. Pedestrian fatalities had been following a downward trajectory until their lowest point in 2009 (4,109 fatalities); after which they have steadily risen until, in 2020, reaching their highest point since 1990 (6,516 fatalities). From 2004 to 2019, the number of pedestrians involved in injury-only crashes ranged from 58,706 to 86,358 but has generally hovered around 70,000. However, in 2020 there was a statistically significant 28% decrease in pedestrian injuries from 2019 (from 75,650 injuries in 2019 down to 54,769 injuries in 2020). This finding of inequitable changes between the number of pedestrian fatalities and injuries compels researchers and practitioners to consider the range of factors that are interacting to make pedestrian crashes more fatal. While lower when compared to pedestrians, the number of bicyclist fatalities vary more from year to year revealing no clear trend. For the period 2010 to 2020, bicyclist fatalities ranged from 623 to 938 with a yearly average of 725. Although the number of fatalities showed a significant increase, bicyclist fatalities have comprised a relatively unchanged proportion of total motor vehicle related fatalities (~2.3%). Estimated injury-only crashes involving motor vehicles hovered around a yearly average of 48,500.[1]

The trends in pedestrian and bicyclist crashes observed to date also vary substantially over time and by region. Sunbelt States appear to be most affected by the increase in pedestrian fatalities observed since 2008 (Zaccaro, 2019). By examining FARS data from 1977-2016, Schneider (2020) confirmed that the five States with the highest population-based fatality rates during the 40-year study period were all sunbelt States: New Mexico, Florida, Arizona, South Carolina, and Louisiana. Looking at differences by region also provides context for national trends. Just as

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[1] Queries of NHTSA's Fatality and Injury Reporting System Tool. Data sources: Fatality Analysis Reporting System (FARS) and General Estimates System (GES)/Crash Report Sampling System (CRSS). https://cdan.dot.gov/query.

sunbelt States are overrepresented in pedestrian fatalities, the Southeast can generally be seen as less pedestrian- and bicycle-friendly since most of the States are at the top of lists of fatality rates (per bicycle or pedestrian commuter) and the bottom of the lists of commute mode share for bicycling and walking (both measures use Census data) (Godwin & Price, 2016). These simplistic measures are influenced by a complex combination of factors including differences in population growth, population health, climate, and urbanization patterns. A separate analysis that used National Household Travel Survey data to calculate fatality rates, identified the most dangerous regions for walking and bicycling and the safest regions for walking and bicycling (Schneider et al., 2017). The study authors concluded that many of the safest regions had central cities that have been nationally recognized for investing in bicycle and pedestrian infrastructure and programs. This type of finding adds to the growing body of literature focused on understanding the relationship between mode share and safety (more information on this in Crashes and Exposure, below).

Differences by Demographics

Gaining a better understanding of the different experiences of people walking and bicycling and how risks and outcomes may vary across populations is crucial to identifying, prioritizing, and implementing safety interventions.

Race and ethnicity

Black, Hispanic, and American Indian or Alaska Native pedestrians are disproportionately struck by motorists and experience worse mortality outcomes (CDC, 2013; Maybury et al., 2010; Zaccaro, 2019). Analysis of death certificate data from 2001 to 2010 showed that American Indian and Alaska Native people had the highest traffic-related pedestrian death rates of any race/ethnicity among both males and females (males 7.73; females 2.22 per 100,000 population) (CDC, 2013). Hispanic and Black males had the next highest death rates (3.93 and 3.73 per 100,000 population, respectively) and Asian/Pacific Islander, Black, and Hispanic females had the next highest death rates (1.46, 1.31, and 1.27 per 100,000 population, respectively). White males and females had the lowest pedestrian death rates (males 1.78; females 0.79). Race and ethnicity data were not collected by FARS until 1999 and while these variables are missing or unknown for about 14% of reported pedestrian fatalities since then, analyses that extend beyond 2010 data found that American Indian or Alaska Native and Black people are overrepresented in pedestrian fatalities while pedestrian fatalities for people with Asian and Hispanic backgrounds are closer to their share of the national population (Schneider, 2020; Zaccaro, 2019).

Studies that used trauma data to study pedestrian injuries have also found racial disparities. A study of national trauma data where patients self-categorized as Black, White, or Hispanic found that Black or Hispanic race were independent risk factors for mortality among patients hospitalized after pedestrian trauma, which creates a double-burden among these communities that already experience higher rates of pedestrian injury (Maybury et al., 2010). A separate study in North Carolina linking 5 years of police-reported crash data with emergency department data found that over half of all injured pedestrians from birth to age 14 (52.6%) and 15-24 (50.5%) were identified in the crash data as Black/African American (the only other options were White or Other) (Harmon et al., 2020). Although, only 21.5% of the North Carolina's population self-reported as Black or African American alone in 2010.[2]

Very little research exists on pedestrian crashes and Native American populations despite their overrepresentation in fatality data (CDC, 2013; Schneider, 2020). Pedestrian safety was identified as one of seven top priority areas in the Tribal Transportation Strategic Safety Plan, and also emerged as a top concern in a recent survey of tribal governments around the country led by the Humphrey School of Public Affairs and the Office of Tribal Transportation in FHWA (Quick et al., 2019; Shinstine & Ksaibati, 2013; Tribal Transportation Safety Management System Steering Committee, 2017). Narváez et al. (2016) maintains that available epidemiological analyses fail to capture the greater context of pedestrian safety in diverse and disparately geolocated American Indian populations.

Differences in crashes and fatalities for bicyclists by race are less commonly reported. In a review of more than 7,000 bicyclist crashes in California's San Francisco Bay Area, among five racial/ethnic groups, Black bicyclists were involved in the most crashes per person per distance traveled, despite being the smallest racial/ethnic group in the region (distance traveled was calculated using National Household Travel Survey annualized weighted data) (Barajas, 2018). The crash rate per person per distance traveled for Black bicyclists was nearly eight times that of White bicyclists; the rate for Hispanic bicyclists was 2.5 times greater than that of White bicyclists.

Age

Adults over 65 walk and bicycle less than other age groups (Buehler et al., 2020; Pucher et al., 2011). However, in 2020, 18% of all pedestrian fatalities with known age were those 65 and older (NCSA, 2022c). Bicyclists over 65 had near average crash rates per population in 2020, with the age groups of 65 to 69, 70 to 74, and 75 to 79 having about equal rates of involvement in fatal crashes with a motor vehicle among older bicyclists (NCSA, 2022d). Moreover, when a collision occurs, the risk for more acute injury is higher in older people (Niebuhr et al., 2016).

Children and older adults are particularly vulnerable in the event of a crash and experience disproportionately higher rates of injuries and fatalities (Cripton et al., 2015; Fischer & Retting, 2017; Moore et al., 2011). Research about the spatial patterns associated with pedestrian crashes found there is some clustering by age group, meaning that older pedestrians and younger pedestrians are being injured in different parts of cities (Grisé et al., 2018; Toran Pour et al., 2018). For example, the analysis by Grisé et al. (2018) in Toronto, Canada, found that severe injury crashes involving child pedestrians were concentrated in the inner suburbs. The researchers concluded that this was consistent with other research summarized by Morency et al. (2012), which found that children from lower income families have a greater risk of injury because they cross more roads and encounter higher vehicle volumes.

Pedestrian fatalities among the youngest pedestrians have been steadily decreasing for decades. In the late 1970s, children younger than 15 represented 18% of all pedestrian fatality victims and by 2020 they represented just 2.7% of all pedestrian fatalities (NCSA, 2022c; Schneider, 2020).

[2] Social Explorer, U.S. Census Bureau; 2010 Census of Population and Housing, Summary File 1, Table T54. Race.

These decreases correspond with reduced rates of walking by children as measured by national surveys of household travel (Buehler et al., 2020; Kontou et al., 2020; Schneider, 2020).

Young people's spatial travel patterns are associated with crash likelihoods. School-age pedestrians' safety outcomes are affected by the built environment and safe walking and bicycling facilities provided to them in their school neighborhood (Hwang et al., 2017). But walking and biking near schools is not the only location of concern for younger people. An analysis of child pedestrian fatalities in six major U.S. cities revealed higher concentrations near parks in comparison to schools (Ferenchak et al., 2019; Jerrett et al., 2016). In the Los Angeles Metropolitan area, geolocated bicyclist and pedestrian crash data showed that crashes near parks were higher overall (Jerrett et al., 2016). These locations tend to draw high traffic volumes and may be less likely to have traffic calming treatments like those near schools.

Older pedestrians are more likely to suffer increased levels of injury if they are struck compared to younger pedestrians (Niebuhr et al., 2016; L. Thomas, Sandt, et al., 2018). Being physically more fragile, the impact on their bodies often results in more severe injuries that contributes to the higher rates of injuries and fatalities. Earlier crash type studies found that older pedestrians were also more likely to be involved in certain types, including crashes at intersections and backing vehicle crashes (Hunter et al., 1996). Older adults more often complied with traffic signals and were struck by motorists who failed to yield or were trapped by a signal change.

In 2020 the average age of bicyclists killed in traffic crashes was 48 (NCSA, 2022d). This average has been increasing steadily for more than two decades. In 1992 the average age of bicyclists killed in traffic crashes was 28 and in 2002 it was 36 (NCSA, 2002). The highest bicyclist fatality rates (per million population) were associated with people 60 to 64 years old (NCSA, 2022b). Adults 65 and older accounted for 18% of bicyclist fatalities in 2020, which is about the same as their share of the total population (NCSA, 2022d). Children younger than 15 accounted for 5% of bicyclist fatalities in 2018, which is less than their share of the population.

Gender

Men are three times more likely to ride bicycles than women but were seven times more likely to be involved in fatal bicycle crashes involving motor vehicles. While walking rates are similar for men and women, men are more than twice as likely to be killed in crashes as pedestrians (Buehler et al., 2020; NCSA, 2022c, 2022d; Pucher et al., 2011). Men have consistently represented about 70% of pedestrian fatality victims since 1977 (Schneider, 2020).

For bicyclists, other contributing factors in addition to exposure may be related to differences in bicyclist and motorist behavior. For example, male bicyclists may be more likely to put themselves in harm's way (Behnood & Mannering, 2017; Bíl et al., 2010; Eluru et al., 2008; Kim et al., 2007; C. Wu et al., 2012). Similarly, female bicyclists may be more likely to restrict their bicycling to safer riding conditions (Dill et al., 2014; Garrard et al., 2008). It is also possible that motorists behave differently when driving next to male and female bicyclists; however, naturalistic research on this topic is inconclusive. One experiment conducted in England found that, on average, motorists left significantly more space for a bicyclist when the bicyclist was wearing a feminine-looking wig (Walker, 2007), while a separate experiment conducted in Minnesota found that of documented passing events that resulted in encroachments (motorist passing the bicyclist within 36 inches or less), 73% occurred when the bicyclist was female (Evans et al., 2018).

Other demographic characteristics

While there are only so many fields that could fit on the crash reporting forms used by law enforcement at the scenes of crashes, cities and States that are able to link police-reported crash data and healthcare data for analysis can discover how other populations are affected by pedestrian and bicycle crashes. For example, in North Carolina, this type of analysis using death certificate data revealed that veterans were overrepresented in the State's pedestrian deaths (10.6% of all pedestrian fatalities) in relation to their makeup in the population (6.4%) (Harmon & Sandt, 2020). The opportunities and challenges of linking different data sources are briefly addressed in Part 4.

Crash Context/Environment

National fatality data indicate that most bicyclist fatalities occur in urban areas (82% in 2020), which is where more bicyclists are riding (NCSA, 2022d). In urban areas, bicyclists are likely to be riding in areas with on-street parking, near intersections with high volumes of turning vehicles and high potential for conflict between users, and along segments with little separation between users. Urban areas also have a much higher density of intersections than rural areas. These differences help explain why there tend to be more intersection- and turning-related crashes in urban areas compared to rural areas (L. Thomas et al., 2019). Among crashes of all injury severity levels, the most common crash types may differ slightly across different urban areas. This is likely due to differences in roadway infrastructure, bicycle facilities, the built environment, and motorist and bicyclist volumes. For example, in the urban areas in North Carolina and in Boulder, Colorado, the majority of the top 10 most common crash types were related to intersections or crossings, but different crash types were associated with different shares of crashes. For example, right-hook crashes were associated with 6% of all-severity urban crashes in North Carolina and 16% of all-severity crashes in Boulder. Left-hook crashes were associated with 11% of all-severity crashes in urban areas in North Carolina and 15% of all-severity crashes in Boulder. In rural areas, bicyclists are likely to be riding adjacent to motorists traveling at high speeds along roads with small shoulders or no shoulders.

Data using varying definitions of "urban" shows that most pedestrian fatalities occur in developed areas—74% of pedestrian fatalities nationwide occurred in urbanized areas (UAs) and 89% in metropolitan statistical areas. When a 0.75-mile buffer around urbanized areas was used, 96% of all pedestrian fatalities occurred in these areas. Four of the largest urbanized counties—Los Angeles County, California; Maricopa County, Arizona; Miami-Dade County, Florida; and Harris County, Texas—accounted for 10% of all pedestrian fatalities nationwide from 2014 to 2018 (C. Webb, 2019). Pedestrian fatalities in urban areas have risen steadily, by a total of about 69% from 2009 to 2018, compared to a fluctuating, but generally flat trend in rural areas (Figure 1).

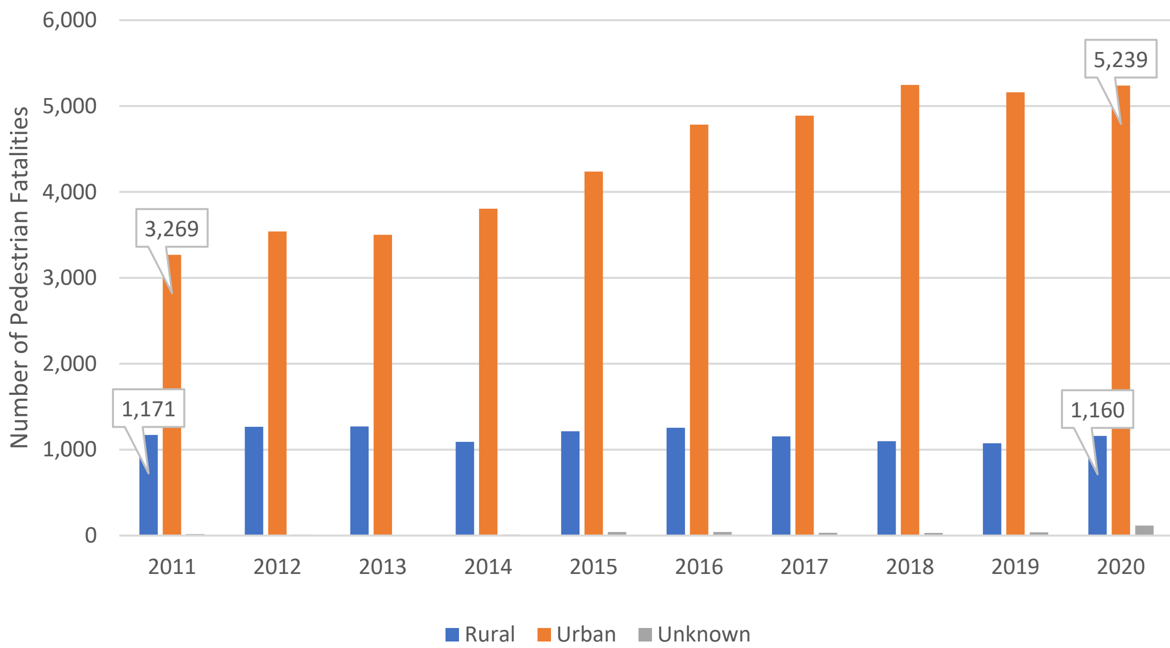

Figure 1. Ten-year trend in U.S. rural and urban pedestrian fatalities
Source: Data from FARS. N = 55,775 pedestrians in fatal crashes.

At the State-level, using available data from North Carolina as an example, crash data also indicate that 74% of pedestrian crashes of all severities happen in urban areas (restricted to "inside a municipality" as the measure of urban). This percentage has risen steadily over the 10-year period from 2009 to 2018; the urban percentage has increased 46% compared to a 23% increase in rural pedestrian crashes in the State (data not shown).

Proportionally, data from North Carolina shows that although rural crashes are less frequent, pedestrians are, on average, more likely to die when struck in rural locations (12% of those struck were killed) compared to urban areas (4% of those struck were killed). This difference is likely due to factors such as higher travel speeds, lower presence of supplemental lighting, less pedestrian infrastructure, and motorists being less likely to expect the presence of people walking. However, the spatial analyses from NHTSA suggest that many crashes designated as "rural" may actually be in developed, or developing, areas or very close to developed areas (C. Webb, 2019). The presence and quality of pedestrian infrastructure in these outlying areas may not reflect changes to the built environment or populations of users that have led to more people walking in such areas.

Location along the roadway

Whether urban, or rural (or suburban), the majority of pedestrian fatalities nationally occur at non-intersection locations (W. Hu & Cicchino, 2018a; NCSA, 2022c). Even in urban areas, 70% of pedestrians killed are struck at non-intersection locations; urban non-intersection locations accounted for an average of 57% of all pedestrian fatalities from 2016 to 2020 (Figure 2). In rural areas, the proportion of those killed at non-intersection locations was higher at 91% of those struck; rural non-intersection crashes accounted for 17% of people killed from 2016 to 2020.

It is not only a matter of more people walking being struck at non-intersection locations, which account for most of the roadway network. Data from North Carolina (and other jurisdictions) also suggest that pedestrians are proportionally more likely to be killed or seriously injured when struck at non-intersection locations (74% of fatal and disabling injury crashes, compared to 60% of all crashes), compared to intersections (L. Thomas, Sandt, et al., 2018).

Most bicyclist fatalities also occur at non-intersection locations (62% for 2016 to 2020, see Figure 2). This is unsurprising given that the most common crash type is motorist overtaking a bicyclist, which likely occurs more frequently along roadway segments than at intersections. In addition, a greater share of a bicyclist's trip occurs while riding along segments than through intersections. In rural areas, 81% of bicyclist fatalities occur at non-intersection locations, but in urban areas fatalities are more closely split between intersections (42%) and non-intersections (57%).

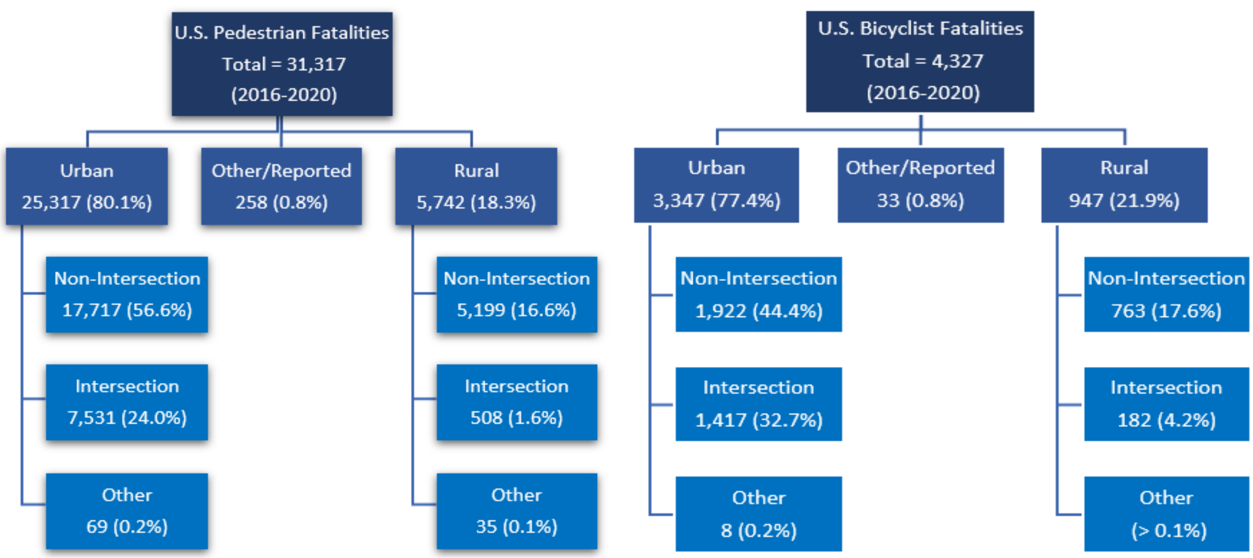

Figure 2. U.S. pedestrian and bicyclist fatalities by rural or urban area type and intersection or non-intersection crash location type

Note: Percentages shown in parentheses represent the percentage of total crashes. For pedestrian fatalities, persons using assistive devices, riding skateboards, etc. were counted in these data. Source: Analysis of 2016 to 2020 FARS data.

Other roadway-related bicyclist crashes

Nationally, sidewalk riding was associated with 12% of bicyclist fatalities involving a motor vehicle from 2014 to 2016 (L. Thomas et al., 2019). Sidewalk riding can be dangerous for pedestrians, bicyclists, and motorists. Bicyclists typically travel faster than pedestrians, who are not expecting them on sidewalks. Motorists may not be expecting bicyclists to be coming from either direction on sidewalks and may fail to see them when crossing an intersection or driveway (Lusk et al., 2011; Wachtel & Lewiston, 1994). Sidewalk riding is particularly risky for bicyclists riding in the opposite direction of traffic. Research suggests that bicyclists riding on a sidewalk may be more likely to fall compared to riding on the roadway due to surface defects and avoidance maneuvers around other users or fixed objects (Aultman-Hall & Adams, 1998;

Moritz, 1998). Sidewalk riding may indicate uncomfortable bicycling conditions such as insufficient separation between motor vehicles and bicyclists, or a lack of bicycle facilities where demand exists.

One crash type that is common in some areas but not well captured in most police databases is referred to as dooring. It occurs when a bicyclist crashes into a vehicle door that is unexpectedly opened in the path of the bicyclist. Dooring crashes typically occur where bicyclists ride adjacent to parked vehicles—they can occur whether there is a bike lane or a shared travel lane. In an analysis of Seattle, Washington crashes, dooring was the fourth most common crash type among all bicycle crashes (5% of all bicycle crashes) and the third highest among severe and fatal bicycle crashes (6% of fatal bicycle crashes) (Seattle DOT, 2016). In Boston, Massachusetts, it is not customary nor required for the police department to report behavioral factors that may have been involved in a crash. But in an analysis of the cases in which motorist behavior was noted, 40% involved dooring from the motorist or vehicle passenger (City of Boston, 2013).

Type of roadway

The largest increases in pedestrian fatalities from 2011 to 2020 have occurred on principal arterial roadways (71% increase), with principal arterials accounting for an average of 37% of all pedestrian fatalities (Figure 3). These roads have long accounted for the majority of pedestrian fatalities likely because their emphasis on vehicle throughput translates into higher speeds and wider designs, which also increase the complexity and risk for people crossing on foot. Fatalities on interstates and expressways have also increased by 61%. Minor arterials increased a similar amount – 62%. Part 2 includes more information about risk associated with street types and the roadway network.

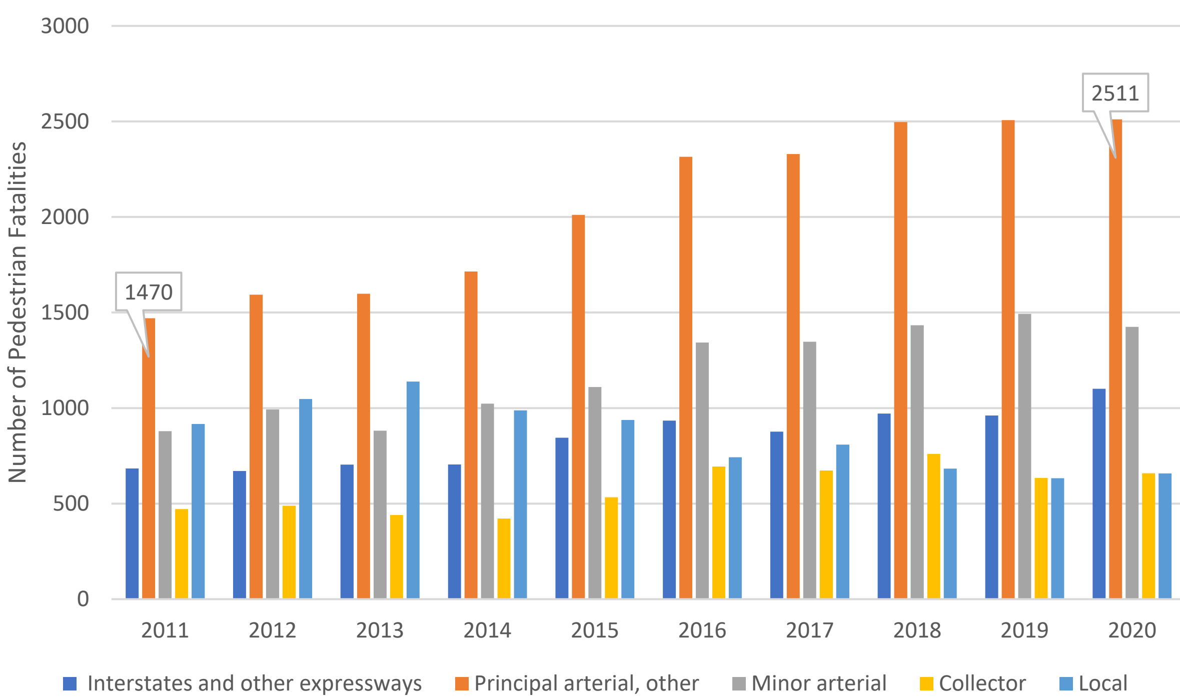

Figure 3. Ten-year trends (2011-2020) in pedestrian fatalities by roadway functional class
Source: Data from FARS. N = 55,775 pedestrians in fatal crashes.

Neighborhood or area-level demographics

Research has consistently demonstrated that areas with lower socioeconomic status and more people of color have higher rates of crashes, including crashes that injure pedestrians, because of higher exposure to traffic and greater presence of major roads (Moradi et al., 2016; Morency et al., 2012; Quistberg et al., 2015; Rosenlieb et al., 2018). A review of literature found that when socioeconomic status was studied in relation to pedestrian crash frequency, the frequency of pedestrian crashes always improved along with socioeconomic status (various measures) (Moradi et al., 2016). It is important to note that even when studies demonstrate an independent "effect" of neighborhood socioeconomic characteristics, it is not poverty that produces road traffic injuries, it is exposure to moving vehicles (Morency et al., 2012).

Schneider et al. (2021) used national-level data to identify fatal pedestrian crash "hot spot" corridors and, in addition to identifying common roadway design and land use characteristics among the 60 unique corridors, the researchers also found that many of the surrounding neighborhoods had low incomes and high proportions of people of color ("hot spot" was defined as 1,000 meter long section of roadway with six or more pedestrian fatalities in an eight-year period). For example, 75% had median household incomes lower than 75% of the area median income, 38% had most residents who were Hispanic, and 15% had a majority of residents who were Black. A study of traffic injuries in Montreal, Canada, found that at intersections in the poorest census tracts, there were 6.3 times more pedestrians injured and 3.9 times more bicyclists injured (on average) and that the excess rate of traffic injuries in the poorest urban areas could be explained by the number of people exposed to crashes, traffic volume, and roadway geometry, including major roads and four-way intersections (Morency et al., 2012). England has a very comprehensive measure of "deprivation" that accounts for more than household wealth and researchers used these data along with crash data and travel behavior data and found that deprivation exacerbates walking fatalities (Feleke et al., 2017).

While it is important to understand how exposure differs across communities and the transportation network, the location of crashes is not the only relevant factor—some researchers are also considering where the motorists involved in the crash are traveling from. Looking specifically at child pedestrian crashes in Toronto, Canada, researchers found that low-income downtown neighborhoods have the highest proportion of non-local traffic and that higher flow-through traffic is associated with higher risk of crashes (Yiannakoulias & Scott, 2013). Researchers have also posited that using the home-address of road users involved in traffic crashes is a way to identify geographic areas where residents have a higher likelihood of involvement in crashes and then focus interventions on those populations (Cherry et al., 2018).

Conditions of Darkness

The first hour of darkness is associated with an increase in fatal pedestrian crashes nationwide throughout the year (Griswold et al., 2011). Nationally, 77% of pedestrian fatalities occurred during dark conditions with another 4% happening during dusk or dawn (NCSA, 2022c). While pedestrian fatalities increased by 46% from 2011 to 2020, the number of nighttime fatalities increased at a higher rate (55%) than daytime fatalities during that period (19%) (NHTSA, 2022). These figures do not account for the presence or quality of lighting from sources like streetlights, nearby buildings, or the moon. For bicyclist fatalities, 45% occurred during dark conditions, with another 5% occurring during dusk or dawn (NCSA, 2022d). Researchers reviewing more than 10,000 bicycle-involved crashes found that the likelihood of a bicyclist experiencing a severe injury is significantly higher among bicycle crashes that occurred in dark conditions, both with and without streetlights, compared to crashes that occurred in daytime (Helak et al., 2017).

Hit-and-Run Crashes

Significant numbers of pedestrian injuries and fatalities are caused by hit-and-run motorists. In 2020, 23% of fatal pedestrian crashes were results of a hit-and-run (NCSA, 2022c) and the figure is slightly higher for pedestrians involved in injury-only crashes (26%). The proportion has been steady over time; according to FARS data, between 2006 and 2019, 20% of *fatal* pedestrian crashes were hit-and-run fatalities with the number of fatalities increasing to 24% in 2020 (NHTSA, 2022). The number of hit-and-run crashes fatalities has been increasing at an average rate of 7.2% per year since 2009, but most of the increase has been in fatal crashes involving nonvehicle occupants, mostly pedestrians (Benson et al., 2017).

As with other crash problems there can be significant regional variation; MacLeod et al. (2012)'s analysis of FARS data from 1998 to 2007 found that hit-and-run crashes accounted for 6.6.% of pedestrian fatalities in Mississippi and 29.8% in the District of Columbia. Victims of hit-and-run crashes may experience greater injury severity due to a delay in receiving medical treatment (B. Dong et al., 2018). Common environmental and temporal factors surrounding hit-and-run crashes include poor lighting conditions, early morning time frame, and occurrence on the weekend.

Based on what is known about motorists who are involved in hit-and-run crashes, data show that alcohol use and invalid driver's licenses are among the commonly identified characteristics. Lack of pedestrian volume data and fundamental lack of information on motorists due to the nature of the act itself present a barrier in fully assessing the nature of hit-and-run crashes. In-depth research on known motorist populations and research on pedestrian-involved hit-and-run crashes in general could shed more light on this problem (MacLeod et al., 2012; Solnick & Hemenway, 1994).

Characteristics of bicyclist crashes caused by hit-and-run motorists have not been discussed in recent reports that aggregate and analyze bicyclist fatalities (Fischer & Retting, 2017; NCSA, 2022d), but FARS data for 2020 show that hit-and-run crashes constitute about one out of every five bicyclist fatalities —21.5% (NHTSA, 2022). Over the 10 prior years (2010 to 2019), hit-and-runs of bicyclists averaged 18% of all bicyclist fatalities.

Motorists Involved in Crashes With Pedestrian and Bicyclists

Based on crash data analysis from Ohio, the likelihood of pedestrian injury in a crash with a motorist increased when the motorist was male, alcohol-impaired, and on a dark or poorly lit roadway (Kemnitzer et al., 2019). Researchers in Canada examining child pedestrian crashes, found that the motorist characteristics and behaviors most strongly associated with a crash were motorist age (specifically 16 to 24 and 55+), no seat belt use, the presence of a child in the vehicle, alcohol impairment, and commute hours (Fridman et al., 2019).

There is little research around the characteristics of motorists who are involved in motor vehicle-bicycle crashes and the studies that do examine this are limited by the fact that they do not analyze how prevalent the characteristics and behaviors are in the rest of the driving population who did not end up involved in a reported crash. Dong et al. (2019) analyzed bicyclist (and pedestrian) crash data from FARS and found that among other things, motorist impairment, past recorded crashes, and the presence of vehicle occupants in addition to the driver influenced the severity of bicyclist injury in a police-reported crash. Another paper that looked at motorist characteristics and behaviors for crashes resulting in *severe* bicyclist injury found that being young, male, impaired, driving on the wrong side of the road, and driving at an unsafe speed increased the likelihood of severe injury for the bicyclist (Behnood & Mannering, 2017).

Crash Types

While reading about the prevalence of different crash types below, it is important to keep in mind that many other factors (e.g., driver, pedestrian, and bicyclist alcohol impairment, traffic speed, larger and more powerful vehicles) may increase the risk of certain crash types and the risk of injury when these types do occur (L. Thomas, Sandt, et al., 2018). These factors are discussed in Part 2.

Bicycle Crash Types

The most common crash types among bicycle-vehicle crashes vary depending on the geography, data source, and types of crashes analyzed. For example, some crash types may be more commonly associated with fatal or severe injury crashes than non-severe injury crashes (L. Thomas et al., 2019).

By far the top crash type killing bicyclists in both urban *and* rural areas is motorists overtaking bicyclists. Motorists overtaking bicyclists represented nearly a third (30%) of all fatalities in the U.S. for 2016 to 2020 (NHTSA, 2022). Motorist overtaking crashes commonly occur on two-lane, two-way undivided roads in both rural and urban areas. The next most common crash types are in the single digits. Other common crash types include crashes in which the bicyclist fails to yield (either at a sign-controlled or signalized intersection), when bicyclists and motorists cross paths at intersections, and when a motorist turns left while the bicyclist is traveling straight and moving in the opposite direction of the motorist. Table 1 shows the prevailing crash types associated with *fatal* bicycle crashes included in FARS.

Table 1. Top Crash Types Among Bicycle Fatal Crashes in the United States, 2016 to 2020

Crash Type	**Share of *Intersection (or related)* Fatal Crashes**		**Share of *Total* Fatal Crashes**
Motorist overtaking	7%		30%
Parallel paths - Other/Unknown	2%		6%
Bicyclist ride through/out - Signalized intersection	19%		7%
Bicyclist ride through/out - Sign-controlled intersection	18%		7%
Crossing paths at intersection	10%		4%
Bicyclist failed to yield/midblock	1%		8%
Loss of control/turning error	5%		4%

Crash Type	Share of *Intersection (or related)* Fatal Crashes		Share of *Total* Fatal Crashes
Motorist left turn	7%		3%
Motorist right turn	6%		2%
All other crash types	25%		28%

Source: Data from FARS, July 2022.

A crash analysis conducted by Thomas et al. (2020) investigated fatal and non-fatal bicycle crash types using crash data from FARS, North Carolina, and Boulder, Colorado. These datasets were used because they were the most complete and readily available datasets at the time of the analysis and demonstrate how trends can vary by scale (i.e., local, State, and national). The results of the analysis indicate that there are seven prominent crash types across all three datasets, including:

- Motorist overtaking – parallel paths, same direction;
- Motorist drive out of driveway – perpendicular paths;
- Motorist drive out of two-way stop controlled – perpendicular paths;
- Motorist turned left across bicyclist path – parallel paths, opposite direction;
- Bicyclist ride out of driveway or alley – perpendicular paths;
- Bicyclist ride out at stop-controlled intersection – perpendicular paths; and
- Bicyclist turned left across motorist path – parallel paths, same direction.

The above analyses indicate that the most common bicyclist crash types among bicycle-vehicle crashes of all injury severity levels are associated with motorists overtaking bicyclists, either party failing to yield, and motorist turning movements. Note that motorist drive-out (i.e., the motorist stopped or yielded and then proceeded into the path of the bicyclist) crashes were among the top seven crashes in the analysis completed by Thomas et al. (2020), which included fatal and non-fatal bicycle crashes, whereas this crash type was not among the top seven fatal crash types presented in Table 1. In fact, these two crash types were associated with 11% of non-fatal bicyclist crashes and 1% of fatal bicyclist crashes. Below is a more detailed discussion of these common bicyclist crash types.

Motorist overtaking

A motorist overtaking crash involves a situation where the motorist and bicyclist are on parallel paths and traveling in the same direction (Figure 4). For these types of crashes, the exact cause of the crash is often unknown—whether it was the motorist misjudging the space needed to pass, failing to see the bicyclist, or the bicyclist swerving into the path of the motorist (L. Thomas, Levitt, et al., 2018). While the cause of the exact movement that led to the crash is unknown, a prevalence of these types of crashes may indicate insufficient operating space or separation between users or poor visibility conditions. These crashes typically occur in the middle of the block or along rural roads, rather than at intersections.

A review of State and local crash analyses from across the United States indicates that this is a common crash type among bicyclist crashes of all injury severity levels in many jurisdictions

(Chicago DOT, 2012; NYC DOT, 2017b; Schneider & Stefanich, 2015; L. Thomas et al., 2019). In North Carolina, motorists overtaking bicyclists was the most common crash type among bicycle crashes of all injury severity levels. This crash type was associated with 40% of crashes resulting in a bicyclist injury in Chicago, Illinois (Chicago DOT, 2012).

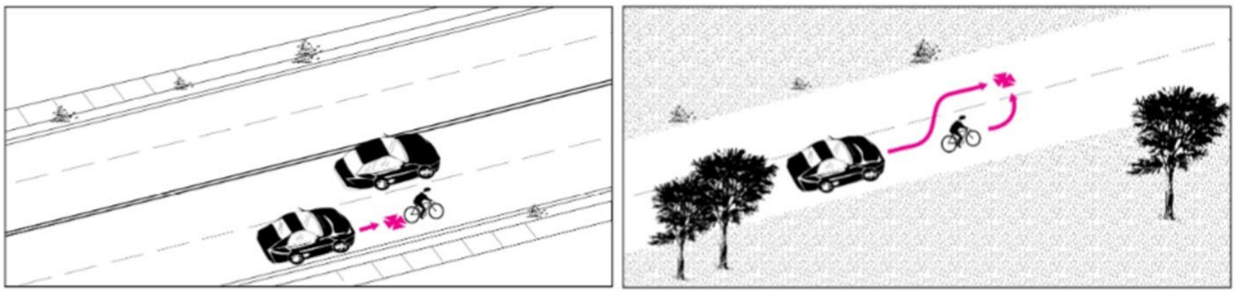

Figure 4. Example diagrams of a motorist overtaking a bicyclist
Source: PBCAT.

Turning crashes

Crashes involving vehicle turning movements are also common, particularly in urban areas. While turning movement crashes are often not associated with as many *fatal* crashes as motorist overtaking crashes, in urban areas with large volumes of bicyclists these crashes are still associated with a notable share of fatal and severe injury crashes (NYC DOT, 2017b; Seattle DOT, 2016). These crashes may also be more severe when they involve specific types of vehicles, such as large trucks. The two most common types of turning crashes are left hooks and right hooks. Figure 5 illustrates these crash types along with the percentages from Seattle, Washington.

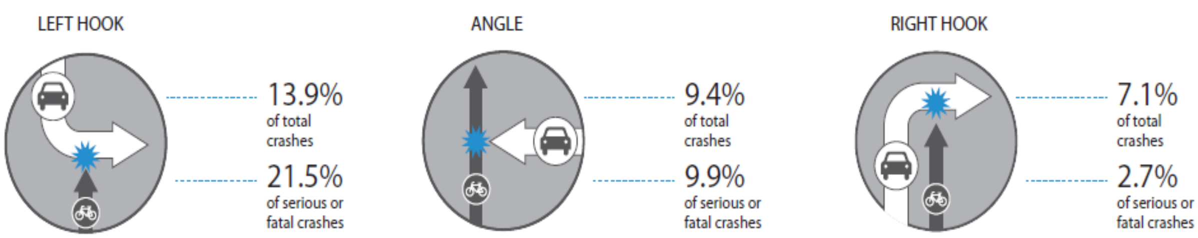

Figure 5. Top three bicycle crash types in Seattle, Washington
Source: SDOT (2016), p.8.

A left hook typically occurs when a motorist is turning left across the path of a bicyclist who is traveling straight ahead in the opposite direction (see Figure 5). The motorist may be paying more attention to oncoming cars than approaching bicyclists or may have misjudged the speed of the bicyclist (Sanders, Schultheiss, et al., 2020). Left hooks are common among bicyclist fatal and non-fatal injury crashes nationwide (Seattle DOT, 2016; L. Thomas et al., 2019). Among bicycle intersection crashes in urban areas in the FARS, North Carolina, and Boulder, Colorado crash datasets, a motorist turning left was among the top five crash types across all three datasets. Such crashes are associated with approximately 8% of U.S. urban intersection bicyclist *fatalities* and 14 to 17% of crashes of all severity levels (L. Thomas et al., 2019).

A right hook typically occurs at an intersection or merge area, when a motorist turns right across the path of a bicyclist who is traveling straight in the same direction (see Figure 5). The motorist may not see the bicyclist approaching (if stopped at an intersection) or may have passed the bicyclist and misjudged the speed of the bicyclist (Sanders, Schultheiss, et al., 2020). The prevalence of right hooks and left hooks varies by location. For example, when examining crashes of all severity levels in the urban areas of North Carolina and Boulder, Colorado, Thomas et al. (2019) found that a motorist turning left prior to a crash was nearly twice as common as a motorist turning right in North Carolina, whereas in Boulder a similar share of these types of crashes involved motorists turning left or right.

Failure to yield or obey traffic control

Crashes associated with a bicyclist or motorist failing to yield or disobeying the traffic control are common throughout the United States. These crashes include those where a road user fails to yield to another road user at a midblock crossing or an intersection. A few of the most common crash types in this category are motorist failed to yield, bicyclist failed to yield, crossing paths, and motorist or bicyclist ride through/out.[3] Among bicyclist intersection crashes in *urban* areas in the FARS, North Carolina, and Boulder crash datasets, a *bicyclist* failing to yield at a signalized intersection was among the top five crash types across all three datasets. Such crashes are associated with nearly 22% of urban intersection bicyclist fatalities in the United States (L. Thomas et al., 2019). Among the North Carolina (urban areas) and Boulder crash datasets, which included crashes of all severity levels, a *motorist* failing to yield at a sign-controlled intersection was the most common crash type and was associated with approximately 20% of crashes, whereas a *bicyclist* failing to yield at a signalized intersection was associated with 11% and 7% of crashes, respectively (L. Thomas et al., 2019).

Pedestrian Crash Types

This subsection mainly includes crash type data from 2014 to 2016 as analyzed by the UNC Highway Safety Research Center for the Pedestrian and Bicycle Information Center. A closer look at intersection-related crashes comes from the National Cooperative Highway Research Program's (NCHRP) project *Guidance to Improve Pedestrian and Bicyclist Safety at Intersections* (Sanders, Schultheiss, et al., 2020).

Readers should keep in mind that prevalent crash types have also been found to change over time, even when study methods and areas were consistent (Preusser et al., 2002). For example, midblock dash/dart-out (typically associated with child pedestrians) types declined from 37% of total pedestrian crashes in the Baltimore-Washington, D.C., area to 15% several years later. Crashes involving motorists turning across the pedestrian path (most typically at signalized intersections) meanwhile increased from 9% to 25% of the crashes. The study authors acknowledge that there had been little roadway infrastructure change given the cities' mature roadway network, but travel patterns may have altered due to increasing transit presence, changing land uses, and changing populations.

[3] A *bicyclist ride through* refers to a situation where the bicyclist does not obey the traffic control and proceeds into the intersection without stopping or yielding appropriately. A *bicyclist ride-out* refers to a situation where the bicyclist obeys the traffic control and is stopped before proceeding into the intersection and crashing with the motorist.

Whether at an intersection or non-intersection location along a roadway, national fatality data show that pedestrians are most often killed in crashes in which they are crossing the road and are struck by a motorist who is traveling straight ahead (*Crossing Roadway - Vehicle Not Turning*, 34% of fatalities for 2014 to 2016; Table 2). A similar type involving pedestrians who were apparently standing or walking in the road (but not necessarily crossing, see *Pedestrian in Roadway - Circumstances Unknown* crash type) and were struck by a vehicle traveling straight ahead, accounts for another 7% of fatalities. See Figure 6 for illustrations of these crash types.

The second most frequent type is pedestrian *Walking or Running Along the Roadway* being struck by a parallel path vehicle (from the same or opposite direction; 13% of fatalities) (Table 2). In all, the top eight scenarios (through *Crossing Expressway*) presented in Table 2 accounted for 94% of pedestrian fatalities nationwide from 2014 to 2016. Crashes involving pedestrians dashing or darting into the road (from behind an object/other vehicle) (*Dash/Dart-Out)* and crashes with turning vehicles (*Crossing Roadway - Vehicle Turning*) were also among the top eight types.

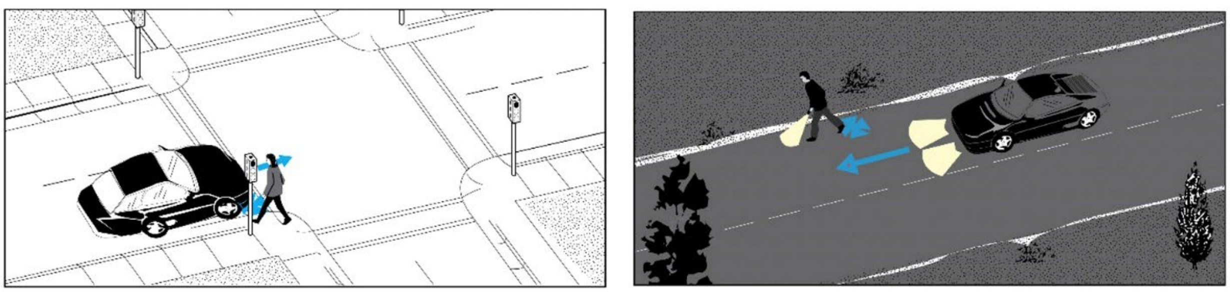

Figure 6. Examples of Pedestrian Crossing Roadway - Vehicle Not Turning (left side) and Pedestrian Walking/Running Along Roadway (right side)
Source: Pedestrian and Bicycle Information Center, Pedestrian Crash Type Images

A number of fatal crashes cannot be coded to a clear type (*Other/Unknown - Insufficient Details*) or involve a variety of *Unusual Circumstances* such as walking or standing near a disabled vehicle, or a prior vehicle to vehicle crash that led to a pedestrian being struck.

The columns in Table 2 show several factors that may be associated with increased risk of fatal pedestrian crash types. While most fatalities (71%) occurred at non-intersection locations, and 80% lacked traffic control for the motorist, 27% of fatalities were indicated to occur at intersections. *Crossing Roadway - Vehicle Not Turning* accounted for 49% of intersection or intersection-related pedestrian fatalities. Sixteen percent of crashes at intersections involved pedestrians being struck while vehicles were turning or preparing to turn (*Crossing Roadway - Vehicle Turning)*.

Pedestrians *Walking Along the Roadway,* is the second most frequent *fatal* pedestrian crash type. Pedestrians killed in this type were most likely to be struck between intersections (93%) and walking in or along the edge of a travel lane at the time. When the direction was known, 78% of pedestrians killed in this type, were walking with their backs to traffic.

Darkness and higher speeds also have been associated with increased fatality risk (L. Thomas, Sandt, et al., 2018). Overall, 71% of all pedestrian fatalities were associated with darkness between 2014 and 2016. The top two crash groups, *Crossing Roadway - Vehicle Not Turning*, and *Walking/Running Along Roadway*, along with pedestrians being in the road under *Unknown*

Circumstances and *Crossing an Expressway* are each more highly associated with nighttime than their overall prevalence (see highlighted/bolded cells in Table 2, which denote crash types that are more highly represented for various crash factor subsets compared to the crash type percentage of all fatal pedestrian crashes). The largest number of fatalities overall occurred on roads with speed limits of 40 to 45 mph (29%). An even higher percentage (47%) of pedestrians who died *Crossing Roadway - Vehicle Not Turning*, were struck on roads with speed limits of 40 to 45 mph. Overall, another 30% of pedestrian fatalities happened on roads with speed limits of 50 mph and higher; 16% on roads with limits of 35 mph, with about 9% each happening on roads with lower speeds (25 mph and 30 mph; these data are not shown in Table 2). Along with the ability for motorists to notice pedestrians at sufficient stopping distance at night, travel speeds may be higher during uncongested times of day (including at night) and the potential for road users to be experiencing fatigue and/or impairment are likely higher. The combination of these likely contributes to the high proportion of pedestrian fatalities that occur at night.

Overall pedestrians younger than 18 were involved in less than 8% of fatalities. *Walking/ Running Along Roadway* and *Dash/Dart-Out* types are more highly associated with pedestrians under 18 than their overall population representation. In part, this situation may be an artifact of smaller stature, as well as behaviors, with child pedestrians more likely to be obscured by parked cars and other objects along the roadside. Better data are needed to fully understand the risks to younger-aged pedestrians.

Pedestrians 65 and older accounted for 19% of all fatalities, but nearly 50% of all the *Crossing Roadway - Vehicle Turning* and 24% of *Crossing Roadway - Vehicle Not Turning* fatalities. These two types, respectively, account for 44% and 12% of pedestrian fatalities 65 and older (Table 2).

