AASHTO Council on Active Transportation Research Roadmap

Research Review

July 2021

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Contents

Introduction

Overview of the Roadmap

This Research Roadmap aims to assist the AASHTO Council on Active Transportation (CAT) implement its Strategic Plan, which includes goals and strategies related to research. The Roadmap was developed through the National Cooperative Highway Research Program (NCHRP) Project 20-123, which provides support to any AASHTO committee or council to help advance and implement its strategic goals. The Research Roadmap project consists of three products:

- **The Roadmap**. Section I of the Roadmap provides an introduction and description of the process and methods used to develop the Roadmap. Section II consists of a set of 110 prioritized research needs.
- A **Research Review** (this document) that summarizes the existing and ongoing research on 22 topics.
- A **Continuity and Implementation Plan** that provides the CAT with tools and steps to implement the Roadmap.

The Research Review

This Research Review aimed to summarize research on the topics most relevant to the Roadmap. The summaries can be used by the CAT to help implement the Roadmap and to inform other activities, including communicating the value of active transportation, and provide a quick reference of existing research. The Research Review will also be of use to others practicing and doing research in active transportation.

The Research Review is not comprehensive. There are several active transportation topics that are not included. We prioritized topics that were most directly influenced by state DOTs, and where filling research gaps may have the largest effect on improving safety and mobility for people who walk, bicycle, and roll. This was informed by the outreach process for the Roadmap and by the project Panel.

The process to develop the Research Review is described in the methods section of the Roadmap. To the extent possible, we relied on existing reviews of the research. We also focused on more recent research (often published in 2015 or later), on research from North America (though not exclusively), and on research with findings most relevant to practice. The Research Review was first completed in April 2020. It was updated in spring 2021 with research published in the previous year, though we did not conduct a comprehensive search for new research.

The Research Review consists of 22 research summaries, each focused on a subject. For each subject, the research summary first answers the question—what do we know?—which highlights the most relevant key findings. Next, we identify the research gaps using both gaps identified in the research and by the team from assessing the existing research findings. The next section explains how research on the topic is conducted. This information was useful in developing research problem statements and strategies for identifying possible pathways to getting the research initiated. The summary then lists relevant ongoing research projects which may help fill the gaps. The sources used in the review appear at the end of each review topic. There is also a table with the most common index terms associated with those sources in the Transport Research International Documentation (TRID) database. These terms should help in conducting future TRID searches for new research on the same subject. These are all terms from the Transportation Research Thesaurus (https://trt.trb.org).

The subjects of the 22 research summaries touch on or overlap with one or more of the six topical categories that organize the research needs presented in the main Roadmap document: data; design; equity and accessibility; planning; policy and practice; and, technology and micromobility. Table 1 identifies which research review (each row) covers information relevant to each of the Roadmap topical categories (columns across).

Table 1 Connections between the 22 research summaries and the Roadmap topic areas

	Roadmap Topic Areas						
	Data	Design	Equity and Access-ibility	Planning	Policy and Practice	Safety	Tech. and Micro-mobility
Access management and active transportation		■				■	
Accessibility for pedestrians and cyclists with disabilities		■	■			■	
Autonomous and connected vehicles				■			■
Bicycle and pedestrian data: Emerging user-based data	■			■			■
Bicycle and pedestrian data: Location-based counts	■			■			
Bicycle and pedestrian data: Safety	■			■		■	
Bicycle and pedestrian data: Surveys	■			■			
Bicycles at intersections: Design and safety		■				■	
Bike share							■
Bikeways: Safety and design		■				■	
Bikeways: Ridership and demand		■		■			
Distraction and impairment: Effects on pedestrian and bicyclist safety					■	■	
Economic benefits of walking and bicycling				■	■		
Equity and bicycling		■	■	■	■	■	
Equity and pedestrian travel		■	■	■	■	■	
Equity and personal safety					■	■	
Micromobility, including e-scooters						■	■
Modeling and traffic impact analysis	■			■			
Pedestrian crossings: Design and safety		■				■	
Policy, planning and decision-making				■	■		
Rural and small urban areas		■		■		■	
Speed management and active transportation		■			■	■	