Table 2. Pedestrian crash type groups among U.S. pedestrians in fatal crashes, 2014 to 2016. (Source: FARS)

Pedestrian Crash Group/Crash Type	Total	% of Total Fatalities	% Intersection or Related	% Not at Intersection	% of No Traffic Control	% of Dark - All	% of 40 - 45 mph	% Ped. < 18 years	% Ped. 65+ years
Crossing Roadway - Vehicle Not Turning	6,165	33.9%	**48.7%**	29.3%	32.4%	**37.5%**	**46.8%**	22.6%	**44.0%**
Walking/Running Along Roadway	2,409	13.3%	3.3%	**17.5%**	**15.6%**	**14.5%**	11.7%	**15.3%**	7.2%
Other/Unknown - Insufficient Details	2,139	11.8%	11.9%	11.4%	11.9%	12.2%	2.1%	10.3%	10.4%
Unusual Circumstances	2,097	11.5%	5.1%	**13.6%**	12.2%	9.9%	**12.5%**	11.6%	6.3%
Dash/Dart-Out	1,379	7.6%	**8.9%**	7.3%	7.7%	7.4%	6.4%	**17.1%**	6.0%
Pedestrian in Roadway - Circumstances Unknown	1,277	7.0%	3.0%	**8.8%**	**8.1%**	**8.9%**	9.0%	4.1%	4.3%
Crossing Roadway - Vehicle Turning	841	4.6%	**16.0%**	0.4%	1.0%	1.7%	**6.9%**	3.9%	**12.1%**
Crossing Expressway	786	4.3%	0.0%	**6.1%**	5.1%	**5.1%**	0.1%	2.3%	2.0%
Backing Vehicle	213	1.2%	0.6%	1.3%	1.3%	0.3%	0.6%	3.2%	**2.6%**
Working or Playing in Roadway	196	1.1%	0.5%	1.3%	1.0%	0.6%	1.2%	2.5%	0.1%
Non-Trafficway	187	1.0%	0.0%	0.0%	1.1%	0.4%	0.8%	1.6%	1.1%
Unique Midblock	183	1.0%	0.2%	1.3%	1.2%	0.7%	0.4%	1.2%	1.5%
Bus-Related	99	0.5%	0.7%	0.5%	0.5%	0.3%	0.6%	1.7%	0.5%
Driveway Access/Driveway Access Related	94	0.5%	0.2%	0.7%	0.5%	0.2%	0.5%	1.5%	1.2%
Multiple Threat/Trapped	74	0.4%	0.8%	0.3%	0.3%	0.3%	0.3%	0.8%	0.5%
Waiting to Cross	32	0.2%	0.3%	0.1%	0.1%	0.1%	0.1%	0.3%	0.0%

Pedestrian Crash Group/Crash Type	**Total**	**% of Total Fatalities**	**% Intersection or Related**	**% Not at Intersection**	**% of No Traffic Control**	**% of Dark - All**	**% of 40 - 45 mph**	**% Ped. < 18 years**	**% Ped. 65+ years**
Total	18,171	100.0%	4,912 (27.0%)	12,867 (70.8%)	14,489 (79.7%)	12,986 (71.5%)	5,236 (28.8%)	1,381 (7.6%)	3,406 (18.7%)

Row percent is of column total.

Column total is of percent of total.

Highlighted/bold figures = Crash Types that are more highly represented for various crash factor subsets compared to the Crash Types % of all fatal pedestrian crashes.

Table 3. Frequent intersection crash types among national fatalities, statewide fatal (K-type) and disabling (A-type) injury crashes, and city-wide all severity pedestrian crashes

Crash Types from PBCAT	**National Fatalities** **FARS data, 2014-2015** **n = 2,954 intersection/intersection-related fatalities**	**Statewide Fatalities and Severe Injuries** **NC K + A data, 2008-2014** **n = 2,257 intersection /intersection-related crashes**	**City All Injuries** **Boulder data, 2008-2014** **n = 228 intersection/intersection-related crashes**
Pedestrian Failed to Yield (motorist not turning)	1018 (34.5%)	620 (27.5%)	n/a
Motorist Failed to Yield to Pedestrian (motorist not turning)	427 (14.5%)	123 (5.4%)	26 (11.4%)
At Intersection - Other/Unknown	344 (11.6%)	n/a	n/a
Motorist Left Turn - Parallel Paths	309 (10.5%)	363 (16.1%)	72 (31.6%)
Pedestrian Dash	235 (8%)	237 (10.5%)	36 (15.8%)
Walking Along Roadway with Traffic - Hit from Behind	n/a	74 (3.3%)	n/a
Motorist Right Turn - Parallel Paths	n/a	n/a	26 (11.4%)
Motorist Right Turn - Perpendicular paths	n/a	n/a	14 (6.1%)
Top 5, cumulatively	2,333 (79%)	1417 (62.8%)	174 (76.3%)

K = fatal; A = disabling injury at the time of these data.

Source: Adapted from Sanders et al. (2020).

Intersection crash types

Although non-intersection locations account for most pedestrian fatalities, well-functioning intersections may help to reduce the number of people crossing outside of intersections where they are even more vulnerable to severe injury (Toole et al., 2013). Prevalent intersection crash types were identified in the NCHRP 15-63 study that produced *Guidance to Improve Pedestrian and Bicycle Safety at Intersections* (Sanders, Schultheiss, et al., 2020). The most frequent fatal types of pedestrian crashes for intersections also involved motorists traveling straight through and either the pedestrian or motorist not yielding right of way (*Pedestrian Failed to Yield, Motorist Failed to Yield*, and *Pedestrian Dash*) (see Table 3). To offer examples from a State and a city: these were also common among fatal and severe types in North Carolina, but less so among all severity types in Boulder, Colorado. In Boulder, crashes involving motorists turning left at intersections were most common.

Turning crashes, especially those involving left turns striking pedestrians crossing the parallel crosswalk were also common among all three jurisdictions and severity types but were most common among all severity crashes at the city-level in Boulder. Differences in prevalent types may relate to infrastructure and other differences among the jurisdictions, but also potentially to relationships to severity. It is important to note that exposure was not assessed in these analyses, as is the case with many crash type analyses.

Non-roadway and backover crashes

In response to Federal surface transportation funding requirements, NHTSA developed the Not in Traffic Surveillance (NiTS) (now called Non-Traffic Surveillance - NTS) system to collect information about all non-traffic crashes, including non-traffic backover crashes, which often occur in parking lots, driveways, and other non-road rights-of-way. The most recent NTS study reported on backing-vehicle related crashes from surveillance data to supplement in-traffic data already available in FARS and the Crash Reporting Sampling System (CRSS) from 2016 to 2020 (NCSA, 2023). On average there were 264 backover fatalities and 11,592 injuries annually. Typically, several times more back-over related fatalities and injuries occur in non-trafficway situations such as driveways and parking lots as on roadways as captured in FARS and CRSS data. Children five and younger and older adults seem to face higher risk of being killed or injured in a backover crash. These trends may be affected by changes in demographics and other societal and technological shifts (including back-up cameras on vehicles and other technologies). Additional studies may be needed to examine ongoing trends by age groups, demographics, exposure, and perhaps other measures of physical vulnerability that may remain. A discussion of vehicle technology countermeasures, and the need for additional research, is included in Part 3.

Solo bicycle crashes and pedestrian falls

Not all bicycle crashes involve another road user or vehicle. For example, bicyclists may fall due to their wheels getting stuck in surface imperfections or in rail tracks, slipping on debris in the roadway, avoidance maneuvers, or a bike malfunction. Crashes that do not involve a motor vehicle are unlikely to be reported to the police. Therefore, relatively little information is known about the circumstances contributing to solo bicycle crashes and how prevalent they are in the United States. Research suggests that a much greater share of falls is associated with avoiding a collision compared to loss of balance, bike malfunctions, braking too hard, or having an item caught in a wheel (Teschke et al., 2014). The City of Boston (2013) completed a bicycle safety analysis using data from both police reports and EMS and found that among the crashes in the police database, 91% involved a bicycle and motor vehicle and only 4% were solo bicycle crashes, whereas in the EMS dataset, 63% of crashes involved a bicycle and a motor vehicle and 29% involved solo bicycle crashes.

The literature suggests that the prevalence of solo bicycle crashes among fatalities and non-fatal injuries differs. Schepers et al. (2014) conducted a review of 26 studies of bicyclist fatalities and non-fatal injuries that resulted in a visit to the hospital or emergency department from countries in Europe, Asia, North America, and Australia. On average, 17% of bicyclist fatalities were the result of solo bicycle crashes (datasets ranged from 5% to 30%). Note that the fatality data included only police-reported fatality data from European countries. In comparison, between 60% and 95% of bicyclists admitted to hospitals or emergency departments for injuries were the result of solo bicycle crashes. Similarly, Cripton et al. (2015) studied bicycle-related injuries among adult emergency room and hospital visits in Toronto and Vancouver, Canada, and found that 60% of crashes were solo bicycle crashes.

Older pedestrians also face higher likelihood of falling while walking, and frailty in older adults means injury outcomes are more severe (Harmon et al., 2020; Oxley et al., 2018; Wisch et al., 2017). Researchers using national-level emergency department data from 2001 to 2006 found that, on average, 52,482 people 65 and older were treated for non-fatal pedestrian injuries (Naumann et al., 2011). Of those injuries, 77.5% listed falling as the leading mechanism of injury. Crashes involving motor vehicle drivers resulted in 15% of these ER injuries.

Limitations of using crash data to understand safety

Much of what we know about bicyclist and pedestrian behavior is based on monitoring those who are currently walking or riding a bicycle on streets. In some cases, the only measure we may have is crash data, but in a small community there may not be enough to paint a true picture. Observing interactions and near misses on local streets may be an effective means of understanding where interventions are needed (Cloutier et al., 2017). It is also necessary to understand the nature of trips that are not taken. Research has linked walking and bicycling behavior to perception of safety, and if certain locations feel unsafe, there may simply be no bicyclist or pedestrian traffic in that spot. Thus, working to measure suppressed trips, is also important if we are to gain a more complete understanding of safety problems (Ferenchak & Marshall, 2019b).

Perception of safety and risk affects bicycling and walking behavior for everyone. Perception of safety is the idea that an individual may experience harm based on environmental conditions. Perceptions of risk may vary between people and lived experiences. A Canadian study measured perceived safety in comparison with observed relative risk, and found that perceptions and observed safety risks were aligned in many instances, though not all (Winters et al., 2012). Several studies have explored risk perception as shaped by individual attitudes and experiences and how they influence bicycling behavior, and noted variations between genders (Garrard et al., 2008; Ma et al., 2014; Sallis et al., 2006; Sallis, 2009; Xing et al., 2018).

The study of perceived risk and near misses is a small, but growing area of research that can provide important insights into bicycle safety, including the frequency of risky situations and behaviors. It is especially pertinent to trends among bicycling-related incidents because bicycle crashes are relatively rare and are not always documented. Understanding trends among near misses can help jurisdictions proactively implement countermeasures and minimize potential crash risks. Research indicates that while a relatively small share of the bicycling population has been involved in bicycle crashes, most bicyclists, regardless of how frequently they bicycle, have been involved in a near miss (Aldred, 2016; Joshi et al., 2001; Sanders, 2015). Among near misses, the most common types of incidents involve dooring, motorists turning, motorists driving too close to bicyclists, motorists blocking bicycle lanes, and motorists pulling in or out across a bicyclist's path (Aldred, 2016; Sanders, 2015).

Experiencing a near miss or crash, or knowing someone that has, can influence perceptions of bicycling and decisions about whether to bicycle in the future (Aldred & Crosweller, 2015; Sanders, 2015). Therefore, understanding trends among both crashes and near misses, and determining ways to mitigate risks among both types of incidents, are important components of making bicycling safer and encouraging more people to bicycle.

Perception of personal security can affect women's travel habits, including where and when to walk, use transit, or ride a bicycle (Clifton & Livi, 2005; Loukaitou-Sideris & Fink, 2009). For example, women tend to walk less after dark (Bernhoft & Carstensen, 2008; Dymén & Ceccato, 2012). Certain transportation facilities or locations can be sources of anxiety due to factors in their design or their surroundings (Loukaitou-Sideris, 2011). In a walkability index for women in San Francisco, California, women ranked crime, the presence of people who appear unhoused, and lack of street/sidewalk cleanliness as the three top factors that decrease walkability and perceptions of comfort and safety (Golan et al., 2019).

Significant gender disparities exist in bicycling in the United States. Studies have considered barriers to bicycling for women, which exist on several levels—individual, social, and physical-environmental. Individual and social barriers include differences in attitudes, feelings of self-efficacy, household responsibilities, and differing perceptions of safety (Emond et al., 2009; Heesch et al., 2012). Women tend to report a broader set of concerns such as weather, exhaust from automobiles, and other factors that men tend not to cite, in addition to safety and time constraints (Heesch et al., 2012). However, as Dill et al. (2014) point out, gender parity in bicycling does exist in countries where women face similar individual and social pressures, but where they might have fewer concerns about safety, such as the Netherlands and Denmark.

Crashes and Exposure

While this report does not focus expressly on strategies to increase trips made by walking and bicycling, the topic of walking and bicycling volume (sometimes generally referred to as mode share or exposure) is intertwined with safety, often through discussion of the concept "safety in numbers." The complex and non-linear[4] relationship between crashes and volume highlights the fact that the absolute number of crashes is often an imperfect indicator of danger for pedestrians and bicyclists, and thus, why strategies focused on increasing mode share and improving safety are often considered in tandem. The phrase safety in numbers describes the concept whereby the risk to an individual bicyclist or pedestrian of being seriously injured decreases as walking and bicycling increases (i.e., the number of crashes increases less than proportionally to volume) in a given location or area.

[4] A non-linear relationship between crashes and volume indicates that crashes and volume do not increase or decrease at the same rate. A linear relationship between crashes and volume is when an increase in crashes results in the same rate of increase in volume, and vice versa.

The safety in numbers effect for walking and bicycling has been well-documented in an increasing body of evidence that spans geographic levels (i.e., intersection, area, municipality, country) (See Kehoe et al., 2022 for an overview). Nearly all studies reviewed for a meta-analysis documented a safety in numbers effect (Elvik & Goel, 2019). However, questions remain about the strength of the safety in numbers effect and the behavioral and environmental explanatory mechanisms that underpin the effect (Elvik, 2017; P. L. Jacobsen et al., 2015). Additionally, there is a wide range in the maximum and minimum values ascribed to the safety in numbers effect (i.e., the values represent how weak or strong the effect is) across different studies and that range seems to be widening in more recent studies, so there is no convergence on a common value for the expected strength of the effect (Elvik & Goel, 2019). While safety in numbers is more often mentioned in relation to bicycling, the meta-analysis found that the effect is stronger for walking. Kehoe et al. (2022) conducted a literature review and analysis on safety in numbers considering a breadth of fields including engineering, planning and land use, sociology, psychology, education, public health, enforcement, and human factors and concluded that the effect is stronger for bicycling. Additional research investigating underlying factors (e.g., the built environment, behavioral changes, road user demographics and characteristics, safety culture) may help better explain the effect.

Research has demonstrated the correlation in places with higher levels of safety and higher volumes of people walking or bicycling, but the causation in the relationship is yet to be determined (Schneider et al., 2017). Possible hypotheses include the design, regulation, and operation of streets; the behavior of people walking or bicycling; or the behavior of people driving (P. L. Jacobsen et al., 2015). While nearly all studies are cross-sectional and relatively few studies control for more than a handful of confounding factors, some studies have found that the safety in numbers effect persists even when controlling for the presence of typical infrastructure that is generally considered to be less hospitable to walking and bicycling (e.g., additional traffic lanes) and that the effect varies seasonally, which means that the effect exists somewhat independently from infrastructure (Elvik & Goel, 2019; P. L. Jacobsen et al., 2015). This means that the effect may be more attributable to differing behaviors of different road users in relation to each other based on factors such as experience, expectations, risk-taking, etc.

Important research gaps for understanding safety in numbers include the lack of studies that control for several confounding variables and a dearth of longitudinal examinations of the effect. Longitudinal studies can help answer the question of places that become safer (or less safe) given changes in volume. A team of researchers used the same data to conduct a longitudinal *and* cross-sectional analysis for bicycling in Britain for three Census periods: 1991, 2001, and 2011 (Aldred, Goel, et al., 2017). Using commute and injury data from 202 jurisdictions and controlling for population size, they found that the safety in number effect existed cross-sectionally in each Census year and longitudinally at the national level, but that the effect can coexist with increased injury risk per commuter.

Safe System Approach

Although a traditional, crash-based approach to safety management may produce some safety improvements for pedestrians and bicyclists through the use of engineering treatments at high-crash locations, many risks to road users outside the vehicle exist and can increase or decrease in unexpected ways due to the complex systems that propel infrastructure development, land use, and travel mode or access (Naumann et al., 2020a, 2020b). Traditional safety management methods may improve safety at high-crash locations by providing safer infrastructure, but they may be unable to reduce the network-wide risks that can discourage road users from walking or bicycling. Therefore, traditional safety management approaches may not always produce the desirable safety in numbers effects if they do not motivate increased walking or bicycling through a transportation network. Moreover, particularly risky spots (e.g., higher speed multi-lane roads without crosswalks or sidewalks and minimal or no lighting) with minimal crash histories may be missed entirely in a traditional safety approach, despite the fact that treating these sites may improve safety (Kumfer, LaJeunesse, et al., 2019; Kumfer, Thomas, et al., 2019; L. Thomas, Sandt, et al., 2018) and motivate more road users to walk or bicycle. Therefore, this report extensively covers recent literature that is focused on traffic safety frameworks of risk reduction and management.

One such framework for managing safety is the Safe System Approach (SSA). This road safety management system was first adopted in Europe and has been implemented under different names in a variety of countries, but the general tenets of the SSA are consistently reported. Those tenets, as listed by Dumbaugh et al. (2019), include:

- The human body has a known and limited ability to tolerate crash forces.
- People make mistakes that lead to crashes.
- System designers share responsibility with road users for crash prevention.
- All elements of the system should be strengthened to multiply their effects.

Embedded in these tenets, particularly the first, is the recognition that humans are inherently vulnerable to the energy levels produced by the modern transportation system. In the case of motor vehicle crashes, the energy is kinetic energy that is the energy generated by the vehicle in motion. Modern vehicle designs mitigate much of this energy impact, but pedestrians, bicyclists, and other road users not in vehicles remain particularly susceptible to the deadly energies that exist on roadways (Kumfer, LaJeunesse, et al., 2019). For that reason, SSA operations are born from the understanding that reducing not just raw crash numbers but the energies and risks that create death and serious injury is paramount to creating an equitable transportation system that is safe for all road users (Dumbaugh et al., 2019). Furthermore, the U.S. DOT adopted the SSA as the "guiding paradigm to address roadway safety" (2022) in its National Roadway Safety Strategy. The strategy emphasized as a principle that death and serious injuries are unacceptable.

Due to their susceptibility to crash energies, pedestrians and bicyclists are especially vulnerable to the types of inherent risks born through land development and engineering choices that may seem reasonable for vehicular traffic such as higher speeds, few places to cross streets, and no bike lanes or sidewalks (Dumbaugh et al., 2019). Mitigating these risks by acknowledging the shared responsibility of road users, designers, and stakeholders requires recognizing how safety problems—like high speeds that lead to high kinetic energies—can and should be treated using a variety of risk management tools (Kumfer, LaJeunesse, et al., 2019). Enforcement, planning, engineering, and technology all interact to create or limit latent risks, so Part 2 of this report is framed around these topics (i.e., people, the environment, and the vehicle) and demonstrates how these elements interact to create safety problems and how solutions may require thinking beyond specific site properties or particular road users to create a safer environment in which pedestrians, bicyclists, and vehicles can interact.

The Role of Media Coverage

In a traditional traffic safety management framework, the prevailing paradigm is that responsibility for safety resides with the personal user and not the system designer. However, as reflected in the SSA and recent literature (Naumann et al., 2020a, 2020b), risks to safety are outputs of the complex transportation system, so there is a need to reconsider how education and information efforts reflect the systemic nature of safety. The way that transportation practitioners and safety professionals interpret the safety trends discussed and present them to different audiences matters and can shape public discourse.

One critical element of the system that influences perceptions and the efficacy of information and education is the media, particularly how traffic crashes and risks are reported. If the media, and agency officials providing information to the media, consistently frame pedestrian and bicycle crashes as isolated events that are only the result of individual behavior, there may be less motivation for the public to request changes and for planners, engineers, law enforcement, and elected officials to prioritize more systemic approaches to improving safety.

Researchers and advocates are increasingly using lessons and methods from the field of media studies to understand how the media frames crashes involving pedestrians and bicyclists and how coverage may influence the degree of public concern about traffic crashes and the type of policy responses supported by the public and decisionmakers (Bond et al., 2019; Goddard et al., 2019; LaJeunesse et al., 2020; Macmillan et al., 2016; Ralph et al., 2019).

Media reports tend to focus on the behavior of road users along with some details about the crash, like weather conditions or time of day, with little to no discussion about roadway design, history of crashes in the area, or personal details that might humanize the victim. This episodic framing places the blame on road users outside the vehicle and forgoes thematic framing, which could highlight the public health nature of crashes and introduce systemic solutions related to the design of the roadway or the design of motor vehicles (Bond et al., 2019; Ralph et al., 2019). Ralph et al. (2019) point out that thematic framing aligns with the Vision Zero approach, which seeks to shift the burden of responsibility for road safety away from individual users and to the designers and operators of the transportation system as well as those responsible for the design and regulation of vehicles. To test whether editorial patterns *influence* public perception, researchers conducted an experiment in which subjects (n=999) were asked to read and respond to one of three versions of a news story about a fatal pedestrian crash (Goddard et al., 2019). They found that editorial patterns affected how readers apportioned blame for the hypothetical crash and shaped the readers' perceptions about punishments and solutions (i.e., shifting to driver-focused language reduced victim-blaming compared to pedestrian-focused language, while a thematic frame significantly increased support for infrastructure improvements).

Media report content aside, researchers in the United Kingdom have also considered the relationship between media coverage and ridership when it comes to reporting on bicycle crashes (Macmillan et al., 2016). This work is relevant in the context of concepts like SSA and safety in numbers. Researchers took police-reported bicyclist fatalities in London from 1992 to 2012 and identified whether they received media coverage. During the study period, bicycling trips doubled in London while the total number of bicyclist fatalities remained stable, but the proportion of fatalities covered in local media increased from 6% to 75% whereas there was little change during the study period in the number of articles reported per motorcyclist fatality. There was an increase in bicycling that led to no increase in the number of fatalities, but a significant increase in media coverage. Looking at motorcyclists for a comparison group helped the researchers confirm that there was not a broad change in traffic crash reporting during this time period. While the findings may not extend to other parts of the world, they serve as a reminder to consider the complex relationship between bicycling numbers, bicyclist crashes and fatalities, and responses by the media, including volume of coverage and the content of that coverage.

Frameworks for Understanding Behaviors

Many transportation practitioners are focused on one area related to the safety of people walking and bicycling (e.g., planning, roadway design, education, etc.) so it can be useful to take a step back and think about how human behavior is deliberative and intuitive, that humans are not exclusively rational, logical beings, and that behavior is heavily influence by the environment (both the built environment and social contexts like policies and social norms) (Gelinne et al., 2017). The theories and frameworks covered in brief below should help guide our thinking about behavior and the way that we design and implement interventions.

Individual Behavior

Certain conceptual frameworks have been commonly applied in research aiming to understand the behavior of road users (Robertson & Pashley, 2015). One often used lens is the Theory of Planned Behavior (TPB), which states that intention and self-efficacy—in addition to social norms, attitudes, and beliefs—determine behavior, especially intentional behavior. That is, when a person intends to carry out an action, they will be influenced by their own feelings of self-efficacy around the behavior, their attitude towards the behavior itself, and perception of how the behavior will be viewed by others, or how it fits within social norms. TPB is limited in terms of considering the environment and other broader influence such as past experience or economic impacts (Ajzen, 1991). Some have made the case for including perception of risk or safety in TPB (Holland & Hill, 2007). An example application of TPB to understand pedestrian behaviors comes from researchers who have examined pedestrian distraction for clues about how interventions could more specifically influence target behaviors (Barton et al., 2016; Lennon et al., 2017).

Socioecological Model for Communities

Borrowing from public heath, transportation researchers have looked at interventions that can be applied on several levels. By addressing problems on a social, cultural, organizational, or policy level, a greater proportion of the population can be affected with an intervention.

Socioecological models have also been commonly applied to understand pedestrian and bicycling behavior in the context of social, organizational, community, and policy environments. By taking a wider view, one can understand the ecological structure that may determine behaviors. Elements such as community values, social relationships and individual abilities combine to play a role in behavior outcomes (Götschi et al., 2017; Pikora et al., 2003).

The model can be used to draw attention to various points of entry for safety interventions. Winters et al. provide a review of policy interventions for increasing safe, active travel applied on several levels (e.g., route-level, city-level, society level) using a socioecological approach, but authors stress that policy interventions should be accompanied by built environment and other targeted improvements (Winters et al., 2017).

Culture of Safety

Safety culture is a term that has been increasingly employed to reference elements of human behavior in relationship with transportation safety. Building on ideas around organizational safety culture, traffic safety culture has become a topic of interest when trying to understand road user behaviors. The research journal *Transportation Research Part F: Traffic Psychology and Behavior* dedicated an issue to unpacking the concept of traffic safety culture. In the issue, traffic safety culture is described as an effort to understand and acknowledge psychological and societal factors that influence individual behavior with the goal of being able to target broader cultural ideas that influence safety decision making in people. Frameworks such as TPB look at underlying "cognitions" that determine behavior, such as values, beliefs, perceived norms, and attitudes. Research around traffic safety culture is an attempt to understand how these cognitions come to exist in the first place, and how they can be targeted to improve safety outcomes (Ward & Özkan, 2014).

A central focus of traffic safety culture is on group membership and how sharing experiences and culture (often termed "belonging") affects the individual members of that group. Groups can exist on very local levels, all the way up to national level. Groups possess a common identity and general perspective, and social context. To improve road safety, some maintain we must create a cultural shift in the groups that people "belong to." Ward et al. (2014) argue that the effect of traditional methods for improving traffic safety has plateaued, suggesting that our culture has come to accommodate high risk driving behaviors like speeding. With cultural resistance in place, the United States cannot achieve zero traffic deaths and "a new paradigm of traffic safety based on culture is needed to instill the social imperative necessary to reject risk behaviors, engage in protective behaviors, and embrace traffic safety policies" (p. 292).

Some contend that the definition of safety culture has become too broad and does not present a direct link to causality in terms of safety outcomes. By understanding behavior based solely on what we characterize as "safety culture," such as individual and group attitudes, beliefs, and social norms and how such factors in turn determine human behavior, we may miss the opportunity to examine larger institutional structures that may also play a role in determining the actions of road users (Myers et al., 2014; Otto et al., 2016).

Theoretical models capture the fact that many of the issues faced around road safety are complex and multifaceted. Theories such as these underscore the idea that persistent safety problems should be addressed on several levels with a suite of interventions that target not only individual behavior but also higher-level structures, and that behavior change will not result from one-dimensional approaches. Applying an intervention at the individual level may have some effects but it would be more impactful to look at the issue on a larger scale.

Report Outline

The following is an outline of the remaining parts of this report. Part 2 introduces the research about the risk factors that interact to create (or limit) latent risks for bicyclists and pedestrians. Part 3 details what is known (and unknown) about the effectiveness of countermeasures at each level of intervention from the population level to the individual level. Part 4 defines key terms to measure and monitor bicyclist and pedestrian safety and identifies potential improvements for data collection practices.

Part 2: What Creates and Mitigates Risk for Bicyclists and Pedestrians?

- **The Role of People** – Discusses research findings related to individual-level behaviors and how they may affect pedestrian and bicycle safety outcomes. Topics include risky behaviors exhibited by drivers, pedestrians, and bicyclists like distraction and impairment and differences among bicyclists and pedestrians based on age, gender, and perceptions.
- **The Role of the Environment** – Focuses on role of the physical environment in creating or mitigating risks to the safety of people walking or bicycling. Topics include the relationship between physical space and safety and the relationship between roadway infrastructure and safety.
- **The Role of the Vehicle** – Covers the role that vehicle design and vehicle mass play in the risk of a crash with a person walking or bicycling and the severity of a crash, should one occur. This section also includes a discussion about the role of vehicle testing.
- **Emerging Safety Concerns** – Briefly explores emerging safety concerns mostly due to changes in motorized traffic, including vehicle automation, electrification, and emergent transportation modes.

Part 3: Effectiveness for Safety Interventions for Pedestrians and Bicyclists

- **Laws and Policies** – Briefly covers laws targeted at drivers (including speed limits) before presenting what is known about bicycle helmet laws and bicycle passing laws.
- **Programs for Behavior Change** – Covers the effectiveness of comprehensive programs that employ several interventions (e.g., education and enforcement), programs focused on changing the behavior of users through education (typically aimed at children), and broader road safety campaigns that include a marketing component.
- **Crossing- and Corridor-Specific Safety Interventions** – Presents a review of engineering interventions that can be used to improve safety for people walking and bicycling, including overarching interventions such as speed management.

Part 4: Measuring and Monitoring Bicyclist and Pedestrian Safety

- **Defines Key Terms** – Defines exposure, risk, and crash severity.
- **Data Collection Improvements** – Focuses on the types of data needed to quantify safety issues, pros and cons associated with various sources, and methodological considerations in studying traffic safety for these modes.

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Part 2. What Creates and Mitigates Risk for Bicyclists and Pedestrians

Part 2 tells the story of the behaviors, personal characteristics, built environment features, and motor vehicle factors that interact to create, or mitigate, the risk of crashes involving people walking or bicycling. The last section briefly explores emerging safety concerns mostly due to changes in motorized traffic, including automation, electrification, and emergent transportation modes.

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The Role of People

Human behavior is complex. People respond to the physical environment through which they travel based on social and cultural norms they were directly or subconsciously taught; habits formed through actions taken and responsive feedback received when traveling in a similar nature previously; and an individual's physiological and cognitive ability (Carter et al., 2017). Further, most actions taken are guided by the intuitive or unconscious system for making decisions. This means that most human behavior is not the result of logical, conscious reasoning but that of nearly instantaneous decisions based on previous experiences. For example, a person who regularly drives 5 to 10 mph over the posted speed limit along the same network of roads and has never crashed or has always been able to avoid a crash will likely continue to speed even if the person knows that driving at higher speeds is riskier. Each specific experience of driving over the speed limit builds to form a practice of behavior that translates into habit—the person does it without even thinking about it. Further, the visual cues that a motorist receives—such as wide lanes, speeds of other motorists, and few to no horizontal or vertical curves—additionally reinforces the message that the road still "feels safe" at the higher speed. This person may now mistakenly believe that he or she is capable of "safely" speeding.

Even when people consciously make decisions, there are many factors that influence how the information available to us is processed. As people factor in their customs, moral beliefs, emotions, convenience, finances, and interactions between these factors the ultimate result may not reflect what others would deem to be a rational outcome and, in some cases, may actually risk their health and wellbeing (Carter et al., 2017). For example, a person who lives less than two miles from their office may choose to drive every day out of habit, a perception that walking is unsafe, or that driving is more convenient even if the route is walkable, takes no longer than driving (due to congestion or time to locate parking), and is a good way to achieve health goals through physical activity.

Ideally, then, the road environment would be designed and controlled to induce desired behaviors out of road users that are safe based on what research and observations have shown will elicit those actual behaviors—i.e., a "self-regulating" system. However, while people are heavily influenced by their environment (both physical and sociopolitical), people also make mistakes. These errors may be more likely from people with less experience (i.e., with more practice, our intuitive processes are better refined), or who are engaging in activities that impair their judgement. Mistakes can manifest in predictable patterns, but human error is inevitable (Carter et al., 2017). As humans design, engineer, and maintain our transportation system, the vehicles that operate in it, and laws and policies that govern this system, the role people play in the safety of pedestrians and bicyclists in this system must consider a broader context than the behavior of the road user alone.

It is important to understand the context in which certain behaviors of interest occur. When considering the role of road users in the context of bicycle and pedestrian safety, one must understand the factors that influence the behaviors of motorists, pedestrians, and bicyclists. Research around behavior typically relies on observational studies, simulation-based studies, self-report, or crash-typing to understand how road users behave in a context, why they may undertake risky behaviors, and what other factors may contribute to a given behavior. Examination of the behavior itself is essential, but the environment in which it takes place is critical as well.

Much of what we know about bicyclist and pedestrian behavior is based on monitoring those who are currently walking or riding a bicycle on streets. In some cases, the only measure we may have is crash data, but in a small area (or short duration of time) there may not be enough to paint a true picture. Observing interactions and near misses on streets may be an effective means of understanding where interventions are needed (Cloutier et al., 2017). It is also necessary to understand the nature of trips that are not taken. Research has linked walking and bicycling behavior to perception of safety, and if certain locations feel unsafe, there may simply be no bicyclist or pedestrian traffic in that spot. Thus, working to measure suppressed trips, is also important if we are to gain a more complete understanding of safety problems (Ferenchak & Marshall, 2019b).

This section discusses research findings related to individual-level behaviors and how they may affect pedestrian and bicycle safety outcomes. Motorist behaviors such as speed, yielding/passing, distraction, and impairment are covered briefly. The body of knowledge around road user behavior as it relates to drivers of motorized vehicles is vast, but interest in behavior and how it affects people on bicycles and on foot is still an emerging field of study.

Motorists

This subsection covers research that estimates the relationship between environmental factors and motorist behaviors, primarily where the behavior is the research outcome of interest (e.g., motorist speed, yielding, and passing).

Speed and Risk

Vehicle travel speeds are a byproduct of environmental, policy, and behavioral factors (Sanders et al., 2019). Policy (i.e., speed limits) is covered in Part 3, while the environment is covered in the next subsection, Role of the Environment.

Vehicle speed is a key component of risk for pedestrians and bicyclists. Travel speed affects the severity of crashes because speed is a key determinant of crash forces. Pedestrians and bicyclists, as unprotected or vulnerable road users, are more susceptible to crash forces than are vehicle occupants who receive protection from the safety features installed in motor vehicles, so speed is a special concern for these road users. There is also reason to expect that with higher speeds, there will be more crashes, but the relationship between speed and crash frequency is less obvious than the relationship between speed and severity.

Although speed is frequently included as a contributing factor in crash analyses and prediction models, the relationship between speed countermeasures and pedestrian and bicyclist safety is less established in the literature. While many researchers and practitioners recognize the need to manage speed as a means of reducing the dangerous crash forces driving global trends in fatalities—especially pedestrian deaths—much more research and guidance is needed on how to effectively reduce speeds in a given built environment context (Sanders et al., 2019). The act of speeding is not synonymous with speed; speeding is the act of exceeding a posted speed limit or driving too fast for conditions. Speeding is, therefore, a specific case of speed in relation to the built environment since speed limits are set with consideration for the roadway design. This section is more concerned with speed itself as a factor that affects risk and will focus primarily on this topic and its relation to pedestrian and bicyclist safety. For a comprehensive synthesis on speed management and countermeasures that may reduce speed, the NCHRP Synthesis

Pedestrian Safety Relative to Traffic-Speed Management is a resource for identifying appropriate solutions for speed and speeding (Sanders et al., 2019).

Speed is a major concern for pedestrian safety globally. This fact is documented throughout the literature and reaffirmed by L. Thomas, Sandt, et al. (2018) both in a synthesis of risk factors identified from 38 pedestrian safety analysis studies and in the development of an SPF for collisions between motor vehicles and pedestrians in all light conditions and dark conditions. In their literature scan, Thomas et al. found positive associations between crash severity and crash frequency and *speed limits* greater than 25 mph along roadway segments; positive associations between pedestrian injury severity and speed limits greater than 25mph along roadway segments; and positive associations between crash severity and travel speed at intersections. In the SPF for frequency of nighttime pedestrian collisions along road segments, the researchers also found that pedestrian crash frequency risk was higher for streets with 30 or 35 mph speed limits than for those with 25 mph speed limits. These positive associations indicate that speed can increase both crash frequency and crash severity for pedestrians, and risk may be heightened at night because it may be harder to see pedestrians when traveling at higher speeds in low light conditions. Thomas et al. (2018) report that many jurisdictions lack enough speed data to properly characterize the risk to pedestrians on their roadways so speed limit data may be used as an imperfect surrogate. Travel speed data should be collected wherever possible to better understand how the built environment induces different travel speeds and how those travel speeds then increase or decrease the risk to pedestrians in those contexts.

Sanders et al. (2019) synthesized several studies of impact speed and pedestrian fatalities and produced a table of this relationship. Table 4 below is adapted from the Sanders et al. (2019) work.

Table 4. Crash impact speed and associated risk of pedestrian fatality

Impact Speed (mph)	Risk of Fatality (percent)
24-33	10
33-41	25
41-48	50
48-55	75
54-63	90

Source: Sanders et al. (2019).

In addition to pedestrian safety, speed also affects the safety of bicyclists. Most bicycling fatalities occur in non-intersection locations and speed is frequently a factor in these fatalities due to the kinetic energy involved when a faster, heavier vehicle strikes a slower moving bicyclist (Cushing et al., 2016). Research has shown that the likelihood of a crash becoming fatal increases substantially when vehicle speeds exceed 20 mph; Cushing et al. (2016) synthesized a number of sources to identify the factors by which the chance of a bicyclist fatality increases as vehicle speeds increase. See Table 5 for the results of this study.

Table 5. Vehicle travel speed and multiplier for chance of bicyclist fatality

Vehicle Travel Speed (mph)	Multiplier for Fatality Risk
30	2
40	11
50	16

Source: Cushing et al. (2016).

This chance of fatality may be mitigated by facility separation for bicyclists, but intersections remain dangerous conflict points for bicyclists. Locations where separated bike lanes or shared use paths intersect with roadways may also be locations where vehicle speeds and limited visibility interact to increase bicyclist risk. These intersection types often have limited traffic control and motorists may not be watching for bicyclists who can cross their paths, resulting in high-crash-energy potential. At traditional intersections, bicyclists are also exposed to potentially dangerous energies from turning motorists who may decelerate insufficiently before a bicycle lane intersects with a turning lane. Therefore, speeds remain a major concern for bicyclists at both intersections and along segments (Cushing et al., 2016).

Motorist Yielding to Pedestrians

Pedestrians are most likely to interact with motorists at intersections or crossing locations. Motorist yielding-to-pedestrian behavior has been shown to be associated with the environment, enforcement activities, characteristics of the pedestrian and/or the motorist, and other social factors. Motorists tend to yield less on urban two-lane roads with higher 85th percentile speed, based on findings from a study of eight locations in Boston (Bertulis & Dulaski, 2014). Locations where 85th percentile speeds were in the 40-mph range had 17% to 19% yield rates, whereas crosswalks located on roads where speeds were 20 mph were as high as 75%. Motorists may also be less likely to stop at marked midblock crosswalks when they have come from a freeway or have already passed through a green signal indication (Figliozzi & Tipagornwong, 2016). At marked uncontrolled crosswalks in five North Carolina municipalities, motorist yielding was associated with lower speed roads and high-visibility crosswalk markings. This association held when accounting for the effect of law enforcement intervention and other factors that influence yielding (Sandt et al., 2016).

Stapleton et al. (2017) tested motorist yielding compliance on different types of crosswalks in a college town in Michigan. Motorist yielding was shown to be strongly associated with crosswalk design, and compliance rates were much greater in locations where PHB, RRFB, or in-street signs were present. The use and effectiveness of each of these three crosswalk treatments are discussed in Part 3.

Some research, carried out under daytime conditions, suggests that pedestrians may be more cautious when crossing at unmarked locations and hurry their crossing, while motorists may be less likely to yield at unmarked locations (Mitman et al., 2010) or when driving at higher speeds (Bertulis & Dulaski, 2014; Gårder, 2004). To some extent, these findings may relate to lack of motorist recognition of unmarked crosswalks or knowledge of right of way laws as it applies to unmarked crosswalks by motorists and pedestrians (Hatfield et al., 2007; Mitman & Ragland, 2007; Mitman et al., 2010). Crosswalks are the extension of the sidewalk or shoulder across the intersection; these can be marked (painted lines directing pedestrian flow) or unmarked.

Yielding may also vary based on motorist perception of the persons attempting to cross. Researchers filmed interactions at two study crossing sites in Montana that were equipped with RRFBs. They found that at both study sites, the motorist yielding rate to pedestrians was statistically significantly higher when one or more of the pedestrians was either a child or older adult (65 and older). This result held regardless of whether the RRFB was activated. The researchers also examined motorist yielding rates to bicyclists, and these rates tended to be higher than yielding rates to pedestrians, likely due to greater visibility (Al-Kaisy et al., 2018).

If motorists are attuned to the presence of pedestrians, safety can improve. A small case study in Minnesota evaluated the degree to which a marked crosswalk influenced motorist behavior. Results showed that removal of crosswalk markings resulted in less yielding and an increase in stopping distances closer to the pedestrian. The authors propose that a crosswalk serves to "prime" motorists' expectations as to the presence of pedestrians, and thus improves safety (Craig et al., 2019). This analysis used a subset of the data that were collected for a larger study presented in the Part 3 subsection, Behavior Change Programs (N. L. Morris et al., 2019). The subsection, Behavior Change Programs, also covers the effectiveness of education and enforcement programs designed to improve motorist yielding.

Schneider and Sanders's (2015) survey of practitioners revealed common perceptions of what influences motorist yielding behavior at uncontrolled crosswalks to include:

> Education about the law, enforcement of the law, urban design and roadway design, vehicle speed, vehicle volume, driver alertness, driver behavioral norms, driver sociodemographic characteristics, land use and pedestrian volume, pedestrian assertiveness, pedestrian predictability, pedestrian visibility, pedestrian behavioral norms, pedestrian sociodemographic characteristics, and social fabric. (p. 40)

Of the 15 factors commonly cited in survey responses, "driver behavior norms" was the most often referenced by respondents. Results from the study suggest that such norms differ based on geographic location and that while social norms are important, local built environment and policy factors play a large role in yielding behavior as well. Given that social norms vary across the country, the authors emphasize the need to account for this in recommending safety treatments and measuring motorist yielding behavior.

Motorists Passing Bicyclists

Studies examining motorist behavior in relation to bicyclists during passing events are important because *Motorist Overtaking Bicyclist* crashes are the most common crash type for bicyclist fatalities in urban and rural areas (more information on crashes and crash types is in Part 1); however, research on this topic has not addressed the relationship between lateral passing distance and the objective risk of an overtaking crash (Rubie et al., 2020). Lateral passing distance is also important for the perceived safety of bicyclists (Aldred & Goodman, 2018). Studies have used instrumented motor vehicles, instrumented bicycles, or other video data to record passing distance, among other variables related to roadway configuration, traffic conditions, and vehicle/motorist/bicyclist characteristics. The effectiveness of laws related to motorist passing distance is covered in Part 3.

In a study of naturalistic driving data in Michigan researchers found that when a bicycle lane or paved shoulder was present, dashed lines separating two vehicle lanes traveling in the same direction were associated with significantly less lane-crossing distance and closer distance to the bike lane/shoulder than a solid centerline (Feng et al., 2018). When no bike lane/paved shoulder was present, motorists crossed a dashed line significantly more than a centerline (with no left-side traffic, either oncoming or adjacent), but this becomes not significant with the presence of left-side traffic. Even though Michigan law prohibits crossing a solid centerline to pass another vehicle, researchers documented a substantial amount of overtaking where motorists crossed the center line. The study authors hypothesize that it takes motorists more mental and physical effort to cross the dashed lane (having to look for both adjacent and oncoming traffic) compared to a solid center line; in the latter case the motorist only must look for oncoming traffic.

One study using instrumented bicycles in Minnesota found that passing distance was often lower for larger vehicles and that average passing distances varied depending on the bicycle facility type, but motorists conceded more space to people riding bicycles on facilities with more separation (i.e., separated or buffered bike lanes) (Evans et al., 2018). Another study using instrumented bicycles in Wisconsin found that, on average, motorists allowed more space than necessary to pass a bicyclist, though in around 10% of cases motorists performed hazardous maneuvers such as passing on a blind hill or crossing the solid yellow line when oncoming traffic was present (Chapman & Noyce, 2012).

A simulator study conducted in Italy focused on different cross-sections for rural, two-lane roads (all with the same total roadway width), where the severity of overtaking crashes is higher than in urban areas, and found that wider bicycle lanes ensured higher lateral clearance but that the presence/absence of a bicyclist was not statistically significant on overtaking speed, meaning that motorists were rarely slowing down to pass (Bella & Silvestri, 2017).

Bicyclists and Pedestrians

Behaviors while riding a bicycle and walking can diverge between women and men while patterns of behavior shift with age. Between early childhood, adulthood, and later years, our physical and cognitive abilities develop and change, and with experience and changing motivations our decision-making processes adapt and adjust to our abilities and the environment.

For example, as discussed below, some populations are more associated with risk taking behavior, and thus less likely to use safety equipment or choose the safest moment to cross the street. Women's attitudes, social norms, travel purposes, and considerations around safety differ from men's, and this affects when, where, and how they choose to walk and bicycle. While not covered in more detail below, socioeconomic status and motivations for travel (e.g., utilitarian versus recreational) have also been shown to influence walking rates (Mondschein, 2018).

Gender

The built environment has been shown to influence women's decision making in terms of whether to ride a bicycle, and where. Women are more likely than men to ride where they feel comfortable. Women on average ride more slowly, which may play a role in where they choose to ride and in how vulnerable they feel in certain road conditions (Aldred et al., 2018; Schleinitz et al., 2018). Studies looking at preferences by gender commonly show that women display stronger preferences for separated bikeways, though ultimately both men and women say they would feel more comfortable riding apart from motorized traffic (Aldred et al., 2018; Aldred, Elliott, et al., 2017; Garrard et al., 2008; Krizek et al., 2005; McNeil et al., 2015; Monsere et al., 2012). A revealed preferences study using smartphone data in Atlanta, Georgia, showed that female bicyclists tended to choose routes with less traffic and better bicycling infrastructure

(Misra & Watkins, 2018). Surveys and travel data have demonstrated that women are more likely to travel an extra distance to reach a preferred bicycling facility (Dill et al., 2014; Krizek et al., 2005).

Pedestrian behavior can also differ with gender. For the most part, women and men walk at similar rates for leisure, for transportation, and in total (Buehler et al., 2020; Pollard & Wagnild, 2017), but their behavior as pedestrians can be distinct. The general understanding is that men engage in more risk-taking behavior while walking, for example, crossing during smaller gaps between moving vehicles. But some have found that men and women exhibit different levels of risk acceptance as they age (Ferenchak, 2016; Herrero-Fernández et al., 2016; Holland & Hill, 2010).

A study conducted in Montreal, found men committed more pedestrian crossing violations irrespective of wait time or danger (Brosseau et al., 2013). Men have also been shown to exhibit more impulsive behavior, especially younger men (Herrero-Fernández et al., 2016). Overall, women may perceive more risk and are less likely to cross a road where danger is apparent (Holland & Hill, 2007). One study found that women and people traveling with children are likely to accept longer wait times (i.e., pedestrian delay) before crossing (Hamed, 2001). An international study found that gap acceptance for street crossing, which is defined as "the time headway between two successive vehicles," in men was lower than for women (Sahani et al., 2018). Other factors that could influence pedestrian behavior, such as social norms, have been examined by researchers, but their effect is nuanced and danger perception has been shown to be a stronger predictor of behavior in terms of road crossing intentions (Zhou et al., 2009). For older women, additional factors may affect their walking behavior and increase their exposure as a pedestrian including the fact that they often cease driving earlier, and the fact that they walk more slowly and may face a decline in walking speed earlier than men (Bernhoft & Carstensen, 2008; Holland & Hill, 2010; Webb et al., 2017).

Age Groups

Age, experience, and physical characteristics of the road user influence travel behaviors and risk of injury. The types of pedestrian injuries sustained in a crash also vary across the life span. For example, an analysis of 5 years of pedestrian injury data in North Carolina found that children and older adults were less likely to be injured in on-trafficway, higher speed crashes, these age groups were more likely to be diagnosed with injuries associated with prolonged disability and increased risk of complications like traumatic brain injuries, open wounds, amputations (study population was people receiving treatment in an emergency department after involvement in a police-reported pedestrian-motor vehicle crash) (Harmon et al., 2020).

Children

Injuries sustained in crashes involving motor vehicles are leading causes of disability in children and can lead to ongoing physical and mental challenges (Peden et al., 2008).

For children, their smaller size, lack of experience, and limited cognitive and motor skills put them at higher risk. At different ages, young people's travel patterns and uses of the roadway environment varies. Very young children are more likely to be pedestrians, often accompanied by a caregiver. As children grow, they become more independent and may ride a bicycle or walk unaccompanied (Peden et al., 2008). Injury risk to child pedestrians also changes based on their own developmental state (Schwebel, Davis, et al., 2012).

Cognitive development is a key factor in children's road safety outcomes. In a road environment, a pedestrian must have strong attention and focus skills, must be able to process information quickly, and must also be able to handle several tasks at once and then make decisions quickly (Schwebel, Davis, et al., 2012). Developmentally, these skills may be beyond the range of some children's abilities. For example, children may struggle to safely judge gaps in traffic where crossing the street can be completed safely (Schwebel, Shen, et al., 2016). Lack of understanding several risks in the environment may also lead to challenges identifying the safest location to cross a street (Schwebel, Davis, et al., 2012). Results from a simulator experiment show that impulse control can also be a concern for very young pedestrians or bicyclists (Barton & Schwebel, 2007).

Naturalistic bicycling data reveal that children also have less experience with the roadway environment and route selection and are prone to more errors in handling a bicycle (Hamann & Peek-Asa, 2013). At a young age, people are not as skilled at perceiving elements in their environments. A child pedestrian might recognize an oncoming vehicle as a hazard but may not be able to successfully judge its speed or distance away from them. Their visual scanning and understanding of other roadway elements that may cause problems are often undeveloped, compared to mature adults (Schwebel, Davis, et al., 2012). Observations of younger road users have shown that older children may ride out or dart out into traffic without checking for oncoming vehicles and without obeying traffic controls (Gitelman, Carmel, Pesahov, & Chen, 2017). Eye-tracking research suggests that children may not be scanning road environments comprehensively for the most salient cues (Biassoni et al., 2018).

Moreover, children may not be aware of their limitations. Observational research has shown that some tend to overestimate their knowledge and strength and underestimate their likelihood of injury (Almeida et al., 2016; Joshi et al., 2018; Plumert & Schwebel, 1997). Younger pedestrians have been shown to accept a shorter gap in traffic to cross a street, per naturalistic observations assessed via video analysis (Sahani et al., 2018).

Children are shorter than adults, which affects the point of view from which they are scanning for traffic. Their visual field is reduced, often blocked by parked cars, street furniture, or landscaping, which may otherwise not be a barrier to taller people. Shorter heights also mean that motorists are less likely to see young road users, or they may see children as "small adults" standing farther away and not judge the distance to the child accurately. Additionally, children's bodies are still growing and developing, making them more susceptible to impacts of their injuries (Peden et al., 2008).

Parents and other authoritative figures, peers, and one's culture further influence and shape how children learn to interpret cues in their environment, so modeling safe behavior while children are practicing these skills is important. Unfortunately, role models do not always exemplify correct behaviors as pedestrians (Quraishi et al., 2005), bicyclists, or motorists, and often parents overestimate their own child's competencies (MacGregor et al., 1999). Further, the timing for when parents can most effectively influence children's decisions about where to ride their bicycle and to wear a helmet may be before adolescence. Research by Hamann et al. (2019) found that the observed bicycling behaviors of children 10 to 15 poorly reflected the instructions given by parents, and in fact when asking both the children and the parents about what instructions they had received/given, agreement was low overall.

A pedestrian's ability to comprehend vehicular travel speed also varies by age. All pedestrians must assess traffic conditions when choosing to cross a roadway, so pedestrians rely on predictions of vehicular speed when choosing appropriate gaps in traffic. This prediction is a complex task and is dependent on a variety of factors, including cognitive abilities and familiarity with the built environment. Older pedestrians—even cautious ones—with diminished cognitive capabilities may be unable to accurately predict safe crossing gaps in a traffic stream (Butler et al., 2016). This finding is especially concerning given the increased vulnerability of older pedestrians, but other research demonstrates that even adults 45 to 64 years old and young children are at increased risk when traffic speeds are higher (Sanders et al., 2019).

Older adults

The overall population in the United States is aging and more people are turning to walking or biking to maintain health. Thus, the need to address the safety needs of older adults outside of the vehicle is mounting. In addition, the general population is becoming more urban, and many people, including seniors, live in more densely populated, walkable neighborhoods that is linked to more active travel in older adults (Cerin et al., 2017). Older adults may exhibit different behavior based on their cognitive and physiological functions. Age-related declines in sensory, cognitive, and physical abilities play a role in a person's capacity to navigate the built environment safely (Tournier et al., 2016). In general, seniors may walk at a slower pace, have difficulty negotiating poor walking surface conditions and difficulty planning the journey and wayfinding along a route.

In many pedestrian environments, factors other than walking itself demand the attention of those on the street. Facing more than one task, walking function may decline even further in older adults due to cognitive decline (Eggenberger et al., 2017). When crossing a street, older pedestrians are not as good at making safe decisions as younger pedestrians (Dommes et al., 2015). They are more likely to struggle to identify the best location to cross (Dommes et al., 2014; Tournier et al., 2016). Gap identification is a known problem for older persons, and once a gap in traffic is found, an older person might take more time to step away from the curb, adding to the already longer time needed to cross the street (Dommes et al., 2014; Hoschopf et al., 2017; Tournier et al., 2016). One study revealed that older persons spend more time looking at the ground than those from other age groups and less time looking across the street at the destination (Zito et al., 2015). Other behavioral research has verified that as people age, there is greater use of crosswalks, but also a need for longer gaps, whereas younger ages and males tend to accept shorter gaps, which generates more conflicts (and potential for collisions) (Ferenchak, 2016).

Walking speed itself is a major concern for many older pedestrians. Around the world, a walking speed of about 4 feet per second (1.2 meters per second) is the average assumed walking speed used to determine pedestrian signal timing, and many older adults do not walk this fast. Over age 65, walking speed is decreased to an average of 2.9 feet per second in men and 2.6 feet per second in women (Asher et al., 2012). Walking speed has been found to be a strong predictor for unsafe crossing behaviors (Dommes et al., 2014; Geraghty et al., 2016; Holland & Hill, 2010). A British study of longitudinal health data found that walking speeds were slower for women, those with less wealth, and those with poorer health. Walking speeds for women seemed to decline faster than for men (E. A. Webb et al., 2017).

Route choices differ significantly between older pedestrians and their younger peers (Bernhoft & Carstensen, 2008). Older pedestrians are more likely to choose the routes with better infrastructure such as sidewalks, smooth surfaces, and signalized crossings. They appreciate having more time to cross at a signalized intersection. Bicyclists overall strongly prefer separated, shared use paths for bicycling and older bicyclists have an especially strong stated preference for good pavement conditions. Older bicyclists will choose the route with the most comfortable infrastructure such as bicycle paths, compared to younger riders who may opt for the most direct/fastest route.

NHTSA's *Traffic Safety for Older People – 5-Year Plan* covers some strategies being pursued on the national level, including support for simply avoiding the crash, with pedestrian crash avoidance mitigation (PCAM, now generally called pedestrian automatic emergency braking or PAEB) technologies and recent changes in guidelines for hybrid and electric vehicles regarding noise (for more information, see Part 3, section Technology-Based Interventions). One focus of the plan included monitoring older pedestrian-motor vehicle crashes in parking lots NHTSA, 2013).

Direction of Travel

While safety programs often recommend pedestrians walk facing traffic in locations with no sidewalks or other pedestrian facilities, it is difficult to study this safety issue due to questions of exposure related to direction of travel (i.e., how many people walk in each direction of travel and are not struck). Although no studies from the United States were identified, at least one study of rural, two-lane roads lacking pedestrian facilities or paved shoulders in Finland attempted to measure a safety effect for walking facing against oncoming traffic by conducting observations of walking directions on roads where pedestrians had been killed (Luoma & Peltola, 2013). Proportionally, about 61% of those injured or killed (using 4 years of crash data) were walking in the same direction with traffic; whereas, an eight-month observation period on the study group of roads showed that only 26% of pedestrians walked in the same direction with traffic. This finding suggests a protective effect of walking facing traffic if the walking patterns were comparable over the entire crash period of the study. The researchers estimated a protective effect of 77% reduced risk of fatal injury or nonfatal injury if pedestrians walked facing traffic instead of with their backs toward oncoming traffic in the near lane on these roads.

All States require cyclists to ride in the same direction as traffic (League of American Bicyclists, n.d.). Wrong-way riding (either in the street or on a sidewalk) is a risky behavior among bicyclists. Motorists and roadway users, including other bicyclists, do not expect bicyclists to be facing traffic and may not see them in time to prevent a crash. Wrong-way riding crashes often occur while the wrong-way riding bicyclist is crossing a driveway or crosswalk or riding on a sidewalk. Nationally, 5% of bicyclist fatalities were associated with wrong-way riding (L. Thomas et al., 2019).

Bicycle and Pedestrian Conspicuity Equipment

Conspicuity has been defined as "the ability of an object to be attention-getting" (Brookshire et al., 2016). Most importantly, a conspicuous object is one that is not only *visible* but that *stands out* from the surrounding environment and commands attention. The French researcher Rogé proposed that conspicuity can be sensory and/or cognitive. Sensory conspicuity is the ability to detect and distinguish an object in the landscape. Cognitive conspicuity relates to the whether the object is expected to be in the environment and can be seen and simultaneously understood (Rogé et al., 2017; Tin Tin et al., 2013, 2015). There has been continuing research on motorists' ability to detect other road users, and whether conspicuity or visibility aids can improve detection and thus safety; often this research is focused on motorcyclists. A small body of knowledge exists around conspicuity of bicyclists and pedestrians.

A review of literature on pedestrian conspicuity examined a variety of visual limitations for motorists that may compound difficulties in pedestrian detection. Motorists are often guilty of underestimating their visual limitations and not adjusting their own speeds appropriately. Changes in vision during twilight hours and at night, headlamp glare, and age-related decline in visual function are among the challenges to pedestrian detection faced by motorists (Tyrrell et al., 2016; J. M. Wood et al., 2014).

The hypothesis that high-visibility clothing increases detection of bicyclists by motorists has been explored in several studies. A systematic review looked at studies evaluating effectiveness of visibility aids for pedestrians and bicyclists (Kwan & Mapstone, 2009). The visibility aids could include fluorescent materials (used during the day) and lamps, flashing lights, and retroreflective materials (used at night). Especially effective at improving pedestrian detection were visibility aids that take advantage of human motion, called “biomotion” aids (e.g., retroreflective markings placed on a person’s ankles, wrists, waist, and head). Findings by Tyrrell et al. (2016) similarly support the effectiveness of biomotion visibility aids for increasing pedestrian detection at night. Overall, visibility aids improved detection and recognition of the pedestrians or bicyclists by motorists, but no studies were found that linked the use of the visibility aids to a decrease in crashes (Kwan & Mapstone, 2009). It is important to note that conspicuity enhancement is unlikely to overcome risky behaviors like motorist distraction (Szubski et al., 2019).

In Portland, Oregon, researchers found no indication that bicyclists who wore reflective clothing had a reduced risk of a traumatic event (Hoffman et al., 2010). A study conducted over 6 years in New Zealand measured both cognitive and sensory conspicuity and found that in terms of crash outcomes, conspicuity aids were predictive of safety but that cognitive conspicuity, which was characterized by regional travel characteristics such as population time spent bicycling and time spent driving, had a stronger association with improved safety outcomes (Tin Tin et al., 2015). An analysis of the same data showed that using lights at night had a much larger positive safety outcome, though wearing reflective materials and fluorescent colors had a small positive effect (Tin Tin et al., 2013). Walker et al. (2014) tested whether bicyclist appearance would cause motorists to adjust how much clearance they allowed in passing a bicyclist when passing and found no effect of high-visibility clothing on motorist passing distance during the daylight hours.

The question of whether clothing or protective apparel other than helmets could reduce injury risk in the event of an actual crash has also been explored. De Rome et al. (2014) looked at injury outcomes from bicyclists who had presented at hospitals in the Australian Capital Territory with injuries from a crash that happened on a public road or paved shared use path. Based on the injuries sustained by those wearing long sleeves and long pants compared to those with exposed legs or arms, the authors suggest that simply covering these parts of the body may reduce injuries to bicyclists. Another study conducted in Israel investigated injury profiles of young bicyclists admitted to a particular trauma center, and suggested that many serious injuries were to the abdomen and that these injuries could be prevented by protective apparel (Abu-Kishk et al., 2010). However, adult bicyclists whose injuries were recorded in the Southern Alberta Trauma Database revealed different patterns. Overall injury profiles were different for mountain bikers and street bicyclists, but after head injuries, thoracic spinal injuries were the most frequently recorded amongst both groups (Roberts et al., 2013). The above studies used hospital trauma data, which means that injuries sustained by trauma patients while riding a bicycle may or may not have been the result of a collision with a motor vehicle and that only more serious injuries were likely included in the studies.

Risky Behavior

Risky behaviors such as distraction and impairment can increase the likelihood of a crash and the severity of a crash, should one occur.

Distraction

Distraction is considered anything that diverts a traveler's attention from the primary task of navigating the roadway environment and responding to critical events. This can include talking, eating, engaging in other tasks, visual and sound distraction, as well as technological distraction. In recent years, the use of mobile devices and its impact on road safety has become a primary area of concern. Eighty-five percent of all Americans now own a smartphone (Pew Research Center, 2021). Based on a combination of self-report and observational data, NHTSA estimated that roughly 7.9% of motorists in 2020 were likely using a device, either handheld or handsfree, while driving in a typical daylight moment (NCSA, 2021). However, the use of a phone and how it affects crash risk has only been evaluated in naturalistic studies (Insurance Institute for Highway Safety, 2020a). Distraction is not a standard variable in police crash reports across jurisdictions, so counts of crashes with motorists, bicyclists, or pedestrians that are directly caused by distraction should be interpreted with caution (NCSA, 2022a). The extent to which distracted pedestrians and bicyclists are a threat to themselves or others is also poorly understood. The use of a cellphone has been shown to affect pedestrian and bicyclist reaction times, walking, or riding speeds, as well as their ability to detect visual and audio clues in their environments. However, the direct link to safety is unknown (Scopatz & Zhou, 2016).

In studying police-reported fatal crashes between 2005 and 2010 where distraction was noted as a contributing factor, researchers found that pedestrian and bicyclist fatality rates per vehicle mile traveled increased during that time (Stimpson et al., 2013). This study period was before widespread use of smartphones. The motorist was categorized as distracted if the police report stated that they were using a technological device or if they were otherwise engaged in "distracting" activities, which could include eating, adjusting the radio, or using an electric razor, among other things.

When it comes to detection of pedestrians and behavior around bicyclists, studies in virtual and naturalistic settings have revealed troubling results. Haque et al. (2014) found that motorists' ability to detect a virtual pedestrian approaching a crosswalk was "impaired significantly" when the motorist was engaged in a phone conversation that placed demands on their cognitive capacity. Feng et al. (2018) used naturalistic driving data from instrumented motor vehicles to examine events where motorists passed bicyclists and found that approximately 7.8% motorists in passing events were actively engaged with using their cell phones and that those motorists conceded less space to bicyclists than non-distracted motorists. For a bicyclist, this means that one in 13 passing events may involve a distracted driver. More information on the Feng et al. (2018) study can be found under the subsection Motorist Behavior in Relation to Bicyclists.

A driving simulator experiment undertaken by researchers in Louisiana tested the concept of inattentional blindness, which they defined as "a failure to notice unexpected events due to an individual performing an attention-demanding task, even if the unexpected event occurs in the individual's line of sight" (Ericson et al., 2014). They tasked motorists with navigating a complex road environment while counting movements of other vehicles. An "unexpected" pedestrian crossed the road during the experiment and the investigators measured the motorists' reaction times, finding that while all motorists detected the pedestrian, a significant proportion of the motorists failed to react in time to avoid a collision.

Pedestrian distraction

There is growing concern around mobile device use amongst pedestrians. Gary et al. (2018) reviewed 51 studies related to distracted walking and found that observational studies documented that between 1.1% to 8.4% of people were distracted by their smartphones while crossing the street, and that use of a phone while walking is more common among younger pedestrians and is associated with more risky pedestrian behaviors.

While wearing headphones is common among pedestrians, whether they play a direct role in pedestrian crashes is unclear (Basch et al., 2014; Ethan et al., 2016). Questions have been raised as to whether headphone use can lead to "inattentional blindness," or divided attention, which could affect reaction time, and "environmental isolation," or sensory deprivation, which could cause a pedestrian to miss auditory cues in the street environment (Lichenstein et al., 2012). An observational study conducted in New York City, found that one in four pedestrians were walking while using electronic devices, but this figure included either smartphones or headphones or both (Basch et al., 2014). In some cases, wait times for a pedestrian signal increased the use of cell phones at particular intersections (Russo et al., 2018).

There are a few studies that use simulation to examine the relationship between electronic device use (e.g., texting, surfing the internet) and pedestrian behaviors (e.g., crossing the street). Findings from these studies are not consistent and sample sizes are often small, so conclusions cannot be understood to be indisputable. It is generally understood that behaviors such as listening to music, talking on the phone, texting, or surfing the internet are distracting and result in less safe behaviors (e.g., choosing smaller gaps in traffic for crossing, less visual scanning, slower walk speeds, or missed crossing opportunities) compared to those not engaged in distracting activities; however, the degree of distraction for the type of activity in relation to each other varies across studies (Byington & Schwebel, 2013; Neider et al., 2010; Schwebel, Stavrinos, et al., 2012; Stavrinos et al., 2011; Tapiro et al., 2016).

One of the simulator studies specifically looked at differences by age. Researchers compared adult crossing behavior while talking on a phone to that of children who were talking on the phone by tracking where they were looking as they made decisions on when to cross the street. Results showed that for every age group there was a reduction in the gap selected an increase in the time taken to begin to cross, and slower response times for those who were talking on the phone versus those who were not. The youngest children, in the age group 7 to 10 were the most affected (Tapiro et al., 2016).

Observational research has generally supported findings from virtual environments. Davis et al. (2017) tested whether talking on a phone would influence the ability to hear approaching vehicles, and their results demonstrated that talking on a cell phone can reduce situational awareness and ability to detect auditory cues when waiting to cross a street, compared to not talking on a phone. Texting was not found to inhibit the ability to detect oncoming vehicles aurally (Davis & Barton, 2017). Pedestrians who were distracted by listening to music, texting, or talking on a phone were observed to take more time to start to cross the street, and were less likely to visually scan the street environment carefully before crossing a street (Gillette et al., 2016; Jiang et al., 2018).

Research on pedestrian distraction overall is still emerging, and while evidence of behavioral effects is at hand, strong conclusions on how this affects pedestrian safety risk have not been reached. Importantly, while distraction has been shown to affect pedestrian crossing behavior, direct links to pedestrian involved crashes has not been established.

Bicyclist distraction

Research on the effects of cell phone use on safety while bicycling has been sparse. A 2014 review of bicycling distraction literature found that most of the studies that have been conducted originate from the Netherlands and that the role of cell phones in crashes is not clear. Some behavior changes were observed as bicyclists used mobile phones, such as slower response times (Mwakalonge et al., 2014). Use of a touchscreen mobile phone while bicycling caused a greater degradation in bicycling performance than a non-smart device, causing riders to perform poorly on visual detection and to take a less safe position in the lane. Using earbuds or headphones to listen to music while bicycling has also been assessed for effect on bicyclist behavior. The authors of that study found that listening to music did not affect bicycling performance, but the use of in-earbuds while riding can reduce the rider's ability to hear cues in the street environment compared to traditional headphones or only one in-earbud (de Waard et al., 2011).

There are other activities that may distract people walking or bicycling from their task of traveling (e.g., carrying parcels, dog walking), but there is little research on these topics, and it is unclear that such research is needed.

Impairment

In 2018 there were 1,225 nonoccupants, i.e., pedestrians, bicyclists, or other road users, who were killed due to being involved in a crash with an alcohol impaired motor vehicle driver (NCSA, 2022a). Thirty of those fatalities were children outside of the vehicles. In 2020 some 41% of *all* fatal pedestrian crashes each involved *either* a motorist or the pedestrian with a blood alcohol concentration (BAC) of more than .08 grams per deciliter (g/dL), with 16% of those crashes involving a motorist who had been drinking, and 31% a pedestrian who had been drinking (NCSA, 2022c). That same year, 34% of all bicyclist fatalities involved alcohol consumption (BAC of .01+g/dL) by *either* the motorist and/or the bicyclist (NCSA, 2022d). A BAC of .08 g/dL is commonly used to indicate impairment in a road user regardless of mode, but research has not established whether this is a meaningful threshold for walking and/or bicycling, which carry vastly different risks from operating a motor vehicle.

The prevalence of alcohol in the systems of motorists involved in crashes has been well-documented in the literature, but less is known about the prevalence of drugs in motorists and other road users. Studies that involve roadside data collection have assessed the prevalence of drinking and drugged driving, but these have not included other road users like pedestrians and people riding bicycles or e-scooters (a brief literature review is included in F. D. Thomas et al. [2020]). A convenience sample of seriously and fatally injured road users suggests that drug and alcohol prevalence is similarly high regardless of mode. The study assessed blood samples from participating Level 1 trauma centers and corresponding medical examiner offices in five metropolitan regions. The blood samples do not establish impairment at the time of the crash.

A review of FARS data looked at bicyclist and pedestrian fatalities where the bicyclists or pedestrians had BACs of more than .08 g/dl (the legal limit for driving in all States except Utah, which uses .05). A large proportion of pedestrians and bicyclists who were fatally injured from 2010 to 2014 had high BACs. Of these bicyclists and pedestrians, males were more likely to have been impaired than females, and the age groups of between 30-39 and 40-49 had the highest odds of having a high BAC. Crashes were more likely in urban environments, at night, and on weekends (Eichelberger et al., 2018). A study that combined crash data and driving record data from five States found that people with prior alcohol related driving offenses may be at greater risk for being killed as a pedestrian with a BAC over .08 g/dL compared to those without prior driving offenses (Blomberg et al., 2019).

Alcohol use is associated with worse injury outcomes for pedestrians. Pedestrian crash victims who have tested positive for alcohol generally have greater injury severity, more hospital admissions, and longer hospital stays (Dultz et al., 2011; Hezaveh & Cherry, 2018; Shah et al., 2015). Physical effects of alcohol can impede treatment and confound medical management of a trauma patient (Dultz & Frangos, 2013).

Researchers looking at all pedestrian crashes in Tennessee where alcohol consumption was evident, regardless of BAC level and screening method, found that while pedestrians with detectable levels of alcohol represented only 7% of all pedestrian crashes, they made up 22% of the *fatalities* during the same period (Hezaveh & Cherry, 2018). Pedestrians who *had* been drinking alcohol were more likely to sustain more severe injuries compared to those who *had not* been drinking. Temporal patterns and characteristics of those involved in crashes was comparable to those indicated on the national level, with crashes happening most often at night, on the weekends, and involving males. Crashes occurred more frequently in areas where speeds were high, and at midblock locations or areas with no traffic control.

Research in New York City examined the spatial distribution of alcohol-related pedestrian and bicyclist crashes, looking specifically at the relationship between crashes and locations of retail outlets that sell alcohol, socioeconomic factors such as income levels, and a "social fragmentation index" that strives to capture social cohesion by using housing characteristics such as proportion of vacant units, proportions of renters versus owners, and others. Positive relationships were found for presence of alcohol sellers and alcohol-related crashes, and more "social fragmentation" increased the risk of being injured in an alcohol-related crash as a pedestrian. Higher median household income was associated with lower pedestrian injury risk (DiMaggio, 2015; DiMaggio et al., 2016). Similarly, an analysis of data from Denver, Colorado, found a positive association between liquor license density and pedestrian-motor vehicle crashes (Sebert Kuhlmann et al., 2009).

Very few studies quantifying behavior changes in impaired pedestrians and/or bicyclists were identified. Oxley et al. (2006) tested safety perception and the ability to make the decision to cross a road and found subtle effects on the cognitive abilities of participants who had a BAC of up to 0.08 g/dL. In New York City, pedestrians who had consumed alcohol were less likely to cross with a signal and more likely to cross against the signal or midblock (Dultz et al., 2011).

Little research exists on the behavior of pedestrians or bicyclists involved in motor vehicle crashes who have also tested positive for drug use. Over a 10-year period in Georgia, where testing for the presence of drugs took place in only about half of all fatal pedestrian crashes, positive screens (all categories of drugs) doubled from 2007 to 2016 with notable fluctuations each year (M. Thomas et al., 2020). The most common category of substances identified were stimulants (45.8% of positive tests), followed by cannabinoids (21.5%), narcotics (including opioids) (14.1%), and depressants (12.1%) and other drugs (6.3%). There was a higher rate of positive drug screens in rural areas. In addition to providing some insight into the characteristics and distribution of these crashes, the study highlights the need for more consistent and standardized testing for substance use in motorists and pedestrians involved in crashes and tracking results in databases such as FARS. In France some prescription medicines were associated with higher likelihood of being involved in a crash (Née et al., 2017). An examination of trauma data from Maryland in 2000 showed that pedestrians were more likely to have been using a controlled substance than motorists, but also underscores the fact that less than half of crash victims were tested for substances other than alcohol, which makes analysis of trends difficult (Soderstrom et al., 2002). An investigation of police crash reports in California details the difficulties in correctly assessing sobriety status of motorists and pedestrians who are involved in crashes, especially nonfatal crashes, and reiterates that the majority of people in these scenarios are not tested for drug or alcohol use (Nesoff et al., 2018).

Perception and Bias Amongst Road Users

Motorists' expectations of the movements of other road users may not align with pedestrians and bicyclists' uses of the road. Bicyclists and pedestrians may adjust their behavior in environments where bicycle or pedestrian facilities are not present or where they feel less safe in general. Road safety literature on how perception, attention, situational awareness, and inattentional blindness affect motorist behavior is voluminous. Literature has documented motorists' tendency to mentally model the road environment based on several factors, but researchers are increasingly investigating how the exclusion of bicyclists and pedestrians from these sets of expectations may influence unsafe behavior on the part of motorists around pedestrians and bicyclists. More research is needed on how motorists, pedestrians, and bicyclists assess, predict, and respond to each other based on their own expectations and mental models.

Jacobsen (2003) argued that the presence of people walking and bicycling causes motorists to adjust their behavior. Walker (2007) famously donned a wig in his study that measured motorist passing distances and behavior changes based on the lateral position of the bicyclist and other characteristics such as physical appearance. His results mainly emphasize the idea that there is "behavioral sensitivity to the appearance of a vulnerable road user."

Direct experience of other modes has been associated with safer behaviors. Johnson et al. (2014) found that motorists who are also bicyclists tended towards safer behavior towards bicyclists on the road. Conversely, pedestrians and bicyclists who did not possess driving licenses were shown to be at higher risk of being involved in a crash with a motor vehicle in Japan (Nakai & Usui, 2017).

Research is beginning to look at how motorists understand pedestrians' intentions to cross the road, for example, primarily with the goal of informing interactions between autonomous vehicles and pedestrians. For example, results from an observational study in Minnesota suggest that a clear hand signal on the part of the pedestrian does increase motorist yielding (Crowley-Koch et al., 2011). However, pedestrians may not always be in the position to raise a hand, for example if they are carrying items or escorting children. These actions are also locality specific as the same action in one locality might get a different response, or no response, from a motorist.

For a pedestrian, the decision-making process as to when and where to cross the street is influenced by not only street conditions, but also by social norms, emotions, motivations, and expectations. Acceptance of risk is balanced with tolerance for delay. The characteristics of the individual pedestrian play a role, as does their social and cultural environment. Expectations are influenced by learned experience of the environment and past interactions with motorists (Cœugnet et al., 2019).

Pedestrians want to get where they are going with minimal delay, just the same as other road users. A review of literature on pedestrian perception and behavior in terms of signal violation reveals that timesaving and signal-timing can be influential in determining pedestrian behavior. Other factors include personal characteristics, pedestrian and motor vehicle traffic volumes, and trip purpose. Pedestrians who were carrying heavy objects tended to be less likely to wait for the signal, as did those who were on their way to catch transit (Mukherjee & Mitra, 2019).

A survey of pedestrians in Colombia examined factors that influenced decision making when it came to utilization of a footbridge over a high-volume highway. Even though crossing the highway was perceived as more dangerous, fewer pedestrians chose to use the bridge, and instead crossed at ground level. Lack of experience using the footbridge played a role in their decision to cross the road directly, as well as perceptions about personal security on the footbridge. Distance and timesaving were additional key factors. The study underscores the complexity of the considerations people make while walking and their behavioral outcomes (Oviedo-Trespalacios & Scott-Parker, 2017).

Implicit/Explicit Bias

Roadway behavior and interactions with other users can be influenced by individual attitudes towards others, whether conscious or unconscious. Implicit or explicit bias may shape much of what occurs when road users encounter one another, though this concept is under-researched.

Pedestrians and racial bias

Crosswalks are critical interaction points between pedestrians and motorists. Kahn et al. (2017) found that while very few motorists yielded at an unmarked crosswalk to any pedestrian, regardless of race; once a crosswalk was marked, distinct yielding patterns emerged. Not only did motorists stop less frequently for Black pedestrians, when they did stop, it was closer to the pedestrian's actual location. Focus group findings confirmed these observations. The authors contend that this motorist behavior has safety implications and likely affects how, when, and where people of color use the streets (Kahn et al., 2017). A study conducted in Las Vegas, Nevada, echoed these findings. There, motorists were more likely to stop for a White female who was already in the crosswalk than for a Black female in the same location (Coughenour et al., 2017).

Motorist attitude and bicyclists

Attitudes and bias toward a category of road user can influence interactions on the roads. One study, which took place in Portland, measured motorists' attitudes and behaviors towards bicyclists using an online cognitive test. Personal identity as a motorist, attitudes towards bicycling in general, and the perceived legitimacy of other road users were among factors identified as affecting motorist behaviors around bicyclists. Motorist attitudes towards people on bicycles was related to numbers of people on bicycles and overall bikeability of a community; a denser, more bicycle friendly setting with more bicycle commuters was associated with a more positive motorist attitude towards bicyclists overall (Goddard, 2017).

In some extreme cases, motorists exhibit aggressive behavior towards bicyclists, based on their belief or perception that the bicyclist was not observing the rules of the road (Piatkowski et al., 2017). A subset of a larger group of people replying to open-ended survey questions regarding general perceptions of bicyclist behavior expressed a propensity for intentional dangerous driving near bicyclists. The authors examined common themes in the responses of this subset group in a separate exploratory study. While this behavior is not common, it does represent a threat to people on bicycles using the road and may play a role in overall safety outcomes.

The Role of the Environment

A discussion about safety for people walking and bicycling cannot be separated from a discussion about the role of the physical environment in creating or mitigating risks to their safety. The reason for this is simple. Pedestrians and bicyclists are far more susceptible to crash energies—due to the limitations of human physiology—and the environment of a transportation system that can propagate the risks that lead to those excessive crash energies (i.e., vehicle speed at point of impact). Risks to pedestrians and bicyclists exist wherever these road users must interact with the built environment under the assumption that motorists should or will yield to them (Hacohen et al., 2018). This section covers the role of the environment with a specific focus on how pedestrians and bicyclists navigate a built environment that greatly influences their safety, and the relationship between physical space and safety and the relationship between roadway infrastructure and safety.

Note that much of the discussion in this section centers on seemingly conflicting studies (e.g., does the number of lanes increase risk or decrease risk?). Some of this discrepancy is due to the nature of risk itself, and whether the referenced study refers to crash severity, crash frequency, or both. The contrasting results are also due to the nature of exposure and how pedestrians and bicyclists interact with the built environment. A pedestrian's risk of being struck by a car may increase to some local maximum until enough pedestrians are using the facility to cause motorists to slow or be more mindful of pedestrian traffic, resulting in a decrease in risk. Due to this phenomenon, the relationship between safety and the built environment is often nonlinear; this complexity can make overarching comments regarding the safety of the built environment difficult. Although we attempt to afford this topic the nuance it merits, readers are encouraged to read more regarding individual subtopics. Essentially, the key relationship between safety and the built environment can be distilled to the following key points:

1. Risk is a complex, nonlinear function of the built environment and the various volumes of different road users using that environment.
2. The risk of a crash can increase while the risk of that crash being severe can decrease (or vice versa) based on the infrastructure in the built environment and how pedestrians or bicyclists interact with the built environment.
3. Exposure to risk depends on the number of road users in a space, and while the overall number of expected crashes may increase as road user volume increases due to infrastructure improvements, the individual risk per person may decrease.
4. The mechanisms of risk for pedestrians and bicyclists are similar due to the susceptibility of these road users to harmful crash energies, but their risks are not the same, nor are the infrastructure improvements that can protect them the same.

The Relationship Between Physical Space and Safety

As pedestrians and bicyclists move through a three-dimensional space, they are exposed to crash risks from a variety of angles and conditions. These risks are dependent on many factors, both intrinsic and extrinsic to the person walking or bicycling. The type of environment in which pedestrians and bicyclists are traveling interacts with the traveler's own capabilities to magnify or mitigate potential crash energies, and even the types of mobility options available (or unavailable) can expose vulnerable travelers to even more risk. These topics, specifically, land development and density, demographics and physiology, and access to other modes, are discussed below as they influence risks to pedestrian and bicyclist safety in the transportation environment. This section also addresses different types of walking or bicycling environment performance measures, such as walkability or level of stress.

Land Development and Density

Pedestrian and bicyclist safety is often measured in terms of potential exposure to crash energies as different traffic volumes converge in a specific land development context (Moradi et al., 2016). Mode choice, trip length, access, and available infrastructure are often (but not always) directly connected to land development, and these factors all influence the routes taken, infrastructure used, and other safety-relevant factors for people bicycling or walking. Land development and density impact exposure, and therefore safety, through two separate but connected mechanisms. First, the sheer density of development in an area can result in more trips into and out of that area, resulting in more exposure to risk for any pedestrians or bicyclists in that physical space (Moradi et al., 2016). Second, specific land uses, like schools, may influence risk and safety by serving as attractors or generators for pedestrian and bicyclist traffic, concentrating those road users along streets where they are exposed to frequent conflicts with motorized traffic (Moradi et al., 2016).

Several studies have shown relationships between land development type and pedestrian or bicyclist risk. For example, studies have indicated links between the presence of an alcohol-serving establishment and crash risk for pedestrians and bicyclists. A study of spatial patterns and pedestrian-motorist collisions in one city linked 4 years of crash and injury data to data on liquor license outlets and land uses and researchers found that pedestrian injuries are clustered along major arterial streets and that liquor license outlet density is spatially correlated to collisions between motorists and pedestrians (Sebert Kuhlmann et al., 2009). Similarly, DiMaggio et al. (2016) used spatial regression models, along with 10 years of crash data, and found that if a Census tract contains even one alcohol license outlet, the risk of a pedestrian or bicyclist being struck by a car increases 47%. These studies, considered together, suggest that risk for people walking or bicycling is increased due to either the traffic attracted to liquor license outlets or the potential for impaired road use.

Other studies have synthesized two or more land development factors into singular risk models. In their wide-ranging investigation of risk factors to pedestrians for the FHWA's National Cooperative Highway Research Program research report 893, *Systemic Pedestrian Safety Analysis,* researchers analyzed 38 pedestrian studies and identified a variety of data types and important variables to capture and characterize pedestrian exposure to risk (L. Thomas, Sandt, et al., 2018). These variables include commercial land uses (which influences density), household density, employment density, university proximity, and other urban density measures (such as building volumes). Thomas et al. then examined available density measures and other exposure variables while developing a SPF for two different types of motor vehicle-pedestrian collisions: collisions between motorists traveling straight on a segment and pedestrians, and more narrowly defined, collisions between motorists and pedestrians on roadway segments under dark conditions (see Part 4 for more information on SPFs). The final, statistically significant SPF developed for these two crash types found a positive correlation between commercial property density and both crash types, and a positive correlation between "urban village" designation (a special land development designation in Seattle for mixed use land development) and both crash types. These results show that when traffic attractors or generators in a region, such as commercial development or mixed land development, account for more pedestrian traffic, there is a corresponding increase in risk potential for people walking. This study did not investigate crashes with bicyclists, but given the similarities between pedestrian and bicyclist risks, similar relationships between bicyclist exposure and land development/density may exist.

The connection between commercial land development and safety has also been identified by researchers beyond L. Thomas, Sandt, et al. (2018). A systematic review of research about spatial factors and pedestrian crashes found that four out of five relevant studies demonstrated a statistically significant link between commercial development and pedestrian crash risk (Moradi et al., 2016). An international study by Fuentes et al. (2013) used 2 years of crash data from a large city in Mexico and spatial analysis to find a higher probability of a motor-vehicle-pedestrian collision in Census tracts with high proportions of commercial or retail land uses. This crash risk was also linked to pedestrian age, where pedestrians 65 and older were more at risk of being struck by a motorist, demonstrating that population density and demographics also interact with the density of development.

However, commercial development may not be simply related to crash risk but also to risk of *fatality*. In a 2018 study, Mansfield et al. used 5 years of fatal crash data from FARS linked to annual average daily traffic (AADT) data from the Highway Performance Monitoring System, Census tract data, transit data from the American Community Survey (ACS), land diversity data from ACS, and more to identify land use, travel, and sociodemographic variables positively correlated with pedestrian fatalities. The researchers found that in urban tracts, retail density is positively associated with pedestrian fatalities, while population density has a small negative association with the risk of fatality. These observations largely hold in rural tracts, with retail density maintaining its positive association with fatality risk. The Mansfield et al. (2018) study also showed differences in fatal injury risk for commercial development compared to other development types. Two separate international studies found that commercial development may pose greater risks for pedestrians than other development types. Prato et al. (2018) found that residential areas and shopping areas are positively associated with a reduction in pedestrian injury severity compared to other development types in Denmark, and Lizarazo et al. (2018) found a similar result examining 7 years of crash data in Medellin, Colombia.

A study from Gladhill et al. (2012) correlates commercial development and business or retail density to increased risk to pedestrians or bicyclists. The researchers used 3 years of crash data from Portland, to develop regression models for pedestrian, bicyclist, and motor vehicle crashes. Although the study found a lack of significance for certain feature densities (e.g., street connectivity and intersection density), business density was positively associated with increases in crashes for both pedestrians and bicyclists. Again, these results likely indicate that development types that attract pedestrians and bicyclists and expose them to crash risks on busy streets significantly influence safety. A similar result to business density was found by Quistberg et al. (2015) for restaurant density in Seattle; using 7 years of crash data, the researchers found higher crash rates on busy, nonresidential roads and a positive association between restaurant density and collisions with pedestrians. Clearly, land development that attracts pedestrians also poses a threat to those pedestrians by increasing their exposure to potential crashes.

Based on the aforementioned studies, land development primarily affects safety as a mechanism for exposure. In contrast to Moradi et al. (2016), Rothman et al. (2017) found no statistically significant link between increased walking to school and motor vehicle-child pedestrian crashes in Canada. In fact, the researchers found a “protective effect” of residential land density on child pedestrians when controlling for the built environment (Rothman et al., 2017).

Despite all the studies indicating positive associations between land density and risk of crash or injury for vulnerable road users, one novel study in China demonstrated that the relationship may not be entirely linear. Wang et al. (2017) examined spatial correlations to safety in Shanghai using hierarchical models. The researchers used crash data spatially linked to 263 traffic analysis zones to identify land use intensity (or density) patterns linked to pedestrian crashes. Their study found that although road length and land use intensity were both positively correlated with probability of pedestrian crashes, the positive association was not equal for all land use intensities. The researchers found that the correlation for medium land use intensity was greater than that for low and high land use intensity. This convex shape may indicate that exposure is low when land use intensity is low; it may also indicate a safety in numbers effect for high land use intensity. When a significant number of pedestrians are present, traffic speeds may slow, lowering both crash likelihood and risk of injury. Therefore, these results seem to indicate that land development of any type, if it attracts enough road users to create conflicts, may increase risk to those road users, but that risk may vary based on development type and density. Indeed, some risks may even be mitigated by the types of facilities present in typically denser locations due to a concentration of financial resources (i.e., a greater tax base and business incentives).

Land Development and Demographics

Although the type and density of land development can create risks for pedestrians and bicyclists by functionally attracting more trips into locations with more motor vehicle traffic traveling at higher speeds, they can also create risks by concentrating specific vulnerable populations into areas of high exposure. As mentioned, an important determinant of crash outcomes is the physiology of the human body; some road user populations, due to physiology, may be at more risk of death or serious injury than others if exposed to the same crash energy. For example, research has shown that senior populations may be at higher risk of injury or being struck while walking (Fuentes & Hernandez, 2013). This increased risk may be due to physiological issues, including physical and cognitive decline, and due to increased exposure that results from greater dependence on walking as a travel mode (Y. Choi et al., 2018). A recent Australian study specified several built environment features that can act as points of conflict or increase the potential for injury due to excessive crash energies, including (Mantilla & Burtt, 2016):

- Driveways.
- Midblock crosswalks.
- Intersection crossing points.
- At-grade facilities near high-speed roadways.

While these risk points are not unique to older pedestrians, the researchers did find through an investigation of crashes between motorists and pedestrians that treating these risks is especially important near residences with older adults due to the aforementioned physiological limitations of older travelers.

Children, too, may be uniquely at risk in the roadway environment. All the listed risks (e.g., driveways and other crossings) present risks for children as well, but one unique concern for children was identified through a simulator study (Tapiro et al., 2018). Children, due to cognitive development, or rather lack thereof, may be more prone to distraction and less capable of attentional focus. Researchers studied 52 pedestrians (38 of whom were elementary school-aged children) in a simulated roadside environment to identify potential distractions during different crossing scenarios. The researchers found that both auditory and visual distractions (e.g., continuous loud noises or prominent visual elements near the crossing location) drew pedestrian attention away from the crossing task, resulting in smaller crossing gaps or slower responses to crossing opportunities. In this finding, the distractions affected younger pedestrians (less than 11 years old) more than older pedestrians (greater than 14 years old), raising concerns that children may be more susceptible to auditory and visual cues and may be more accepting of unsafe traffic gaps than adults. These results merit consideration for roadside design to create spaces where children cross traffic undistracted. The limited sample size and simulated nature of the crossing environment suggest more research is needed to understand this problem and potential solutions.

In addition to age, economic status of pedestrian and bicyclist populations may influence crash risks. Research shows that socioeconomic status plays an important role in both mode choice and trip choice for people, and socioeconomics (including vehicle use, access, ownership, and affordability) are therefore often used as proxies for exposure. Moradi et al. found that studies tended to show that as socioeconomic status increases (i.e., as travelers have more income and therefore access to more costly neighborhoods that may have more infrastructure investment), pedestrian crash risk decreases (Moradi et al., 2016). Guo et al. (2018) found a similar association for injury risk and socioeconomic status; through a logistic regression model pedestrian injury severity spatially linked to demographic characteristics, the researchers found that higher socioeconomic status (SES) is associated with lower risk of severe injury for pedestrians involved in crashes. The researchers offered safer infrastructure as a potential explanation for the decrease in risk. Their study found that higher income areas (where travelers of higher socioeconomic status may live) tend to have better investment in street lighting than areas with lower socioeconomic status, so pedestrians in these neighborhoods may benefit from heightened visibility. In a Seattle-area study, researchers found that locations with higher value residential properties had decreased risk of pedestrian collisions (Quistberg et al., 2015).

The previously mentioned Sebert Kuhlmann et al. (2009) study found that walking to work is associated with an increased risk of injury for pedestrians (likely as a function for exposure), demonstrating the link between vehicle ownership and access, walking, and safety. However, this link between walking and risk is complex and likely dependent on socioeconomic factors. Using negative binomial regression to model fatal and severe injury crashes in different neighborhoods of different economic status, Dumbaugh et al. (2020) found that sidewalks were associated with an increased risk of crashes involving pedestrians in high-income neighborhoods. In low-income neighborhoods, however, sidewalks and sidewalk buffers were associated with decreases in pedestrian crashes. While some authors may attribute these types of differences in safety between neighborhoods to demographic factors (e.g., Xin et al., 2017) a likely explanation is that socioeconomic status affects likelihood or dependence on walking, so neighborhoods with extensive pedestrian infrastructure may still have appear to have high rates of pedestrian risks if pedestrian trips are less common (Dumbaugh et al., 2020). Conversely, neighborhoods with more frequent pedestrian traffic may have lower rates of severe pedestrian crashes, even if the amount of sidewalks available is lower than in high-SES neighborhoods, due to an increased expectation of pedestrian travel in the area (Xin et al., 2017). The interplay between demographics, vehicular access, and safety is clearly nonlinear.

An Australian study captured the complexity in socioeconomics for vulnerable road user safety. This study, a regression tree analysis of motor vehicle-pedestrian crashes in Melbourne from 2004-2013, identified several significant variables that increase the risk of pedestrians being struck by vehicles. These variables include socioeconomic factors like national origin, motorist education level, motorist and pedestrian age, access and use of additional modes, and employment type. Although these results may not reflect the reality of safety in the United States, they do indicate that safety is dependent on a variety of factors, including the socioeconomics of road users in a specific built environment (Toran Pour et al., 2017).

How populations concentrate in a given built environment also affects how risk propagates for pedestrians and bicyclists. A regression analysis of crash data from 1965-2014 from Organization for Economic Cooperation and Development (OECD) nations (including the United States) concluded that higher population areas tend to be more walkable, resulting in fewer trips taken by vehicle, and thereby fewer collisions with pedestrians (Cho, 2018). Although specific conclusions regarding the built environment are lacking in this analysis, the results do lend credence to the idea that population density can have a protective effect for pedestrians. Mansfield et al. (2018) also arrived at this conclusion specifically for pedestrian fatalities.

However, some studies have noted the opposite relationship between density and safety, especially when potentially confounding infrastructure variables are considered. Sebert Kuhlmann et al. (2009) and Quistberg et al. (2015) each demonstrated that more walking trips may increase pedestrian exposure to risk of injury, especially if these walking trips are made where sidewalks are absent (Abou-Senna et al., 2016). This finding also demonstrates the safety benefit that some neighborhoods may receive from more concentrated funding and economic development. Domestic studies (Pulugurtha & Sambhara, 2011) and international studies (Fuentes & Hernandez, 2013) demonstrate that the number of predicted crashes between motorists and pedestrians may increase as population density increases; the systematic review from Moradi et al. (2016) also seems to confirm this result. Although there is less research on this topic for bicyclist safety, the aforementioned study using Portland, crash data also show a similar relationship between density and crashes involving bicyclists (Gladhill & Monsere, 2012).

Ultimately, socioeconomics and demographic factors provide one mechanism for the built environment to influence the risk of crashes and injuries for vulnerable road users by influencing who uses the roadways, in what number, and on what facilities. However, as illustrated through the various studies highlighted here, the relationship between population density, socioeconomic status, modal access, and safety is complex and makes drawing broader conclusions difficult. As Chang et al. (2016) illustrated in a large-scale regression analysis of pedestrian and total traffic fatalities in cities of different sizes in the United States, pedestrian fatalities tend to increase linearly with population, but only to a certain point. Large cities (i.e., cities with a population greater than 600,000) may have a lower rate of pedestrian fatalities per capita than cities with smaller populations, and the relationship becomes even more dramatic for cities with populations greater than 1 million compared to smaller cities. An implication of this may be that larger cities induce (and perhaps support) more walking, so there is a safety in numbers phenomenon in effect. More people walking or bicycling results in more exposure to risk for that population but given a certain volume of people walking and bicycling, available facilities, and attractive trip destinations, motorists may be driving slower that mitigates harmful crash energies. (Safety in numbers is briefly discussed in Part 1.) These nonlinear relationships are important to consider as populations shift in the future; if populations in cities continue to grow, more and more pedestrians and bicyclists will be exposed to crash risks until safe saturation levels and better infrastructure investment are achieved (Chang et al., 2016; Y. Hu et al., 2018).

Availability and Access to Transit

Intrinsic in the discussion of socioeconomic factors and the built environment is mode choice. As hinted through the previous section, some travelers, particularly those living in neighborhoods with lower levels of transportation investment, may be more at risk of death or injury due to reliance on walking or bicycling as the primary travel mode. Important, too, are access to safer facilities and transit options, although these options may depend on local taxes, project prioritization, infrastructure investment, and land development. Therefore, the safety effects of modal choice and access are intrinsically linked to the topics of land development and population. Since the previous section discussed the relationship between modal access and walking as a primary mode, this section focuses more on transit access.

Research demonstrates that many transit trips begin with walking or bicycling; therefore, transit stops serve as potential centers of risk by concentrating vulnerable road users near specific points along a roadway. Numerous studies have identified this relationship between trip attraction and risk of crash or injury. A spatially linked structural equation analysis in Washington, DC, found an association between transit stop traffic attraction and increased pedestrian crash risk by looking at traffic behavior in specific planning zones or tracts (Aguilar & Hamdar, 2018). Meta-analyses of safety studies demonstrate this result for both bus stops and train stops (Moradi et al., 2016), while international studies have indicated increased risk of injury for pedestrians traveling to bus stations (Moradi et al., 2018).

There is a second transit-specific risk that should be considered when planning transit stop location and roadside design. Pedestrians and bicyclists attempting to cross the street to or from a stop may be obscured by the transit vehicle, positioning themselves in conflict with motorists traveling through (L. Thomas, Sandt, et al., 2018). In their analysis of pedestrian crashes in Portland, Gladhill and Monsere (2012) found a statistically significant relationship between pedestrian crashes and transit entrances and exits. The authors noted that all bus users are pedestrians (or bicyclists) for at least a brief period of time before and after using the bus, so the association is intuitive given the clustering of pedestrians exposed to potentially dangerous sight lines and vehicular traffic. Some studies have shown that different transit facility designs may eliminate some of the visually obscuring elements that can make it difficult for road users to look and see each other, but these alternatives may not always be feasible given space requirements. An analysis of bus rapid transit (BRT) stops in New York City compared pedestrian safety benefits at four types of BRT facilities (Beaton et al., 2013):

- Typical roadside (i.e., existing conditions without BRT facilities).
- Curbside bus lanes (i.e., existing parking lane on roadside converted to bus lane).
- Offset bus lanes (i.e., right travel lane converted into bus lane restricted to buses and right-turning vehicles).
- Median bus lanes (i.e., leftmost travel lane converted into dedicated bus lane with left-turn restrictions).

Researchers collected surrogate safety data (crossing distances, refuge island accommodation, and pedestrian space displacement) and concluded that offset bus lanes provide the most pedestrian benefit. However, the qualitative nature of this analysis and the focus on BRT makes it difficult for one to generalize the results.

The planning and location of transit stops on a route may also affect pedestrian safety. In a spatially linked analysis of pedestrian crashes near intersections in North Carolina, researchers found that an increase in the number of transit stops in a quarter-mile buffer of an intersection increased the number of predicted pedestrian crashes at those intersections (Pulugurtha & Sambhara, 2011). This result is intuitive given that locating transit stops near intersections can increase exposure of people accessing transit to several conflicts with motor vehicle traffic. The study of pedestrian crashes in Seattle also produced findings relevant to bus stop locations. The authors found that the number of pedestrian crashes increased 12% per five daily bus passenger entrances and exits per acre (Quistberg et al., 2015). Considered together, these studies demonstrate that bus stops increase pedestrian exposure to crash risk, and that those seeking to address pedestrian crashes should consider the placement and design of transit stops.

A crash prediction study conducted in Montreal used crash data, injury data, traffic volumes, and pedestrian and bicycle flow estimates to develop safety performance functions (SPFs) for motorized and nonmotorized crash predictions at intersections (refer to Part 4 for more information on SPFs). This study found a statistically significant association between the presence of bus stops at signalized intersections and the number of predicted bicyclist injuries. Bus stops located at intersections (i.e., in the span of vehicles queuing at the intersection during normal operations) increased the occurrence of a bicyclist injury by 40%. The reason for this increase is likely bus stop locations; the authors note that, in Montreal, bus stops are typically located along busy arterials, so bicyclists traveling through intersections must contend with higher speed vehicle streams, pedestrian traffic, and buses, making safe maneuvers difficult (Strauss et al., 2014). Therefore, bus stop location is critical for both pedestrian and bicyclist safety. International studies confirm the importance of transit access and crossing locations for safety (Gitelman et al., 2018).