Access management and active transportation

Access management (AM) employs techniques to manage the location and design of access points onto and off of roadways for vehicle safety and efficiency, but there has been limited research on the relationship between access management and multimodal operations (Butorac et al., 2018). Access management techniques can reduce the number of conflict points, reduce crossing distances, and separate movements in ways that offer safety benefits for pedestrians and bicyclists (Chimba et al., 2017). However, access management approaches can also lead to increased vehicle speeds or lengthen distances between signalized crossings, which can have negative safety impacts on pedestrians and bicyclists. This review focuses on the possible effects of access management on pedestrian and bicycle travel and safety.

Related review topics

Research on designs and policies to improve pedestrian and bicycle operations and safety by managing motor vehicle speed is covered in the *Speed management and active transportation*.

Common access management techniques

Access management techniques aim to manage the access of vehicles onto and off of major roads, such as arterials and highways, generally with the goal of improving roadway operations and safety. Common techniques include:

- Driveway closure, consolidation, or relocation
- Limited-movement designs for driveways (such as right-in/right-out only)
- Raised medians that preclude across-roadway movements
- Intersection designs such as roundabouts or those with reduced left-turn conflicts (such as J-turns, median U-turns, etc.)
- Turn lanes (i.e., left-only, right-only, or interior two-way left)
- Lower speed one-way or two-way, off-arterial circulation roads

What do we know?

Some access management techniques offer benefits for active transportation.

- Access management approaches that offer a particular benefit for pedestrians include adding median crossing islands, driveway improvements including consolidating driveways, sidewalk setbacks, improved right-turn lane slip designs, and left-turn prohibitions (Federal Highway Administration, 2017; Zegeer et al., 2013).
- Access management techniques that offer a particular benefit for bicyclists include medians and crossing islands, driveway improvements, and path intersection treatments (Federal Highway Administration, 2017; Sundstrom et al., 2014).
- According to an FHWA fact sheet, access management measures along a corridor can reduce total crashes on rural two-lane roads by 5 to 23%, and injury and fatal crashes on urban and suburban arterials by 25 to 31% (Federal Highway Administration, 2017).
- Multiple studies have found that higher levels of access density, or the number of access points to a road, are correlated with more pedestrian crashes (Chimba et al., 2017). Access management aims to reduce access density.

- Access management techniques may also increase motor vehicle speeds, and therefore present the potential to increase safety risk for pedestrians and bicycles (Butorac et al., 2018).

A major focus of access management includes reorganizing or removing driveways to reduce the number of conflict points and the likelihood of severe conflicts with pedestrians.

- Decreasing the number of driveways (increasing driveway spacing) reduces the number of motor vehicle and pedestrian conflicts points and conflicts (Butorac et al., 2018; Layton et al., 1998; Schultz et al., 2006).
- Aside from, but related to, having fewer driveways is having more separation between driveways, which reduces the overlap driveway areas on which drivers and pedestrians have to concentrate, allowing them to focus on one conflict point at a time (Schultz et al., 2006).
- Various measures to increase driveway sight distance, including regulating minimum sight distances, restricting on-street parking next to driveways, and adding visual cues, can provide enough distance for drivers to see and react to pedestrians and bicyclists (Butorac et al., 2018).
- Tighter turn radii for driveways allows for a shorter crossing distance and less exposure for pedestrians (Potts et al., 2006).
- Moving sidewalk-driveway crossings laterally away from the roadway can increase pedestrian safety by moving the conflict location back and giving drivers a place to stop and yield to crossing pedestrians and bicyclists (Butorac et al., 2018).

Access management includes reorganizing or removing driveways to reduce the number of conflict points. (Photo: Nicole Schneider, pedbikeimages.org)

Right-turn lanes for driveways offer the potential to slow down turning traffic but may have a negative impact on pedestrian safety due to wider crossings.