Despite these potential crash risks, however, locating bus stops near pedestrian and bicyclist facilities may produce safety benefits. A regression analysis of pedestrian bus access in Los Angeles, California, showed a significant, positive relationship between sidewalk connectivity and BRT ridership (Woldeamanuel & Kent, 2016). Because bus ridership removes some car trips, providing easy connectivity to buses likely both increases exposure to risk for pedestrians while also reducing that risk by reducing motor vehicle trips. In fact, a cross-sectional analysis of transit access in California based on the California Household Travel Survey indicated that pedestrians are likely willing to travel further than expected to access transit (e.g., if a transit access point is two miles away, respondents were equally likely to walk or drive to transit) (Durand et al., 2016). Therefore, careful location of transit points may yield substantial benefits for reducing motorized traffic.

Schedules are also important for realizing safety benefits from transit. An Australian study of observed pedestrian behaviors at three train crossing points showed that frequent and reliable train schedules are critical for minimizing risks (Naweed et al., 2016). When pedestrians feel they are likely to miss a train and be late due to the infrequency or unreliability of arrivals, they are more willing to engage in risky behaviors, such as stopping on rails or walking around lowered boom gates. Although these results are specific to at-grade rail crossings in Australia, they do have implications for carefully planning transit access points and scheduling arrivals/frequency to discourage unsafe access.

Although bike share is less prevalent than transit, it is important to note that bike-sharing and docking station location may influence risk for people walking and bicycling. An international study focused on bicycle rental facilities in Taiwan evaluated risks to bicyclists as created or mitigated by rental facility location. Bicyclist risk was influenced by intersection density and separation of traffic flows, so updated planning guides for rental facility locations were needed (J.-J. Lin et al., 2018).

Spatial Measures of Level of Service and Risk

Over the last few decades, researchers have developed numerous contextual measures to evaluate the walkability or bikeability of the built environment. These spatial correlates, or levels of service, often focus on key measures of comfort, like connectivity, accessibility, and stress. As illustrated throughout this subsection, research has demonstrated that these factors also affect safety. There is a clear link between stress and safety, so designing countermeasures to reduce stress is likely to improve safety (Caviedes & Figliozzi, 2018). The reason for this is that risks are often created by, or mitigated by, different factors in the environment and may not be consistent between locations. Researchers have also found that highly walkable environments are quite different from highly bikeable environments (Muhs & Clifton, 2015). Some features that can create risk may, in some contexts, be more dangerous to bicyclists and pedestrians than in others. Therefore, it is important for researchers and practitioners to always take careful stock of the spatial context of safety rather than purely assessing crashes or conflicts (Lakes, 2017).

Spatial measures for pedestrians

Pedestrians are often forced to use facilities they deem unsafe or uncomfortable despite a general desire to avoid these types of locations because no other modes are available. A meta-analysis of pedestrian-related literature published between 1975 and 2016, with a special focus on space syntax, found four common measures (Sharmin & Kamruzzaman, 2017):

- Integration (a measure of how close a street is to all other streets);
- Choice (extent to which a street offers the shortest path between any two streets);
- Connectivity (the number of streets directly connected to a sample street); and
- Control (measure of traffic control or access control to a street).

Although the authors did not explicitly examine safety in the meta-analysis, they did find that as integration, choice, and connectivity increase, pedestrian activity increases. Further, increasing pedestrian activity can deter vehicular traffic (as an alternative mode to driving), resulting in less exposure to risk. Therefore, these spatial elements can directly influence risk, so spatial measures of comfort may provide insights into pedestrian and bicyclist risks.

In fact, other researchers have made the link between spatial context and mode choice even more explicit. Through an analysis of two waves of data from the United Kingdom Household Longitudinal Study, researchers identified criteria changes that can motivate travelers to change modes for commuting (employed people 16 or older were interviewed one year apart) (Clark et al., 2016). Although life events and attitude orientation play critical roles in mode choice, the authors also found significance in spatial context. Measures such as access to transit and proximity to employment (i.e., choice) play critical roles in adoption of bicycling or other non-car-commuting. Although these results are not derived for the United States, they do indicate the importance of spatial correlates for mode choice, and mode choice is linked to risk and safety.

Supporting this analysis is a study of intersection safety using 5 years of crash data from Florida for motorists, bicyclists, and pedestrians (J. Wang et al., 2017). The researchers used typical crash prediction models (i.e., negative binomial models) to analyze crashes based on both exposure and macroscopic environmental elements (e.g., total trips generated per geographical area). While the authors found differences in the statistically significant causal factors in each crash type, a key finding from the study was the importance of including spatial/zonal factors for predicting crashes involving pedestrians and bicyclists, especially when critical exposure data, such as pedestrian and bicyclist trips, are limited. The spatial context in which a crash occurs matters.

For studies about pedestrians, measures of spatial correlates tend to look at network properties (specifically sidewalks), many of which are standardized by the Americans With Disabilities Act (ADA) that requires accessible walkways. The ADA specifies regulations regarding connectivity and availability of sidewalks, walkway designs, and minimum grades because these elements influence both comfort and safe use of public facilities. Not all spatial correlates or measured variables intersect with ADA values, but it is common for researchers and practitioners to investigate network properties like connectivity (i.e., the ease of traveling from an origin to a destination on sidewalks or separated facilities), completeness or coverage (i.e., the amount of streets featuring sidewalks or separated facilities), and accessibility (i.e., ease of use of the network by pedestrians of all ability levels).

Several parameters covered by the ADA have been examined in the literature to find connections to safety. In a macro-level (i.e., network-oriented) analysis of pedestrian crashes intended to use predictive models to identify relevant safety factors in Vancouver, Canada, researchers investigated several measures of pedestrian facilities that account for walkability (Osama & Sayed, 2017). These parameters included:

- Connectivity – A network property measured by intersection density, degree of connectivity, degree of network coverage, network density, and network complexity;
- Directness – A network property measured by network orientation/continuity (ratio of sidewalks to segments and ratio of total sidewalk length to access points) and linearity (the relationship between the desired straight path and the available path); and
- Topography – A measure of the slopes of available sidewalks, including both total length of pedestrian facilities and the average weighted slope of facilities.

The study found higher continuity, linearity, degree of network coverage, and weighted slope were associated with lower crash occurrence. Conversely, degree of connectivity was associated with higher crash occurrence. Most of these results are intuitive and indicate network properties valued by people walking. Continuity allows pedestrians to reach destinations uninterrupted by conflicts that can reduce safety. Linearity indicates ease of navigation. Coverage refers to the number of streets with sidewalks present, so it follows that a higher number of separated facilities would improve pedestrian safety. The slope result, though counterintuitive at first, may account for motorists reducing speed when grades are sharper (or traveling slower up a sharp slope), resulting in lower likelihood of crashes. Finally, network connectivity in the study served as a measure of exposure; with more pedestrians using an interconnected road network, more pedestrians are exposed to potential crash energies.

In fact, so important are connectivity and access for safety that providing these attributes is a legal concern. Cities must legally comply with the ADA and provide ready access to people with disabilities with this provision being of an explicitly legal nature. According to the ADA, when an alteration is made to a road surface or other facility, any adjacent pedestrian facilities must be suitably upgraded to provide access for people with disabilities. A jurisdiction's failure to do so often triggers a tort claim (i.e., in the absence of contracts or specific legislation, plaintiffs seek a judicial decision based on common law to hold people accountable for actions that unintentionally or intentionally caused harm), but a full legal discussion is beyond the scope of this report. The key concern for the report is that all jurisdictions are required by Federal law to plan for and progress toward a transportation system that provides access and connectivity for people with disabilities, and this provision ultimately benefits all people by requiring agencies to design and construct safer facilities (Parker et al., 2015).

Analysts seeking to better account for pedestrian risks are encouraged to collect, validate, and use spatial data for roadways under investigation (i.e., via GIS). These types of data, when linked to pedestrian exposure measures and crash data, can be useful for identifying high risk locations. This process may even identify locations where crashes may occur because of endemic risky elements in the spatial context. Therefore, understanding spatial correlates can help road safety professionals be more proactive in addressing pedestrian risks (Fitzpatrick et al., 2018).

Spatial measures for bicyclists

Connectivity and accessibility are similarly important for bicyclists. Many researchers and practitioners use a four-stage level of traffic stress (LTS) spatial correlate to link concepts like connectivity and accessibility to bicyclist safety. For a definition of LTS levels, see Table 6, adapted from Moran et al. (2018).

Table 6. Common Measures of LTS

Level of Traffic Stress	Sufficiently Comfortable for:	Characteristics
1	Most people	Lowest stress; comfortable for most ages and abilities
2	Interested but concerned bicyclists	Suitable for most adults; presenting little traffic stress
3	Enthused and confident bicyclists	Moderate traffic stress; comfortable for those already riding bikes in American cities
4	Strong and fearless bicyclists	High traffic stress; multilane, fast-moving traffic

Source**:** Moran et al., 2018.

Labeling a street with an LTS designation allows researchers and practitioners to assess the relative comfort of a street for a bicyclist to get a better sense of environmentally borne risks to bicyclists. These risks can be mitigated both by improving the connectivity between low LTS streets and by improving facilities on existing high LTS streets to improve safety, thereby lowering LTS. Therefore, as Moran et al. (2018) show in their geospatial analysis of LTS for Philadelphia, Pennsylvania, connectivity is intrinsically linked to safety; where connectivity is poor, bicyclists are forced to integrate with high vehicular volumes that both raise stress levels and exposure to harmful crash energies. By considering connectivity, traffic volumes, and LTS, thereby accounting for risks along the transportation network, the authors concluded that if connectivity is better, more people will likely travel by bicycle.

Other researchers have explored level of stress spatial correlates but linked stress to risk exposure, as created by traffic volumes and potential conflicts, rather than connectivity. As an alternative to LTS, which is largely dependent on connectivity and other geometric configurations, some researchers use bicycle level of stress (BLS) as a spatial correlate for safety (Caviedes & Figliozzi, 2018). Regardless of which measure is used, both spatial correlates attempt to link risks induced by the built environment to bicycling as a mode choice. Caviedes et al. (2018) attempted to gather a purer measure of bicyclist stress due to different environmental factors by measuring bicyclists' galvanic skin reactions (GSR), a physiological chemical response that can be induced by stress, as it related to the built environment. For their study, they filmed bicyclist behaviors on-street and off-street and correlated the spatial data to GSR measures. They found several important factors that can trigger stress, including:

- High traffic volumes adjacent to bicyclist facilities;
- High cross-traffic volumes;
- Presence of two right-turn lanes;
- Regular bike lane (compared to separated bike lane);
- Rough pavement surface;
- Narrow passages (for off-street facilities);
- Several conflict points (including with pedestrians); and
- Vehicle parking activity.

The authors concluded that the four most important stress factors are: proximity to motor vehicles, motor vehicles encroaching into bike lanes, vehicles turning at intersections, and pedestrians walking into bike lanes. Based on these results, it is clear that exposure to motor vehicle traffic, especially in locations with a number of conflict points due to the environmental characteristics, induces stress while simultaneously increasing crash or injury risk. Designing countermeasures to reduce stress is likely to improve safety (Caviedes & Figliozzi, 2018). International research confirms this conclusion and links other stress indicators to crash risk (e.g., anger or compromised emotional state) (Huemer et al., 2018).

Infrastructure and Safety

As has been set forth throughout this section, the built environment can create or mitigate risks for pedestrians and bicyclists traveling along a roadway. Many of these risks are effectively built into the standard roadway environment itself—through design elements like lane widths, intersections, and more—and can be exaggerated or mediated through changes to these elements and with specific infrastructure for people walking and bicycling. This section discusses the general relationship between roadway design and pedestrian and bicyclist safety.

In the literature review for NCHRP Report 893, Thomas et al. (2018) synthesized 38 pedestrian safety studies and identified several environmental risk factors that can increase risk of pedestrian crash frequency at both intersections and segments. These variables, that include functional classification, number of nearby driveways, and more, are highlighted in Table 7. Note that some variables, such as lack of median islands, may increase pedestrian crash frequency at both intersections and segments. Other variables, like speeds greater than 25 mph, were only found to be positively associated with crash risk on segments.

Roadway Design Elements

In the United States, roadways are typically designed for motor vehicles first and foremost. Typical transportation design standards and guidelines focus almost entirely on meeting the needs of motor vehicle users, but many of these design elements can create specific risks for people walking or bicycling by exposing them to conflicts and potential crash energies, as has been illustrated throughout this section (Abou-Senna et al., 2016; Y. Hu et al., 2018). However, where the previous subsections focused on how the *built environment* and mode choice can affect exposure and therefore, risk, this subsection focuses on *design elements* themselves, including street type, vehicle parking, traffic control, access control, and geometric properties.

Street type and roadway network

Roadway design is typically conducted by specifying a functional classification for a planned roadway; this functional classification entails certain design considerations based on the prescribed balance between mobility and accessibility. Higher functional classification roadways, such as arterials, have higher speed limits, greater number of lanes, and limited access points. Lower functional classification roadways, such as local roads, typically comprise low-speed and narrow streets used to provide access to homes and commercial properties. Pedestrians' safety and risk are directly related to functional classification (Mansfield et al., 2018), as are safety correlates like walkability (Galanis et al., 2017). In urban areas, risk of pedestrian fatality can vary depending on functional classification; but in general, all roadway types seem to become riskier for pedestrians as traffic increases (measured in increments of one thousand vehicle miles traveled, squared) (Mansfield et al., 2018). This finding indicates that arterials likely present significant risk to pedestrians as these roadways are designed to carry the highest traffic volumes at the highest speeds with access limitations. These factors all interact to increase exposure to severe crash injuries for pedestrians (Quistberg et al., 2015; Sebert Kuhlmann et al., 2009) and bicyclists (L. Thomas et al., 2017). In rural areas, the researchers found risk to be uniform across all roadway types and directly tied to traffic volume in a specified area (i.e., traffic density) (Mansfield et al., 2018).

Table 7. Risk Factors for Pedestrian Crashes at Intersections and Segments

Variable/Risk Factor	Intersections	Segments
Traffic volume	+ (generally positive, but not linear)	+ (generally positive, but not linear)
High turning volumes	Unknown threshold	n/a
Functional classes - arterials and collectors compared with local streets	+	+
Proportion of truck/bus traffic in traffic stream	+ (crash severity)	+ (crash severity)
Proportion of local streets at intersection (potential surrogate for annual average daily traffic [AADT])	-	n/a
Pedestrian volume	+ (but not linear)	+ (but not linear)
Number of legs > 3 (may also be partial traffic surrogate)	+	n/a
Total lanes on largest leg (5+)	+	n/a
No median/median island	+ (less certain than for segments)	+
Presence/number of transit stops	+	+
Presence of on-street parking	+	+
Presence/number of driveways	+	Unknown (theoretically yes)
Presence of signal	+ with crash frequencies - with crash severity	n/a
Lack of separate turning movements from walk phase (all red walk phase, or walk and restricted turn phase) (signalized intersections)	+	n/a
Lack of leading pedestrian interval (signalized intersections)	+	-
Presence of 4 or more through lanes; Higher numbers of total lanes	Theoretically	+

Variable/Risk Factor	Intersections	Segments
Presence of TWLTL	n/a	+
Speed limit > 25 mph	n/a	+ with crash severity + with frequency in a few studies
Vehicle speed	+ with severity	+ with severity

Source: Thomas et al., 2018.

Note: + indicates a positive relationship between the variable/risk factor and intersection/segment locations indicating increased risk. - indicates a negative relationship between the variable/risk factor and intersection/segment locations indicating decreased risk.

As functional classification is linked to the utility of a roadway in the broader network of streets that comprise a transportation system in a location; the arrangement and connections between roadways of different functional classifications can increase or mitigate risks to pedestrians or bicyclists. The broader alignment of the transportation network, whether as a grid or in some other configuration, can increase the likelihood of pedestrians or bicyclists coming into conflict with motorists. In an analysis of 3 years of crash data in Portland, Gladhill and Monsere (2012) found statistically significant positive relationships between bicycle crashes and network alignment features, such as a street grid characterized by high density of four-leg intersections. For pedestrian crash prediction related to street layout, none of the variables included in the study were statistically significant. What is known for pedestrians is that as roadway volumes increase (as can happen due to arterial design and configuration in a network), pedestrian risk also tends to increase (Moradi et al., 2016).

Vehicle parking

Parking along roadways is linked to both roadway functional classification and land development (and local policies) and is therefore a potential mediator of risk for both pedestrians and bicyclists. However, the explanation for this risk may vary by mode. For pedestrians, the relationship between on-street parking and crash risk is likely nonlinear. The aforementioned OEC study demonstrated that roadway designs that facilitate through movements of vehicles tend to decrease safety for pedestrians, so roadways with more parking may correspond to lower speeds and less throughput, which may indicate reduced risk (Cho, 2018). However, several studies have demonstrated that on-street parking may hide pedestrians from traffic, thereby increasing the risk of conflicts, particularly if other roadway design elements facilitate higher speeds (Cao et al., 2017; L. Thomas, Sandt, et al., 2018). Off-street parking, too, may be associated with increased risks to pedestrians, particularly school children walking off the roadway, due to the number of potential conflicts and blind spots in those environments (Jamshidi et al., 2017). For bicyclists, on-street parking is often associated with “dooring” type crashes due to the proximity between on-street bicycle facilities and motorists opening their doors. In a review of bicycle-motor vehicle crashes (including raw crash data and previously published studies of crash data), Schimek (2017) found that 12% to 27% of all urban bicyclist-motor vehicle crashes may be dooring-type crashes, but the true extent of this problem is unknown due to this crash type’s absence from most crash forms.

Traffic control

Traffic control can have a variety of impacts on pedestrian and bicyclist safety due to the range of ways in which control can be deployed; however, it can only mitigate so much risk when exposure to motor vehicle traffic is high. Most germane to this report is the use of traffic control to manage and eliminate the various conflicts between different road users at intersections, although other forms of signage and markings may be used to delineate specific paths for motorists to reduce harm to pedestrians and bicyclists. Intersection design is discussed more thoroughly in a subsequent subsection; in this subsection, the focus is on traffic control at intersections and in other unique applications. Evaluations of specific traffic control strategies are included in Part 3.

As Lu et al. (2018) note, traffic control is used to manage antagonistic streams of vehicles that may come into conflict with people walking or bicycling and subject them to harmful crash forces. However, different types of traffic control may be warranted under different traffic flows and functional classifications, so the impacts on vulnerable road users can vary from one type of control to another. Just as different roadway cross-sections can be used to separate pedestrians and bicyclists from conflicts, intersection control can be used to grant pedestrians and bicyclists separate movements, thereby protecting them from conflicting traffic streams. Intersection control can be classified as uncontrolled, stop-controlled, or signal-controlled, and each of these control types can affect pedestrian and bicyclist safety differently. One study spatially linked 7 years of crash data with intersections to identify risk-increasing roadway characteristics for pedestrian and bicyclist crashes (Y. Hu et al., 2018). At uncontrolled intersections, the primary concerns for pedestrians and bicyclists were exposure to continuous traffic flow and potentially, high vehicle speeds.

Because uncontrolled intersections inadequately restrict flow from access points, the number of potential conflicts is high; however, the researchers found that crashes were less likely to occur at these types of intersections than at signalized intersections, likely since uncontrolled intersections are typically only used in lower speed, residential areas (Y. Hu et al., 2018). At stop-controlled intersections, the chief concerns for pedestrians and bicyclists were lacking crosswalks and mixed traffic streams (i.e., heavy vehicles traveling among light vehicles and bicyclists) teeing into major streets. Essentially, the lack of control on major legs at these intersections (when the intersection is only stop-controlled on the minor approach), can cause motorists attempting to turn from the minor approaches to have inattentional blindness because they are looking for gaps in traffic and fail to see people walking or bicycling. At signalized intersections, which theoretically offer more protection for vulnerable road users, the risk factors were traffic mix, high posted speed limits, and different signal timing/control for different modes. Signals are often employed on higher volume roadways, which may in turn have higher speed limits due to the functional classification, so the potential crash forces that may exist at conflict points is substantial. Moreover, pedestrians and bicyclists may be at risk from turning traffic streams if these turning vehicles are allowed to turn when pedestrians and bicyclists might also be crossing. Therefore, although traffic control can be used to protect pedestrians and bicyclists by reducing conflicts through separate phases for different traffic types, traffic signal density and variable speed limits may not limit some of the risks posed by the types of roadways that need signalized traffic control in the first place (Y. Hu et al., 2018).

Using data from Montreal, Strauss et al. (2014) developed pedestrian and bicyclist SPFs at signalized intersections indicating that bicyclists and pedestrians are at 14 and 12 times the risk of injury than motor vehicle occupants, respectively. The reason for this high risk is directly linked to geometric design and will be discussed more thoroughly in a subsequent subsection, but this finding does demonstrate that traffic control can only mitigate so much risk for vulnerable road users when exposure to motor vehicles is high. All-red exclusive signal phases, along with a right turn on red restriction, can be used to protect pedestrians by eliminating crossing vehicular streams while pedestrians complete their crossing movements, but these phases may be too short in duration to allow pedestrians to complete their crossing movements, nor are they present at all traffic signals.

Further complicating this relationship between traffic control and safety is the fact that some measures that can protect pedestrians may not improve safety for bicyclists. Lu et al. (2018) assessed the safety of bicyclists using surrogate measures like vehicle braking and conflicts in a simulated intersection environment with a traffic control scheme that adapted to bicyclist travel patterns. Although these results may not be fully applicable to real intersections due to the limitations of simulation, the researchers found that traffic control plans that do not grant priority to bicyclists likely increase bicyclist risk by exposing them to potentially fast-moving motor vehicle traffic. Moreover, in the cross-sectional analysis of reported pedestrian risk factors, L. Thomas, Sandt, et al. (2018) found a complex relationship between traffic control and pedestrian risk. While stop-control is likely correlated with increasing injury severity compared to signals or no control, the evidence for this relationship is not strong and may depend on other geometric elements, like the presence of stop bars. The relationship between risk and signalization is also complicated; while evidence shows that signals are positively correlated with crash frequency, they are negatively correlated with crash severity. This result may indicate more exposure to risk for pedestrians at signalized intersections (likely due to the increased traffic volume on the types of roadways that are signal-controlled) but decreased potential crash energies as motorists slow approaching the signal. Pedestrian activity at these locations, too, may be higher due to the types of land development where roadways that require signal-control are located (Aguilar & Hamdar, 2018; Quistberg et al., 2015). Improved demarcation of pedestrian crossings (Fuentes & Hernandez, 2013) and leading pedestrian intervals (L. Thomas, Sandt, et al., 2018) may be used to reduce pedestrian exposure to risk while simultaneously reducing stress on pedestrians.

While traffic control does influence safety, the precise mechanism of this relationship—especially under different roadway operations and control types—needs further research.

Access points

Although traffic control can be used to limit vehicular access to a roadway in some locations (i.e., at intersections), other access points along a roadway may increase risk for people walking and bicycling. Driveways especially increase exposure to conflicts from turning motorists who may pull onto a sidewalk or across a bike lane, sometimes forcing a person to step or steer into an even more dangerous traffic stream (Burbidge, 2018; L. Thomas, Sandt, et al., 2018). In a spatially linked analysis of pedestrian and bicyclist crashes at 39 intersections near 21 rail transit stations that served as pedestrian and bicyclist attractors in four Utah counties, Burbidge (2018) found that nonresidential driveways and large building setbacks (i.e., an average setback of 85 feet from the roadway) were linked to significant increases in pedestrian and bicycle crashes. The number of potential conflicts also increases as the number of access points along a corridor increases. In a study of pedestrian collisions along eight major roadways in Tennessee, researchers found access density to be a statistically significant predictor of increasing pedestrian crashes (Chimba & Ajieh, 2017). Access management may be one effective measure of reducing risk to pedestrians and bicyclists, as well as motorists.

Geometric design elements

A variety of studies have indicated relationships between pedestrian and bicyclist safety and the roadway design parameters discussed in the previous sections. These design elements are highlighted below along with relevant research:

- **Roadway length** – The analysis of spatially linked pedestrian and bicycle crashes in Portland determined that the length of a roadway is positively associated with bicycle crashes (Gladhill & Monsere, 2012). In this study, roadway length may serve as a proxy measure of bicyclist exposure to risk since the study lacked exposure data, but the authors could not draw further conclusions with their limited dataset.
- **Roadway width** – Roadway width may influence risk to pedestrians and bicyclists through three mechanisms. First, roadways with more lanes are wider, and therefore provide more capacity for vehicular volume. This increased vehicular volume that corresponds to wider roads then increases the exposure to crash risk for both pedestrians (L. Thomas, Sandt, et al., 2018) and bicyclists (L. Thomas et al., 2017). Second, wider roads require more time to cross and may entail a greater number of lanes that can carry conflicting vehicular traffic. Numerous studies have shown wider roads to be positively associated with increased pedestrian crash risk (Mohan et al., 2017; Quistberg et al., 2015). In fact, Anciaes et al. (2017) found that pedestrian crossing behavior accounts for a personal risk assessment (i.e., a certain internal measure of the risk involved in any potential crossing decision) directly linked to the number of lanes required to cross, and wider roads deter crossing behavior.
- **Roadway separation** – Roadway separation, through medians or lane restrictions, has a complicated relationship with safety and may either increase or decrease risk to vulnerable road users. In the meta-analysis of crash risks to pedestrians, L. Thomas, Sandt et al. (2018) found that a median's effect on safety depends on the presence of a pedestrian refuge. When refuges are present, pedestrians may be sheltered from dangerous crash energies, but if refuges are not provided, medians can act as barriers to safe and timely crossing maneuvers. Conversely, the aforementioned study by Strauss et al. (2014) found that raised medians can reduce bicyclist risk of injury at intersections by protecting bicyclists from conflicting turning maneuvers. A case study of a road diet in California found evidence of decreased travel times and increased bicyclist volumes at the study site (Gudz et al., 2016). These changes to the traffic stream may have complicated effects on safety, as the modifications may provide safer roadway elements for bicyclists while also increasing the likelihood of a collision through the exposure increase that corresponds to increased bicyclist volume. Conversely, two-way center turn lanes may increase crash risk for bicyclists by increasing the number of potential conflicts to which bicyclists are exposed (L. Thomas et al., 2017).

- **Curvature and grade** – There is limited research on the impacts of roadway curvature and grade on pedestrian and bicyclist safety. These roadway features may affect vehicular speed, but they may also provide psychological cues to motorists in the event of a crash. For example, an international study from Ghana, found that, compared to straight and flat roads, roads that were both curved and inclined were associated with a decreased likelihood that a motorist would flee after hitting a pedestrian (Amoh-Gyimah et al., 2017).
- **One-way configuration** – Like many other environmental factors, one-way streets may affect pedestrian and bicyclist safety in complicated, nonlinear ways. At least two studies have suggested that one-way streets are associated negatively with pedestrian crashes (Quistberg et al., 2015; L. Thomas, Sandt, et al., 2018). Although the mechanism of this relationship is not well understood, one-way streets may reduce the potential conflicts pedestrians encounter while allowing them to focus on only one traffic stream while crossing midblock (L. Thomas, Sandt, et al., 2018). Conversely, in a cross-sectional study of 5 years of crash data in Louisville, Kentucky, Riggs et al. (2017) found an association between multilane one-way streets and crash and injury incidence for both pedestrians and bicyclists when compared to two-way streets. The authors extrapolate that this safety impact may be due to a variety of spatial factors that affect level of service for pedestrians and bicyclists, but one potential explanation may be that one-way streets afford higher speeds, and these higher speeds may in turn increase the risk of both crashes and injuries for pedestrians and bicyclists. This analysis did not include single lane one-way streets.

Marked and unmarked crossings

Risks to pedestrians exist anywhere that pedestrians can or must interact with vehicles under the expectation that motorists should or will yield (Hacohen et al., 2018). For this reason, crossing locations may be the epicenters of environmental risk for pedestrians. It is at crossing locations where exposure to harmful conflicts is greatest. This exposure to risk is dependent on a variety of other environmental factors, as have been previously illustrated. Wider rights-of-way, two or more lanes, and medians can all affect the amount of time during which a pedestrian is exposed to a potential crash, as can the lengths of protected signal phases or dedicated signage (e.g., no right turn on red). However, risk may also be dependent on other environmental factors, like built features that obscure crossing locations from motorist vision or speed limits that influence motorist speed at the pedestrian crossing location.

Generally, Hacohen et al. (2018) characterize the risk of crossing a roadway as an outcome of land development, traffic speed, and vehicle types; based on an (often unconscious) risk assessment, pedestrians at crossing locations must choose their trajectory and crossing speed so as to minimize exposure to harm. The choice to cross at a marked or unmarked crossing—or to seek a different location—depends on this internal calculation. Therefore, although crosswalks may be a means of mitigating risk to pedestrians, not all crashes with pedestrians occur at crosswalks or at or near other types of official crossings (e.g., pedestrian bridges). In fact, many pedestrians will not use dedicated crossing facilities, even if they provide complete separation from vehicular traffic (e.g., pedestrian overpasses), if those crossing facilities are not sufficiently convenient and accessible to outweigh personal calculations of risk (Alver & Onelcin, 2018).

However, because many crosswalks (or official crossing locations) are chosen by pedestrians for crossing maneuvers, crosswalks are major locations where pedestrians are exposed to crash risks. Therefore, many researchers use crosswalk length as a key measure of exposure in pedestrian safety analyses (Chimba & Ajieh, 2017; L. Thomas, Sandt, et al., 2018). This relationship between crosswalk length and exposure to risk is not linear and can vary by type of crosswalk or other roadway features.

More information on the effectiveness of marked crosswalks is included in Part 3 of this report.

Intersection-Specific Concerns

Intersections are the primary locations where conflicting traffic streams come into contact and they entail a variety of design elements that may pose environmental hazards to people walking and bicycling. The prior subsection considered traffic control specifically, but intersection design must also account for turning lanes, number of legs, skew angles, and functional form. Generally, as intersection density—or number of intersections along a roadway segment—increases, so too does the risk for pedestrians (Aguilar & Hamdar, 2018; Mansfield et al., 2018; Moradi et al., 2016, 2018) and bicyclists (Gladhill & Monsere, 2012) due to the increasing number of potential conflicts with vehicular traffic. However, increased intersection density may also slow vehicular speeds and provide more crossing opportunities to pedestrians, so some roadway segments with densely located intersections may actually correspond to lower pedestrian crash rates (Quistberg et al., 2015). Again, the published research indicates the complex nature of exposure as it relates to safety.

One of those factors that influence pedestrian safety at intersections is the presence of turn lanes. Both right-turn lanes and left-turn lanes may bring conflicting vehicular traffic into the path of the crossing pedestrians, especially if the intersection does not restrict right-turns-on-red and/or employ leading pedestrian intervals (LPIs) or other signal phasing strategies. In the crash prediction model analysis of pedestrian crashes in Seattle, L. Thomas, Sandt et al. (2018) found that the presence of a right-turn only lane at an adjacent intersection was positively associated with midblock pedestrian crashes. These types of turn lanes may enable quick vehicular streams to suddenly appear on segments, which then creates risk upstream for pedestrians crossing away from the intersection. L. Thomas, Sandt et al. also cite several sources recommending protected left-turn phasing in conjunction with exclusive left-turn lanes to protect pedestrians when left turns are permitted at intersections. Strauss et al. (2014) identified turning movements as risks for pedestrians while also noting that both right and left turning flows are positively linked to bicyclist injuries at signalized intersections. In fact, Strauss et al. note that bicyclist injuries are expected to increase slightly as vehicular turning movements (both left and right) also increase. Although this finding does not explicitly identify the turn lanes themselves as risk-inducing, the authors note the importance of protected phases and red-light phases for limiting turning movement risks to bicyclists and pedestrians. Clearly lane configurations can increase or mitigate risks for pedestrians and bicyclists at some intersection types.

One potential mediator of turning movement risks for pedestrians and bicyclists at intersections is the number of legs at intersections. Several studies have shown that more roadway legs converging at an intersection (i.e., the number of conflicting roadways that cross at the same point) are associated with increased crash risk for pedestrians (Gitelman, Carmel, Pesahov, & Hakkert, 2017; Pulugurtha & Sambhara, 2011; L. Thomas, Sandt, et al., 2018). This increased risk is likely a function of both the increased exposure to motor vehicle traffic that results from more roadways converging into a single control point and the number of lanes pedestrians must cross, which is also a function of exposure. However, three-leg intersections are not without risks for pedestrians. In a study to develop pedestrian crash prediction models for urban intersections in Toronto, Lyon et al. (2002) found a positive association between left-turning volumes at stop-controlled, three-legged intersections and pedestrian crashes. The authors also found a similar relationship for left-turning vehicles at four-leg, signalized intersections, indicating that conflicting traffic streams remain a consistent threat to pedestrians across varying intersection types.

Intersection skew, too, may influence safety of pedestrians and bicyclists at intersections. The skew angle refers to the angle between two intersecting roadways and may be either obtuse or acute. Although the effect on safety for pedestrians is unknown at this time, intersection skew may result in longer crossing distances across intersection legs, thereby increasing the potential exposure to risk for pedestrians (L. Thomas, Sandt, et al., 2018). Skew angle likely interacts with the number of legs at an intersection to influence safety, so further research is merited.

A final mechanism by which intersection design may influence safety is through the functional form or intersection type itself. A variety of new intersection types (e.g., turbo roundabouts (roundabouts that require drivers to decide on their direction before entering the roundabout) or elevated intersections with a raised central space) have been proposed and developed in recent years, especially in Safe System-practicing countries seeking to mitigate the crash forces that result from unsafe combinations of vehicle speed and angle. Each of these types present different potential effects on pedestrian and bicyclist safety due to a wide variety of configurations, each with different human factors and operational demands. However, a full review of alternative intersection types is beyond the scope of this section, so readers are encouraged to examine the work of Candappa et al. (2015) to see how Safe System-oriented infrastructure can reduce crash forces and potentially improve safety for all road users. Substantial international literature exists that demonstrates that alternative intersection types may change both the frequency and severity of pedestrian and bicycle crashes, and that these changes may at times be counterintuitive, depending on other environmental factors, like land development, transit use, median coverage, and more (Daniels et al., 2008). Further research is needed to identify the impacts of alternative intersection types in the United States.

Roadway Lighting

The last general component of the built roadway environment considered in this section is lighting. A full discussion of conspicuity is beyond the scope of this section, but ambient light conditions certainly do have a relationship to the safety of pedestrians and bicyclists. The nature of that relationship, however, is complex. Well-designed lighting allows pedestrians and bicyclists to be seen more clearly (if motorists are looking for them), thereby potentially improving safety for people walking and bicycling. However, an attractive, well-lit roadway may correspond to areas of heightened activity and through sheer volume of pedestrian or bicyclist activity may in turn correspond to clusters of crashes as a surrogate for exposure (Nabavi Niaki et al., 2016; L. Thomas, Sandt, et al., 2018).

At locations where pedestrian and bicyclist volumes are high, the presence of roadway lighting may be a surrogate for exposure to risk, but improved lighting may also reduce some environmental risks for pedestrians and bicyclists through increased illumination of the surrounding environment (Helak et al., 2017; Kim et al., 2007; Mead et al., 2014; L. Thomas et al., 2016; Wanvik, 2009; Wei et al., 2016). Wei et al. (2016) modeled the effect of illuminance on nighttime crashes involving both pedestrians and bicyclists at urban signalized intersections in Florida. Their probit model found that an increase in illuminance from low (<0.2 foot-candles) to medium (0.2 foot-candles to 1.1 foot-candles) was associated with a decrease in fatalities and severe injuries in pedestrian and bicycle crashes and crashes involving drug or alcohol impairment. However, the authors did find a slight increase in crash probability when illuminance exceed 1.1 foot-candles, so too much illuminance may actually reduce visibility or affect motorist perception in some other way.

Conclusion: Role of the Environment

As illustrated throughout this chapter, the built environment can both facilitate and mitigate risks to pedestrians and bicyclists. This risk profile is complex, and measures meant to improve safety may also correlate with increases in crashes due to changes in travel patterns and behaviors. This risk can be measured as exposure to potential crash energies, and exposure is often quantified both by crash frequency and crash severity. Separation in space and time can affect both types of exposures, but these effects may contrast in nature; some elements of the built environment can reduce vehicle travel speeds, thereby reducing exposure to fatal crash injuries, but they may also cluster pedestrians or bicyclists into certain locations where the total chance of crashes occurring increases. Practitioners seeking to improve safety for pedestrians and bicyclists must keep these conflicting environmental impacts in mind. They must also account for travel behaviors and psychologies, as many pedestrians and bicyclists may choose to use facilities based on travel needs and ease of accessibility rather than safety considerations. Feelings of insecurity may deter pedestrians and bicyclists from using specific facilities in the built environment, but perceptions of safety may not always align with measured safety (Dadpour et al., 2016). Therefore, it is critical for practitioners to collect data related to risk exposure when determining how to address pedestrian and bicyclist safety problems, whether through site-specific treatments, corridor-level enhancements, long-term network improvements, or technological and policy solutions. Part 3 of this report will synthesize literature about treatments to address safety problems at the different levels of intervention.

The Role of the Vehicle

This section covers the role that vehicle design and technology could play in the risk of a crash with a person walking or bicycling and the severity of a crash, should one occur. A previous section covered the problems of vehicle speed, which combines with the mass of an object, in this case a motor vehicle, to create the kinetic energy that is transferred during a crash event and that is so harmful to the human body.

Vehicle Type

Vehicle weight, size, and power, have been explored in several studies with respect to the risk of fatality and injury when a pedestrian is struck. Although involvement of all types of passenger vehicles and medium or heavy trucks in pedestrian fatalities increased from 2009 to 2016, the rate of increase was reported to be highest among SUV-class vehicles (81% or an average increase of nearly 8% per year) compared to minivans and large vans (15%), and passenger cars (41%) (W. Hu & Cicchino, 2018). During this time, the number of registered SUVs had increased by 37%.

Passenger Cars and Light Trucks

Most fatal crashes between motorists and pedestrians or bicyclists involve passenger cars or light trucks, and the person on foot or on a bicycle is most frequently struck by the front of the vehicle (about 90% for pedestrian fatalities and about 89% of bicyclist fatalities) (NCSA, 2022c, 2022d). One analysis reported that 85% of all pedestrian injuries were caused by the impact with vehicle, even if the pedestrian struck the pavement (J. Hu & Klinich, 2012).

SUVs

An association between increased pedestrian injury severity and the growing popularity of SUVs was reported in Australia (D'elia & Newstead, 2015). Similar trends have emerged in the United States, with an increasing number of SUVs purchased and involved in pedestrian crashes (J. Hu & Klinich, 2012; W. Hu & Cicchino, 2018; Monfort & Mueller, 2020).

Large Trucks

Between 2018 and 2020, 7.4% of all pedestrian fatalities and 9.5% of all bicyclist fatalities involved a large truck (defined in FARS as a truck with a gross vehicle weight rating greater than 10,000 pounds) (Federal Motor Carrier Safety Administration, 2022). While most people walking or bicycling who are fatally struck by a motorist are initially struck by the front of the vehicle, large trucks make up the highest percentage of right-side impact and rear impacts in pedestrian and bicyclist fatalities (NCSA, 2022c, 2022d). For bicyclist fatalities, more than one-half of bicyclists killed in a single-vehicle crash with a large truck (77 fatalities in 2020) were struck by the front of the truck (47 or 61%) (NCSA, 2022d). British and German research that has specifically examined bicyclist fatalities and severe injuries involving large trucks, sometimes referred to as freight vehicles, has reported that in urban areas more than half of the fatalities resulted from situations where the truck driver was making a turn (Malczyk & Bende, 2017; Morgan et al., 2010; Talbot et al., 2017).

Vehicle Testing and Regulation in the United States

Under Title 49 of the U.S. Code, NHTSA has a legislative authority to issue Federal Motor Vehicle Safety Standards. All motor vehicles sold in the United States must comply with applicable regulations, at a minimum (NHTSA, 2011). Rules related to vehicle safety are evolving, and readers are encouraged to go to NHTSA's website for the latest information on vehicle regulations.

NHTSA also executes a consumer information program called the New Car Assessment Program (NCAP). Under the NCAP program, vehicles are subject to crash testing and evaluated for their crashworthiness and rollover propensity. Based on these results vehicles are given a safety rating that can inform consumers about their safety. The NCAP also currently recommends certain crash avoidance/advanced driver assistance systems, including: Forward Collision Warning, Lane Departure Warning, and Automatic Emergency Braking (NHTSA, n.d.-b). The program is intended to give the public comparative crashworthiness and crash avoidance safety information and leverage market forces to lead the industry to improve safety features in vehicles (Hershman, 2001).

At the time of report preparation, NCAP vehicle testing in the United States does not explicitly factor in pedestrian or bicyclist safety. In their *Special Investigation Report on Pedestrian Safety*, the National Transportation Safety Board (NTSB) recommended incorporating pedestrian injury mitigation into vehicle designs and into the NCAP ratings system (National Transportation Safety Board, 2018). In 2023, NHTSA released proposed changes to NCAP (New Car Assessment Program, 2023). Included in the list of potential changes was adding pedestrian automatic emergency braking (PAEB) to NCAP along with test criteria for evaluating PAEB. NHTSA issued a separate notice in 2023 that proposed crashworthiness pedestrian protection procedures and criteria for use in NCAP testing.

The Insurance Institute for Highway Safety (IIHS) carries out vehicle testing on behalf of the motor vehicle insurance industry. In February 2019, IIHS introduced a rating for vehicle-based pedestrian crash prevention technology. However, IIHS has not introduced testing of vehicle design modifications that might mitigate pedestrian injury once a crash occurs (IIHS, 2019).

Euro NCAP Vehicle Testing and Applications in the United States

Following the lead from NHTSA's NCAP program, the European New Car Assessment Program (Euro NCAP) was established in 1997. Pedestrian safety testing was incorporated into Euro NCAP vehicle testing in 2009 (van Ratingen, 2016). European NCAP vehicle testing measures injury risk to the head and lower extremities since those are the most common injuries to pedestrians from crashes with motor vehicles. The Euro NCAP tests focus on the bumper, hood leading edge, and areas where a person's head might strike the hood of the vehicle. Vehicle design as it relates to torso injuries, which are more common in pedestrian crashes with SUVs or LTVs, is not evaluated (J. Hu & Klinich, 2012).

Researchers have analyzed pedestrian crash health outcomes in Europe since Euro NCAP began factoring in vehicle design testing around pedestrian safety. In a comparison of pedestrian crash data from Germany and the United States, one study suggested that if the star ratings for vehicles sold in the United States had included evaluation of pedestrian protection, as it has in Europe, health outcomes as a result of pedestrian crashes would have been improved (D. Moran et al., 2017). In an often-cited study, Strandroth et al. (2011) found a strong relationship between lesser pedestrian injury severity and higher Euro NCAP star ratings. When the vehicles with higher star ratings were also outfitted with automated emergency brake assist, the reduction in injury severity was even more pronounced. Moreover, the reductions in severity were higher for the more severe injury categories.

Research on vehicle design and bicyclist injury is less common. Ohlin et al. (2017) combined Swedish hospital records, police data, and vehicle registry data to look at the combined effects of countermeasures for reducing bicyclists' injuries and correlations with Euro NCAP scores. The study suggested that, in many ways, protections that have advanced pedestrian safety have also improved bicyclists' safety, however, the nature of some injuries was observed to be more specific to bicycling. The Ohlin et al. (2017) study recommended, among other things, including bicyclists' safety in the Euro NCAP evaluation. Provisions for AEB for cyclists and large truck blind spot information system (BSIS) detection of bicycles are now part of Euro NCAP *(Euro NCAP | AEB Cyclist, 2020*; UN Regulation No. 151, 2020).

A report by NHTSA's Vehicle Research and Test Center applied Euro NCAP test procedures to vehicles available to consumers in the United States (Suntay et al., 2019). Vehicles that were sold in the United States and have no European variant tested much worse on pedestrian safety tests (specifically lower and upper legform and headform impacts) than vehicles that are also sold on the European market. Of the vehicles that are sold in both the United States and Europe, the variants available in the United States were comparable or tested poorly compared to the same vehicle model sold in Europe.

Vehicle Design Changes

Two important measures for reducing pedestrian injuries should a crash occur are to reduce the impact energy of the crash (by reducing speed or mass) and increasing the duration of the impact (by decreasing stiffness and increasing the crush depth). Since injuries occur as a sequence of impacts, however, the shape of the vehicle is also a factor (J. Hu & Klinich, 2012; G. Li et al., 2018).

Safer Passenger Vehicles

The bumper is often the first point of contact with a pedestrian during a crash event. Bumpers can be of varying heights, depths, and stiffness. Adding energy-absorbing material to the bumper can help protect pedestrians. Similarly, researchers have suggested that a bumper that is vertically larger could prevent certain injuries (Desapriya et al., 2010; J. Hu & Klinich, 2012). Researchers and manufacturers have explored how different hood designs may improve pedestrian safety by better distributing and absorbing the energy of the crash impact. While manufacturers were found to have made positive changes in front bumper shape, passenger car models manufactured for the European market after 2005 (compared to those produced before 2000) were found to have higher hood leading edges, which can lead to more serious femur and/or pelvis injuries when striking a pedestrian (G. Li et al., 2018). Additionally, reducing the stiffness of a windshield is difficult and could lead to safety concerns for the occupants, but some suggest that windshield airbags could protect pedestrians who might strike the windshield (J. Hu & Klinich, 2012; Jakobsson et al., 2013).

Hybrid and Electric Vehicles and External Auditory Warnings

The lack of sound from hybrid and electric vehicles (HEVs) has raised safety concerns for pedestrians and bicyclists. In 2016 NHTSA issued a final rule regarding the sounds made by HEVs: Federal Motor Vehicle Safety Standard No. 141, *Minimum Requirements for Hybrid and Electric Vehicles.* The rule was later amended in 2018 and took effect late 2019 with newer model year HEVs including sound at low speed on a staggered basis. The rule states that a vehicle must make a noise while stationary, while backing up, and while traveling at speeds up to 30 km/h and specifies the parameters of the sound itself (Federal Motor Vehicle Safety Standards; Minimum Sound Requirements for Hybrid and Electric Vehicles, 2016). However, many HEVs that predate this rule remain in the fleet.

This problem of quiet vehicles is more prevalent at lower speeds, and motorists traveling at low speeds are more likely be in locations where people are walking or bicycling, such as a parking lot or a more densely populated area. In 2017 NHTSA reported that the odds of a pedestrian and HEV crash were 20% higher than odds of a crash between a pedestrian and a vehicle with an internal combustion engine (J. Wu, 2017). That number increases to 50% if crashes only at low speeds are considered. For bicyclists, the odds of being in a crash with an HEV were 50% higher than with an internal combustion vehicle.

Older adults, children, and those who are visually impaired may have more difficulties detecting the presence of a vehicle without sound (Fleury et al., 2016; Stelling-Kończak et al., 2016). Ability to detect the warning sounds is also dependent on the environmental setting and levels of background noise. Dense urban areas pose more of a challenge to listeners than more rural settings. In those areas, the sound emitted by the HEV needs to be discriminable amongst many other sounds (Poveda-Martínez et al., 2017).

Although now more than a decade old, but still applicable and valid, the report *Quieter Cars and the Safety of Blind Pedestrians* reviews a selection of countermeasures that might to some degree alleviate this problem but acknowledges that most have major limitations (Garay-Vega et al., 2010). Accessible pedestrian signals are one approach, but they are only helpful at signalized crossings. Automated pedestrian detection, which would alert a motorist to the presence of a pedestrian at a crosswalk, could be implemented at uncontrolled crosswalks but this technology is still being refined (Garay-Vega et al., 2010; Lin et al., 2019). Lowering ambient noise overall could improve detectability of HEVs for visually impaired persons, but this solution is not feasible in the short term (Garay-Vega et al., 2010). Orientation and mobility specialists could travel train those blind pedestrians who use guide dogs, but this measure would only apply to a subset of the visually impaired population.

Emerging Safety Concerns

Transportation Network Companies

Another important transformation in motorized traffic is the emergence of transportation network companies (TNCs). These companies hire drivers as contractors who drive their own personal vehicles for ridesharing. Although TNCs do not operate in every city and are subject to varying regulations across States, TNCs undoubtedly affect transportation because they use public infrastructure and contribute to congestion and exposure. To better account for these public impacts and manage TNCs in relation to transit needs, many jurisdictions are seeking new legislation and, in some cases, partnering with TNCs to provide first- and last-mile access for those who solely rely on public transit (San Francisco County Transportation Authority, 2017).

Despite potential benefits, however, TNCs affect safety for pedestrians and bicyclists through a variety of mechanisms. First, TNCs, as users of public infrastructure, generate substantial traffic in many operational jurisdictions, and this increased traffic may increase crash exposure to other modes. Erhardt et al. (2019) conducted a before-after analysis of traffic volumes in San Francisco, using observed travel time data converted to volume delay functions and data scraped from two TNC interfaces to measure the change in traffic congestion in the city pre- and post-widespread TNC deployment (i.e., 2010 versus 2016). Researchers found that weekday vehicle hours of delay increased by 62% compared to the projected 22% expected had TNCs not deployed in this time. Although these models may not represent traffic congestion in all cities where TNCs are deployed, they do indicate that TNCs likely produce non-negligible changes in traffic volume in urban areas. Other researchers have highlighted local reports from cities that indicate TNCs add more vehicle miles of travel to urban roadways (Barrios et al., 2018). While some TNC trips may be trips that would have previously been made by foot, bicycle, or transit, further research is needed to understand what this percentage is and how it affects pedestrian and bicyclist crash exposure.

Second, TNCs influence curbside activities that may expose pedestrians and bicyclists to more vehicular conflicts. Functionally, TNCs can attract more pedestrians to curbsides for ride hailing and ride sharing, and the pedestrian activity at curbsides may increase pedestrian exposure to conflicts. Curbside activities may also affect exposure to dooring crashes for bicyclists. However, at the time of writing, these conclusions are not yet well-supported in the literature, and more research is warranted to explain the possible connections between TNCs and risk. Some initial studies do indicate that TNCs decrease safety for pedestrians. For example, Barrios et al. (2018) analyzed FARS data around TNC introductions in major cities, accounting for temporal trends using differences-in-differences specification with fixed effects, to identify a 2% to 4% increase in motor vehicle fatalities. The analysis also found a similar increase in the number of fatal crashes involving pedestrians, suggesting that TNCs may impose some risk (likely through exposure or conflicts) on pedestrians.

However, more research is needed to better quantify the impacts of TNCs on pedestrians and bicyclists. Barrios et al. (2018) do not draw conclusions for bicyclists aside from noting that city travel survey data indicate some pedestrians and bicyclists may be choosing TNCs for some trips rather than walking or bicycling. If this is true, then the frequency of pedestrian and bicyclist fatalities may appear to decline in some jurisdictions if fewer travelers are walking and bicycling, although crash rates may increase. This effect could technically be considered a safety benefit, although the true relationship between TNCs and pedestrian and bicyclist safety and health requires further research.

Automation of the Vehicle Fleet

Vehicle automation—whether incremental through advanced driver-assistance systems (ADAS), connectivity, and/or Automated Driving Systems (ADS)—has the potential to profoundly affect pedestrian and bicyclist safety. For the most up-to-date research, readers are encouraged to go to the NHTSA website.

Emergent Transportation Modes

Although measures to improve safety for vulnerable road users tend to focus on pedestrians, bicyclists, and motorcyclists, new modes and adaptations of existing modes are changing the nature of road safety for people traveling outside the confines of a vehicle. Electric assist bicycles (e-bikes) have dominated bicycling in many countries, and bikeshare systems can facilitate the first and last mile of trips where another mode may have been selected previously. Electric sitting or standing scooters (e-scooters), too, are transforming first- and last-mile trips, but their impact on pedestrian and bicyclist safety is not yet well understood. This section briefly highlights research on e-scooters, e-bikes, bike sharing, and other modes. The Pedestrian and Bicycle Information Center resource, *The Basics of Micromobility and Related Motorized Devices for Personal Transport* (Sandt, 2019), includes a comparison of different devices and associated images.

E-Scooters and Pedestrian and Bicyclist Safety

Due to their rapid and recent deployment, little is yet known about the effects of e-scooters on pedestrian and bicyclist safety. E-scooters are a complicated technology in that most e-scooter riders are also pedestrians at some point along their trip and e-scooter riders may use pedestrian infrastructure, bicycle infrastructure, and roadway infrastructure depending on their level of comfort and State or local regulations (Ognissanto et al., 2018). Therefore, e-scooter riders may be subject to the same risks as pedestrians and bicyclists when interacting with the built environment, but they may also pose new conflicts for people walking or riding bicycles. Many research projects are underway to quantify e-scooter safety concerns and transportation benefits so consensus has not yet been reached on their usage and safety in the broader context of the transportation system.

Initial injury estimates in Austin, Texas, identified 160 *confirmed* e-scooter injuries and 32 *probable* injuries based on hospital data and patient interviews between September 5, 2018, and November 30, 2018. The majority of those injured were males and were between 18 to 29 years old. Of the 192 injured riders in the dataset, 48% had head injuries and 70% sustained upper limb injuries. Austin Public Health identified injury locations for 77% of the injured riders and found that 55% of the 125 interviewed riders were injured in the street. Comparatively, 33% were injured while operating on the sidewalk. Taken together, these findings seem to indicate that in some cities, e-scooter riders expose themselves to risk of injury while operating in the street, although these risks may be due to falls and other mechanisms beyond motor vehicle collisions (Epidemiology and Disease Surveillance Unit, 2019). More research will be needed to compare these injury profiles to those in other cities to better quantify the risks to and posed by this new mode.

Bike Sharing

Bike sharing is widely deployed in many urban areas and this technology enables new riders who typically do not bicycle and current bicyclists who can't or don't want to bring their personal bicycle for certain trips, to travel quickly and easily. While the research generally indicates that bike sharing provides both health (Otero et al., 2018) and safety (Fishman & Schepers, 2018; Martin et al., 2016) benefits, there are safety concerns, especially for novice bicycle riders. As a benefit, access to bike share may reduce vehicular trips, thereby eliminating some motorized traffic from the roadway that could conflict with other modes. In fact, some research indicates that bikeshare users are likely to take even longer routes if risk is not high (W. Lu et al., 2018). However, these longer trips and increased bicycle volumes on the roadway may work to increase the net exposure to crash risk for bicyclists on the network, even if crash rates decline. This could be concerning given that bike sharing in many regions is associated with lower helmet usage and less average rider experience (Martin et al., 2016). Some research indicates that bike share risk is related to pricing, location, and supply. Users are less likely to benefit from the reduced conflict effect if they must use high-speed routes or if bike share docking stations are not provided in easily accessible locations (Conrow, Murray, et al., 2018). Security, too, may be a concern for some users, especially if the bike share station locations expose them to risks as pedestrians (Y. Li et al., 2018). Therefore, more research is needed to optimize the safety benefits of bike share technologies.

The safety effects of e-bikes, too, are complicated. An array of international studies conveys conflicting results regarding e-bicyclist safety and injury. Some studies found associations between e-bike use and orthopedic injuries (Tenenbaum et al., 2017), likely due to the higher speeds and power that can be accommodated by e-bikes (Haustein & Møller, 2016). Other studies found no difference in injury level between e-bicyclists and bicyclists involved in solo crashes and crashes involving motorists (J. P. Schepers et al., 2014; Weber et al., 2014). Much of the research on e-bike safety is conducted in countries with different mode share percentages, including e-bikes versus traditional bicycles, and infrastructure than the United States, and most domestic research focuses on operations and user characteristics, so risks may be different for e-bicyclists here. If that is the case, e-bike safety may require unique safety countermeasures and infrastructure to alleviate those risks (Dozza et al., 2016). Whatever the case, more research into domestic applications is needed.

Other Modalities and Safety

An overarching safety concern for nonmotorized traffic is the rapid emergence of new and unique modes or services. In this section, we discussed e-scooters, e-bikes, and bike share, but these devices and services offer a range of options for electric-assist, and differences in performance and safety features vary as weight and speed change. For example, some research indicates that powered two-wheelers may impose risks on their riders due to high speeds and low helmet use (Bouaoun et al., 2015); these devices may also conflict with bicyclists on bicycle-specific infrastructure (Y. Guo et al., 2018), but the magnitude of any effects on safety is not yet known. Complicating research conclusions is the fact that many of these modes can be owned or shared, and access levels may vary by region. A full survey of all the types of two-wheeled mobility devices available is beyond the scope of this report (e.g., e-bikes, e-scooters, e-skateboards, e-skates, and self-balancing devices like hoverboards).

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Part 3. Effectiveness of Safety Interventions for Pedestrians and Bicyclists

While Part 2 of the report was focusing on describing the scope of the safety problem for people walking and bicycling, this section introduces what is known (and unknown) about the effectiveness of interventions (sometimes referred to as countermeasures or treatments) that address those safety problems. Part 3 starts with population-level interventions including laws and policies and programs designed to influence human behavior. This is also the main section of the report that covers bicycle helmet use and effectiveness, along with helmet laws. Next, there is a section about treatments that can be applied at individual sites, along or in a corridor, or systemically throughout a network (i.e., roadway design and operational improvements). Lastly, there is a section about technology-based interventions for vehicles or the roadway that may be implemented to improve safety for people traveling outside of vehicles.

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Laws and Policies

Laws Targeted at Motorist Behaviors

Speeding motorists, or those who drive too fast for conditions, increase their risk of a collision with a person walking or bicycling and numerous studies have shown that as motor vehicle impact speed increases so does the risk of severe injury or death (see Table 7 and Figure 7). Other dangerous behaviors that exacerbate the risk of a crash include impairment from drugs and alcohol and inattention or distraction by motorists. Speeding, impairment, and distraction are behaviors that are typically targeted by deterrence—enacting laws that prohibit the behavior (ideally practical, sound, broadly accepted laws), publicizing and enforcing those laws, and punishing the offenders (Richard et al., 2018).

Speed limits are in effect on all road segments in all States and, as with any law, are only effective when they are enforced and obeyed. Other laws related to speed have to do with type of enforcement, i.e., whether States allow the use of automated speed enforcement. For distracted driving, there is little research about the effectiveness of laws, enforcement, and sanctions, especially since the proliferation of smartphones. Graduated driver licensing (GDL) requirements might be the most significant legal countermeasure related to motorist distraction because novice motorists are at a higher risk for a crash when engaged in distracting behaviors compared to adults (Richard et al., 2018). Restrictions on nighttime driving and passengers are the elements of laws most closely related to preventing distracted or drowsy driving. For impaired driving, there is less research about the effectiveness of laws compared to the effectiveness of other deterrence strategies like enforcement and prosecution.

Speed Limit Reductions

While research demonstrates that travel speeds are influenced by infrastructure elements, speed limits are also important determinants of risky operating speeds. In a panel analysis of pedestrian fatality rates and contributing factors in different OECD countries (Organisation for Economic Cooperation and Development), of which the United States is a member, Cho (2018) identified speed as a major concern for pedestrian safety and remarked that "reducing urban speed limits should be the number one policy priority in such nations as have recorded higher pedestrian fatality rates" (p. 3167). This international recommendation is supported by a study of pedestrian crashes along corridors in Utah where researchers found that lower speed limits (30 to 40 mph compared to 45 to 55 mph) are associated with decreased pedestrian crash frequency (Chimba & Ajieh, 2017). However, it should be noted that actual travel speeds often exceed posted or statutory speed limits and posted speed limits often exceed safe travel speeds. A 2018 meta-analysis of speed limit setting discusses this point further and notes that the optimal speeds for safe and efficient travel tend to be lower than posted speed limits; in fact, Elvik (2018) argues that safety and other system benefits can be more easily achieved in urban areas with low speed limits closer to 30 km/h (18.6 mph). Research commonly supports this low speed limit of 20 mph for reducing risk of crash severity to pedestrians and bicyclists (H. Li & Graham, 2016; Prato et al., 2018). Therefore, speed limits should be considered alongside design elements as tools for reducing risks to pedestrians and bicyclists.

Several studies have shown that higher vehicle speeds produce more frequent and more serious pedestrian crashes and deaths. Much of the research about changes to speed limits has studied the effect of raising the speed limit on already higher speed roads like freeways. These studies found modest increases in speed and an increase in traffic fatalities (Richard et al., 2018). Only a few studies have examined the safety effects of speed limit changes on lower-speed roads. No U.S.-based studies that specifically examine the relationship between speed limit reductions and bicycle or pedestrian crashes were identified through the literature search, but it is broadly accepted that slower vehicle speeds create a safer environment for walking and bicycling as reflected in Figure 7 depicting risk of severe injury and death by vehicle impact speed (see Tefft, 2011). A study in Canada, where pedestrian fatalities make up about 15% of all traffic fatalities, found a promising reduction in pedestrian-motorist collisions on streets where the speed limit was reduced from 40 to 30 km/h (24.8 to 18.6 mph) (Fridman et al., 2020). However, the decline in the crash rate on study streets (28% decrease in pedestrian-motorist crash incidence rate) was not statistically greater than the reduction observed on comparison streets.

When Boston, Massachusetts, reduced its default speed limit from 30 to 25 mph, researchers conducted a before-after study using Providence, Rhode Island, as a control site (Hu & Cicchino, 2019). The study found statistically significant reductions in the odds of motorists exceeding 25 mph (2.9% lower), 30 mph (8.5% lower), and 35 mph (29.3%). The difference in mean vehicle speeds was not statistically significant (researchers noted that there was an increase in speeds at the low end and a decrease at the high end). This research reinforces the need to look at multiple measures of speed, not just a simple measure of over/under the speed limit, when evaluating speed limit reductions or other efforts to reduce vehicle speeds. Other measures may include distribution of speeds, excessive speeding, or the speeds at which 85% or 50% of all motorists are traveling during free-flow conditions. For example, another study that examined the entire distribution of speed also found that speed limit reductions can reduce speed, but the effect may not be the same on *excessive* speeding (80 km/h was considered excessive speeding in Montreal, where 50km/h sites had their speed limit reduced to 40 km/h) (Heydari et al., 2014).

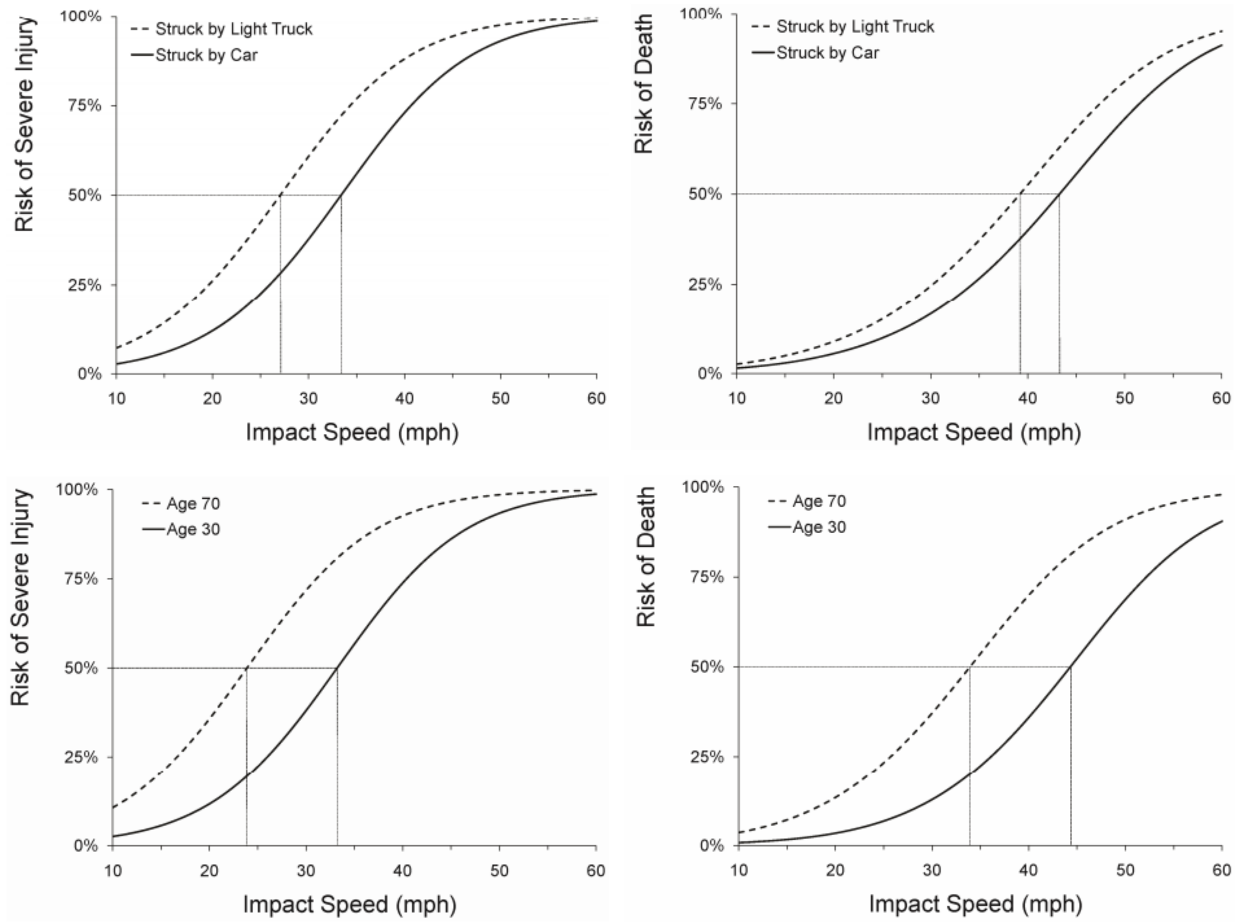

Figure 7. Risk of severe injury or death, by age or vehicle type
Source: Tefft, 2011.

Bicycle Helmets and Helmet Laws

Helmet Effectiveness

Several meta-analyses conducted over the past two decades have concluded that bicycle helmets are effective at reducing head injuries among bicyclists involved in a fall *or* a crash with a motor vehicle (Attewell et al., 2001; Elvik, 2013; Høye, 2018; Olivier & Creighton, 2017; D. C. Thompson et al., 2000). The size of the effects varies—the earliest analyses showed the largest reductions in head injuries, while newer studies have arrived at more conservative estimates. The most recent meta-analysis found that the use of bicycle helmets reduced head injuries by 48%, serious head injury by 60%, traumatic brain injury by 53%, face injury by 23%, and the total number of killed or seriously injured bicyclists by 34% (Høye, 2018). It is likely that helmets have a larger effect in single bicycle crashes than in bicycle crashes with motor vehicles because of the forces involved (Høye, 2018). Neck injury has not been shown to be associated with helmet use (Høye, 2018; Olivier & Creighton, 2017).

To be sold in the United States, bicycle helmets are subjected to pass/fail tests from the Consumer Product Safety Commission (CPSC). The CPSC does not differentiate performance among helmets that meet the CPSC standard. A 2018 research study replicated the impact scenarios specified by the CPSC and tested additional “real-world” scenarios (Bland et al., 2018). Researchers concluded that differences between the 10 helmets tested were more pronounced at the temporal location rather than the frontal location and that there may be important differences between the style of helmet.

Helmet Use

In a national survey of attitudes and self-reported behaviors, 46% of adults who had ridden a bicycle in the past year reported never wearing a helmet (P. Schroeder & Wilbur, 2013). Frequency of bicycling and gender do not appear to be correlated with self-reported helmet use, but higher income (>$75,000 in 2012) may be an important predictor of wearing a helmet while riding (Porter et al., 2016). Helmet use among high school students may be even lower than for adults—81% of bicycle-riding students self-reported rarely or never wearing a helmet (Kann et al., 2016). Although, there has been a statistically significant decrease since the early 1990s in the prevalence of high school students rarely or never wearing a helmet, there are regional differences for helmet non-use. Across States and large urban school districts, non-use can range from 53% to 95.6%.

Analyses of injury surveillance data have shown that among children who were injured while riding a bicycle, helmet use decreases with age and that children who are minorities or from lower income households (using Medicaid as surrogate measure) may be less likely to wear a helmet (Gulack et al., 2015; McAdams et al., 2018; Sullins et al., 2014). In analyses of two national-level data sets, helmet use was between 23% and 27% for children who presented at hospitals with bicycle-related injuries (Gulack et al., 2015; McAdams et al., 2018), but again there may be regional difference; for example an analyses of Los Angeles-area hospital data revealed 11% helmet use (Sullins et al., 2014).

Helmet Laws

The effectiveness of laws requiring the use of bicycle helmets may be measured by changes in helmet use, head injury, or mortality. As of May 2022, there were 21 States and the District of Columbia that have helmet laws for young bicyclists and no States have laws that apply to bicycle riders of all ages (IIHS, 2022a). A systematic review of studies in the United States, Canada and the Pacific-region found that legislation increases the use of helmets, but the effect was smaller in areas with a higher baseline proportion of helmet use (Karkhaneh et al., 2006). In a study where parents were asked to self-report helmet use for their children 5 to 14 years old, the existence of a statewide law was a strong predictor of helmet use (Dellinger & Kresnow, 2010).

Since it is not possible to randomly assign people to live in States or regions with helmet laws, some studies have employed a contemporary control method to examine the effect of helmet laws on head injuries in the target population. This method uses adults as the control group in areas where helmet laws were targeted toward children or other injuries as the control for head injuries. Two of three contemporary control studies included in a systemic review found that helmet legislation had a significant protective effect on bicycle-related head injuries, while the third reported non-significant results (Macpherson & Spinks, 2008).

Seattle was the largest municipality in the United States with an all-ages helmet law until it was repealed in early 2022. (The repeal covered most of King County as well as Seattle.) By examining trauma data for the 2 years preceding the law and the 7 years following the law, researchers concluded that helmet *use* among injured bicyclists increased and while there was no significant decrease in head injuries, there was a decrease in the *severity* of head injuries and in bicycle-related fatalities (when compared to the surrounding King County, which had an all ages helmet law for about 10 years prior to the Seattle law) (Kett et al., 2016). They noted that while helmet use and ridership were not available for the whole city or county, there was an increase in the incidence of all bicycle-related trauma, which may indicate an increase in ridership.

An often-stated concern with mandatory helmet laws is that they suppress bicycle ridership. Many of the studies touching on this issue are conducted outside the United States, primarily in Canada and Australia. Early studies of the helmet law in Australia suggested that there was decreased ridership among children, but not adolescents or adults (Cameron et al., 1994; Robinson, 1996). Two more recent studies, one international and one U.S.-based, examined the effectiveness of helmet laws in increasing helmet use among adolescents and reported limited or no evidence of reduced bicycle riding (Kraemer, 2016; Molina-García & Queralt, 2016). A study of three Canadian provinces using national-level cross-sectional survey data found that helmet legislation was not associated with changes in ridership (J. Dennis et al., 2010). No studies have been published showing that helmet promotion or mandatory helmet laws have reduced bicycling in a U.S. community (Kett et al., 2016). The relationship between bicycle helmet laws and bicycle ridership is a challenging question to study due to inconsistent exposure data for bicycling, but it is not an insignificant question because the possibility of suppressing ridership has implications related to the health benefit that comes from the physical activity of bicycling and the complex, non-linear relationship between crashes and volume (i.e., safety in numbers). Mandatory laws also introduce the possibility of inequitable law enforcement. While the literature search did not uncover academic studies about traffic stops and citations related to *bicycling* infractions, journalistic investigations in cities including New York; Chicago, Illinois; and Tampa, Florida, have documented that Black and/or Latino bicyclists receive a disproportionate share of bicycling-related tickets (in terms of ridership or population). The question of whether mandatory helmet laws hinder the uptake of public bike sharing systems is another interesting question that is outside the scope of this report.

Bicycle Passing and Stop as Yield Laws

While the pace of States and local agencies adopting mandatory helmet laws has dramatically slowed since the late 1990s and early 2000s, the trend in States adopting laws that define the "safe distance" for motorists to pass bicyclists has been strong since the mid-2000s (McLeod, 2016). Considering that "motorist overtaking" is the most common crash type among *fatal* bicycle crashes, bicycle passing laws are of interest because they focus on a motorist behavior that is very dangerous for bicyclists; however, evidence about the effectiveness of these laws is limited because most study designs have not employed before/after or comparison methods. As with most laws, their effectiveness may be linked to actual or perceived enforcement. Other shortcomings may be related to insufficient required passing distance and loopholes. Variations in State bicycle passing laws include whether motorists can cross the double yellow line to pass, whether distance is specified, differences in the distance specified, and in one case, South Dakota requires more distance for roads with higher speed limits (McLeod, 2016). The National Conference of State Legislatures (2022) maintains a list of statutes, by State (www.ncsl.org/transportation/safely-passing-bicyclists-chart.

Three studies based in the United States have used instrumented bicycles to examine motorist passing distances in communities with bicycle passing laws (Blomberg et al., 2022; Love et al., 2012; Van Houten et al., 2018). These studies yielded baseline data that could be used for future evaluations of the effectiveness of bicycle passing laws, but their most useful findings are about the potential relationships between passing distance, user/vehicle characteristics, and roadway infrastructure. In the Michigan study, researchers found that motorists' overtaking distances were significantly greater in the three study communities with 5-foot passing ordinances than in two comparison communities (one without a law and one with a 3-foot law) (Van Houten et al., 2018). In another study conducted by Blomberg et al. (2022), after implementing an HVE (high-visibility enforcement) program, passing distance increased and violations decreased. The only U.S.-based study to examine the relationship between State-level safe passing laws and bicyclist fatalities (using FARS data from 1990 to 2014) did not find any significant effect of these laws after controlling for differences in weather, demographics, bicycling commuter rates, State-level traffic, and time variation (Nehiba, 2018).

A study conducted in Queensland, Australia, examined bicycle passing laws using a naturalistic study design (as opposed to using research staff or volunteers familiar with the study) (Debnath et al., 2018). This study found that 15.7% of the 1,846 recorded passing events were non-compliant and characteristics of the bicyclist (e.g., age, gender, helmet status, type of clothing, type of bicycle, and individual or group riding) were not statistically significant indicators of passing distance. The Queensland law requires minimum lateral passing distance of three feet in speed zones of 37 mph or less and five feet when the limit is greater than 37 mph. Previous work by the same researchers established that motorist and bicyclist knowledge of the Queensland passing law was high (94%-98%) (Schramm et al., 2016). Each study about bicycle passing laws draws some conclusions about the relationship between roadway design, bicycle facilities, and vehicle passing distance, but there are no broadly applicable findings.

Several States have implemented the "Idaho Stop" rule, which allows people on bicycles to treat stop signs as yield signs. The intention of this law is to adapt a traffic control device devised for motor vehicles to the needs of bicyclists. The person on a bicycle must slow and yield to oncoming traffic but is not required to come to a full stop. Since people on bicycles are traveling at slower speeds, and have a better view of the road environment, this maneuver is somewhat intuitive. After Idaho adopted the law, bicyclist injuries from traffic crashes declined by 14.5% the following year (Meggs, 2010). In 2017 Delaware adopted a similar, limited stop-as-yield law. Traffic crashes involving bicyclists at stop sign intersections decreased by 23% in the 30 months after the law's passage, compared to the previous 30 months. As of July 2022, eight States (Arkansas, Delaware, Idaho, North Dakota, Oklahoma, Oregon, Utah, and Washington) have similar laws. These laws do not negate a bicyclist's responsibility to yield to other traffic before crossing an intersection or to follow all work zone traffic rules. Rigorous research on the safety implications of Idaho Stop has not been conducted, but analysis of crashes in Idaho and Delaware showed no adverse safety implications (Bike Delaware, n.d.; Meggs, 2010).

Jackson et al. (2021) explored the impact of six bicycle safety laws on improving bicyclist safety using police-reported crash data from 34 States. The six laws examined were safe passing, mandatory helmet use, bicycling under the influence, where-to-ride, sidewalk riding, and the Idaho stop. States with safe passing and where-to-ride laws experienced 23% and 13% fewer cyclist crashes, respectively, compared to States without a law; however, looking year over year post-law enactment indicated some increases in injuries. Helmet use was 20% higher and use increased 7% yearly in States with mandatory helmet use laws (the State laws only covered minors) than States without a law. Likewise, States with bicycling-under-the-influence laws experienced 38% fewer crashes involving intoxicated bicyclists than States without a law. Permissive sidewalk-riding was associated with 94% fewer intersection-related roadway crashes, but 656% more intersection-related sidewalk crashes.

Laws and policies relevant to bicyclist and pedestrian safety for which no evaluations were identified include disallowing motorist right-turn-on-red, crosswalk laws mandating yield versus stop, laws related to the classification of bicycles, and Complete Streets or Vision Zero policies.

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Programs for Behavior Change

This section addresses the effectiveness of comprehensive programs that employ several interventions (e.g., education and enforcement) to address an issue that affects the safety of people walking and/or bicycling, programs focused on changing the behavior of users through education (typically aimed at children), and broader road safety campaigns that include a marketing component.

Measures of effectiveness

The ideal measure of effectiveness for any intervention intended to improve road user safety is a change in the number, type, or severity of crashes or injuries. However, there are instances where crash data are not available or reliable and surrogate measures, such as behaviors (e.g., reduced vehicle speed, proper road crossing, yielding), are used to measure the effectiveness of an intervention. Sometimes changes in knowledge are used to assess whether a design, law, or program was effective, but measures of pre-post knowledge tend to capture short-term memory capacity more than they capture whether participants have learned a life skill such as safe driving or bicycle safety (Assailly, 2017). It is important for practitioners to keep these distinctions in mind when interpreting an evaluation or designing their own evaluation.

Comprehensive Programs

It is challenging to evaluate the effectiveness of comprehensive programs because there are many variables and nuances in their implementation. The term “comprehensive” is usually invoked when several intervention types are employed to address at least one road safety problem. To be considered a comprehensive program, interventions should come from more than one of the traditional “Es”—engineering, enforcement, and education—to integrate environmental improvements with behavior-change programs while building broader social or policy supports for improved safety (Brookshire et al., 2016). Many current comprehensive programs emphasize the 5 Es that also include equity and EMS. NHTSA’s *Countermeasures That Work* (Richard et al., 2018) is focused on individual behavioral countermeasures, but it does include a few comprehensive approaches that include engineering countermeasures like Safe Routes to School programs and the concept of “pedestrian safety zones.”

The most robust evaluation of a comprehensive program using pedestrian crashes as the measure of effectiveness is the Miami-Dade study that targeted four zones comprising less than 1% of the land area, but accounting for 20% of pedestrian crashes (Zegeer, Blomberg, et al., 2008). This comprehensive approach is typically described as an example of the “pedestrian safety zone” countermeasure. Sixteen education, enforcement, and engineering pedestrian safety countermeasures were implemented in Miami-Dade County especially in the four zones, and several control groups were used to help analyze the impact of the overall pedestrian safety program. The peak of the program’s effect during the 3-year “after” period was estimated to be an 8.5% to 13.3% reduction in pedestrian crash rates (depending on which of the three control groups was used for the analysis). Researchers also examined changes in the number of crashes for different target population groups and crash types in each zone. Generally, the greatest crash reductions were for children and adults, while there was no effect for crashes involving older adults. More specifically, a variety of educational countermeasures (in English and Spanish) were not successful at reducing the high prevalence of crashes involving older, Spanish-speaking pedestrians. Researchers hypothesized that more intensive education (along with enforcement and engineering) treatments may be needed for a clear reduction in crashes for older pedestrians.

The Pedestrian Safety Initiative in Montgomery County, Maryland, also used all three Es when focusing comprehensive efforts in 10 areas with a high incidence of pedestrian crashes (Dunckel et al., 2014). The descriptive statistics for this program sound promising, but it's hard for researchers to understand the effectiveness without the use of control sites or statistical analysis. For example, study authors note that pedestrian collisions in the targeted areas decreased by 43%, but also report that non-high incidence areas that received traffic calming treatments *without* targeted education and enforcement saw a 50% decrease in pedestrian crashes.

Another example of a comprehensive pedestrian safety program involving the traditional Es, plus a social norming approach, employed a different measure of effectiveness—motorist behavior—specifically, compliance with Minnesota crosswalk laws in Saint Paul (N. L. Morris et al., 2019). The phased approach implemented over 18 months included distributing education materials, conducing four waves of high-visibility enforcement (HVE), social norming feedback signs that displayed site-specific and citywide yielding averages, different installations of the in-street yield sign (MUTCD R1-6), and a before-after survey. The 16 study sites were marked crosswalks at unsignalized locations on 30 mph roads; eight sites were treatment sites that received HVE and a low-cost engineering treatment. Researchers decided that changing motorist behavior hinges on the ability to convince people that a problem exists (i.e., pedestrian crashes) and inviting them to be a part of the solution using coordinated education materials and the feedback signs, both of which were relevant citywide, not just at the study sites. Ultimately, weekly average yielding at treatment sites grew from as low as 26% in the baseline period to 78% during the final phase, while generalization sites grew from 31% to 61%. Researchers also noted a decrease in multiple threat passes at both site types, which was a secondary measure of effectiveness for the program.

In Gainesville, Florida, researchers also demonstrated that a concerted focus on pedestrian right-of-way enforcement with accompanying publicity and social norming can improve motorist yielding and that the effect can be sustained over years. Initial implementation of the high-visibility enforcement effort included flyers given to stopped motorists, information sent home with school children, feedback signs displaying yielding rates, and earned and paid media (Van Houten et al., 2013). With six treatment sites and six control sites, yielding rates rose throughout the 1-year study period. Four years later, researchers collected data from staged and natural pedestrian crossings at the same study sites. Yielding behavior increased at enforcement sites and control sites suggesting "a fundamental change in motorist behavior likely resulting from a tipping-point effect," which is often defined as a small change that tips the balance of a system and results in widespread change (Van Houten et al., 2017). It is important to note wide variation in yielding rates across the uncontrolled marked crosswalk sites near pedestrian trip generators (bus stops, parks, etc.), but average observed yielding at enforcement and generalization sites was nearly identical (76 to 77%) 4 years after the intervention. Since the end of the intervention period 4 years prior, yielding at enforcement sites increased by 8% and increased at generalization sites by 20%.

These examples from Miami-Dade County, Montgomery County, and Saint Paul, required significant investment, either in terms of money and/or staff time and commitment. The Miami-Dade researchers found that the zones with the most extensive countermeasure implementation also saw a substantial decrease in pedestrian crashes. However, in the Saint Paul and Gainesville cases, researchers were able to point to a diffusion effect from the HVE that was focused on fewer than 10 sites.

North Carolina's Watch for Me NC program (WFMNC) is a long-running education and enforcement program that targets motorist, bicyclist, and pedestrian behavior and has demonstrated improvements in pedestrian safety. It started in 2012 with four pilot communities and over the course of 6 years (2012 to 2017) came to include 41 communities from 29 counties. Activities targeted at improving bicycle and pedestrian safety have included paid media, earned media, law enforcement training, enforcement operations, and community action planning, but their implementation has varied across time and across communities. Early evaluations of the program focused on motorist yielding behavior. A pre-post study of 16 sites in WFMNC communities found that treatment sites that received enhanced law enforcement activities and low-cost engineering improvements saw statistically significant improvements in yielding (between four and seven percentage points) while sites that did not receive enhancements did not experience changes in motorist yielding from before to after (Sandt et al., 2016). A later study of the program employed a crash-based analysis that included all 29 counties with participating communities. The study found a statistically significant 12.8% reduction in pedestrian crashes along with a 21.7% reduction in nighttime crashes and a 9.5% reduction in the "failed to yield" crash type (Saleem et al., 2018).

The last type of comprehensive program focused on pedestrian and/or bicycle safety are Safe Routes to School (SRTS) programs, which focus on making it safer for youth to walk and bike to school and encourage more walking and biking where safety is not a barrier. Research has demonstrated that SRTS programs can lead to increases in walking and bicycling to school (McDonald et al., 2014; Stewart et al., 2014). The most rigorous study looked at treatment and control schools in three States and the District of Columbia and found that engineering improvements are associated with an 18% relative increase in walking and bicycling and the effects of education and encouragement programs are cumulative—each additional year of program participation was associated with an absolute increase of 1% in the proportion of students walking and bicycling to school (McDonald et al., 2014). Studies about the connection between SRTS and safety have been less common, but two studies focused on the effect of SRTS-funded engineering treatments found improved outcomes for pedestrian safety. In New York City, researchers analyzed 10 years of crash data and found that the annual rate of pedestrian injury decreased 33% for school-age children and 14% for all other ages in Census tracts that received SRTS projects compared to no change in rates for other Census tracts (Dimaggio & Li, 2013). In California, researchers looked at 75 constructed countermeasures at 47 schools and compared changes in crashes in a 250-foot buffer around each treatment to crashes beyond the 250-foot buffer, but in a quarter mile of the school. They found a statistically significant decrease in all pedestrian-vehicle crashes, but the decrease for 5- to 18-year-olds was not statistically significant (Ragland et al., 2014).

Educating Children About Safe Walking and Bicycling

Basics of Child Development and Learning

Understanding the difference in achieving knowledge change versus behavior change is especially important when designing and evaluating traffic safety education programs for children. For example, learning that one must stop their bicycle at a stop sign does not mean that a child will do it (Ellis, 2014). Learning theory and research about safety programs suggest that the most successful programs will incorporate interactive training with opportunities to practice the safe behaviors and positive reinforcement. To move beyond the stage of developing knowledge, children need opportunities to develop problem-solving skills. Program effectiveness may also be improved with parental participation in their child's safety education; however, there is little research about parental involvement (Percer, 2009).

A key difference that distinguishes bicycle and pedestrian safety education from traditional subjects taught to school children in a classroom-like setting is that pedestrian and bicycle education involves the development of a skill, rather than solely the development of knowledge. Skills require a lot of practice because skill acquisition involves three stages: cognitive, associative, and autonomous. For example, programs that only involve videos, workbooks, and presentations are only focused on the cognitive development stage. In the associative stage, individuals practice skills obtained in the cognitive development stage. The third stage, autonomous, means that a skill requires less cognitive effort so that mental resources can be devoted to problem-solving (Percer, 2009). Any education program will have at least one behavior that it intends to modify, at least one activity designed to modify the behaviors, and it should have an evaluation that measures the effect of the activities on the intended behaviors.

For more on this topic, Percer (2009) and Ellis (2014) include accessible summaries of the relevant research related to cognitive development, motor skills development, and learning theory. They are essential reading for practitioners involved with developing and/or implementing traffic safety education programs for children. Percer (2009) concludes by explaining that in an ideal scenario, children 5 to 9 would learn the basics of traffic safety through pedestrian education and then learn about bicycle safety as they become more independent closer to adolescence, with their safety skills building through each stage, eventually including driving.

Child Pedestrian Education

No studies have been able to use crashes or injuries as the measure of effectiveness for education programs (Schwebel, Barton, et al., 2014). Even though some of the SRTS programs mentioned above included educational components, the evaluations were focused on the effectiveness of engineering interventions. Overall, a somewhat limited body of research indicates that repeated exposure to experiential learning in a small group setting has the greatest chance of success for reinforcing positive pedestrian behaviors in children. A systematic review and meta-analysis of behavioral interventions found that education programs focus on at least one of the following behaviors (Schwebel, Barton, et al., 2014):

1. crossing safely at midblock locations,
2. crossing at junctions (intersections),
3. crossing between parked cars,
4. preventing dash-out crossings,
5. judging the speed of oncoming traffic, and
6. selecting safe routes to cross intersections.

Of the 25 studies included in the review, the majority were international, including 14 from the United Kingdom. Interventions targeting crossing between parked cars, preventing dash-out crossings, and selecting safe routes to cross intersections were generally effective. The behavior of crossing safely at midblock locations was resistant to educational interventions, which is somewhat unsurprising considering this is one of the most complex tasks for a person walking. Only one study looked at children's ability to judge the speed of oncoming traffic.

In addition to the behaviors listed above, education programs can also be categorized by the type of intervention: individualized or small-group training, classroom training, computer-based or virtual reality training, board games or peer-group activities, and films or videos. The meta-analysis found that individual or small-group trainings are generally effective, but there were mixed results for the other interventions due the small sample of studies for the remaining types of interventions and individual differences for the studies that assessed each type (Schwebel, Barton, et al., 2014).

To further explore the effect of different interventions, researchers used data from a randomized control trial to examine three strategies designed to train 7- to 8-year-old children in pedestrian safety at midblock crossings on a two-lane road: video/websites, non-immersive virtual reality (VR), and actual street-side training (Schwebel & McClure, 2014). Pre-test and post-test (immediately after completion and six months later) measures were collected via assessment of knowledge, behaviors in virtual reality lab, and behaviors in the field. Children who received training via videos, software, and internet programs gained safety knowledge, but their behavior measured in the lab and in the field did not improve, while children that received street-side training showed improvement in knowledge *and* behavior that was retained over a six-month period. The research team found null results for their hypotheses about the relationship between knowledge and behavior but conclude that additional research is needed and that it is likely that their measures of knowledge and behaviors may have been too disparate to be associated.

The literature also does not provide a clear answer for the question of which age groups are most receptive to educational interventions. This means that effectiveness is likely most strongly influenced by program design. In an evaluation of North Carolina's close adaptation of NHTSA's Child Pedestrian Safety Curriculum, researchers found that the curriculum was especially effective in improving the self-reported pedestrian knowledge and supervised crossing behaviors of students in third through fifth grade (F. D. Thomas et al., 2017). An earlier evaluation of a program in Miami called WalkSafe, which involved similar education materials and program duration, found that improvements in knowledge were more consistent for kindergarten through third grade than fourth and fifth (Hotz et al., 2004, 2009). Behaviors in the Miami example were also reportedly improved in the short term, but not three months later, and the North Carolina example only evaluated the immediate after period. A few studies documented in NHTSA's Countermeasures That Work (Richard et al., 2018) show the importance of repeated exposures to a given pedestrian safety program.

Child Bicycle Education

There is less evidence about the effectiveness of bicycle safety education programs for children, most likely because it is an even more complicated skill to teach compared to pedestrian safety and access to bicycles for training can be a barrier to sustaining a bicycle safety education program. In general, program evaluations demonstrate knowledge by children and, in some cases improved behavior in controlled settings, but there are no clear findings on whether this translates into safe behavior in the real world (Ellis, 2014; Pomares et al., 2018; Richmond et al., 2014).

Riding a bicycle is a motor skill—in addition to the physical safety skills of searching for traffic, identifying gaps, etc., children must master basic handling skills like balancing, pedaling, steering, and braking. The intervention “bicycle education” also encompasses events known as skills clinics, bike rodeos, and bike fairs. These are typically one-time events that are rarely evaluated beyond a simple before/after or exit survey.

A systematic review of observational and experimental studies of bicycle skills training interventions included studies with outcome measures including injury frequency/severity (n=7), behavior (n=13), knowledge (n=16), and attitude (n=2) (Richmond et al., 2014). Researchers concluded that the studies were of modest quality and that none of the demonstrated interventions were highly effective. Studies that used surrogate measures for safety were the higher quality studies. Of the 16 that assessed knowledge, eight demonstrated improvements and eight demonstrated mixed or null results; however, it was unclear whether improved knowledge was a result of bicycle skill and/or safety training. A New Zealand study sought to tease out the differences between training in a controlled environment (i.e., school playground) and training on-road (Mandic et al., 2018). While the study assessed a relatively in-depth program in a large sample of children (n=429), the measures of effectiveness are not directly related to safety—knowledge of road rules, self-reported confidence, and rates of bicycling. Citing the findings from Richmond et al. (2014), the New Zealand researchers emphasize the importance of pairing bicycle skills training with other interventions like built environment changes that can reduce the risk of bicycle-related injuries in children.

Bicycle Helmet Promotion for Children

Education and skills interventions focused on bicycle safety often emphasize proper helmet use (Richmond et al., 2014). A review of studies that evaluated non-legislative approaches to increasing observed helmet use found that the most effective interventions were community-based education programs and those that provide free helmets (Owen et al., 2011). Providing free helmets is likely the most effective intervention for increasing helmet use. Interventions may be more effective if they are targeted at younger children (<11 years old) than older children (11 to 18 years old). Programs based in schools were also effective. There was insufficient evidence about the effectiveness of providing subsidized helmets.

Pedestrian Distraction

Coinciding with the proliferation of smartphones, pedestrian distraction became a research topic of interest beginning around 2012. Researchers have attempted to measure the effect of distraction in crash data, naturalistic behavioral observations, virtual environment simulator studies, and the laboratory, as well as measure the prevalence of perceived distraction in the real-world (Scopatz & Zhou, 2016). However, the magnitude of the problem is still somewhat unknown (especially in relation to other traffic safety problems like motorist distraction or speeding) and few countermeasures have been implemented and evaluated.

Interventions targeted at pedestrian distraction fall into four categories: technology-based (i.e., smartphone applications), built environment, education/communication, and a few laws. Examples of research studies about countermeasures for pedestrian distraction often include a virtual reality component. For example, one study used an immersive simulator to examine the effect of warning alerts via cell phone (Kearney & Plumert, 2017) while another study paired traditional and social marketing with an opportunity for college campus community members to experience a virtual street environment while text-messaging (Schwebel et al., 2017). In the latter example, researchers found mixed results—self-reported intentions improved among people who participated in the simulated pedestrian environment, but researchers did not witness evidence of changed community norms before and after the intervention compared to a another college campus that was used as a control location (Schwebel et al., 2017).

Road Safety Campaigns

Road safety campaign is a very broad term that encompasses communications and outreach activities designed to spread a safety message. The following is a useful definition from Delhomme et al. (2009):

> Purposeful attempts to inform, persuade, and motivate people in view of changing their beliefs and/or behaviour in order to improve road safety as a whole or in a specific, well-defined large audience, typically within a given time period by means of organised communication activities involving specific media channels often combined with interpersonal support and/or other supportive activities such as enforcement, education, legislation, enhancing personal commitment, rewards, etc. (p. 82).

Media channels typically include radio, television, print, and the internet. Campaign messages may be spread through paid media (i.e., advertisements) and/or earned media (i.e., local news story). While each of the programs discussed under the subsection "Comprehensive Programs" includes a campaign element, *there are no evaluations that isolate the effect of campaigns focused on pedestrian and/or bicyclist safety*. However, there are relevant findings from other road safety campaigns that are useful for those in a position to design and evaluate campaigns focused on improving safety for people bicycling and walking.

A meta-analysis of 67 international studies conducted from 1975 to 2007 estimated that the overall effect of road safety campaigns is a 9 to 12% reduction in crashes (Phillips et al., 2011), depending on the type of model. The meta-analysis also included a variety of subgroup analyses looking at differences by study method, method of delivery, content of the message, and change over time in the effectiveness of campaigns. Some caveats with the meta-analysis are that most of the campaigns reviewed were accompanied by enforcement efforts and that researchers could not assess factors that were not reported on frequently or those that had little variation across studies (Richard et al., 2018).

The most salient findings of the meta-analysis are that the largest effects came from campaigns that were combined with police enforcement, campaigns based on face-to-face communication, and those in which the message was delivered roadside, in real traffic conditions (as opposed to mass media) (Elvik, 2016). Before designing and implementing a road safety campaign, agencies should engage local stakeholders to help determine what role, if any, law enforcement should have in the campaign activities. An increasing body of research has demonstrated the racial disparities in policing specifically related to traffic stops (Baumgartner et al., 2018; Epp et al., 2017; Pierson et al., 2020). For example, analysis of more than 100 million traffic stops in the United States showed that Black motorists were stopped 40% more frequently than White motorists (Pierson et al., 2020).

NHTSA's *Countermeasures That Work's* (Richard et al., 2018) sections about communication and outreach emphasize the importance of pre-testing campaign messages to make sure they are relevant to the target audience and highlight the importance of coordinating with law enforcement efforts while discouraging the use of fear appeals, which can potentially *increase* undesirable behaviors (Richard et al., 2018). Fear appeals present people with the negative outcomes that they may experience if they engage in what is depicted as an unsafe and/or illegal behavior (Lewis et al., 2007). Canada's Traffic Injury Research Foundation also discourages the use of fear appeals in the report, Road Safety Campaigns: What the Research Tells Us (Robertson & Pashley, 2015).

While not an evaluation of campaign effectiveness, Elvik (2016) offers a theoretical perspective on road safety communication campaigns, starting with a description of why road user behavior should be considered subjectively rational (i.e., people behave the way they think is best, according to their own values and preferences). If road users try to be as rational as they can, then it should also be possible to motivate them to change behavior that deviates from apparent rationality. Keeping the following "failures of rationality" in mind may be important when defining the safety problem and designing a communication campaign to address that problem:

1. Unconscious errors.
2. Not choosing the best option.
3. Wishful thinking (i.e., overly optimistic beliefs about one's own skill).
4. Lack of knowledge.
5. Failure to coordinate behavior with other road users.

Elvik (2016) outlines evidence that informative or persuasive messages can be effective in changing behaviors related to numbers one, two, and four in the list above. For number two, social norms media marketing has been found to be especially effective (this is a concept that was employed in the Gainesville, Florida, and St. Paul, Minnesota, studies described in the section Comprehensive Programs). There is little evidence for numbers three and five above, but while addressing number three is likely difficult, it is reasonable to assume that informative messages can affect number five.

Methods for Evaluating Behavior Change Efforts

While Part 4 includes more detail about the methods and data needs for measuring bicyclist and pedestrian safety, this subsection includes a few notes specifically related to the evaluation of the type of behavioral interventions mentioned above.

An experimental study design is less commonly used in the field of transportation safety because there are obvious ethical issues and logistical challenges with placing people, especially children, in situations that may be dangerous. Observational studies, which can be cross-sectional or before-after, are much more common. An example of an experimental design is the study that randomly assigned 7- and 8-year-olds to different types of pedestrian safety educational interventions (Schwebel & McClure, 2014), while an example of an observational design is the before-after study of speed limit reductions in Boston compared to speeds in a control city (Hu & Cicchino, 2019). The most direct measure of a study about transportation safety is crashes, but since bicyclist and pedestrian crashes are less frequent than motorist only, surrogate measures like observed behaviors are often used to measure change. When it is not possible to measure behaviors in real-world settings, sometimes researchers rely on behaviors in simulated environments or measures of knowledge change under the assumption that knowledge change is a precursor to behavior change.

A couple of papers about education programs reviewed for this section were more focused on the evaluation methods used to assess behavior change rather than evaluating the behaviors themselves. It is generally problematic to instigate and observe children's walking or bicycling behaviors in real traffic environments, so researchers have explored the use of other methods such as VR and instrumented bicycles. Prior research has demonstrated the potential for VR to offer children repeated practice with street crossing tasks (Schwebel, McClure, et al., 2014). In a within-subjects study of a semi-mobile, semi-immersive virtual pedestrian environment with a small sample of 44 seven- and eight-year-olds, researchers concluded that VR in a community setting (i.e., schools or community centers) may be effective but that further research is needed, especially research focused on the duration of training and the effect of repeated feedback (Schwebel, Combs, et al., 2016). In the VR study, students were assessed in a lab setting before they completed six 15-minute lessons in the virtual setting and then they were assessed again in the lab setting. In general, students made more efficient crossings in the after-period, but there were no significant changes in the rate of unsafe crossings. In a separate study exploring the use of technology to record behaviors, researchers used instrumented bicycles to collect data on "day-to-day" safety-relevant behaviors among 12 middle school-age students (six who received a bicycle training program and six who did not) (Hatfield et al., 2017). The small sample does not allow for evaluation of results, but the study provides methodological lessons. Teachers were asked to identify children who regularly bicycle, and researchers approached those families about substituting the research bicycle for their own bicycle for any trips they would make by bicycle for a one to two-week period. The research process is relevant for agencies or organizations interested in collecting naturalistic data before the widespread implementation of a safety program to evaluate and refine the program.

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Crossing- and Corridor-Specific Safety Interventions

This section presents a review of engineering interventions that can be used to improve safety for people walking and bicycling. Given the state of research on pedestrian and bicyclist safety, this section includes information from a mixture of published academic literature and a few reports from government entities. Throughout this section, the terms "countermeasure," "intervention," and "treatment" are used synonymously. In general, there is more research on the effectiveness of safety interventions for pedestrians than for bicyclists, but many treatments apply to both types of road users since they often face similar risks and challenges when interacting with motorists. The treatments in this section are organized by applicable location (at crossing locations versus along a corridor), rather than by roadway user type.