- Right-turn lanes prior to a driveway entrance can allow drivers to slow before turning, while allowing for reducing turn radius and narrower crossings due to slower vehicle speeds (Layton et al., 1998).
- If adding a turn lane requires widening a road, that has the potential to widen major street crossings for pedestrians (particularly at intersections) while bringing cars closer to the sidewalk, increasing pedestrian exposure (Butorac et al., 2018).

Medians and removing left-turn options have been shown to reduce motor vehicle speeds and increase pedestrian safety.

- Roads with more left turns are associated with increased vehicle-to-vehicle, vehicle-to-pedestrian and cyclist conflicts. Medians can reduce left turns and improve roadway operations and safety (Gluck & Lorenz, 2010).
- Studies have found that raised medians result in fewer vehicle-pedestrian crashes than undivided or two-way, left-turn lane configurations (Layton et al., 1998). Further, raised medians provide a refuge area for crossing pedestrians, allowing them to concentrate on traffic coming from one direction at a time (Gluck & Lorenz, 2010).

- Raised medians can also narrow the roadway and have been found to reduce motor vehicle speeds from 2 mph to 8 mph. They also have been found to have CMFs of 0.54 to 0.75 in most cases (Federal Highway Administration, 2014; Sanders et al., 2019).
- NCHRP Report 900 found that closing median openings and installing non-traversable medians have positive safety effects for pedestrians and bicyclists, although installing non-traversable medians may lead to increased vehicle speeds and reduced pedestrian level of service (Butorac et al., 2018).
- A study in New York City found that restricting left turns resulted in 41% fewer pedestrian and bicycle injuries, while adding left-turn-only signals resulted in 33% fewer such injuries (New York City Department of Transportation, 2016).

Other access management elements that can affect pedestrians and bicyclists include frontage streets and roundabouts.

- Frontage or service roads may help break up pedestrian crossings and separate out conflict points, while providing lower-speed travel options for bicycles. Frontage roads may be less likely to have signalized crossings, however, making crossing them (and perpendicular major roads) more challenging (Butorac et al., 2018).
- Roundabouts are one treatment that organizes and limits vehicle access into an intersection, which has generally positive safety impacts for pedestrians and bicycles due to fewer conflict points, shorter crossing distances and lower vehicle speeds (Butorac et al., 2018; Federal Highway Administration, 2014). But roundabouts can present challenges to visually impaired pedestrians due to the challenges in detecting gaps to cross (Butorac et al., 2018).

What are the research gaps?

- Research points to the potential trade-off between the potential higher vehicular speeds with some access management techniques versus other potential safety and operations benefits for pedestrians and bicyclists. However, we found little research weighing these trade-offs.
- Designs that increase speeds or increase crossing distances could discourage active transportation, while other techniques that reduce the potential for conflict with motor vehicles might improve the experience and increase use. We found limited research on how these impacts of access management techniques might influence the decision to walk or bicycle.

How is research on this topic done?

To empirically evaluate the impacts of AM techniques, researchers have used before-and-after studies, including analyzing pedestrian- or bicycle-involved crashes before and after restricting left turns (New York City Department of Transportation, 2016). Other researchers have analyzed pedestrian or bicycle crash rates with various midblock or intersection street cross-sections (Butorac et al., 2018).

Researchers have also used a number of modeling or predictive methods, including assessing pedestrian or bicycle operations effects and level of service using Highway Capacity Manual calculations based on vehicle speed, crossing delay or other factors (Butorac et al., 2018). Others have used microsimulation tools (e.g., VISSIM and VISWALK) to examine the effect of access density and signal density, along with median presence or type on pedestrian operations (e.g., delay and average speeds) (Chimba & Soloka, 2017).