There are a limited number of evaluations of countermeasures (peer-reviewed or otherwise) that directly measure impacts on pedestrian and bicyclist safety in terms of injuries, fatalities, or crashes. However, there is a growing body of evidence on the effectiveness of various countermeasures to improve safety through the increased prevalence of safe behaviors (or a decrease in unsafe behaviors). These behaviors, or surrogates for safety, typically include travel speed, yielding, safe passing distance, signal or other traffic law compliance, and motorist encroachments into spaces designated for bicyclists. Another way that treatments are evaluated is through perceived safety and comfort; metrics that are particularly common in bicycle research because bicycle crashes are less common than pedestrian crashes. In instances where no other measure of safety is reported in the research, perceived safety and comfort findings are included throughout this section. It is important to keep in mind that there is no proven relationship between most of these surrogate measures and actual crashes.

Crash modification factors (CMFs) are presented when available. CMFs are used to calculate the anticipated number of crashes that are expected to occur after implementing a countermeasure compared to the "before" period at a specific location. However, the availability and quality of CMFs for bicycle and pedestrian countermeasures are limited by factors such as low crash frequencies at potential treatments sites and poor exposure data. A CMF of less than one indicates that crashes are expected to decrease, whereas a CMF of more than one indicates that crashes are expected to increase after the countermeasure is installed. For example, a CMF of 0.80 corresponds to an expected 20% reduction in crashes because of a given treatment. For more information about how safety is measured in pedestrian and bicyclist studies see Part 4.

For images of any of the countermeasures listed in this subsection, consider visiting the websites for FHWA's Proven Safety Countermeasures, Safe Transportation for Every Pedestrian (STEP), or Pedestrian or Bicycle Safety Guide and Countermeasure Selection System; NHTSA's Advancing Pedestrian and Bicyclist Safety: A Primer for Highway Safety Professionals; or the National Association of City Transportation Officials' (NACTO) Urban Street Design Guide.

Overarching Safety Treatments

This subsection includes a review of engineering or roadway treatments that address safety risks that can be implemented in most roadway environments to mitigate two major threats to pedestrian and bicyclist safety—motorist speed and darkness. These threats also overlap to create even more risk for people walking and bicycling. The use of the overarching safety treatments described below is often supported by policies or statutes that guide where, when, and how the treatments can be installed. For example, many jurisdictions have programs or policies for neighborhood traffic calming or automated enforcement of speed limits.

Speed Management

Speeds incompatible with pedestrian and bicyclist safety can be induced by a variety of factors, but they may also be mediated by design considerations and statutory limits. Practitioners seeking to understand speed as a risk for pedestrians and bicyclists should survey the infrastructure elements in a jurisdiction to identify potential risk factors that can induce high speeds. Similarly, speed limits may affect travel speeds.

The actual operating speed of motorists along a roadway is influenced by a variety of design elements. In a survey of 300 sites distributed across urban, suburban, and rural locations in Connecticut, researchers measured free flow traffic speeds and modeled the roadway and roadside factors that induced these speeds (Ivan et al., 2009). They found that higher average vehicle travel speeds are associated with wide shoulders, large building setbacks, and zones consisting of single- and multi-family housing units at medium to large densities. Conversely, lower average running speeds are associated with on-street parking, sidewalks, and commercial development. The authors noted that the locations with lower speeds provided more significant visual friction that “hemmed in” motorists, causing natural, subconscious speed reductions.

Although the Connecticut speed study did not explicitly consider pedestrian and bicyclist activity, there are clear implications for these modes. Built environments that induce more pedestrian traffic with sidewalk connectivity and traffic attractors may also induce slower speeds. In these types of environments, crash frequencies may increase due to the higher pedestrian volumes and access points (Chimba & Ajieh, 2017), but severities may decrease due to lower vehicle speeds. For example, commercial locations with a number of crosswalks may condition motorists to be more alert for pedestrian activity and naturally lead to slower speeds and reduced risk. Conversely, residential or suburban locations that facilitate higher speeds due to “wide open” designs may increase risk of severe crashes for bicyclists due to the higher induced speeds. However, this relationship is complex, as various studies (see Gladhill & Monsere, 2012, for example) find negative associations between high speeds and bicycle crash frequency. Researchers often attribute this relationship to the fact that greater average free-flow speeds tend to be produced by lower traffic volumes, so the exposure to potential crashes decreases while the risk of a fatality occurring increases (Gladhill & Monsere, 2012). Therefore, practitioners may consider design elements that create the visual illusion of a narrowing road where high-speed traffic may interact with pedestrian and bicyclist streams without separation; when traffic volumes are high, but speeds still exceed 20 mph, separate facilities may be needed. For a more thorough discussion of risk and the built environment, please see the section, Role of the Environment, in Part 2.

Traffic calming speed management measures

Traffic calming reduces vehicle speeds or volumes on a single street or a street network mainly through physical measures to improve the safety and comfort of people outside of vehicles (FHWA, 2017). This report focuses on traffic calming speed management measures, which encompass geometric treatments installed to manage motorist operating speeds. Previous sections of this report detail the relationship between motorist speed and the safety of people walking and bicycling. Vertical deflection treatments (e.g., speed humps) physically raise the height of the roadway in a specific area to require vehicles to slow as they drive over them. Horizontal deflection treatments reduce operating speeds by laterally shifting the line of travel. Street width reduction treatments encourage slower operating speeds by physically or visually narrowing the path of travel for motorists (FHWA, 2017). Some studies have shown that design treatments with vertical deflection are more effective at reducing vehicle speeds than those with horizontal deflection or enforcement strategies, including automated speed enforcement cameras (FHWA, 2014; Gonzalo-Orden et al., 2016; Mountain et al., 2005).

Treatments with vertical deflection include speed humps, speed lumps (also called speed cushions), and speed tables/raised crossings. These treatments have been shown to significantly reduce average vehicle speeds, 85th percentile speeds, and the share of motorists traveling above the speed limit (Sanders et al., 2019). Crash modification factors for these types of treatments for vehicle-pedestrian crashes range from 0.45 to 0.74 for raised crossings and speed humps (L. Chen et al., 2013; Elvik & Vaa, 2004; Rothman et al., 2015).

Treatments that use horizontal deflection include chicanes, neckdowns, chokers, and mini-traffic circles. These treatments have been shown to reduce motorist speeds as measured by average speeds and 85th percentile speed (Sanders et al., 2019).

Treatments that physically or visually reduce the width of the roadway, such as curb extensions, crossing islands, medians, street trees, provision of on-street parking, provision of bicycle lanes, lane narrowing, or road reconfigurations that reduce the number of travel lanes are also associated with reduced motorist travel speeds; however, their impacts on safety are less uniform. For example, research findings on whether narrowing lane width through pavement markings reduces vehicle speeds (alone) are mixed; reviews conducted for recent syntheses suggest that the impacts on bicyclist and pedestrian crashes are minimal, if any (Sanders et al., 2019; L. Thomas et al., 2016). Research completed by Fitzpatrick et al. (2001) indicates that narrowing travel lanes is associated with reductions in motorist speeds; however, it is likely that the number of travel lanes, shoulder width, and installation of other treatments (e.g., bike lanes) affect the effectiveness of narrowing lane widths on pedestrian and bicyclist safety. Several studies have shown reductions in motorist speeds after road reconfigurations (also called road diets); however, in many cases, the road diets were accompanied by additional treatments beyond changes in the number of lanes so it is difficult to determine the exact impact of reducing the number of lanes on motorist speed (Sanders et al., 2019). Road diets are covered in additional detail under Corridor Safety Interventions.

There is very little research on the effect of traffic calming treatments specifically for bicycle travel; however, bicyclists can also benefit from these types of treatments in addition to the benefits for pedestrians since they are both vulnerable to higher risks of severe and fatal injuries when traffic speeds are higher. Bicyclists may be even more vulnerable than pedestrians in situations where pedestrians can travel along sidewalks and bicyclists must travel in the roadway, either sharing a lane with motorists or riding in a paved shoulder or striped bike lane.

Automated enforcement

Automated speed enforcement (ASE) is generally considered to be the most effective form of enforcement for reducing vehicle speeds because it provides speed enforcement regardless of whether officers are present (Richard et al., 2018). Automated speed enforcement involves the use of a fixed or mobile camera to measure vehicle speeds and photograph vehicles that exceed the speed limit by a certain amount. This countermeasure has been used to reduce motorist speeds in areas where people are expected to be walking and bicycling, such as along arterial and residential streets and in school zones (Cunningham et al., 2008; Freedman et al., 2006; W. Hu & McCartt, 2016; Sanders et al., 2019). On average, studies examining the effectiveness of ASE find a 20 to 25% reduction in injury crashes (all crashes, not necessarily pedestrian or bicyclist crashes) (Poole et al., 2017). For a summary of the effectiveness of ASE, see Poole et al. (2017).

While proven effective, the use of this treatment is not widespread because in many States the act of issuing citations based on video data from a camera is not allowed. About 150 communities have speed camera programs; only 16 States and the District of Columbia allow them (IIHS, 2022b). Some communities have implemented programs without State enabling legislation, but these programs have been more susceptible to legal challenges (Poole et al., 2017). Restrictions on the use of ASE often stem from concerns about privacy and public perceptions that ASE is used primarily to generate revenue or that speeding is not a pressing safety issue.

Speed feedback signs

Speed feedback signs either show the travel speed of all motorists as they pass by the sign or are only activated when an approaching vehicle is exceeding a pre-determined speed. These signs are sometimes used in conjunction with police officer enforcement. The NCHRP Synthesis 852 *Pedestrian Safety Relative to Traffic Speed Management* cites three different studies on speed feedback signs, which show that the devices are associated with decreases in average speeds, 85th percentile speeds, and the share of vehicles traveling over the speed limit (Sanders et al., 2019). However, these studies usually only examined a few speed feedback (or speed-activated) signs in a single jurisdiction. Across the three studies, decreases in 85th percentile speed ranged from 4 mph to 9 mph (FHWA, 2014; Hallmark et al., 2013; Ullman & Rose, 2005). The Hallmark et al. (2013) study examined both types of speed feedback signs along main roads in small Iowa communities and found that the percentage of motorists traveling 5, 10, or 15 mph over the limit decreased, with the largest decreases in the fastest category. Less dramatic reductions persisted 12 months after installation. A more recent literature review and meta-analysis of 43 published speed feedback sign studies found that, when activated, overall reductions of 4 mph were detected at the sign sites for passenger vehicles, and reductions of 2 to 4 mph were detected for all vehicle types across different roadway contexts (Fisher et al., 2021a,b).

Lighting

While other strategies that improve visibility for the motorist, slow vehicle speeds, and reduce the occurrence of alcohol-impaired travel have a role to play in reducing pedestrian and bicycle fatalities at nighttime, studies from the United States and abroad indicate that providing street lighting at night can improve safety by improving visibility, increasing motorist yielding, reducing crash risk, and reducing the risk of severe and non-severe injuries (Helak et al., 2017; Kim et al., 2007; Nambisan et al., 2009; L. Thomas et al., 2016; Wanvik, 2009; Wei et al., 2016). While pedestrian fatalities increased overall between 2009 and 2018, the number of nighttime fatalities increased at a higher rate (67%) than daytime fatalities during that period (16%) (Retting, 2020). In 2020, 77% of pedestrian fatalities occurred in dark conditions with another 4% occurring during dusk or dawn (NCSA, 2022c). These figures do not account for the presence or quality of lighting from sources like streetlights, nearby buildings, or the moon. However, analyses of data from FARS and California's Transportation Injury Mapping System indicate that fatalities are more likely in dark, unlit conditions than dark, lit conditions (Sanders, Schneider, et al., 2020). For bicyclist fatalities, 47% occurred during dark conditions, with another 4% occurring during dusk or dawn (NCSA, 2022d). Researchers reviewing more than 10,000 bicycle-involved crashes found that the likelihood of a bicyclist experiencing a severe injury is significantly higher among bicycle crashes that occurred in dark conditions, both with and without streetlights, compared to crashes that occurred in daytime (Helak et al., 2017).

Lighting along segments, at approaches to intersections, and at crossings can help improve the visibility and safety of all road users and is particularly important for people walking and bicycling (DiGioia et al., 2017; Helak et al., 2017; Reynolds et al., 2009). Several studies about street lighting highlight the importance of light quality and placement on road user safety. Research completed at urban, signalized intersections indicates that street lighting with higher illuminance ratings is associated with a significantly reduced risk of fatal and severe injuries among crashes involving pedestrians and bicyclists—benefits were also observed among motorist only crashes (Wei et al., 2016). Several studies have found that placing streetlights (or other pedestrian lighting) in advance of a crosswalk (on all approaches) rather than directly overhead is associated with improved visibility of people walking (Bullough et al., 2012; Gibbons et al., 2008).

Slow Zones

Slow zones are streets designed to slow motorists to make the area more comfortable for people walking and bicycling. Areas are typically defined using signage at entry and exit points and apply a combination of traffic calming treatments to reduce traffic speeds to 15 or 20 mph. Slow zones are being used in some U.S. cities like New York and Seattle due to the success of the robust program in London, England (Grundy et al., 2009; H. Li & Graham, 2016). The exact design of each of London's slow zones varies, but they typically include signs at the entrances and exits and engineering treatments such as speed humps, chicanes, crossing islands, and raised crossings, placed every 110 yards (100 meters). London's program was associated with a 24% to 32% reduction in pedestrian fatalities (Grundy et al., 2009; H. Li & Graham, 2016). New York City reduced the speed limit from 25 to 20 mph and added pavement markings, signs, and speed humps to help encourage slower speeds in designated areas as part of the city's neighborhood slow zone program. Evaluations of this effort indicate that motorist speeds and the total number of traffic crashes and injuries decreased in slow zone areas (and crashes were not displaced to adjacent streets) (Jiao et al., 2019). It is unclear whether New York City's program has improved safety specifically for bicyclists and pedestrians. An evaluation using 2 years of post-installation crash data indicated that the number of pedestrian and bicyclist fatalities (combined) did not decrease; however, bicycle and pedestrian crashes of all severity levels and related volume data were not included in this analysis. It is also worth noting that London's program used a much higher density and diversity of traffic calming treatments compared to New York City's program (Hagen, 2018).

Crossing Safety Interventions

Infrastructure treatments that provide separation between motorists and bicyclists and pedestrians improve safety by increasing the visibility of users, improving predictability of user position or movement, and/or encouraging motorists to yield to pedestrians and bicyclists. This is true for crossings that are controlled by traffic control devices like a traffic signal or stop sign and for uncontrolled crossings, which occur where sidewalks or designated walkways intersect a roadway at a location without traffic control. The interventions in the bullets below include measures that may be applicable in both uncontrolled and controlled crossing environments. These measures are not listed in a particular order. As discussed in the introduction to this section, CMFs for each treatment are provided when available.

People walking or bicycling can face unsafe situations in many circumstances while trying to cross a street or driveway. They are more likely to come into conflict with motorists at intersections when motorists are turning or when they (or a motorist) disobey a traffic control or fail to yield appropriately. The treatments discussed below are designed to reduce the risks associated with these situations; many of them are used specifically to mitigate issues associated with poor visibility, crossing distance, motorist speeds, failure to yield, or turning movements. These treatments include the following.

- Crosswalk markings
- Advance stop/yield markings and signs
- Conflict area pavement markings
- Raised crossings
- Crossing islands
- Curb extensions
- Parking restrictions near intersections
- Curb radii reductions
- In-street signs
- Uncontrolled crossings
    - Pedestrian hybrid beacons
    - Rectangular rapid-flashing beacons
- Controlled crossings
    - Protected intersections
    - Two-stage left turn boxes
    - Bike boxes
    - Mixing zone treatments
    - Signalization strategies
- Roundabouts

Crosswalk markings

A large body of research suggests that motorists are more aware of pedestrians, reduce their speeds, and are more likely to yield at marked crosswalks than at unmarked crosswalks. The definition of an unmarked crosswalk varies slightly according to State laws, but generally they occur when a sidewalk ends at an intersection and continues on the other side of the intersection but there are no pavement markings that reinforce a pedestrian's right of way. At non-intersection locations crosswalk markings legally establish the crosswalk (see FHWA's Manual of Uniform Traffic Control Devices, Section 3B.18). The two most common outcomes used to measure the safety effect of crosswalks, and many other pedestrian safety treatments covered below, are pedestrian-vehicle crashes and motorist yielding/stopping. In terms of the type of crosswalk marking, research has established that high-visibility crosswalks (e.g., ladder style or continental) are more *visible* to both motorists and pedestrians compared to transverse lines (Fitzpatrick et al., 2010). It is more challenging to study the *effectiveness* of crosswalk markings in terms of yielding or crashes because is difficult for researchers to isolate the effect of the pavement marking from other treatments like signage, beacons, signals, refuge islands, etc.

Two studies established the efficacy of high-visibility crosswalks in reducing pedestrian-vehicle crashes, but in very specific circumstances: intersections in New York City and school zones in San Francisco. The New York City study used a quasi-experimental design to evaluate 20 years of crash data to evaluate high-visibility crosswalk markings (along with 13 other safety countermeasures) (L. Chen et al., 2013). Study authors estimate that high-visibility markings led to a 48% reduction in pedestrian crashes. Comparison sites also experienced a reduction in crashes, but the further reduction at treatment sites was statistically significant. The San Francisco study examined the effect of yellow, continental-style high-visibility markings at signalized, stop-controlled, and uncontrolled intersections in school zones (Feldman et al., 2010). Researchers estimated reduction in crashes was 37%. Study authors noted that their analysis method may not have fully accounted for the citywide downward trend in pedestrian-vehicle collisions that was taking place at the time of their study.

Research on crosswalks had been controversial because early studies found negative impacts on safety. However, many of these studies did not control for vehicle volumes, vehicle speeds, the number of travel lanes, or changes in pedestrian volumes before and after crosswalks were removed or installed, which may explain the results of these studies (Zegeer, Stewart, Huang, Lagerwey, et al., 2005).

Advance stop/yield markings and signs

Advance stop or yield markings and signs are used widely across the United States to increase motorist yielding and improve stopping sight distance (Blackburn et al., 2017; Fitzpatrick et al., 2006; L. Thomas et al., 2016; Zegeer et al., 2017). This treatment is associated with a CMF of 0.75 for pedestrian crashes (i.e., a 25 % reduction in anticipated pedestrian crashed) (Zegeer et al., 2017). Zegeer et al. reviewed 11 studies on this treatment, 10 of which reported that adding this treatment to a marked crosswalk reduced vehicle-pedestrian conflicts and increased motorist yielding at greater distances from the crosswalk. As noted by L. Thomas et al. (2016), the key benefit of this treatment may not be a large increase in motorist yielding, rather it is the notable increase in the distance at which motorists stop or yield to pedestrians. This larger yielding distance improves sight lines and can help reduce multiple threat crashes.

Conflict area/intersection pavement markings for bicyclists

Like crosswalk markings, extensions of bicycle lane pavement markings through intersections are intended to provide bicyclists with a clear, highly visible pathway through an intersection. They also help to alert motorists to the presence of bicycle through-traffic and may increase the predictability of bicyclist behavior. Studies indicate that this treatment can improve bicyclist safety via increased motorist yielding, reduced conflicts with turning vehicles, and increased predictability of a bicyclist’s travel path; however, a CMF has not been determined (Duthie et al., 2010; Hunter et al., 2000; Jensen, 2008). Hunter et al. (2000) found that more bicyclists traveled on the “correct path” through the intersection after the treatment was added, and motorist yielding behavior increased from 72% before to 92% after the treatment was installed. The number of bicyclist–motorist conflicts decreased from 0.95 per 100 entering bicyclists before to

0.59 after the treatment was installed (Hunter et al., 2000).[5] Similar findings were observed with the addition of green pavement markings at an intersection in Florida. The share of motorists yielding to bicyclists increased from 87% to 96% after the treatment was installed (Hunter et al., 2008).

Raised crossings

Raised crossings typically include a speed table with high-visibility crosswalk markings. The effects of raised crossings on motorist yielding and on pedestrian crashes are not well-documented. However, a few studies have found this treatment to be associated with lower motorist speeds; one study also observed an increase in motorist yielding; and another study found an increase in pedestrian crosswalk compliance (Sanders et al., 2019; L. Thomas et al., 2016; Zegeer et al., 2017). Elvik et al. (2004) suggest a CMF of 0.55 for vehicle-pedestrian crashes when used at an uncontrolled crossing; however, this study received a one-star rating from the Crash Modification Factor Clearinghouse due to methodological limitations including small sample sizes and low levels of confidence in the CMF.

The effectiveness of this treatment for bicyclists in the United States is not well understood; however, Schepers et al. (2011) reported a CMF of 0.49 for vehicle-bicycle crashes for raised crossings at unsignalized intersections in the Netherlands. This treatment may be particularly helpful for bicycle crossings at junctions with shared use paths or separated bike lanes.

Crossing islands

Crossing islands (also called raised median islands or pedestrian refuge islands) provide a refuge for pedestrians (or bicyclists) crossing the street and reduce their exposure to motor vehicles. This treatment can reduce vehicle speeding, improve visibility, and reduce vehicle-pedestrian crashes (Kang, 2019; Zegeer et al., 2017). FHWA recognizes this treatment as a proven safety countermeasure. Motorist yielding rates vary widely across sites with crossing islands and marked crosswalks with motorist yielding decreasing as the number of through lanes and posted speed limit increases (Fitzpatrick et al., 2006). Additional treatments will be necessary to improve the effectiveness of this treatment and encourage motorist yielding at multilane, higher speed, uncontrolled crossings. The CMF for this treatment ranges from 0.54 to 0.75, depending on context (Gan et al., 2005; Zegeer et al., 2002; Zegeer, Stewart, Huang, Lagerwey, et al., 2005; Zegeer et al., 2017). This treatment can be used at all crossing environments, and while it is typically used for pedestrians, it can help bicyclists at multilane uncontrolled crossings and is recommended for bicyclists in NACTO's *Urban Bikeway Design Guide*.

Curb extensions

Curb extensions shorten crossing distances, increase visibility of pedestrians and motorists, and when used at an intersection, they reduce corner radii. There are very few formal studies of this treatment and the results of existing research studies on the impacts of this treatment on pedestrian safety are not uniform. At some locations, curb extensions have been shown to improve motorist yielding behaviors, slow vehicles, reduce vehicle-pedestrian conflicts, and reduce vehicle-pedestrian crash severity (Kang, 2019; Sanders et al., 2019; Sanders, Schultheiss,

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[5] A conflict was defined as an interaction where at least one of the parties had to make a sudden change in speed or direction to avoid the other.

et al., 2020; L. Thomas et al., 2016; Zegeer et al., 2017). The impact of this treatment on bicyclist safety is unknown, but curb extensions can hinder bicycle travel if their design blocks the path of bicyclists.

Parking restrictions near intersections

Restricting parking near intersections, often referred to as daylighting, improves visibility for all road users and can reduce conflicts at crossing locations. The impacts of this treatment are not well-studied; however, one study reports a CMF for vehicle-pedestrian crashes of 0.70 (Gan et al. 2005, as cited in Blackburn et al. (2017)). This treatment has not been used specifically to improve bicyclist safety, but it is likely that bicyclists traveling along or across a roadway would benefit from the increased visibility that this treatment provides.

Curb radii reduction

Large curb radii enable motorists to make high-speed turns, which may increase crash risk and injury severity for people walking and bicycling. This treatment is not well-studied in the literature; however, observations and engineering principles suggest that reducing corner radii reduces motorist turning speeds that can result in increased motorist yielding and improve pedestrian and bicyclist safety (Sanders, Schultheiss, et al., 2020; Zangenehpour et al., 2017).

In-street signs (MUTCD, R1-6)

In-street signs have been associated with slight increases in motorist yielding and decreases in motorist speeds in some circumstances (Gedafa et al., 2014; Kannel et al., 2003; L. Thomas et al., 2016). There are few studies of this treatment and the lack of uniform results and differences in study sites make it difficult to distill general conclusions. The use of three of these signs in a gateway configuration, rather than a single sign, may be more effective than pre-treatment conditions at increasing motorist yielding and reducing motorist speeds (Bennett et al., 2014; Van Houten & Hochmuth, 2017). This gateway configuration has also been shown to increase motorist yielding when used in conjunction with a pedestrian hybrid beacon (Bennett et al., 2014). In-street signs are typically used at midblock crossings or multilane uncontrolled crossings.

Treatments for Uncontrolled Crossings

The primary risks to both bicyclists and pedestrians attempting to cross at an uncontrolled crossing location are motorists failing to see them and/or motorists failing to yield appropriately. The treatments discussed above, such as crosswalk markings, raised crossings, crossing islands, curb extensions, daylighting, in-street signs, and advance stop/yield markings and signs can all be used to improve safety at uncontrolled crossings. The effectiveness of most treatments at uncontrolled crossings, such as high-visibility crosswalk markings, rectangular rapid-flashing beacons, pedestrian hybrid beacons, and pedestrian refuge islands are influenced by motorist operating speed, motor vehicle volume, roadway width, and crossing distance (Zegeer et al., 2017). Crash modification factors for these treatments are included below. At uncontrolled crossings, bicyclists will typically encounter a street crossing from in the road (exercising their rights as a motorist) or as a pedestrian (exercising their rights as a pedestrian) if operating on a sidewalk, trail, or shared use path.

High-visibility crosswalk markings

The use of high-visibility crosswalk markings *specifically at uncontrolled crossings* has been shown to increase safe motorist driving behaviors such as reducing speeds and increasing motorist brake application and throttle pedal actuation (Sarwar et al., 2017). However, research indicates that marked crosswalks *alone* at uncontrolled, multilane crossings on roadways with 10,000+ vehicles per day will not improve pedestrian safety and can increase pedestrian crashes unless other more substantial treatments are used in conjunction with them (Fitzpatrick et al., 2006; Zegeer, Stewart, Huang, Lagerway, et al., 2005).

When looking at motorist yielding as a measure of effectiveness, NCHRP Report 562, *Improving Pedestrian Safety at Unsignalized Crossings* (Fitzpatrick et al., 2006), did not isolate the effect of high-visibility crosswalks, but confirmed that compliance can vary widely across sites. For example, motorist compliance at three sites with high-visibility crosswalks *and* high-visibility signs could be from 4% to 35% on a 35-mph street or 60% to 90% on a 25-mph street.

High-visibility crosswalk markings are also addressed at the beginning of the section, Crossing Safety Interventions.

Pedestrian hybrid beacons and rectangular rapid-flashing beacons

PHBs and RRFBs can be used to supplement marked crosswalks and improve safety at locations where pedestrians (or bicyclists) need to cross but have higher volumes or operating speeds of motorists. PHBs use a red indication to require motorists to stop while RRFBs use yellow indications as a warning for motorists to yield or stop when pedestrians are present. Both RRFBs and PHBs are person-actuated and have been used in a wide variety of circumstances to improve motorist yielding and reduce vehicle-pedestrian conflicts. For example, RRFBs and PHBs have been shown to increase motorist yielding during the day and at night, on roadways with speeds of 25 to 45 mph, and at midblock and four-way intersections (Fitzpatrick et al., 2017; Mishra, 2015; Stapleton et al., 2017; Zegeer et al., 2017). In general, RRFBs are better suited for lower speed (35 mph or less), lower volume roadways (15,000 ADT or less) with only one or two travel lanes in each direction, unless installed with a raised median or crossing island (Blackburn et al., 2017). PHBs are typically used at higher speed, multilane crossings often on arterial roads.

Fitzpatrick et al. (2017) found that motorist yielding at crosswalks with RRFBs was better at midblock sites compared to four-leg intersections. They also found that as the distance being crossed increased, motorists were less likely to stop for a crossing pedestrian. Crash Modification Factors for RRFBs for vehicle-pedestrian crashes have been reported as 0.53 and 0.64; however, the two studies reporting these CMFs received two- and one-star ratings from the Crash Modification Factor Clearinghouse for these specific treatments due to methodological limitations such as small sample sizes and low levels of confidence in the CMFs (Monsere et al., 2017; Zegeer et al., 2017). Zegeer et al. (2017) found that PHBs installed with advance stop/yield markings and signs had a CMF of 0.43 and were more effective at reducing vehicle-pedestrian crashes than RRFBs, pedestrian refuge islands, and advance stop/yield markings (alone). Stapleton et al. (2017) notes that motorist yielding compliance may be closely related to motorist familiarity with the treatment. There is no research on the use of PHBs or RRFBs on bicyclist safety, but they are recommended as a treatment in rural areas or to assist with shared use path crossings in numerous best practice design guides.

Treatments for Controlled Crossings

Controlled crossings usually have higher volumes of all road users, which can create increased potential for conflict between users. However, they also present an opportunity to restrict or discourage movements and behaviors that can lead to pedestrian and bicyclist crashes, such as right- and left-turns and crossing violations. Most of the treatments listed below are specific to bicycling, but the subsection on signalization strategies that follows addresses bicycling and walking.

Protected intersections

Protected intersections (see Figure 8) are designed to improve motorist yielding by:

- Minimizing the available turning radius for motorists.
- Re-aligning bike lanes or paths away from travel lanes to improve sight distance to bicyclists and pedestrians.
- Creating space for motorists to yield.
- Providing a protected waiting area in advance of stopped motorists to give bicyclists and pedestrians a head-start (like a leading pedestrian interval or leading bicycle interval, described with “signalization strategies”) upon receiving a green signal indication.

They often are commonly designed with a protected island defined by curbs or bollards. Protected intersections are used abroad and are growing in popularity in the United States.

To date, there is very little research in North America on the impact of protected intersections on pedestrians or bicyclists; however, the protective design suggests that they may improve safety outcomes. The design suggests that this treatment may be especially effective at minimizing conflict points, reducing the speed of turning motorists, and mitigating right-hook and left-hook crashes. The literature indicates that protected intersections can reduce vehicle-bicycle conflicts and right-turning motorist speeds if designed appropriately, but additional research is needed to assess the magnitude of their impact on pedestrian safety, in general, and on crashes involving bicyclists or pedestrians (Madsen & Lahrmann, 2017; San Francisco Municipal Transportation Agency, 2018; Sanders, Schultheiss, et al., 2020).

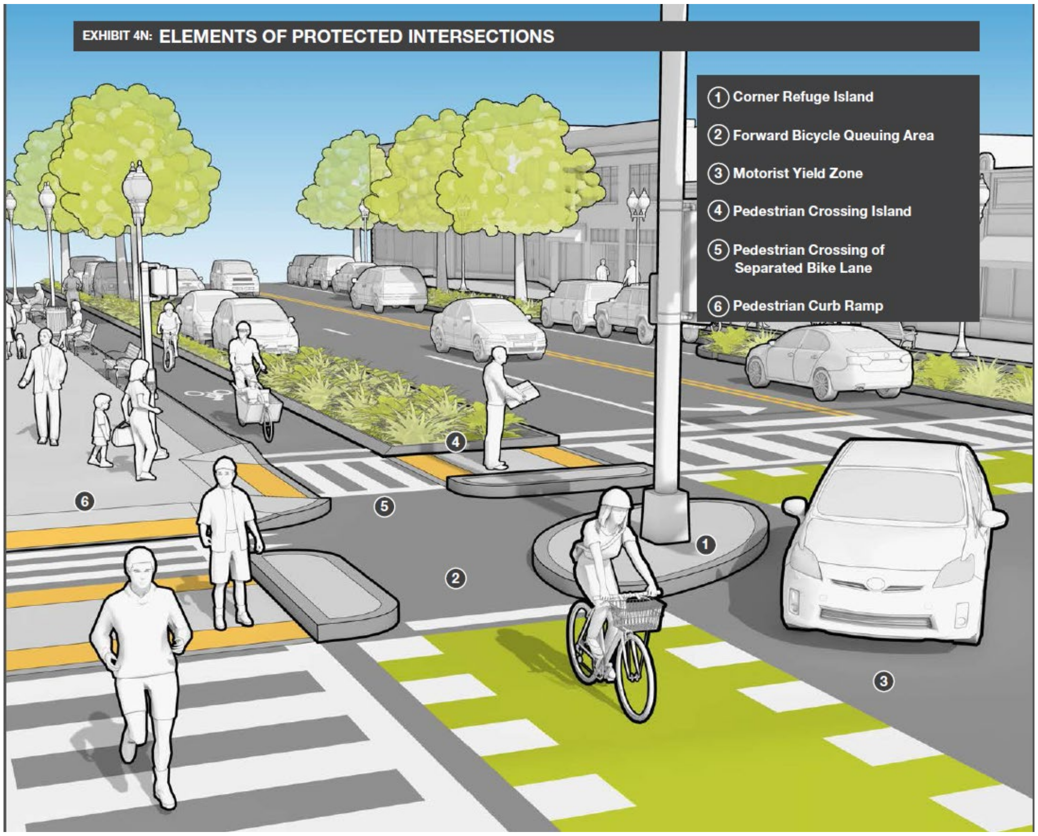

Figure 8. Key elements of a protected intersection
Source: *Separated Bike Lane Planning & Design Guide* 2015 (Massachusetts DOT, 2015), p. 69.

Research completed by Schepers et al. (2011) suggests that protected intersections may increase bicyclist safety because of the increased separation (also referred to as offset) between the motor vehicle travel lane and the bicycle facility. In their research of unsignalized intersections in urban areas, they found that significantly fewer vehicle-bicycle crashes occurred at intersections where the bicyclists' travel path at intersection approaches were offset 6.5 feet to 16 feet (two to five meters) away from motor vehicle travel lanes (P. Schepers et al., 2011). This treatment was especially effective at reducing crashes with through-bicyclists on priority roads crossing minor roads (i.e., crashes where the bicyclists have the right of way). New York City installed two offset intersections with a 15-foot-offset between a separated bike lane and the adjacent motor vehicle lane to improve bicyclist safety at intersections with turning traffic. An evaluation of this treatment showed that offset intersections were associated with an increase in bicyclists yielding to turning motorists, very high perceived safety and comfort ratings, and slightly fewer vehicle-bicycle conflicts compared to mixing zone treatments (Sundstrom et al., 2018). However, the treatment did not reduce motorist turning speeds as anticipated; the authors suggest that using a design with a tighter turning radius may be more effective.

Two-stage turn boxes

Two-stage turn boxes (also called "Copenhagen lefts" or jug-handle turns) use pavement markings to designate an area outside of the vehicle travel lane for bicyclists to wait for traffic to clear (or the signal to change) before proceeding in a perpendicular direction of travel (NACTO, 2011). They are most often used to help bicyclists complete left turns in situations where it may be difficult or physically impossible for bicyclists to merge into a left travel lane or left-turn lane due to high vehicle volumes or speeds, or due to physically separated bicycle facilities.

This treatment may improve safety by decreasing points of conflict between users and increasing movement predictability. However, there are very few studies on the effectiveness of this treatment and there is no documentation of its impact on crashes or injuries (DiGioia et al., 2017). An online visual preference survey with 1,300 respondents from a college campus community found that people with varying levels of experience with bicycling felt that riding through an intersection with a two-stage turn box significantly increased the likelihood that they would feel "safe" or "very safe" by nearly 8% (Akar & Wang, 2018). A study of bicyclist behavior at signalized intersections with different design configurations in Toronto, Canada, found that left-turning bicyclists' compliance with the law and the intended use of the pavement markings were higher at an intersection with a two-stage turn box compared to two different intersection configurations without this treatment (Casello et al., 2017). This increased compliance suggests that bicyclists' behaviors are more predictable at intersections with two-stage turn boxes than those without, which may result in reduced conflicts and safer outcomes for road users. However, because this study did not use a before-after design, there may be factors beyond the installation of the two-stage turn box that are associated with the higher rate of compliance with the law and the intended use of the facility.

Bike boxes

Like two-stage turn boxes, bike boxes help bicyclists position themselves for safe travel through intersections with traffic control. A bike box provides a space for bicyclists to queue in front of vehicles that are stopped at an intersection to improve their visibility to stopped motorists and to result in bicyclists receiving a head start upon a green traffic signal reducing the potential for conflicts with turning motorists. In many cases, bike boxes are implemented in conjunction with right-turn-on-red restrictions; initial research indicates that pairing these two treatments increases the effectiveness of bike boxes (Loskorn et al., 2013). In some instances, these treatments are used at unsignalized locations to provide predictability of bicyclists' stopping positions. While motorists may sometimes encroach into bike boxes, these treatments are generally accepted as beneficial and can have high user compliance, especially when green paint is used.

In a study of video data from 10 signalized intersections in Portland, Dill et al. (2012) found that even though the volume of bicyclists and right-turning motorists increased at the study intersections, the number of conflicts between users decreased by nearly one-third. Like two-stage turn boxes, surveys indicate that bike boxes make or would make intersections feel safer for bicyclists (Akar & Wang, 2018; Dill et al., 2012). Several other studies have found that bike boxes increase traffic law and signal compliance and increase separation between bicyclists and motorists (Casello et al., 2017; Parks et al., 2012; Zangenehpour et al., 2013). Due to the way that bicyclists have been documented to use bike boxes, and the benefits that have been shown to date, bike boxes can improve the safety of bicyclists traveling straight or turning right, but they may not increase the safety of bicyclists if they span multiple travel lanes to assist with left turns. Education about the proper use of bike boxes, for both bicyclists and motorists, may be needed to help increase the effectiveness of bike boxes, especially when first implemented.

Mixing zone treatments

Mixing zones occur at intersections where bicyclists approach using a bicycle facility that requires turning motorists to enter or cross the bicyclist's travel path. A common mixing zone design involves a bike lane merging with a motorist right-turn lane. Different types of mixing zone treatments use different pavement markings and other materials or signage to delineate the area where bicyclists and motorists converge. Designs that create a clearly defined, slow speed merge point may be the most beneficial in terms of increasing road user predictability and improving the safety of all road users.

Studies of the safety effects of mixing zones for bicyclists show a range of results. Treatments that have been the most successful at improving safe behaviors among bicyclists and motorists (measured correct lane use by turning motorists and through bicyclists at 87 to 91%) are those that incorporate flexpost-restricted entry and markings that clearly define the entry to the merging area (Monsere et al., 2015). Additional research on the different types of mixing zones is needed to better understand which treatments are associated with the safer bicycling conditions.

Signalization strategies

There are a variety of signalization strategies that can be used to improve pedestrian and bicyclist safety at signalized intersections, including adjustments to signal timing and the use of pedestrian and bicycle signals for protected phasing. Compared to an uncontrolled or stop-controlled intersection, signalized intersections can provide designated gaps in traffic flow that allow bicyclists and pedestrians to proceed with a reduced risk of conflict with motorists and/or reduced delay. The strategies discussed below present ways to overcome the potentially unsafe conditions for people walking and bicycling inherent in conventional signalized intersection design.

Traffic signal timing can affect pedestrian and bicyclist safety. Lengthy delays for people walking and bicycling may encourage signal non-compliance. Providing enough crossing time and minimizing pedestrian and bicyclist delay can also improve safety at intersections (Balk et al., 2014; Retting et al., 2002; Van Houten et al., 2006). A review of four signalization strategies in New York City found that increasing cycle length for pedestrian crossing was associated with a greater reduction in vehicle-pedestrian crashes than exclusive pedestrian phases, split signal timing, and signal installation (terms defined below) (L. Chen et al., 2014).

Green waves are traffic control strategies that synchronize the green phase of consecutive traffic signals to promote regulated flow of traffic. Green waves designed for a bicyclist's travel speed can improve bicyclist safety by promoting slower motorist speeds and reducing bicyclist travel time and decreasing the number of stops. They may also reduce red light violations among bicyclists. To date, this treatment has only been used in a few locations in the United States and there is no research documenting the impacts of this treatment on bicyclists in the literature.

Leading pedestrian intervals (LPI) provide pedestrians with a 3- to 7-second head start so they are more visible to motorists once parallel traffic receives a green indication. While the magnitude of the safety impacts varies by study, many studies have shown LPIs to improve pedestrian safety (Fayish & Gross, 2010; Goughnour et al., 2018; Hua et al., 2009; King, 2000; NYC DOT, 2017a; Van Houten et al., 2000). Research conducted in New York City found that the installation of LPIs resulted in a 14% decline in pedestrian and bicyclist injuries and a 56%

decline in pedestrian and bicyclist fatal and severe injuries (Brunson et al., 2017). Research conducted on LPIs in Chicago, New York City, and Charlotte, North Carolina, provided a CMF of 0.87 for vehicle-pedestrian crashes (Goughnour et al., 2018). Overall, LPIs improve safety and reduce conflicts for pedestrians and may be even more effective if used in conjunction with other treatments such as no-right-turn-on-red signs (Hubbard et al., 2008; L. Thomas et al., 2016). Leading pedestrian intervals installed without accessible pedestrian signals (APS) may not improve safety for pedestrians with vision impairments.

Leading bicycle intervals (LBI) serve the same purpose as LPIs but are used to direct bicyclists. They give through-bicyclists a chance to get into the line of sight for stopped motorists and reduce opportunities for right-hook conflicts. The effectiveness of this treatment is not well-documented since this treatment has only been used in a few places; however, LBIs are recommended in the Nation's leading bicycle design guides, such as NACTO's *Urban Bikeway Design Guide* (2013) and the forthcoming update to the AASHTO *Guide for the Development of Bicycle Facilities*, 4th edition (2012)

Leading bicycle intervals remove the risk of conflict between motorists and bicyclists during the lead interval, but the risk of conflict remains during the remaining portion of the green phase. The same situation applies to LPIs (Kothuri et al., 2018). Therefore, these treatments can improve safety outcomes compared to intersections with no phase separation but will have a different effect than exclusive phasing.

Protected or exclusive phasing at intersections provides a way to separate motorists from pedestrian or bicyclist movements and is most often used when there is high potential for conflicts that would result in a right- or left-hook, with either pedestrians or bicyclists. Protected phases are often used to mitigate conflicts between left-turning motorists and other users. A study of left-turn treatments in New York City found that left-turn-only signals (including protected-only and protected-permissive phasing) were associated with notable decreases in left-turn related pedestrian and bicyclist injuries and crashes (Brunson et al., 2017). The effects observed in this study were influenced by the one-way street pattern, the left side placement of bicycle lanes on the study streets, and the volume of street users.

Protected phases can also be used in areas with high volumes of pedestrians to provide an exclusive pedestrian phase, which allows them to cross in any direction, including diagonal (also called Barnes Dance or pedestrian scramble). The CMF for this treatment is 0.66 for vehicle-pedestrian crashes and it has proven to be effective in several studies (L. Chen et al., 2015; Institute of Transportation Engineers, 2004). However, this treatment may also be associated with increased pedestrian delay, increased vehicle delay, and an increase in pedestrian crossing violations (Bechtel et al., 2004). Protected phasing can be beneficial for bicyclists when the best way for bicyclists to reach a bicycle facility is via a diagonal movement or to cross a complicated intersection. Exclusive phasing for bicyclists is typically done with a separate bicycle signal. A bicycle signal is a traffic signal with a green, yellow, and red display intended to control bicycle movements. As of 2018, there is very little research on the safety impacts of bicycle signals. A study of more than 2,600 bicyclists who arrived at an intersection with a bicycle signal on the red indication found that compliance at bicycle signals was about 90% (excluding right turn on red) and comparable to that of traditional signals (S. Thompson et al., 2013).

Split phasing is another strategy that can be used to separate pedestrian movements from turning vehicle movements. With split phasing, pedestrians receive a "walking person" display while parallel motor vehicle traffic receives a green signal but turning vehicle traffic receives a red arrow signal. This strategy has been proven to reduce vehicle-pedestrian conflicts and may be most beneficial for pedestrian safety when used with protected left-turn phasing, which means left-turning motorists only turn on a green arrow signal while all other motorist and pedestrian movements are stopped (L. Chen et al., 2014; Tian et al., 2001).

Pedestrian countdown timers help pedestrians cross the street safely and reduce the likelihood that they will be trapped when the phase changes to "don't walk" (Huitema et al., 2014; Markowitz et al., 2006). Before-after studies of intersections with pedestrian countdown signals have found significant reductions in crashes compared to pretreatment conditions (Boateng et al., 2018; Srinivasan et al., 2019). A before-after empirical Bayes analysis using data from hundreds of intersections in Charlotte and Philadelphia found that pedestrian crashes decreased by about 9%, a finding that was statistically significant at the 90% confidence interval (Srinivasan et al., 2019).

Bicyclist detection devices can be used at signalized intersections to detect the presence of a bicyclist and prompt a signal change. When bicyclists cannot determine if the signal has detected their presence and they experience a long delay, they may be more likely to run a red light. To date, there is little research on the effectiveness of detection devices and the importance of providing feedback to bicyclists that their presence has been detected. Research conducted by Boudart et al. (2016) sought to determine whether bicyclist behavior changed when a blue light feedback device was used to inform bicyclists that their presence had been detected, but the sample size was too small to derive any meaningful results on the impact of bicyclist red-light violations.

No Turn on Red signs are used to restrict free right-turn-on-red movements at designated locations. The purpose of this treatment is to eliminate conflicts between right-turning vehicles and pedestrians or bicyclists when they have a concurrent walk phase. This treatment is also used when a bike box or left-turn queue box is present or when turning vehicles may conflict with high volumes of straight-ahead bicyclists. Research syntheses have documented that No Turn on Red signs lead to changes in motorist behavior that suggest improvements in pedestrian safety, but no studies have documented the effects of this treatment directly on vehicle-pedestrian crashes (P.-S. Lin et al., 2015; Mead et al., 2014; L. Thomas et al., 2016).

There is limited research on the impact of this treatment on bicyclist safety, but studies indicate that right hooks are common in many urban areas and research using crash data from New Orleans, Louisiana; Wisconsin; Ohio; and New York indicates that right-hook crashes involving bicyclists and pedestrians (including right on red crashes) increased substantially after free right-turn-on-reds were made legal (Preusser et al., 1982).

One study using a large naturalistic driving dataset evaluated the effect of four different signs about turning restrictions on motorist compliance and found that No Turn on Red signs had the highest rate of compliance. The other studied signs were Stop Here on Red, Turning Vehicles Yield to Pedestrians, and Right on Red Arrow After Stop (P.-S. Lin et al., 2015). Initial research indicates that dynamic signs, and static signs that take effect during certain times of day, are more effective at improving motorist behavior than static signs that are always in effect (Pecheux et al., 2009; Retting et al., 2002; L. Thomas et al., 2016).

Modern roundabouts

Roundabouts are circular intersections where vehicles travel counterclockwise around a central island and exit to an intersecting road. They are designed to reduce motorist approach speeds and their operating speeds in the intersection to improve yielding and decrease the severity of any crashes that do occur (Institute of Transportation Engineers, 2015). It is a proven safety countermeasure. They are a geometric form of yield-based traffic control, but some may have stop or signal control provided. Because motorists typically do not have signal or stop control, people walking and bicycling can have difficulties navigating along or across the intersection safely, especially at roundabout exits that typically do not have yield-inducing geometry. Modern roundabouts are growing in popularity as a design treatment for unsignalized intersections and an alternative to signalization because they typically have less delay and increase capacity. They can also reduce motorist speeds and reduce conflict points between users. The design of the roundabout heavily influences its impact on motorist speed and pedestrian and bicyclist comfort. Entry and exit radii and widths, roadway width, and circle diameter all affect motorist speed and yielding characteristics. *Roundabouts: An Informational Guide* (Rodegerdts et al., 2010) summarizes relevant research from Europe, which generally concludes that the safety benefits of roundabouts demonstrated for motorists extend to pedestrians, but the findings are more mixed for bicyclists.

Roundabouts and pedestrian safety

Roundabouts present a unique crossing environment for pedestrians because the crosswalks are typically unsignalized and existing geometries do not induce motorist yielding. These crossings can be particularly difficult for people with vision impairments (B. Schroeder et al., 2017). Roundabout design must clearly indicate the location of a crosswalk using accessible design practices, such as directional indicators and accessible pedestrian signals to help people with vision impairments cross safely. Single lane roundabouts are generally considered to be safer for pedestrians than multilane roundabouts, but there is limited research on the impact of single lane roundabouts on pedestrian safety from the United States. European studies indicate that single lane roundabouts have notably lower vehicle-pedestrian crash rates than traditional signalized intersections (Brüde & Larsson, 1999; Brüde, 2000). Multilane roundabouts present additional safety concerns for pedestrians due to the potential for multiple-threat crashes. According to one study, motorists in multilane roundabouts yield to pedestrians less than motorists in single lane roundabouts (Harkey & Carter, 2006). Pedestrian signals, raised crossings, and pedestrian-activated signals, such as PHBs are all suitable ways to enhance the safety of multilane roundabouts, particularly for people with vision impairments (B. Schroeder et al., 2017).

Roundabouts and bicyclist safety

There are few studies on roundabouts and bicyclist safety in the United States. Research indicates that roundabouts that do not slow vehicle speeds and/or do not provide physically separated spaces for bicyclists increase the risk of injury for bicyclists. Roundabouts where bicyclists are directed to share the lane with motorists may not be comfortable for all bicyclists and are not consistently associated with positive safety outcomes. Multilane roundabouts tend to have higher risks of injury for bicyclists than single lane roundabouts. In general, roundabouts that route bicyclists around them using separated bicycle facilities (separated bike lanes or sidepaths) are the safest options for bicyclists. Schramm et al. (2014) indicate that most bicycle-motorist conflicts in roundabouts occur between entering motorists and circulating bicycles.

Designs that reduce motorist speed on the approach/entry and the exits to the roundabout and maximize opportunities for bicyclists to be seen can improve safety. The priority rules between bicyclists and motorist may also affect bicyclist safety. For example, in some locations, bicyclists are given priority, in others, there is a shared yield responsibility, and in other locations, motorists are given priority. A literature review by Silvano et al. (2017) found there is no clear indication of which yielding rules are associated with safer conditions for bicyclists.

Corridor Safety Interventions

This section covers treatments that can be implemented along a corridor to improve the safety and comfort for people walking and bicycling. The treatments that have the biggest effect on safety are those that increase the separation between users and slow the operating speeds of motorists. The last treatment, smooth surfaces and good quality pavement, is important for preventing trips and falls and for ensuring that people walking and bicycling are able to maintain a predictable path of travel. Examples of corridor safety treatments include the following.

- Road diets/rechannelization
- Sidewalks and paved shoulders (for pedestrians)
- Advisory bike lanes and paved shoulders (for bicyclists)
- Shared lane markings
- Bike lanes
- Buffered bike lanes
- Separated bike lanes
- Shared use paths and trails
- Smooth surfaces and good quality pavement

Road diets/rechannelization

A road diet or rechannelization, is a reallocation of a roadway cross-section through a reduction in the number of motor vehicle lanes. They are typically used to reallocate existing dedicated motorist roadway space to better accommodate people walking and bicycling, reduce traffic speeds, improve overall roadway safety, and improve traffic flow. It is a proven safety countermeasure. The literature supports these uses and has documented reductions in *total* crashes and reduced operating speeds at sites with completed road diets (Harkey et al., 2008; Sanders et al., 2019). Road diets can reduce the crossing distance and can create space for access management treatments, pedestrian crossing islands, and bike lanes. While research has not determined a CMF for *pedestrian* (or bicyclist) crashes on roadways that were rechannelized, two- and three-lane roads are associated with reduced pedestrian crash risk when compared to roads with four or more lanes (Zegeer et al., 2002).

Corkle et al. (2001) and Knapp et al. (2001) reported reductions in mean travel speeds and 85th percentile speeds ranging from 1 to 4 mph after studying four-to-three-lane road diets in urban areas. A synthesis of six studies of road diets concluded that, in general, road diets effectively reduce motorist speeds and, in many cases, reduce crashes (L. Thomas, 2013). The synthesis indicates that the largest safety benefits may occur on roadways with a high density of driveways, multilane crossings, a history of severe crashes and/or vehicle-pedestrian crashes, and speeding. The synthesis also notes that vehicle volumes are typically not diminished by road reconfiguration projects. Chen et al. (2017) reviewed 460 sites and found that vehicle-pedestrian crashes reduced by 53% at treatment sites, compared to 4% at control sites. Studies of several lane reduction projects in Seattle have also shown significant decreases in traffic speeds, the percentage of motorists speeding, and in some cases, decreases in vehicle-pedestrian crashes (Sanders et al., 2019).

Sidewalks and paved shoulders for pedestrians

Sidewalks and paved shoulders create space for pedestrians to travel. Sidewalks are particularly beneficial for reducing crashes involving pedestrians walking along the roadway (Gan et al., 2005; McMahon et al., 2002). It is a proven safety countermeasure. Adding paved shoulders to a roadway has been shown to reduce vehicle-pedestrian crashes by 71% (Gan et al., 2005). Similarly, McMahon et al. (2002) found that the likelihood of a site with a sidewalk or wide shoulder (at least 4 feet wide) having a *Walking Along Roadway* pedestrian crash type was 88% lower than a site without a sidewalk or wide shoulder.

The presence of buffers (e.g., landscaping strip) between the sidewalk and roadway are often discussed as a key element of improving safety for pedestrians (real or perceived) (Zegeer et al., 2013). Research by Hanson et al. (2013) indicates that increased pedestrian injury severity is associated with a lack of sidewalks and buffers. It also shows that buffers may provide a safety benefit separate from that of sidewalks. Additional research is needed to assess the impacts of buffers on pedestrian safety.

Advisory bike lanes and paved shoulders for bicyclists

Paved shoulders are typically used in rural areas to provide space for bicyclists. Surface condition and appropriate design, such as the mitigation of irregular edges, drop offs, surface defects, and the appropriate use of pavement markers and rumble strips, are key considerations for bicyclist safety on these types of treatments (Colorado DOT, 2023). The presence of a paved shoulder is associated with a significant increase in perceptions of safe riding conditions (Akar & Wang, 2018; Landis et al., 1997). This trend held true among all types of survey respondents: males, females, and people who self-identified their bicycling experience as novice, intermediate, or advanced. The presence of a paved shoulder increased the likelihood of survey respondents reporting that a roadway environment was “safe” or “very safe” by 15% to 31%.

Advisory bike lanes are continuously dashed bicycle lanes that allow motorists to enter the bike lane to create space for an oncoming vehicle to pass safely on narrow, low-volume streets without center lines. They are most often used on streets with posted speed limits of 25 mph to provide space for bicyclists when right-of-way is limited (Williams, 2019). These treatments are rare, with less than 30 known advisory bike lanes installed in the United States, and evaluations have been sparse (Schultheiss et al., 2018). Williams (2019) identified six North American evaluations, the most robust of which was an evaluation of a pilot installation in Ottawa, Canada, that included a curb-side advisory bike lane on one side of a street and on the other side of the street the advisory bike lane was adjacent to a .5-meter buffer zone between a curb-side parking lane. The pre/post study by Kassim et al. (2019) documented greater lateral separation between users, decreased motorist speeds, and an increase in average bicyclist speed.

Shared lane markings

Shared lane markings, or “sharrows,” are pavement markings used to denote the intended bicyclist travel position in mixed traffic and to alert motorists that they should expect bicyclists in the travel lane. In some locations, shared lane markings are also used to mark the suggested path for bicyclists through an intersection. The literature indicates that standard shared lane markings are moderately successful at encouraging safe driving and bicycling behaviors and may only be appropriate in some situations (Duthie et al., 2010; Hunter et al., 2010, 2011; Kassim et al., 2017; Schimek, 2017). Research on roadway design preferences suggests that most bicyclists (current and potential) and motorists do not feel comfortable on multilane or higher-speed roadways with shared lane markings (Sanders, 2016). Ferenchak et al. (2019) suggest that shared lane markings are associated with a greater share of bicyclist injuries than conventional, buffered, or separated bike lanes. Duhn et al. (2017) examined the impacts of shared lane markings and different types of bike lanes on motorist behavior in Minnesota. The authors found that motorists on roadways with bicycle lanes were less likely to encroach into adjacent lanes, pass, or queue when interacting with bicyclists than motorists on roadways with shared lane markings or signs designating shared lanes.

Current guidance indicates that shared lane markings are suitable for low-volume, low-speed roads, like neighborhood greenways/bicycle boulevards, which are described below (Colorado DOT, 2023). Some cities have used alternative applications of the standard shared lane marking, sometimes referred to as “priority shared lanes” or “super sharrows.” These treatments typically use a higher frequency of symbol placement or place them in a green colored area of pavement to enhance the visibility and conspicuity of the marking. There are very few studies of these advanced shared lane markings because these treatments are rarely used, but research suggests they may have a small impact on discouraging sidewalk riding and encouraging bicyclists to ride in the center of the lane, instead of in the door zone (where an open door of a parked vehicle obstructs the path of the bicyclist) (Foletta et al., 2015; Furth et al., 2011). Additional research is needed to better understand the impacts of these types of treatments.

Neighborhood greenways/bicycle boulevards

Neighborhood greenways (also called bicycle boulevards) are low-volume, low-speed streets designed to be comfortable for bicyclists of all ages and abilities. They often include traffic calming treatments and enhanced street crossing treatments to improve safety. They are typically signed for bicyclists and include wayfinding and shared lane markings. In many cases these are local streets that run parallel to arterials or collectors. Research on perceived safety and comfort indicates that current and potential bicyclists often prefer bicycle boulevards to riding on arterial roadways without separated bike lanes (Blanc & Figliozzi, 2016; Winters & Teschke, 2010).

There are very few studies of conflicts involving bicyclists on neighborhood greenways, but research suggests that these facilities are associated with fewer bicycle-involved crashes than parallel arterials (Minikel, 2012). Research using GPS data from a nonrandom sample of 164 bicyclists in Portland indicates that, after accounting for trade-offs in topography, traffic volumes, and street network characteristics, bicyclists travel out of their way to reach bicycle infrastructure, this is especially true for bicycle boulevards (Broach & Dill, 2016).

Bike lanes

Bike lanes are designated spaces for bicyclists to ride along roadways delineated by pavement markings. While several studies have found that bike lanes improve bicyclist safety along corridors (L. Chen et al., 2012; Jensen, 2008; Nosal & Miranda-Moreno, 2012; Srinivasan et al., 2009), some studies show that bike lanes are associated with a greater number of crashes. However, most of these older studies do not account for factors such as exposure, and therefore may not be accurately representing the impact of bike lanes on bicyclist safety. Studies of bicycle facilities also sometimes fail to capture changes in the presence of on-street parking or bike lane treatments at intersections, both of which can affect bicyclist safety. As noted in The Role of the Environment section, characteristics of the roadway environment can influence the effectiveness of bike lanes, and like shared lane markings, bike lanes may only be perceived as comfortable by the bicyclist in some circumstances, such as along lower volume and lower speed roads.

Buffered bike lanes

Buffered bike lanes provide the same amount of protection as standard bike lanes; however, they include a horizontal, painted buffer, typically 1.5 to 3 feet wide, that separates the bike lane and motor vehicle travel lane. This additional separation between bicyclists and motorists may help bicyclists and motorists to feel more comfortable when traveling along the same roadway.

Buffered bike lanes are perhaps the least studied of all corridor bicycle interventions, and there are no studies of crash risk specifically on buffered bike lanes. However, research on perceived safety and comfort indicates that bicyclists and potential bicyclists prefer buffered bike lanes to standard bike lanes or shared lane markings. Results from a perceived safety survey of a random sample of bicyclists, potential bicyclists, and motorists indicate that when considering bicycling with children or driving, respondents reported that they would feel more comfortable on a roadway with a buffered bike lane on a four-lane roadway compared to a standard bike lane on a two-lane or four-lane roadway (Sanders & Judelman, 2018). While buffered bike lanes may feel more comfortable than standard bike lanes, they are not perceived as more comfortable than separated bike lanes (McNeil et al., 2015). Burbidge et al. (2018) reviewed case studies from across the United States and found that on roadways with buffered or separated bike lanes delineated by flexible, vertical posts, motorists generally gave bicyclists more space while passing and were less likely to encroach into the bike lane than when driving on roadways with other types of bicycle facilities, or no bicycle facilities at all.

Separated bike lanes

Separated bike lanes (also called protected bike lanes or cycle tracks) are buffered bike lanes with a vertical barrier between the motor vehicle travel lane and the bike lane. Separated bike lanes often receive the most support from bicyclists, and in some cases, motorists due the increased separation and comfort that these types of facilities can provide (Dill et al., 2014; Sanders & Judelman, 2018; Sanders, 2016). Some researchers have found that separated bike lanes are associated with safer driving behaviors compared to roadways with traditional or buffered bicycle facilities (Burbidge & Shea, 2018). These facilities are generally considered to be the safest on-street corridor treatment for bicyclists, both in terms of proven safety outcomes and perceived safety (Dill & McNeil, 2012; Goodno et al., 2013; Harris et al., 2013; Lusk et al., 2013; Marshall & Ferenchak, 2019; McNeil et al., 2015; Monsere et al., 2014; Sanders & Judelman, 2018). Separated bike lanes can be either one- or two-way facilities; however, most studies indicate that one-way facilities have fewer bicyclist crashes relative to two-way facilities (J. P. Schepers et al., 2011; B. Thomas & DeRobertis, 2013; Zangenehpour et al., 2016).

Shared use paths and trails

Shared use paths, trails, sidepaths, or multiuse paths are designated spaces for bicyclists (often shared with pedestrians). These facilities are often used by pedestrians and bicyclists of all ages and abilities because they are generally perceived as safe and comfortable since users are separated from motorists except when they cross at an intersection or midblock location. Results from a visual preference survey of randomly selected Michigan residents indicate that bicyclists and potential bicyclists would feel almost equally more comfortable bicycling by themselves, bicycling with children, and driving on a roadway with a sidepath or a separated bike lane compared to all other bike facilities (including the absence of bike facilities) (Sanders & Judelman, 2018). Similarly, crowdsourced comfort ratings of different bicycle facilities in Portland, indicate that separated paths were the most comfortable facilities of all facilities that participating bicyclists rode on (Blanc & Figliozzi, 2016).

Smooth surfaces and good quality pavement

Pavement and surface quality are important considerations at all places where bicyclists ride. As noted in Part 1, falls are usually not reported to police, yet make up a high percentage of bicyclist injuries (e.g., Cripton et al., 2015, found that 60% of bicycle-related injuries among adults treated at hospitals in two Canadian cities were solo bicycle crashes). Landis et al. (1997) developed a statistically calibrated level of service model for roadway segments based on real-time perceptions of bicyclists and found that pavement surface was among the factors found to significantly predict bicyclist perceptions of safety. Reynolds et al. (2009) reviewed more than 20 studies of factors affecting bicyclist safety and found that paved surfaces, along with street lighting and low-angled grades, were associated with increased bicycle safety. Hagel et al. (2015) found that riding on paved surfaces, as opposed to all other surfaces including unpaved, significantly decreased injury risk among bicyclists under age 18.

Pavement and surface quality are also important considerations for pedestrian facilities such as sidewalks and pathways. There are many safety issues that are directly attributable to poorly maintained pedestrian facilities. Improved safety through proper maintenance can be considered in two ways—reduction of crashes with motorists and the reduction in trips, slips, and falls. Poor pedestrian facility maintenance can have an equally profound impact on overall pedestrian mobility, particularly for people with mobility restrictions (Huber et al., 2013).

Part 4. Measuring and Monitoring Bicyclist and Pedestrian Safety

This section describes the methods used to understand bicyclist and pedestrian safety. The primary focus is on the types of data needed to quantify safety issues, pros and cons associated with various sources, and methodological considerations in studying traffic safety for these modes.

To understand traffic safety, three primary types of data are needed:

- Safety/outcome data, which describes crash events or proxies for crash events, such as near-misses.
- Exposure data, which describes the amount of activity in a place or by a group, which is an important predictor of crashes.
- Contextual data, which describes the environment in which travel occurs and can provide insight into potential risk factors associated with crashes.

The remainder of this section is organized as follows. First, some frequently used terminology is defined to preface the discussion. Next, details around safety/outcome data are discussed. The primary type of data in this category is police-reported crashes, although conflict or potential crash measures are also considered. Following that, exposure quantification is discussed. Finally, the last portion of this discusses commonly used methods for studying pedestrian and bicycle safety, both in academic research and in local safety planning efforts.

Safety Analysis Terms

The following terms are used extensively in safety data analysis. Each term is described, along with common uses that aid in analysis.

Exposure

Exposure describes the number of events that could potentially result in a crash. It can be quantified either at a person/cohort-level (e.g., number of miles traveled by female bicyclists in a city), or at a location-specific level (e.g., count of pedestrian crossings at an intersection). It is usually described in distance-based measurements, such as per miles traveled, or by time spent traveling. The use of these different measurements for exposure depend on the contexts and modes (Guler & Grembek, 2016). For example, vehicle miles traveled, or VMT, is often used for assessing exposure for motorists; however, because travel speeds and average distances are so much lower for people walking and bicycling than for motorists, measuring exposure based on distance traveled makes less sense for intermodal comparisons. Exposure for these modes is instead often calculated through temporal measurements (i.e., time spent walking or bicycling), which likely provides a better reflection of the extent of exposure due to the lower travel speeds. Exposure is a crucial aspect of analyzing crash risks because, all other factors being equal, greater use will increase the chance of a crash. High crash figures may simply reflect high pedestrian and/or bicyclist use. Alternatively, a corridor or intersection with low crash figures may be a result of actual or perceived danger that dissuades people from using the facility. Only with exposure data can crash risk—described below—be analyzed.

Risk

Risk describes the probability of a given exposure event resulting in a crash. Crash risk can be affected by various factors, including characteristics of the location where the exposure event takes place (e.g., presence of a traffic signal), characteristics of the parties involved (e.g., whether the motorist is impaired or distracted), and temporal factors (e.g., inhibited vision due to inclement weather). All these aspects are rarely known, so risk quantification typically focuses on a single dimension (e.g., comparison across user groups, comparison based on location types).

Crash Severity

Crash severity is a rating that summarizes the medical outcome of the worst injury sustained in a crash. Several different measurement scales have been used across agencies and regions. The most common scale for police report data is the KABCO Injury Classification Scale developed by the National Safety Council (Herbel et al., 2010). The crash severity levels are listed here.

- K – Fatal
- A – Incapacitating injury
- B – Non-Incapacitating injury
- C – Possible injury
- O – No injury

KABCO scores are commonly used by State Departments of Transportation as well as city and county agencies and police departments. The KABCO score, however, usually relies on the judgments of first responders; consequently, it can be inaccurate because it does not account for injuries that were not detectable in the field.

Another common crash severity metric is the AIS (Abbreviated Injury Scale) developed by the Association for the Advancement of Automotive Medicine and has been used since the 1960s. Unlike the KABCO Scale, the AIS system identifies the type, location, and severity of an injury and converts that to a six-point scale. It is, therefore, more detailed than the KABCO Scale.

Crash severity is important supplemental information to the number of crashes. A corridor or intersection may result in many crashes that cause minor injuries (either because of slow-moving, urban traffic characteristics or because of road geometry). Alternatively, a corridor or intersection may report a low number of severe crashes. Both cases require interventions, but crash severity analysis helps practitioners prioritize those interventions and determine specific strategies. In fact, some interventions may not reduce the number of crashes but may reduce the severity of crashes, which is a safety improvement that would not be identified without information on crash severity.

Safety Data

Outcome-based safety data are critical for understanding pedestrian and bicyclist safety. The most common type of outcome data is reported crashes, either through police-reports or self-reports from road users. Hospital records can be an important supplement, as not all crashes involve police response. In addition to these direct measures of safety-related outcomes, proxy datasets such as near-misses, reported perceived hazardous locations, and immersive technologies like instrumented probe bicycles, eye tracking glasses, and virtual reality environments can help to broaden our understanding of the relative safety of different roadway environments.

Police-Reported Crash Data

States receive crash data from local law enforcement and consolidate it into a consistent, statewide database. Some of these data are then aggregated at the national level into the FARS by NHTSA's National Center for Statistics and Analysis (NHTSA, n.d.-c). NCSA also produces a sample of all collisions involving passenger vehicles under the Crash Reporting Sampling System (CRSS), (formerly known as the General Estimates System or GES). Since 2014 NCSA has used the crash typing framework Pedestrian and Bicycle Crash Analysis Tool (PBCAT) to describe the events and maneuvers that led up to fatal bicyclist and pedestrian crashes (i.e., the crashes included in FARS) (see next subsection for more information on crash typing). States are encouraged to record and report crash data consistent with the Model Minimum Uniform Crash Criteria (MMUCC 5th edition), which is intended to lead to increased consistency over time (NHTSA, n.d.-a).

Police-reported crash data, when recorded completely, often has details on pre-crash maneuvers, crash dynamics, and crash locations. These details allow researchers to analyze the causes and correlations of a crash more effectively and to help agencies identify targets for treatment through roadway design or operational measures, lighting improvements, enforcement actions, vehicle assistive technologies, and other more upstream policies and strategies. Additionally, because police-reported crash data have been collected for many years, trends can be explored and easily analyzed. In some cases, police reports also collect demographic information, such as the race, age, and gender of involved parties, which can facilitate the understanding of the disproportionate impact of traffic crashes on specific groups.

Crash typing

Crash types are variables that describe events and maneuvers of the involved parties in the moments just preceding a crash. Historically, State crash databases derived from law enforcement reported crashes include variables describing the persons and vehicles involved, location and environmental characteristics, and time-related characteristics of crashes. However, information on the pre-crash maneuvers and conflicts have historically been lacking when pedestrians or bicyclists were involved in collisions with motor vehicles (Harkey et al., 2006). This circumstance is changing somewhat with recent national and State efforts to improve and standardize crash data, in part due to increasing implementation of MMUCC recommended crash data elements. But many States have yet to implement MMUCC recommendations on pedestrian- and bicyclist-related pre-crash variables. Among those that do record these variables, there is not much information available on the accuracy and completeness of these variables.

If key variables are collected, crash types may be derived from information entered at the time of the crash investigation by law enforcement agencies, as is commonly done for crashes involving only motor vehicles. Crash types may also be coded through post-crash review and analysis of crash reports, including crash diagrams and narratives, as is more commonly done with pedestrian- and bicycle-involved crashes.

Pedestrian- and bicycle-focused crash type variables are important since crash types are helpful in diagnosing safety issues (i.e., identifying crash patterns that may be targets for effective safety measures). The determination of crash types is valuable for (Sanders, Schultheiss, et al., 2020; L. Thomas, Sandt, et al., 2018):

- Understanding the type of situations that commonly put road users in the same space at the same time.
- Identifying those that lead to more severe outcomes.
- Analyzing the factors that may be contributing to common types so that appropriate treatments can be determined.

Crash type analysis has been used for spot-safety approaches (Sanders, Schultheiss, et al., 2020), neighborhood-based or zonal safety studies (Zegeer, Henderson, et al., 2008), more proactive safety approaches including systemic risk-based approaches (L. Thomas, Sandt, et al., 2018), and identifying design and operational policies to guide planning for safer networks (Shisler, Boulder DOT personal communication). For more information on the systemic risked-based approach, see the subsection, Systemic Analysis and Countermeasure Selection.

Although researchers can now characterize crash types leading to the most fatalities, it is difficult to place this information into a broader context, since there have been few studies that accounted for exposure to identify associated risks, and risks may vary across study areas. Predominant crash types may differ by geographies, injury severity, area type, lighting context, infrastructure facilities, vehicle fleet characteristics, and populations using the facilities. Enforcement and safety norms may also affect crash types (Saleem et al., 2018). Prevalent crash types have been found to change over time, even when study methods and areas were consistent (Preusser et al., 2002).

A brief history of pedestrian and bicycle crash typing is included as the appendix at the end of Part 4.

Disadvantages of police crash data

Data inaccuracy and incompleteness

Although police crash data have the advantage of being the standard used to measure safety, this data source has several disadvantages. First, police crash data rely upon the complete and accurate reporting of crash characteristics by law enforcement officers. Meta-analyses show that crash data often contain missing or erroneous information regarding crash locations and times, severity ratings, crash contributing factors, and involved individuals' demographics (Imprialou & Quddus, 2017). This results in researchers having difficulty determining how data limitations or inaccuracies in these fields impact analysis.

Second, States often do not follow the MMUCC voluntary guidelines for who is classified as a pedestrian and for what constitutes a pedestrian crash, which can lead to inconsistencies in comparing totals across States (Weissman-Pascual & Siegler, 2019). NHTSA defines a pedestrian crash as an incident involving one or more moving vehicles striking any person on foot, walking, running, jogging, hiking, sitting or lying down (NCSA, 2022c). The crash must have originated on a public traffic way and the definition of pedestrian does not include people using personal conveyances (e.g., wheelchairs, strollers, etc.). For example, researchers studied New Jersey's crash database and found that 20% of the total pedestrian fatalities for 2012 should not have been classified as pedestrian fatalities (Noland et al., 2016, 2017). Some were data input errors, although others followed the NHTSA definitions of a pedestrian crash, but likely would not be considered pedestrian-related in a planning decision-making context, either due to people being outside the public right-of-way or on access-controlled highways. Noland et al., argue that this definition is overly broad.

Third, police crash data often do not include incidents where people walking or riding a bike fall and injure themselves because a vehicle must be involved for the incident to be classified as a crash. Many people in the United States and worldwide suffer from falls, including falls incurred while avoiding a collision with a vehicle (Methorst et al., 2017).

Underreporting

Underreporting of pedestrian and bicycling-related crashes by those involved and first responders is very common. Several research efforts in and outside the United States have attempted to determine the level of underreporting by crash severity, underreporting variation by travel mode, and the reasons for underreporting. The prevalence of underreporting implies that crash data should be used carefully and in concert with other reliable data sources.

To help cover this gap, some communities in the United States and abroad have used hospital and EMS data to better understand crash outcomes and compare police crash data or insurance reports against medical intake records to identify aspects of the crashes that could inform engineering solutions, such as the built environment context. Several studies have documented that bicycle and pedestrian crashes are underreported in police databases by up to 50% (de Geus et al., 2012; Elvik & Mysen, 1999; Lopez et al., 2012; Sciortino et al., 2005; Stutts & Hunter, 1998). This underreporting is particularly germane to crashes that do not involve motor vehicles, such as solo bicycle crashes, but also often pertains to lower severity crashes that *do* involve motor vehicles. As discussed in Part 1, many bicycle crashes that do not involve vehicles are associated with falling to avoid a collision or colliding with infrastructure or surface features (Teschke et al., 2014). These types of crashes may still be roadway-related and therefore preventable through planning and engineering efforts.

In Europe, the pattern of lower reporting levels among bicyclists appears to be similar. For example, in the Danish province of Funen between 2003 and 2007, researchers studied road crash injuries that were registered in police databases, hospital databases, or both (Juhra et al., 2012). Bicyclists had lower reporting rates than motor vehicle drivers and more severe crashes corresponded with increased reporting rates. In Germany, Juhra et al. used similar methods to study bicycle crashes in Munster and found that the number of bicycle crashes in 2009 and 2010 was nearly double the number recorded in police databases.

Selection bias – Some researchers believe that selection bias—bias stemming from a non-random sample—is the reason for the discrepancy between the number of crashes in police crash databases and in hospital databases, as well as the discrepancy between police crash databases and insurance data (Tarko & Azam, 2011). In other words, the crashes reflected in a police database may not be reflective of all crashes due to the mechanisms by which police report a crash. This is especially relevant for bicycle and pedestrian crashes, which are known to be underreported. Selection bias also affects assessments of crash severity. For example, more severe crashes are likely to lead people to go to the hospital; those with less severe crashes would be less likely to do so.

Underreporting by group – The limited available research suggests that underreporting in police crash data is affected by demographics. A study conducted in San Francisco found that

Black pedestrians were less likely to be recorded in a police report than non-Black (Sciortino et al., 2005). Additionally, women were more likely to be included in a police report than men. While this report is suggestive of differences, research is relatively scarce on variables driving this difference in reporting.

Reasons for underreporting – There is less research on the reasons for underreporting than on the quantitative level of underreporting (Kaplan et al., 2017). A research effort in Denmark analyzed over 1,500 responses from bicyclists and found that nonreporting is associated with a belief that the data are not used for research and safety analysis, higher levels of police distrust, and an aversion to medical consultation. Researchers also found that many victims perceive that self-reporting crashes is time-intensive (or will take more time than is worthwhile for the benefit). This tendency to not report crashes is especially common for less severe crashes, which are already less likely to be reported than more severe crashes.

Hospital and EMS Data

As mentioned, hospital and EMS data are usually more accurate than police-reported crash data, especially for determining crash severity outcomes. Some hospital and EMS data sources also report significantly more information about the nature of an injury and crash than police-reported crash data. Hospital and EMS data, however, suffer from common drawbacks such as a lack of consistent coding, different severity ratings for one patient at different points in times, data transmittal problems between various EMS providers and hospitals, and underreporting as mentioned in the previous subsection. Health-related datasets are often deidentified, which makes it challenging to link them with other datasets (i.e., police-reported crash data). Sometimes linkage is possible by working with individual States or after negotiating data agreements. There are several common databases that researchers and practitioners can use to locate and analyze data. A description of each follows.

Hospital Discharge Data Systems

HDDS is a large database created by the American Hospital Association that records billing information of patients. The database records sources of patient injuries, health outcomes, and the estimated costs of injuries. This database may be related to other databases through probabilistic linkages, which is a method to identify the most likely match between records in one dataset with records in another dataset that are measuring the same events. However, specific linkages require signing data agreements because of HIPAA (the Health Insurance Portability and Accountability Act of 1996) (Cherry et al., 2018).

The National Trauma Data Bank

The NTDB is the largest database for severe injuries, which includes traffic crashes, falls, gunshot wounds, and other traumas (Cherry et al., 2018). Hospital participation is voluntary, but as of 2018, over 900 hospitals were submitting data and the database contained over 2.7 million records. Researchers can use the database after they apply through the website and receive approval from the American College of Surgeons' Committee on Trauma. Although some guidance on the data collection fields was issued in 2008, data submitted by institutions come from trauma registries with different formats and fields. Most hospitals submit demographic information, codes specifying injury cause, the medical procedures undertaken, diagnoses, length of stay, and in-hospital mortality. Some hospitals submit AIS, a common code that specifies injury type, location, and severity. Linking this data with police crash report data depends on the level of access to the data and the quantity and quality of information submitted by the hospital.

National Emergency Medical Services Information System

NEMSIS is a national database used for EMS data storage. It provides a universal standard for data collection of patient care information; local agencies and States use the required national elements but may also add other elements to meet local needs. For traffic crashes, EMS providers use a common format to record and transmit their data to NHTSA (Cherry et al., 2018). Most States routinely submit data into the NEMSIS database.

Web-Based Injury Statistics Query and Reporting System

WISQARS is an online, interactive database created by the CDC that allows researchers and the public to query crash, severity, and cost of injury data from numerous CDC-approved sources (CDC, 2019). Data are placed into WISQARS from the National Vital Statistics System. WISQARS is an effective source to derive and visualize absolute numbers of crashes, injuries, and fatalities.

Conflict Data/Surrogates

Surrogate indicators are measures that can point to crash potential even when a crash has not occurred or been reported, and therefore, they can be used in more proactive safety planning than can be achieved with crash data (Johnsson et al., 2018). While significant research exists on surrogate indicators for vehicle crashes, there is limited research on appropriate surrogate safety indicators for bicycle- and pedestrian-related crashes. Existing surrogate measures derive the severity of a traffic event from injury risk and collision risk. Collision risk is derived from initial conditions and evasive actions. According to a meta-analysis (Johnsson et al., 2018), relevant surrogate indicators for vulnerable road users, such as people who walk and bike, include:

- **Time-to-Collision (TTC)** – a metric that calculates the remaining time before a collision if relevant road users continue with current speeds and trajectories.
    - **TTCmin** – the minimum TTC value calculated in an event.
    - **Time-to-Accident (TA)** – the TTC value at the instant a user takes an evasive action.
- **Post-Encroachment Time (PET)** – when two users are on a crossing path, it is the time between when the first user passes the crossing point and the moment when the second user crosses that same point. (See Figure 9).
- **Deceleration** – slowing the speed of a vehicle; a common evasive action taken by drivers to avoid collisions.
    - **Deceleration Rate (DR)** – measures the magnitude of deceleration.
    - **Deceleration to Safety Time (DST)** – the minimal deceleration required for a driver to avoid a collision.

Most studies have found lower TTC values to be strongly associated with a higher crash frequency. Additionally, most studies have found a strong negative relationship between PET-related metrics and crashes. However, relatively few validation studies have focused specifically on crashes involving pedestrian and bicyclists. Many researchers use a combination of surrogate measures. Some standard composite indicators are the American conflict technique, the Canadian conflict technique, the Dutch conflict technique, and the Swedish conflict technique

(Johnsson et al., 2018). The American conflict technique, for instance, treats various evasive maneuvers as indicators of conflicts but does not account for exposure. The Canadian technique, on the other hand, uses a combination of the minimum time to collision (TTCmin) and a subjectively determined "Risk of Collision" evaluation to assess conflict severity.

Researchers are increasingly using sophisticated traffic simulation systems such as VISSIM to determine ideal PET and TTC metrics (Jiawei Wu et al., 2018). (Traffic simulation systems are computer programs that run models to predict traffic flow and road user interactions to help with planning and design.) These ideal metrics can then be field-tested with video data. Although traffic simulation systems can be used to estimate ideal traffic signaling, they have been shown to understate dangers to pedestrians because some human activities are uniquely difficult to model, such as crossing midblock and signal violations.

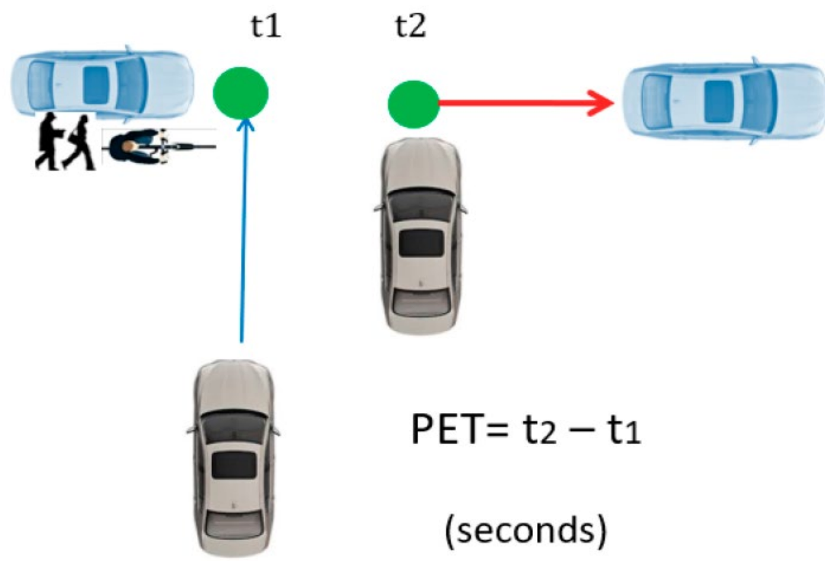

Figure 9. Post-encroachment time (PET)
Source: Scholl et al. (2019).

Research teams have begun to use automated reduction of video data to determine surrogate safety measures. For example, researchers used video measurements to determine PET along streets with separated bike lanes (Zangenehpour et al., 2016). They found that right-side cycle tracks in Montreal were significantly safer than streets without these facilities. This finding was confirmed with crash data. In 2017 another study by the same research team in Montreal used smartphone GPS systems attached to bicycles to analyze deceleration rates and their relationship to crash rates (Strauss et al., 2017). Areas with lower deceleration rates correlated with injuries along segments and at signalized and non-signalized intersections. In theory, smartphone-based GPS data collection has the potential to gather huge amounts of data, assisting with identifying dangerous intersections and corridors in a proactive manner. Correlation rates, however, were around 0.5 to 0.6 and reflect many "false negatives" so more work remains for this method.

Smartphone GPS data offer one avenue for gathering large amounts of data; drones, or unmanned aerial vehicles (UAVs), offer another. UAVs are flexible, inexpensive, and can easily be deployed to locations across sites. Researchers in China used UAVs to collect post encroachment time (PET) and relative-time-to-collision (RTTC) in an urban, high-volume intersection in Beijing, China (P. Chen et al., 2017). The downside of this data collection method is that drones introduce concerns over privacy and often hover at higher altitudes, which makes individual demographics difficult to collect. Drones also carry significant data collection permitting difficulties depending on Federal Aviation Administration and other rules.

Drawbacks of surrogate indicators for vulnerable road users

Surrogate measurements have drawbacks and none of them are appropriate for all situations. Assessing an incident's severity based on the outcome of the event (i.e., a crash outcome) is problematic because it erases the importance of evasive maneuvers and near misses – for vulnerable road users especially, the difference between a near miss and a severe crash can be minor. Conversely, some research attempts to predict crashes based upon the presence and magnitude of evasive maneuvers, or what is perceived as an evasive maneuver. This has two problems: braking, swerving, or sudden stopping does not necessarily indicate a near-miss, and conversely, the absence of such actions does not mean there is no danger. Finally, while there is clearly a relationship between surrogate measurements and crashes, no indicator can be universally applied in all situations, and the overall magnitude of the relationship is also unknown.

Public Surveys and Perceptions of Risk

Public surveys have been used to determine subjective measures of risk and potentially provide earlier detection of high-risk areas. Although objective measures of risk are often the goal in safety analysis, more subjective measures are also important because they provide insight to active transportation usage. Public surveys can also be employed to collect data on near-misses. A recent approach to surveying for near-miss data uses crowdsourcing websites that can gather this information. For example, in Victoria, British Columbia, researchers created an interactive website for residents to input data on bicycling collisions and near misses. This method provides researchers with more geo-located incident data than they would typically have access to. For example, in 2 months the website had captured more incidents (160) than the annual average available through the provincial vehicle insurance carrier (119 to 140) (Nelson et al., 2015). Researchers were satisfied with their finding that 50% of responses had all fields completed and another 10% had all but one field completed.

Surveys can also estimate areas with existing and emerging traffic safety problems. A study based around three college campuses found that crowdsourced locations perceived to be hazardous for bicyclists or pedestrians had statistically significant associations with survey-reported crashes and future police-reported crashes (Medury et al., 2017).

Online surveys can also be used to elicit more qualitative data; for example, a study of bicyclists in London used an online diary method to interview bicyclists about near-misses, emotions surrounding those near misses, future behavior changed from those near-misses, and suggestions on how to prevent those near-misses (Aldred, 2016).

Self-reporting and interviews can be combined with video data to offer a more nuanced view of crashes, near-misses, or uncomfortable situations (Hamann & Peek-Asa, 2017; Werneke et al., 2015). The interviews add qualitative information that can be difficult to determine from video footage while the footage can corroborate and provide depth to the interview.

The National Survey of Bicyclist and Pedestrian Attitudes and Behaviors, administered by NHTSA, provides a national-level snapshot of the bicycling and walking experience in the

United States for people 16 and older. The survey was last conducted in 2012 and is repeated approximately every 10 years.

Drawbacks of public surveys and perceptions of risk

Online diary or interview methods to determine perceptions of risk can take significant resources to summarize. Efforts to combine quantitative or qualitative data with video data can take even longer. Additionally, as with any broadly distributed surveys, issues of self-selection (biases in the subset of the population choosing to participate in the study) can come into play, and it can require a significant effort to achieve a representative sample.

Emerging Data Sources

In addition to the standard outcome data sources described above, researchers in recent years have attempted to assess pedestrian and bicycle safety using a variety of novel data collection mechanisms. These mechanisms generally focus on behavioral cues that might be indicators of decreased safety.

Instrumented bicycles

Several studies have used instrumented bicycles to study either specific behaviors (for example, how drivers and bicyclists behave when drivers pass) or more general behaviors (Chuang et al., 2013; Shackel & Parkin, 2014). Using naturalistic data can have greater reliability than self-reporting alone. It can also help researchers accurately determine exposure. Additionally, instrumented bicycles can pick up on small bicyclist movements that GPS may not record such as swerving behavior. Collecting data with instrumented bicycles, however, is expensive and requires a large sample size, either in number of people or recorded hours.

Eyetracking data

Eyetracking data methods use eyetracking glasses—with inward and outward-facing cameras—that can measure pupil dilation and movements, head movements, and length of time that a gaze was held (Baker, 2018). These micromovements can show how people riding bicycles see their environment and can identify dangers and sources of concern among bicyclists. Eyetracking data are expensive and can only be used on relatively small sample sizes.

Virtual reality

VR technology offers the potential to model human behaviors in areas or locations that would be expensive or difficult to measure in a real-world setting. Researchers have created pedestrian simulators that model pedestrian-vehicle interactions at crossings (Deb et al., 2017). These systems often receive and return information based on the subject's head position, movements, and orientation. When surveyed, participants in Deb et al.'s study ranked the VR system highly in terms of realism. Still, the movement simulated in VR can affect the subject and about 11% of people suffer from motion sickness. VR systems can be adapted to different conditions once the initial prototype is set up; however, they are expensive and require high-technology gear and development that cities and counties are unlikely to have at their disposal for many years. Research that uses VR to study behaviors like distraction and the effectiveness of education programs is mentioned in Part 3 of this report.

Network Data

While not a safety outcome measure, a comprehensive understanding of the transportation network is critical to enhance understanding of safety issues and to inform a proactive safety approach. A GIS dataset that details infrastructure and roadway data is essential for understanding the roadway conditions that bicyclists and pedestrians are exposed to. Incomplete, inaccurate, or outdated network data are a widespread issue for safety analyses. In response to this, FHWA has developed the Model Inventory of Roadway Elements, which details critical and desirable fields for understanding traffic safety issues (FHWA, n.d.-b). Some cities have created comprehensive safety databases to inform analysis, including both the requisite crash data and network data (Black et al., 2017; D. Morris & Wier, 2016).

Temporal discrepancies between datasets are another important consideration for safety analyses. Typically, several years of crash data are compared to network data that represents a static snapshot of built infrastructure conditions. For safety countermeasures, the installation date is a critical data point; analyses must take this date into account to avoid attributing crashes to the countermeasures they were installed in response to (Nordback, 2019).

Exposure Data

Exposure estimation is a critical step for contextualizing safety outcome data and for assessing crash risk. Exposure refers to a quantification of the number of events that could potentially result in a crash, such as the number of pedestrians crossing per year in a given crosswalk or the annual number of bicycle miles traveled throughout a city. All else being equal, higher rates of exposure tend to result in more crashes. The “safety in numbers” effect impacts this relationship, as described in Crash Risk: The Relationship Between Crashes and Exposure below. Exposure complicates the study of crash data, as two locations with the same frequency of crashes could have dramatically different rates of exposure and crash risk.

Exposure is an important component of risk assessment that has historically been omitted from bicycle and pedestrian safety analyses in the past because of practical challenges in estimating and collecting exposure data (Turner et al., 2018). The FHWA project *Scalable Risk Assessment Methodology for Pedestrians and Bicyclists* provides a thorough overview of the topic (Turner et al., 2018). Exposure is a critical consideration for nonmotorized safety analyses because bicycle and pedestrian infrastructure improvements often capitalize on latent demand and can result in increased pedestrian and bicyclist volumes.

Crash Risk: The Relationship Between Crashes and Exposure

In general, most researchers agree on the theoretical definition of risk as “a measure of the probability of a crash to occur given exposure to potential crash events” (Turner et al., 2017). Exposure is commonly used as the denominator by which crash events are normalized. This normalization provides the probability of crash events per unit of exposure (ISW8, 2017; Turner et al., 2017). The relationship between crash events and pedestrian and bicyclist exposure is not always linear,—as exposure increases, the crash events per unit of exposure may decrease (ISW8, 2017; P. L. Jacobsen et al., 2015). Elvik et al. (2017), conducted a systematic review and meta-analysis to demonstrate that the “safety in numbers” effect is indeed defensible. A literature review on the effect concluded that the effect differs by mode and appears to be stronger for bicyclists than pedestrians (Kehoe et al., 2022)

Although risk and exposure are closely related, they are two different concepts. Risk is defined as “the probability of a dangerous event occurring” (Raford, 2003). Exposure can be thought of as the rate of contact with a potential crash event. A high-risk environment may have low pedestrian exposure yet, there may still be a greater likelihood of a harmful event than in the case of a low-risk situation with high exposure. For instance, a small number of pedestrians crossing a dangerous highway intersection have a higher chance of being involved in a collision when compared to a larger number of pedestrians crossing a busy yet safely designed intersection (Raford, 2003).

It is important to consider exposure to quantify relative risk as jurisdictions allocate their resources for safety enhancements at high-crash locations. In addition to informing prioritization among high-crash locations, exposure data can also provide more accurate understanding of crash trends over time and help jurisdictions understand the safety impacts from countermeasures that have been implemented. Raford et al. (2004) illustrate this concept using the image depicted in Figure 10. If a jurisdiction were to allocate funding based on the absolute number of crashes alone, they would prioritize Intersection B, which sees 20 collisions each year. However, when normalized by exposure, Intersection A, which only has 10 collisions each year, has a higher likelihood of a collision and is more dangerous by volume (Raford & Ragland, 2006). In practice, jurisdictions often consider the locations where safety improvements can be made most effectively. This determination is often based on a benefit/cost calculation, where the “benefit” is based on the crash reduction potential of the safety improvements in question, and the “cost” refers to the implementation costs of the safety improvements. In that light, if Intersection A required a significantly more expensive safety treatment than Intersection B, it may not be prioritized above Intersection B due to practical limitations.

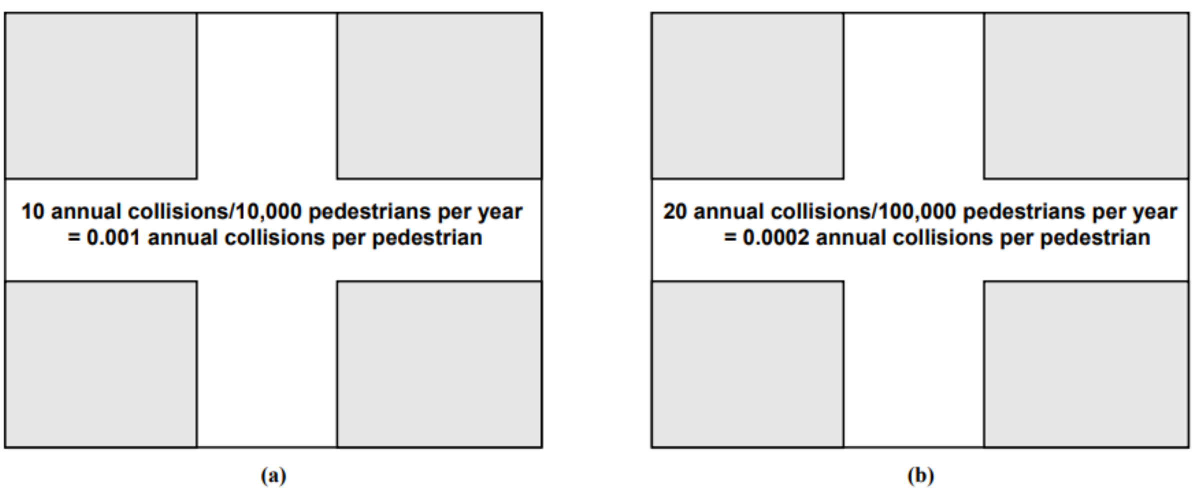

Figure 10. Pedestrian risk as a function of exposure: (a) Intersection A and (b) Intersection B
Source: Raford et al. (2004).

Pedestrian and Bicycle Exposure Definitions

Exposure for pedestrian and bicyclist crash risk has been operationalized in a variety of ways, including: pedestrian or bicyclist volume, travel distance, time traveled, number of pedestrian or bicyclist trips, and population (as measured by the number or percentage of people who walk or bicycle on a regular basis), among others (Turner et al., 2018). Exposure estimation commonly relies either on existing data sources (e.g., travel surveys and Census data) or data that are feasible to gather or estimate (e.g., from direct counts or models) (Turner et al., 2017). The *Guide for Scalable Risk Assessment Methods for Pedestrians and Bicyclists* provides a selection matrix to assist agencies with identifying the proper exposure measure to use in a given context (Figure 11).

Use of different exposure metrics has been found to lead to different estimates of risk, even when comparing the same mode (Greene-Roesel et al., 2007). The choice of exposure metric is particularly important when aiming to understand relative exposure between modes. For instance, a time-based metric allows for a normalized comparison between pedestrian travel versus automobile travel—people walking travel shorter distances at a slower speed than car users (Guler & Grembek, 2016). Guler and Grembek (2016) confirm qualitative research of time-based and trip-based methods with quantitative results obtained by using travel survey data and police crash reports for 10 counties in California. Based on the quantitative results, the authors argue that a time-based metric offers the best understanding of travel risk characteristics of different modes and that time spent traveling is a powerful explanatory variable used to evaluate the risk of a given mode across counties.

Category of Exposure Measure	Typical measures	Typical scale				Typical data sources
		Point	Segment	Network	Region	
Distance Traveled	Miles of travel	○	●	●	●	• Site counts or demand estimation models, multiplied by segment length • Sometimes travel surveys
	Miles crossed per entering vehicle	◐				
Time Traveled	Hours of travel	○	○	●	●	• Travel surveys • Sometimes site counts combined with crossing time or average travel speed data.
	Product of crossing time and vehicle volume	○	○			
Volume/ Count	Volume/count	●	●			• Site counts • Demand estimation models
	Product of pedestrian /bicyclist volumes and motor vehicle volumes	◐	◐			
Trips Made	Number of trips			●	●	• Travel surveys
Population	Number of people that walk or cycle on regular basis			●	●	• U.S. Census data products
	Percent of the population that walk or cycle on regular basis			●	●	

Legend: ○ = to a small extent; ◐ = to a moderate extent; ● = to a great extent.
Note: Each exposure measure will be for a defined time period that matches the risk definition.

Figure 11. Matrix for selecting exposure metrics
Source: Turner et al. (2018) partially adapted from Greene-Roesel et al. (2007).

Geographic scale is another important consideration for defining and estimating exposure. The scale of analysis can vary from the road segment or intersection/midblock crossing level to broader areas (e.g., Census tracts, traffic analysis zones) and regional areas (e.g., cities, counties, or metropolitan statistical areas). In general, analysis at larger geographic scales produces information about broad safety trends, while finer-grained analysis of specific transportation facilities (generally conducted across an entire city) are most often used to prioritize safety improvements. The availability and feasibility of obtaining data vary based on the geographic scale being analyzed, which likely explains the wide variety of exposure metrics used (Turner et al., 2017).

Methods to Estimate Pedestrian and Bicyclist Exposure

There are a wide variety of analytical methods that can be used to quantify exposure. The most appropriate analytical method will depend on the purpose and scale of analysis, the exposure metric used (as discussed above), available resources, data availability, the technical capabilities of staff, and the modes of travel being analyzed.

Count data collection

Count data, either as a standalone data source or in conjunction with other modeling methods, is among the most commonly used exposure metrics, and is typically used to estimate bicycle and pedestrian exposure for specific transportation facilities (Turner et al., 2017, 2018). Greater detail on methods to collect pedestrian and bicycle count data can be found in the FHWA *Traffic Monitoring Guide* (FHWA, 2016), NCHRP Report 797 (Ryus et al., 2014), and the FHWA *Exploring Pedestrian Counting Procedures* (Nordback et al., 2016).

Though the practice of nonmotorized counting has advanced in recent years, it is not yet systematic or widespread in the United States and is not nearly as widespread as motorized traffic monitoring (FHWA, 2016).

Pedestrian and bicycle volumes can be used to quantify exposure and develop crash rates that allow measurement and comparison of before and after safety impacts from facility upgrades. In an example of this approach from Montreal, pedestrian and bicycle count data were used to evaluate the expected change in injuries from changes in intersection demand and infrastructure characteristics, finding that locations with higher bicycle volumes have lower bicycle crash risk lending further support to the Safety in Numbers theory (Strauss et al., 2014).

A key limitation of basing exposure on count data is that it does not account for the amount of time spent walking or biking or, in many cases, the distance traveled (Greene-Roesel et al., 2007). It also does not account for how frequently people cross paths with motorists. Count data can also be used to estimate pedestrian or bicycle miles traveled for regional exposure metrics, but does not provide the full view needed to estimate time spent traveling (Lindsey et al., 2013).

One of the key challenges with nonmotorized count data collection is the selection of count locations. Often, nonmotorized count data are collected at a small number of locations that are not easily translated to represent larger areas or additional locations. This lack of systemwide data impedes development of better predictive methods for pedestrian and bicycle crashes (Ryus et al., 2014). In addition, locations are often selected based on high pedestrian and bicycle activity, which may provide a biased estimate of usage (FHWA, 2016). Pedestrian and bicyclist travel patterns are not constrained to a given path and pedestrian activity, in particular, is localized in nature, posing additional challenges for location selection (FHWA, 2016; Nordback et al., 2016).

Technology limitations also pose challenges for nonmotorized count data collection. While error rates associated with many count technologies are well documented through projects such as NCHRP 797, *Guidebook On Pedestrian and Bicycle Volume Data Collection* (Ryus et al., 2014), some count technologies are still not thoroughly tested. Recently developed video-based systems, in particular, warrant additional testing. Additionally, groupings of pedestrians and bicyclists are difficult for sensors to capture (FHWA, 2016).

Bottom-up/survey-based

Travel survey data are commonly used for areawide exposure analyses, and typically rely on data from one or more of these sources: American Community Survey (ACS), National Household Travel Survey (NHTS), or regional household travel surveys. Results from several surveys may be combined to provide a more complete picture. For instance, some analyses combine ACS data (which includes primarily journey-to-work trips) with NHTS data (which includes all trips). Count data have also been incorporated with survey data to better inform exposure analyses (Turner et al., 2017).

Travel survey data have several advantages for estimating exposure: the data are computationally simple, do not require specific software or expertise, and are based on available data, making the use of travel survey data practical and easy to apply (Turner et al., 2017). On the other hand, because surveys sometimes do not capture very short trips (due to recall bias) or recreational trips (due to emphasis on weekday travel patterns), survey-based volumes may be underestimates (Nordback et al., 2017). Additionally, if respondents who are likely to walk or bicycle are not oversampled in a survey data collection effort, the results of exposure estimates from survey data may be imprecise due to the relative infrequency of these trips. In addition, consensus has not been reached as far as the most appropriate unit for this method. The number of pedestrian or bicyclist trips is a commonly used metric; however, there is variation in how this metric is defined, with some analyses reporting solely on work trips and others reporting on all trips. Pedestrian and bicyclist miles of travel or hours of travel have also been used as metrics (Turner et al., 2017).

When estimating bicycle and pedestrian miles traveled (BMT and PMT), use of count data in conjunction with sample-based estimation offers the most accuracy for estimating BMT, and, because of the difficulty of capturing pedestrian activity by counting, survey data are more appropriate for estimating PMT (Nordback et al., 2017).

Trip-based travel demand modelling, another bottom-up exposure estimation approach, typically consists of four key steps: trip generation, trip distribution, mode share, and traffic assignment. These models have traditionally had limited accuracy in estimating nonmotorized travel, but recent enhancements have attempted to address these issues. These advances include enhanced trip generation models that incorporate land use factors and auto ownership models as an input for estimating nonmotorized trip production (Turner et al., 2017).

Direct-demand modeling

Direct-demand models use regression analysis to relate measured counts of people walking and bicycling to other measured factors, such as transportation and built environment variables, socioeconomic characteristics, weather, and topography. Although a variety of modeling approaches have been used, most studies acknowledge negative binomial models as suitable for predicting pedestrian and bicyclist volume (Munira & Sener, 2017). Studies have explored a wide range of explanatory variables, and several have found that density, accessibility, and proximity to destinations influence pedestrian models. Bicycle models were also influenced by these factors in addition to transportation characteristics such as bicycle lanes, traffic volume, and level of traffic stress (Turner et al., 2017).

Direct-demand models are simple to develop and apply and the necessary data are typically available (Turner et al., 2017). These relatively simple tools enable prediction of nonmotorized traffic in areas where count data are not available, and allow facility-specific counts to be extended to all facilities citywide (Munira & Sener, 2017; Turner et al., 2017). There are, however, disadvantages to these models as well. They are not transferable far into the future or for large areas because inaccuracies can result from differences between people and locations (Munira & Sener, 2017). In addition, activity patterns vary based on location and direct-demand models fail to capture the cause of behaviors represented by non-motorized counts. Kuzmyak et al. (2014) provide several guidelines that can be used to ensure quality analysis when using direct-demand models, one of which includes testing the reliability of the model's ability to predict at specific locations and for the overall study area (Kuzmyak et al., 2014; Munira & Sener, 2017).

Network analysis and space syntax models

Network analysis models are a variation of the four-step travel demand modeling approach based on a representation of the pedestrian or bicycle network (Turner et al., 2017). These models are used to estimate pedestrian exposure by estimating volumes either for individual street segments or for an areawide analyses.

The space syntax model, which was developed by a group of architects and urban theorists in the mid-1980s, is the most widely used network analysis model (Turner et al., 2017). Turner et al. (2017) describe the space syntax model as using "spatial characteristics and relationships to explain the route chosen." Space syntax models are suitable for estimating exposure because they can assign volumes to every street throughout large urban areas. Space syntax models are particularly useful for estimating volumes for future conditions and in areas that lack data. Further research is necessary to verify the accuracy of this approach and to better understand the financial and information management resources required for this model (Raford & Ragland, 2006). Several measures can be used to operationalize the space syntax concept and the choice of measure can significantly affect outcomes (Sharmin & Kamruzzaman, 2017).

Raford et al. (2006) used the space syntax model to accurately describe changes in pedestrian volumes after "the Big Dig" project in Boston. Relatively few studies have used space syntax to understand bicyclist route choice. A 2007 study found a correlation between space syntax measures and aggregate bicyclist volume in London (Liu et al., 2016; Raford et al., 2007). Space syntax does not see widespread use domestically but has been used with relative accuracy in hundreds of large-scale real-world projects in Europe and the United Kingdom (Raford & Ragland, 2006; Turner et al., 2017). Raford et al. (2006) suggest this is because of the specialty software required and because the model is not intuitive for transportation planners, since it does not follow the traditional trip generation and distribution steps.

Crowdsourcing from mobile devices

Crowdsourcing from mobile devices is an innovative and emerging method for gathering walking and bicycling activity data for exposure estimation. There are two approaches to crowdsourcing data: passive monitoring and active monitoring. Passive monitoring relies on location-based services' information from commercial applications such as Google Maps and Facebook. Companies that work in this domain use GPS records associated with smartphones to provide location analytics and insights on behaviors and trends. Active monitoring requires the device user to initiate an application that gathers walking, bicycling, or jogging activity. These applications are typically used for fitness tracking (Turner et al., 2017).

Because passive monitoring does not require users to initiate a specific application, it captures a larger and less biased dataset than active monitoring. Still, certain population groups may be underrepresented in passive monitoring data, including older adults, low-income people, and children. It is also difficult to determine the users' travel modes. Although active monitoring is better able to differentiate travel mode and provides more demographic data, Strava data have been found to be biased in terms of age, gender, and geographic use across a city (Boss et al., 2018; Turner et al., 2017). Despite the small fraction of riders captured by Strava data, Jestico et al. (2016) offered evidence of its reliability. This research found a strong correlation between manual counts and Strava data in Victoria, British Columbia. The authors conclude that bicyclists using fitness apps use similar routes compared to commuter bicyclists in urban areas. A similar evaluation of passively collected GPS data from StreetLight data against permanent bicycle counters in Texas also found promising results (Turner et al., 2020).

Further comparison between crowdsourced data and conventional data has found higher similarity in areas with low population density, greater disadvantage, and low ridership (Conrow, Wentz, et al., 2018). Even in cases when the data may be similar, Watkins et al. (2016) stress the importance of comparing data obtained from bicycling applications with other local data sources and weighting it appropriately. Strauss et al. (2015) proposed methodologies that combine GPS data with short-term and long-term counts. This finding supports the recommendations of Watkins et al. (2016).

Miscellaneous approaches

Other approaches to estimate pedestrian and bicyclist exposure include estimating volumes using Google Street View images, extracting counts from traffic monitoring cameras, and using pedestrian and bicycle detection at signals. Yin et al. (2015) use machine learning to extract pedestrian volumes from Google Street View images, which they found to be a reasonably accurate estimation method.

Pedestrian crosswalk pushbutton actuations have also been used to estimate pedestrian volumes. When using this approach, actuations need to be factored to account for pedestrians crossing during each phase (Turner et al., 2017). When studying the relationship between pedestrian and bicycle counts at an intersection in Portland with pedestrian phase actuations and bicycle lane signal actuation inductive loops, Blanc et al. (2015) found that an average of 1.24 people cross during each pedestrian actuation phase, although this value likely varies widely depending on location and time of day. Day et al. (2014) developed a statistical model to predict pedestrian signal actuator counts at a specific site based on weather, special events, changes in activity patterns, and changes in traffic signal phases. They concluded that although pedestrian signal actuation is an imperfect surrogate measure of pedestrian volumes, it provides insights on relative changes to pedestrian demand and, at intersections with existing pedestrian-actuated phases, these insights can be gleaned cost-effectively. Turner et al. (2017) indicated that more research is necessary before the pedestrian-actuation method of estimating volumes is widely implemented.

Methods for Studying Pedestrian and Bicycling Safety

In analyzing traffic safety, the methods to be used depend on the question being answered. Some of the most common questions that arise in studying pedestrian and a bicycle safety include these questions.

- What are the overall safety trends in a locality?
- Which locations should be prioritized for safety improvements?
- Which countermeasures should be implemented at identified locations?
- What is the change in crash risk associated with a countermeasure/what is the relative risk associated with different types of infrastructure?
- What is the crash risk associated with a behavior, demographic, or other contextual variable?

These questions can broadly be classified into two categories: those that intend to yield generalizable results, and those that drive practical decision-making in a given jurisdiction. This section describes some of the commonly used tools and methods for identifying and addressing pedestrian and bicyclist safety needs in a community, and some of the commonly encountered problems associated with performing these studies.

Prioritizing Locations

Crash heatmaps

Countermeasure selection is largely dependent upon location, and practitioners need to identify the most dangerous areas of the community. Several studies have examined how best to identify these areas. To accurately measure danger, researchers must consider pedestrian and bicyclist volumes and differentiate locations based on rates (i.e., exposure). For example, researchers from the University of California, Los Angeles, analyzed bicycle crash incidence and risk at over 1,000 intersections and roadway segments in Los Angeles County (Liggett et al., 2016). They created a heat map of crashes and then studied the relationship between those crashes and roadway design and operational characteristics, land use patterns, and socioeconomic variables (normalized by bicycle volume data). Generally, the locations with the highest crash risk have below-average bicycle ridership. For some variables, absolute numbers of crashes and crash rates coincide (for example, dedicated right turn lanes or the presence of transit stops). For others, absolute numbers and rates tell a different story (as is the case for the presence of bikeways, which are associated with more crashes, but much higher ridership). The researchers conclude that communities should not automatically assume that high crash numbers make an area or corridor a priority for installing countermeasures. Instead, looking at rates could lead to different conclusions. Specifically, they argue for focusing on moderate ridership corridors with high crash risk and in the absence of State or regional bicycle counting efforts, implementing local bicycle counting. This would allow analysts to differentiate high-risk/moderate volume sites from low-risk/high-volume sites.

Heatmaps are an effective and visual way to show areas and corridors of concentrated crashes (Figure 12). However, as researchers have shown, methods for determining hot spots are often computed based on thresholds used for vehicle travel, which can create problems for pedestrian hot spots in particular. Specifically, heatmaps are usually created through the "network screening" model, whereby a window of fixed length is adjusted along a road network; the number of crashes per area are calculated and smoothed, creating a heatmap. However, this method is better suited for vehicle crashes because its inputs are based around long, linear corridors, causing it to potentially miss localized, small-scale hotspots in the pedestrian network. Researchers used a dynamic programming method that can incorporate network constraints and objectives to provide efficient hot spot definitions for pedestrian crashes. When compared to other methods, dynamic programming was able to generate more hot spots based on higher numbers of crashes, while providing smaller hot spot segment lengths (Medury & Grembek, 2016).

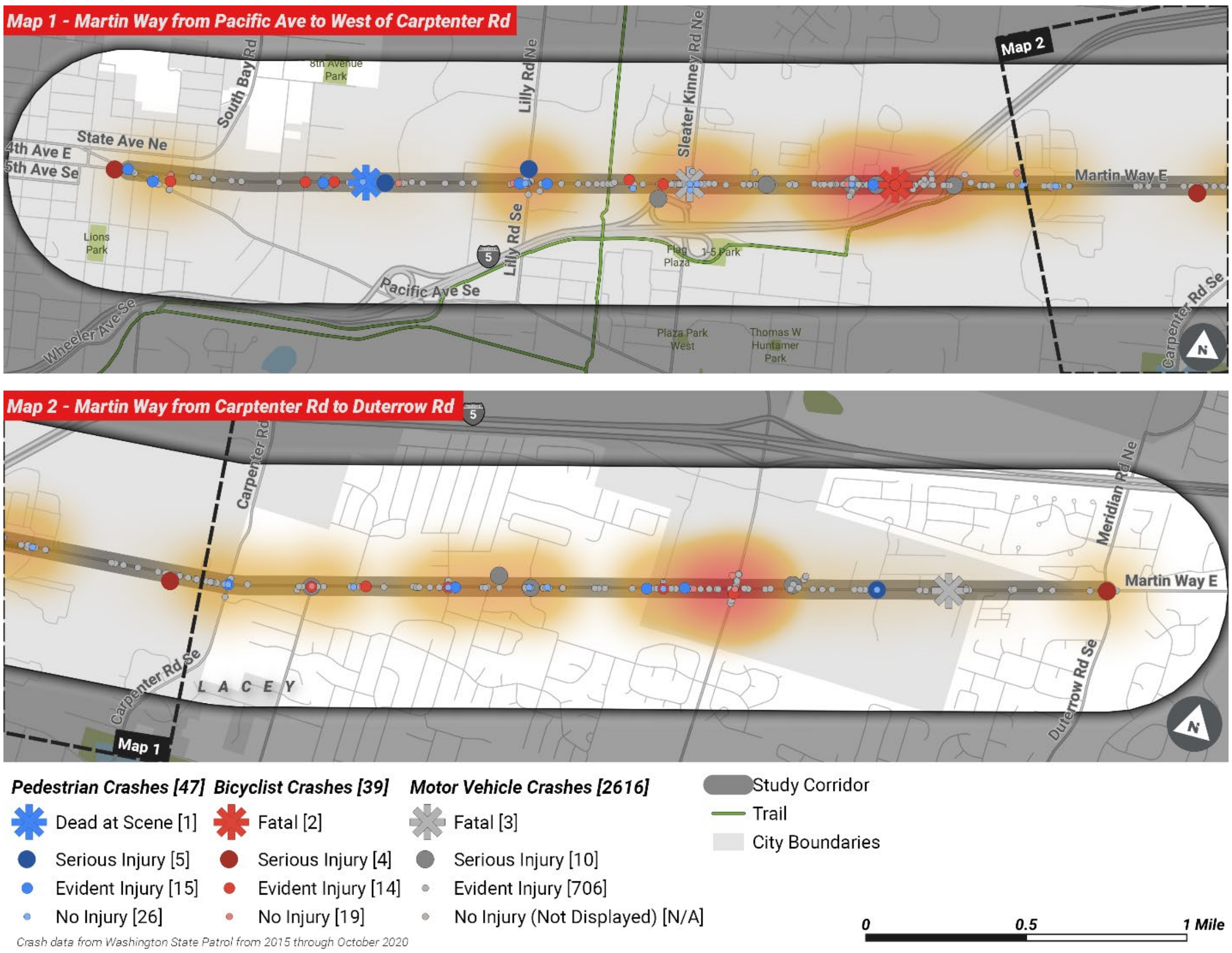

Figure 12. A heatmap displaying pedestrian, bicycle, and motorist crashes
Source: Toole Design.

Heatmaps can also be used to identify possible land use, roadway, and socioeconomic proxies, which can then be used in future safety analyses. For example, researchers in 2009 used this method to identify 32 hotspots in Vancouver that they then used to show that most hot spot locations lacked passive pedestrian safety measures like crosswalks. The study also found an association between density of bars with pedestrian injury, supporting the findings of other studies (Schuurman et al., 2009). A similar study in Washington State used hot spot analysis to determine that pedestrian and bicycle collision locations were associated with intersections (as opposed to midblock) locations, on wider roads, on roads with bicycle lanes, and in low-income and non-white neighborhoods (Moudon & Kang, 2017).

Safety performance functions

SPFs are statistical equations that express the expected number of crashes at a given location as a function of traffic volume and roadway characteristics. SPFs specifically for pedestrian and bicyclist infrastructure are not covered in AASHTO's *Highway Safety Manual* (2010), and various locally developed SPFs also exist. SPFs are useful in prioritizing locations as they can help to inform accurate estimates of the expected number of collisions at a given location. The updated AASHTO manual was published in 2023 under the title, *Pedestrian and Bicycle Safety Performance Functions* (NCHRP Report No. 1064, MRIGlobal et al., 2023).

In the absence of overarching nationally defined SPFs for pedestrian and bicycle facilities in the *Highway Safety Manual* (AASHTO, 2010), researchers have attempted to create SPFs at the State or community level. For example, a 2014 study examined bicyclist safety at Boulder, Colorado's signalized intersections. This study developed SPFs based on motor vehicle traffic, bicycle traffic, and other factors. SPFs were then tested for sensitivity, and the researchers found that motor vehicle and bicycle volumes and bicycling collisions are related, but that individual risk decreases as bicycling use increases (Nordback et al., 2014). In a study in Michigan, researchers first estimated nonmotorized volumes through land use proxies such as WalkScore measurements, bicycle and pedestrian facilities, and demographic data. The studies were limited to urban intersections statewide, and SPFs were recommended after validation (Kwigizile et al., 2016).

Another study used existing SPFs from the *Highway Safety Manual* to determine if the SPFs could accurately describe crashes at urban and suburban intersections in Massachusetts (Xie & Chen, 2016). Using calibration scores, the researchers found that the SPFs could not; actual crashes in Massachusetts were higher than predicted by the national SPFs. The researchers then developed more accurate SPF scores for single-vehicle, vehicle-bicycle, and vehicle-pedestrian crashes. This shows that although national guides can be used as a starting point, practitioners should not assume they apply to local contexts without careful consideration.

Crash Modification Factors

While SPFs are formulas that describe relationships between crashes and crash inputs, Crash Modification Factors (CMFs) are single numbers that describe how the presence of safety interventions modify the chance of a crash (i.e., increase or decrease risk). Key limitations of CMFs for pedestrian and bicycle countermeasures include: (1) low crash frequencies at potential treatment sites, (2) poor exposure data to develop the SPFs needed for CMF development, (3) small samples of treatment sites, and (4) poor recordkeeping on treatment installation (e.g., date or exact location) (Nordback et al., 2019).

CMFs are usually presented from a base of 1.0 (meaning that with no intervention in the built environment, there will be 100%—the same number—of crashes). A CMF lower than 1.0 indicates a *decrease* in crashes, while a CMF higher than 1 indicates an *increase* in crashes. CMFs higher than 1.0, while less common than those below 1.0, may partially be a result of higher facility use (leading to more crashes), or a result of a certain intervention leading to more crashes generally, but less severe crashes (as is the case for traffic circles, for example). The impact between safety interventions and crashes can also be described through Crash Reduction Factors (CRFs), which take the CMF and convert it to a percentage increase or decrease (a countermeasure that reduces crashes will report a negative CRF, while a countermeasure that increases crashes will report a positive CRF).

CMF Clearinghouse

While CMFs and CRFs are useful for practitioners to assess the efficacy of countermeasures based on location and roadway characteristics, it can be difficult for practitioners to identify these metrics and evaluate the quality of research behind these metrics. Additionally, numerous studies—each with different methodologies, assumptions, and data quality inputs—complicate the overall picture. The Crash Modification Factors Clearinghouse consolidates and summarizes available CMFs (FHWA, n.d.-a). Users can search countermeasures and bring up all the relevant CMFs and CRFs; they then can access the studies from which these figures came. The website, www.cmfclearinghouse.org, also provides rankings for each source based on objective qualities of the research (e.g., the number of sample points and the p-value, if applicable). Users can also compare studies of the same countermeasure based on filters and download the spreadsheet.

The CMF Clearinghouse contains values associated with various pedestrian- and bicycle-related countermeasures and indicates whether each CMF is associated with all crashes or just vehicle/pedestrian or vehicle/bicycle crashes. However, many of these measures have low quality ratings, and several bicycle countermeasures are cited on the list of "most wanted" CMFs to be added to the database, indicating the need for additional research.

Systemic Analysis and Countermeasure Selection

In NCHRP Report 893, *Systemic Pedestrian Safety Analysis,* researchers identified the systemic analysis method for safety analysis as a more proactive approach to improving roadway safety than the hot spot method (L. Thomas, Sandt, et al., 2018). While this report is written with pedestrian safety in mind, the same principles apply to analyzing bicycle crash data as well. A systemic approach involves agencies proactively determining risk factors associated with pedestrian- and bicycle-related crashes, identifying where those risks exist on the network, and then picking context-sensitive countermeasures that can lessen those risks. The report notes seven steps of the process.

1. Define study scope
2. Compile data
3. Determine risk factors
4. Identify potential treatment sites
5. Select potential countermeasures
6. Refine and implement treatment plan
7. Evaluate program and project impacts

This approach has the advantage of being more comprehensive, cost-effective, and proactive than the hot spot method. The systemic method has been used in States like Oregon (described in the next paragraph), and in cities like Seattle (Seattle DOT, 2016). Since pedestrian and bicycle crashes can still be relatively infrequent at the site-specific level, crash types are perhaps most valuable for a systemic safety analysis since in this type of approach crash data from an entire network can be analyzed to identify the conditions or risk factors most associated with prevalent crash types. In this type of analysis, crash data are spatially linked with roadway characteristics data, and ideally, land use, transit, and other measures of the built and social environment, and exposure. Depending on what the analysis reveals, engineering (and perhaps other types of) treatments can be applied at sites with similar conditions and crash risks across a network, regardless of whether crashes have already occurred at all such locations (Kumfer, Thomas, et al., 2019; L. Thomas, Sandt, et al., 2018).

Oregon is an example of a State that has aggressively embraced systemic safety analysis. The State divided roadway safety funding into two equal pots: one for countermeasures identified through hot spot analysis and one for countermeasures identified though systemic analysis (Siddique et al., 2016). The systemic analysis section had three key emphasis areas: intersection crashes, road departure crashes, and pedestrian and bicycle crashes; and regions generally divided funds to match the proportion of these crash types. Local jurisdictions then applied for project funding and selected proposed countermeasures based on approved systemic countermeasures.

If crash type data are available for crashes across the whole network, analysis may also help improve the efficiency of problem identification, site determination, and project prioritization process, with sites being bundled together for project development, cost effectiveness assessment, and evaluation. Otherwise practitioners may need to investigate the specific types of conflicts occurring at many locations, which individually may have sparse data, to uncover the types of events that may be leading to crashes (Sanders, Schultheiss, et al., 2020). Further site-specific diagnosis is still recommended by experts before implementing treatments. In NCHRP Report 893, the researchers developed crash types using combinations of variables available in that jurisdiction's crash database—in this case motorist maneuvers and non-motorist actions prior to the crash (L. Thomas, Sandt, et al., 2018). Developing these types did not involve direct review of crash reports or diagrams, and crash records missing either of the variables could not be well-classified, but illustrates the potential if agencies consistently report such variables.

Challenges in Studying Bicycle and Pedestrian Safety

Analyzing and researching pedestrian and bicycle safety carries many specific challenges, which underlie some of the limitations of existing research. These generally are due to the relatively low numbers of people walking and bicycling the United States, leading to low numbers of collisions at any location, a lack of adequate exposure data, missing infrastructure data, and inaccuracies and omissions in police reports such as the pre-crash maneuvers and fault of parties involved in the crash.

Regression to the mean

One of the main problems that safety analysts encounter is regression to the mean (RTM). This statistical phenomenon occurs when an analyst either measures baseline safety metrics at a high or low point. Because crash figures tend to move up and down over time due to random variation, the "true" figures will tend to move toward the mean and away from year-to-year extremes (Herbel et al., 2010). Therefore, selecting crash sites with purposefully extreme figures (such as high-crash locations) can be problematic. Collecting several years of data can increase the sample size and reduce the effect. However, if too many years are selected, the underlying roadway environment and exposure conditions may have changed too substantially for the years to be comparable. This effect also exists for vehicle crashes, but the natural variation is relatively more important when dealing with the small absolute numbers of pedestrian and bicycle crashes.

Underreporting

While underreporting is a problem for all traffic crashes, it is especially troublesome for active transportation, as research suggests that underreporting is extremely common for these types of crashes (and becomes even more common for less severe crashes) (Sciortino et al., 2005;

Winters & Branion-Calles, 2017). Researchers and analysts have a variety of different data sources to draw on, but all have drawbacks. Police-reported crash data are still the most commonly used data source—and the most readily available—but this is among the most underreported. Hospital data can improve accuracy for more serious crashes but are time consuming to join to police report data and often difficult to access. Additionally, less severe crashes are often not found in hospital databases because people who are slightly injured often do not go to the hospital. Asking people in surveys about their experiences, or even attaching sensors to pedestrians or bicyclists, can yield useful data, but is often expensive to collect a representative sample. Underreporting is covered in more detail at the beginning of this section.

Induced exposure

Accurately determining the safety of bicycle and pedestrian networks is continually challenged by the problem of induced exposure; people walk and bicycle more often and for longer distances when facilities are improved (for example, when a bicycle lane is installed, or when a traditional bicycle lane is converted into a separated bike lane). While the facility may result in decreased crash risk, the change could also encourage greater use, thereby increasing the total number of bicycle or pedestrian crashes. This should not be construed as a failing of the countermeasure at improving safety. However, it does dramatically increase the complexity of assessing the relative crash risk associated with active transportation facilities. Moreover, as has been discussed previously in the report, a lack of widespread detailed before- and after-exposure data limits the ability to control for this effect.

Insufficient crash detail

As police reports are the primary source of crash data used in many traffic safety studies, the quality and completeness of this data are paramount. However, despite national guidance in the form of the MMUCC, police report crash data often lack details on critical crash characteristics for pedestrian and bicycle crashes such as the pre-crash maneuvers or the location of parties prior to the crash (e.g., whether a person bicycling was on the sidewalk or not, whether a person walking was in an unmarked crosswalk). Inaccuracies and incompleteness in these fields limits the ability to use these databases to accurately assess the effectiveness of infrastructure interventions.

Appendix A. Evolution and Future of Pedestrian and Bicycle Crash Typing

Researchers in the 1970s and 1990s made strides in defining crash types and identifying common interacting factors that may have contributed to the crash (Cross & Fisher, 1977; Hunter et al., 1996; Snyder & Knoblauch, 1971a, 1971b); there have not been recent updates of these in-depth studies. The crash types defined in those earlier studies were subsequently used to develop computerized crash typing systems in a series of follow-on studies and projects, and ultimately turned into a crash typing tool—the PBCAT (Harkey et al., 2006)—that safety stakeholders can use to type crashes using police crash reports. However, the validity of the associations found and embedded in the PBCAT crash types has not been revisited in more than 25 years. The ability to identify jurisdiction-specific crash type relationships is also affected by how crash types were defined in those studies, which included numerous, non-distinct crash types, and were based on in-depth, on-scene investigations. The data available in those original studies are often not typically available from police-filed crash reports alone (L. Thomas, unpublished review of PBCAT for FHWA).

In the U.S. context, PBCAT has been the most commonly used tool for crash typing. Pedestrian and bicyclist crash type scenarios in tools like PBCAT evolved from the aforementioned, in-depth research studies beginning in the early 1970s. PBCAT, as a software tool, was conceived to help agencies generate crash type variables based largely on the complex typologies developed through the prior research studies and investigations. The sizable number of distinct types (85 bicyclist types and 61 pedestrian types) is affected by incorporating not only movements, angles, and directions of conflict that led up to the crash, but also a variety of behavioral factors (e.g., dart-out, dash, failure to yield, ride through or out), and other contributing or specific circumstances (multiple threat, bus-involvement, dispute-related, and others). As in the original typologies from the 1970s and 1990s, there is no pre-defined logic framework or uniform application of a defined set of variables or parameters to determine types. Thus, a complex decision tool was needed to help coders independently "type" crashes, by applying the hierarchical types of decisions that the researchers earlier applied. An updated version of PBCAT with improved user functionality and crash typing logic that supports coding consistency and objectivity was released in 2021 (available at https://pbcat3.org). This new version complements the data that States collect.

Other crash typing frameworks have also been used to type pedestrian and bicycle crashes. Several of these crash typing frameworks are similar, in that they capture the movements, directions, and positions of the pedestrian or bicyclist relative to the motorist movement and tend not to characterize contributing factors, such as failure to yield, signal violations, etc., which are variables often available in other crash databases. Examples of these more basic crash types include pedestrian intersection crash scenarios in PBCAT v.2, that capture the motor vehicle movements and the pedestrian movements relative to the motorists direction and leg of the intersection where the crash occurred (Figure 13), and the Location–Movement Classification Method (LMCM) for pedestrian and bicycle crash typing (Schneider & Stefanich, 2016).

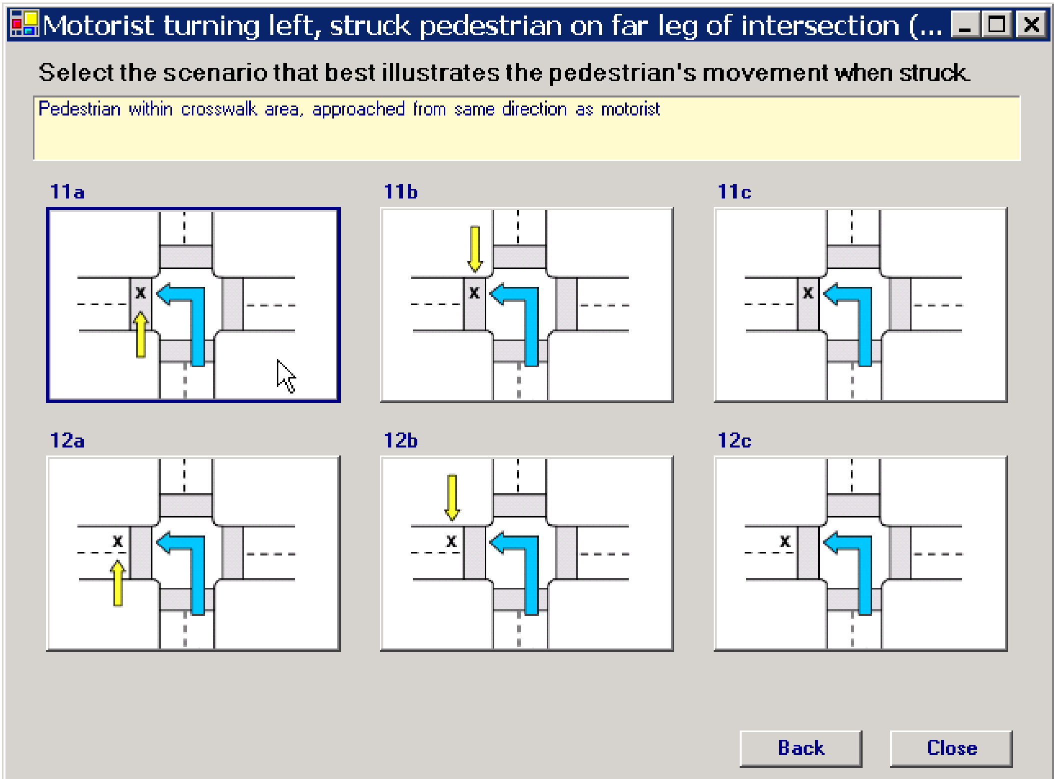

Figure 13. Examples of PBCAT v. 2 Pedestrian Intersection Crash Scenarios showing a motorist turning left and striking a pedestrian at the end of the turn, on the exit leg of the intersection
Source: Harkey et al., 2006.

The LMCM includes 57 crash types that can be applied to either pedestrian or bicycle crashes, and the crash types for intersections are very similar to the PBCAT pedestrian intersection crash scenarios. Crashes categorized as roadway intersection, roadway non-intersection, or parking lot/private property are assigned codes related to the location in the roadway or intersection, motorist movement, and pedestrian or bicycle movement. The authors applied this schema to develop a typology for both bicycle and pedestrian crashes at all roadway location types using data from Wisconsin (Schneider & Stefanich, 2016). The researchers analyzed crash severity and other crash factors (such as contributing behaviors or environmental circumstances) to determine those more prevalent in their LMCM schemas.

Crash typing for crash avoidance technologies research

Some of the crash typing schemes applied since the 2000s were developed to characterize scenarios for the purposes of testing vehicle-based crash avoidance technologies. IIHS identified prevalent U.S. bicycle and pedestrian crash types using FARS and GES data to understand important scenarios for testing (See Figure 14 for an example of bicyclist types identified) (Jermakian & Zuby, 2011; MacAlister & Zuby, 2015). These studies took a similar approach to the LMCM and the PBCAT pedestrian intersection crash scenarios. Findings regarding the most frequent crash scenarios were similar to recent findings using PBCAT crash types (which are presented later in this section)—bicyclist crashes involving overtaking motorists (bicyclist in-line with motor vehicle), and pedestrians crossing the roadway being struck by motor vehicles traveling straight through were identified as most common. IIHS has been testing crash avoidance technologies for some of the more common pedestrian crash types identified, Figure 15 (Harkey, 2020).

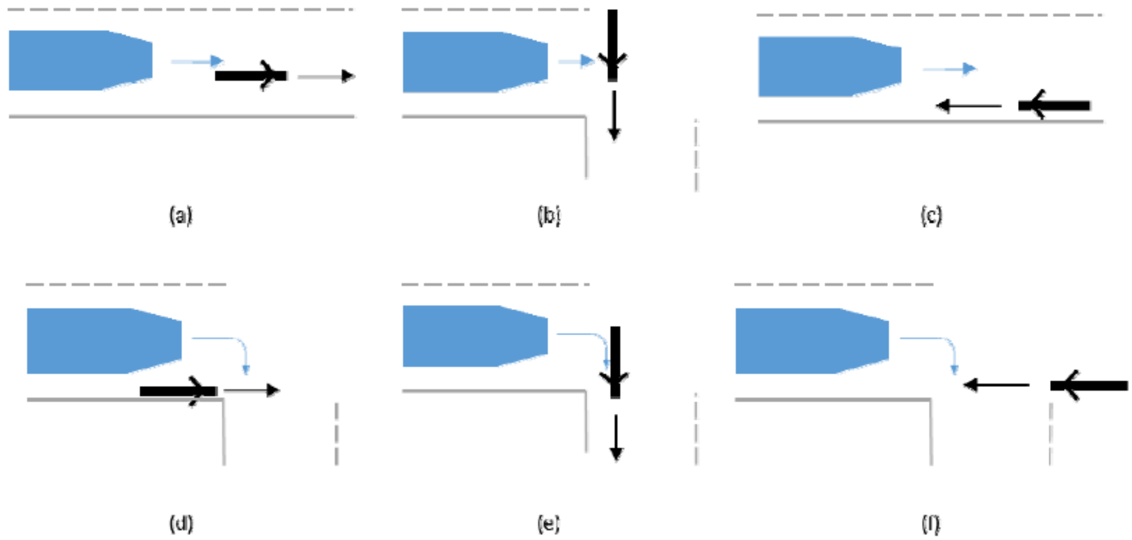

Figure 14. Examples of crash types for investigating vehicle-based technologies for detection/warnings/avoidance
Source: Figure 1 in MacAlister and Zuby (2015).

In 2011 NHTSA began research on PAEB systems focused on in-traffic pedestrian crash scenarios with a project with Volpe and the Crash Avoidance Metrics Partnership (CAMP). Using available crash data, Carpenter et al. (2014) found four common pedestrian pre-crash scenarios: (1) vehicle heading in a straight line and pedestrian crossing the road, (2) vehicle turning right and pedestrian crossing the road, (3) vehicle turning left and pedestrian crossing the road, and (4) vehicle heading in a straight line and pedestrian walking along or against traffic. These pre-crash scenarios led to draft research test methods, test equipment requirements, a preliminary evaluation plan, and development of a 50th percentile adult male mannequin. Subsequent research led to development of additional size and function mannequins (Albrecht, 2017).

NHTSA's 2017 report *Estimation of Potential Safety Benefits for Pedestrian Crash Avoidance/Mitigation Systems* provided an estimate of safety benefits of pedestrian crash avoidance/mitigation (PCAM, now generally called PAEB) systems (Yanagisawa et al., 2017). The study utilized FARS and GES data to reconstruct real crashes using available vehicles with PAEB technology to test for crash avoidance and mitigation outcomes had the PCAM technology been employed in the original crash. Tests were performed for two specific pedestrian-vehicle collision scenarios which PAEB technology could have addressed: when the vehicle was traveling straight ahead and collided with a pedestrian crossing the roadway in front of the vehicle and/or when the vehicle collided with a pedestrian walking adjacent to the roadway. Results showed an estimated range of 10% to 78% for crash avoidance effectiveness for both crash scenarios. Crash avoidance effectiveness estimates were slightly lower for crashes involving child pedestrians. Crash mitigation effectiveness was estimated to be slightly higher overall, resulting in reductions of pedestrian injuries. Some of the variation in the results was due to differing PAEB technology in the vehicles used in the reconstructed test crashes, and some was due to the factors of the reconstructed crashes. Overall, the study showed that PAEB technology can provide positive safety benefits to pedestrians, but that the outcomes of crash avoidance and crash mitigation are still dependent on not only the technology itself but also external factors such as vehicle speed and conditions outside the vehicle.

Researchers in Europe have also applied crash types and various theoretical methods to investigate common scenarios in relation to motor vehicle-based bicyclist and pedestrian detection and crash avoidance technologies and the angles, positions, speed, and trajectories in the moments before a crash to try to determine crash avoidance needs for these systems (Hamdane et al., 2016; Huang et al., 2007; Lenard et al., 2018). Huang et al. estimated that detection angles of 60 degrees were needed to detect all pedestrians in the most common crash scenarios. Lenard et al. (2018) used time-to-collision analysis to estimate the positions of bicyclists and pedestrians in the moments before actual collisions and found, in contrast to Huang et al., that detection systems for automating emergency actions (e.g., braking) would require essentially 180° of side-to-side vision to detect bicyclists prior to a conflict. The detection distance was similar for bicyclists (42 meters at 3 seconds) and pedestrians (50 meters at 3 seconds). Using simulations to reconstruct the moments leading up to actual collisions, other researchers found that 1 second before the impact, only 30% of pedestrians are located in front of the car, but 90% are less than 20 meters from the front of the car (Hamdane et al., 2016).

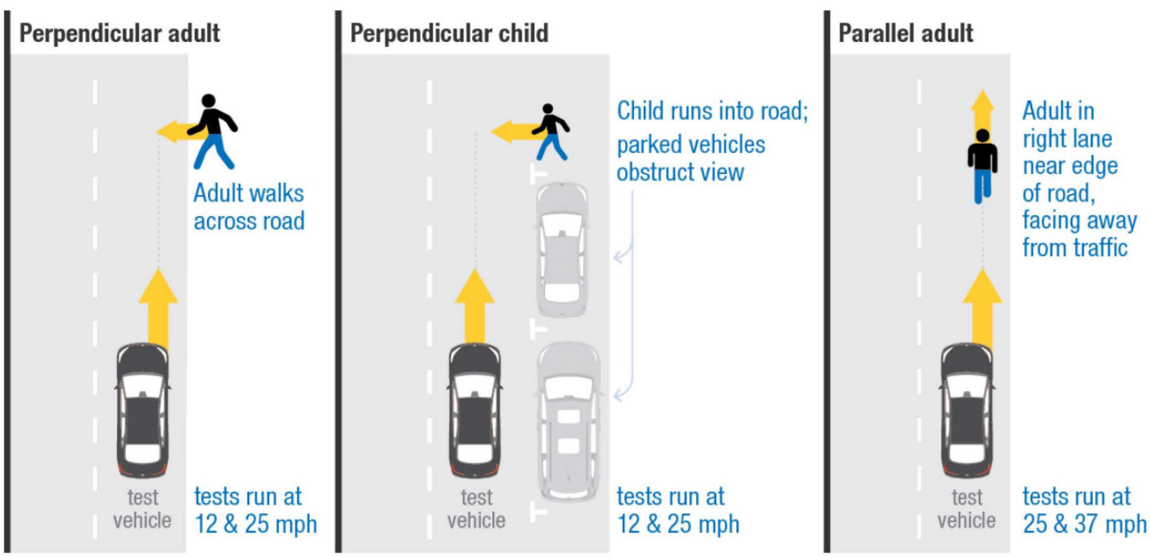

Figure 15. Three test scenarios for vehicle-based crash avoidance technologies used by IIHS
Source: Harkey (2020).

Other crash typing studies

Schepers et al. (2012) developed a typology of bicyclist injuries due to bicycle-only falls and crashes, which is a significant injury load in countries with extensive bicycling for transport. As already mentioned, bicyclist-only crashes and falls, even if on the street network, may also not be reported in most U.S. States. The proposed typology for bicycle-only falls and crashes includes:

- An infrastructure-related group (obstacles, surface conditions, roadsides),
- Bicyclist loss of control or riding behaviors group, and
- Bicycle malfunctions.

The authors acknowledged that there would be overlaps in crashes typed using this scheme.

A variety of other studies have defined different crash types for a variety of specific study purposes. Analysts investigated the location of impacts on motor vehicles (mostly the fronts) and directionality of bicyclists relative to the motorists in bicycle-motor vehicle collisions in Germany (Kuehn et al., 2015); types of collisions including trip purposes in France (Billot-Grasset et al., 2014); relative circumstances and prevalence of factors associated with e-bike-motor vehicle conflicts compared to standard pedal bicycle-motor vehicle conflicts (Petzoldt et al., 2017); bicycle to bicycle collisions (Brand et al., 2013); truck-bicycle collisions (Richrer & Sachs, 2017; Talbot et al., 2017); and bicycle collision patterns with respect to location types (P. Schepers et al., 2011). Regarding e-bikes, intersection conflicts were relatively more frequent among e-bike riders; e-bike speeds approaching intersections also tended to be higher (Petzoldt et al., 2017). Fontaine et al. (1997) identified crash types by characterizing several variables including type of mode (and changes in mode of transport, for example from transit to walking), pedestrian characteristics such as age and impairment, time of day and lighting, and pedestrian actions (running, walking on a country road, etc.).

These studies reveal that a wide range of crash typing frameworks may be of interest, depending on the purpose of the analysis and countermeasure types being considered. However, several of the typologies have similarities in terms of identifying the relative motions, directions, and conflict between the parties to the crash, a type of data that remains frequently lacking from crash reports when vulnerable road users are involved.

Future of Crash Typing

As mentioned earlier, researchers have developed a variety of frameworks for typing bicycle and pedestrian crashes. These typologies were developed for different reasons, including to help provide a link to identifying engineering, behavioral, and policy types of countermeasures, and more recently to investigate vehicle-based technologies for crash avoidance. A crash type is thus simply a way of categorizing crashes by some set of parameters about the pre-crash and crash event, behaviors, or circumstances. The crash typing studies discussed in this section reveal that varied ‘crash types’ may be of interest, depending on the purpose of the analysis and countermeasures or safety framework being considered. Thus, crash types may vary by the parameters selected for categorization, which in turn may be influenced by whether the countermeasure's focus is roadway, environmental, vehicular, behavioral, or some other focus, or combination of interests. However, several of the reviewed typologies have similarities in terms of identifying the relative motions, angles, directions, and conflict between the parties to the crash, a type of data that is frequently lacking from crash reports when vulnerable road users are involved.

Most typically, pedestrian and bicycle crash typing in the United States has focused on identifying situations and participant maneuvers and behaviors just prior to crash occurrence. These typologies have evolved through different studies and study intents but have only—to a limited degree—considered upstream policies, design practices, and user characteristics that may contribute to different conflict types and crash occurrence. Due to the nature of crash reporting, which tends to collect data primarily on the events that immediately led up to a crash, it may be necessary to conduct new types of studies to better understand road user interactions as embedded in the complex transportation system and built environment (Salmon et al., 2013; J. P. Schepers et al., 2011).

Crash reporting

Better crash reporting could reduce the need for post-processing of data and reviews of hard copy images of crash reports to develop crash types. The MMUUC, 5th edition has identified the following variables about crash events and motorist and non-motorist actions that States could consider collecting and improving (if they are not already doing so):

- **Location of First Harmful Event Relative to the Trafficway** – e.g., In Interchange Area, Acceleration/Deceleration Lane, Cross-over Related, Driveway access, Non-intersection, Intersection, and other categories.
- **First and Most Harmful Events** – e.g., Non-collisions; Collisions With Person, Motor Vehicle or Non-Fixed Object; and 21 different "fixed-object" collision types.
- **Motor Vehicle Maneuver/Action** – e.g., Backing, Changing Lanes; Going Straight; Turning Right; Turning Left; and others.
- **Manner of Collision** – e.g. Not a Collision Between Two Motor Vehicles (which includes collisions with Pedestrian and other person types), Angle, Front to Front, Front to Rear, Sideswipe, Opposite or Sideswipe, Same direction, etc.
- **Non-Motorist Action/Circumstance (**prior to the crash) – these actions include a mixture of where the non-motorist was and what they were doing just prior to the crash, e.g., Adjacent to Roadway, Crossing Roadway, Waiting to Cross, Walking/Cycling Along Roadway Against Traffic (In or Adjacent to Travel Lane); and others. Subfields include information on whether the person was going to or from a K-12 school or going to or from transit.
- **Non-Motorist Location at the Time of the Crash** – includes Roadway Facility information (e.g., Intersection - Marked Crosswalk, Intersection - Unmarked Crosswalk, Midblock - Marked Crosswalk, Travel Lane, Median/Crossing Island, etc.); Bicycle Facility Types (e.g., Signed Route, Shared Lane Markings, On-Street Bike Lanes (plus Shared and Buffered), and Off-Street Trails/Sidepaths; and Other Facility types (e.g., Driveway Access, Non-Trafficway Area, Sidewalk and Shared Use Path or Trail).

The rationale for these variables recognizes that these types of data elements are integral to better understanding and preventing crashes with motor vehicles. If adopted and reported accurately by all agencies, these data elements could help fill the historic gap in the ability of analysts to identify types of collisions occurring between motorists and vulnerable road users and to correctly apply available and effective countermeasures as well as to seek new solutions.

There may still be a need to consult crash reports or conduct more in-depth site and human factors investigations to identify more site-specific, crash-specific, person/driver-specific, or vehicle-specific factors. For systemic and high-level analysis to identify prevalent problem types, crash type-related data improvements show promise for helping uncover important risk relationships.

Limitations of crash typing

What is not well-understood, however, is how changing one or a few factors in the system may affect outcomes (and crash types) that at first glance may not appear related. For example, Kumfer et al. (2019) found that presence of right turn lanes at intersections adjacent to segments correlated with increased pedestrian crashes (pedestrian crossing and struck by through motor vehicles) at segment locations. The implication is that something about the presence of right-turn only lanes at intersections has potential to increase the risk that pedestrians may be struck away from the intersection, perhaps increasing risk of injury since speeds may be higher and midblock crashes tend to be more severe. For example, pedestrians may experience both real and perceived threats from a high level of right-turning traffic, as well as a larger number of lanes to cross, and feel safer crossing one direction of traffic at a time along the section of road between intersections, even if they lack right of way at such locations. This scenario could apply to some bicyclists as well. However, research is lacking on many aspects of how the system design (e.g., the distance between controlled intersections or crossings or addition of turning lanes at intersections) or other system factors may affect pedestrian and bicyclist behavior and crash risk.

Different road users may perceive and interpret the same environment in different ways (Salmon et al., 2013). Motorists may not be expecting to encounter more vulnerable road users or searching for them when negotiating intersections or, as crash data suggest, at non-intersection locations, but may be more focused on traffic controls and avoiding other cars and trucks (like when making left turns). Bicyclists (and by extension, pedestrians) are less constrained by intersection features than four-wheeled and larger motor vehicles, but may be in unexpected places from motorists' perspective. Salmon et al. recommend consideration of different road users' interpretation and cognition of environments in designing road features to help reduce conflicts among different types of road users.

Crash type data and analyses are also limited by the fact that the data usually reported focus only on the events and conditions immediately leading up to the crash and typically capture only a fraction of injuries (even of those occurring on public roadways). Most States have requirements that to be "reportable" a crash must involve a collision with a motor vehicle (sometimes the motor vehicle must also be "in transport"), the crash must occur on a public right-of-way, and there are also typically requirements for either an injury or a minimum estimated property damage cost estimate. Therefore, many crashes and falls are not captured in State crash databases. Data from a multistate study of hospital emergency departments from the mid-1990s (the most recent, representative data available), were compared with crash databases, and found that State crash databases may capture less than half of bicyclist crashes occurring in road rights-of-way that were serious enough to require hospital treatment, since about 55% of injuries on a roadway did not involve a direct collision with a motor vehicle. For pedestrians, the average percentage of pedestrian injuries that were included in State crash files was around 30% (Stutts & Hunter, 1999).

Another issue is that the injury and long-term health and social costs of pedestrian and bicycle injuries (or for that matter, vehicle occupant injury) are not well documented in crash data. Investigating officers, not trained medical professionals, must estimate injury severity based on observable characteristics at the scene of a crash (Sandt et al., 2020). This situation limits the ability to assess the full costs relating to these injuries. While linking crash data with medical data can help to capture a more accurate measure of health impacts; data from the medical side have disadvantages as well. Medical data are unlikely to provide details on where the crash or injury occurred and other details of who was involved or what happened in the crash. This reduces the power and ability to characterize the full extent of the types of events and locations leading to injury so that solutions can be identified. Thus, both types of data are important, and improved linkage will further the ability to assess the health and injury impacts of pedestrian and bicycle crashes and falls.

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