Current research

Sponsor	Project Information	Status
National Cooperative Highway Research Program (NCHRP) 25-47 https://rip.trb.org/View/1334521	**How to Measure and Communicate the Value of Access Management** The objective of this research is to develop guidance for transportation agencies on identifying and communicating the value of access management at the program, corridor, and project levels. The guidance will involve techniques to identify, measure, and assess the benefits and costs of access management using both quantitative and qualitative metrics. The effects of access management on active transportation safety is likely to be included.	Estimated completion date: 03/31/21
National Cooperative Research and Evaluation Program (NCREP) https://rip.trb.org/View/1577696	**The Impact of Access Management Techniques on Driver Behaviors** This project will identify a set of access management techniques (AMTs) that may have an impact on driver behaviors and will quantify AMTs' impact on driver behaviors based on emerging datasets such as the Naturalistic Driving Study (NDS).	Estimated completion date: 09/30/21

Research reviews

Butorac, M., Bonneson, J., Connolly, K., Ryus, P., Schroeder, B., Williams, K., Wang, Z., Ozkul, S., & Gluck, J. (2018). *Guide for the Analysis of Multimodal Corridor Access Management* (NCHRP Research Report 900). Transportation Research Board, National Academies Press. http://www.trb.org/Main/Blurbs/178559.aspx

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Schultz, G., Lewis, J., & Boschert, T. (2006). *Assessing the safety benefits of access management techniques* (UT-06.08). Utah Department of Transportation Research and Development Division.

Sundstrom, C., Nabors, D., Hintze, M., Schultheiss, B., Lagerway, P., & Langford. (2014). *BIKESAFE 2014*. BIKESAFE. http://pedbikesafe.org/BIKESAFE/index.cfm

Zegeer, C., Nabors, D., Lagerway, P., Sundstrom, C., Lovas, D., Huber, T., Eldridge, R. J., & Bushell, M. (2013). *PEDSAFE 2013*. PEDSAFE. http://pedbikesafe.org/PEDSAFE/index.cfm

Most common TRID index terms
Access control (Transportation) Pedestrian safety Crosswalks Driveways

Accessibility for pedestrians and cyclists with disabilities

People with disabilities experience multiple, interrelated barriers in the built environment that can lead to social exclusion and isolation. Pedestrian infrastructure poses mobility challenges, limiting social participation and quality of life outcomes (Eisenberg et al., 2020; Gamache et al., 2019). People with disabilities are disproportionately excluded from the streets and experience lower physical activity rates and higher rates of obesity as a result (Clayton et al., 2017).

There is a full range of disabilities (ranging from motor, visual, hearing, to cognitive and developmental, among others) which have particular implications for the design and function of inclusive and accessible infrastructure for all. In the U.S., scholars and activists generally agree that there have been improvements to public infrastructure since the Americans with Disabilities Act (ADA) was passed in 1990. However, litigation examples suggest that local governments have made a limited amount of progress on developing accessible pedestrian infrastructure (Eisenberg et al., 2020). Further, there is limited specific guidance on meeting the diversity of needs of people with disabilities, apart from the recognition that needs are quite different, but that the meeting of the needs of one group can benefit other groups (Clayton et al., 2017).

Several national documents and reports that provide recommendations and guidance on interventions to undergo at a state, and local level in relation to this topic. These are listed at the end of this summary.

Definitions

Tactile Walking Surface Indicators (TWSIs): Tactile pavings produced from various materials consisting of a series of tactile indicators (dot shaped or bar shaped) applied to the walking surface of a pedestrian circulation path. With a variety of tactile patterns, each is meant to convey a different message to pedestrians with vision disabilities.

Detectable warning surfaces: Term for attention surface for hazard warning. Its use is limited to locations in which there is a vehicular hazard.

Directional indicator: Term for guidance surface, rarely used in the United States. Detectable under foot and cane, they can help pedestrians with vision disabilities follow an accessible pathway or navigate a large open space, or be deployed across the pedestrian path of travel to provide guidance to pedestrians with vision disabilities determine when to turn.

Source: *Accessible shared streets* (Elliott et al., 2017)

What do we know?

Pedestrians in wheelchairs experience a disproportionately high number of traffic fatalities

- Wheelchair pedestrians experience a traffic mortality rate that is 36% higher than other pedestrians (Kraemer and Connor, 2015). We did not find comparable statistics for other types of disabilities.

Research generally shows that the built environment has a considerable impact on the activity of people with disabilities.

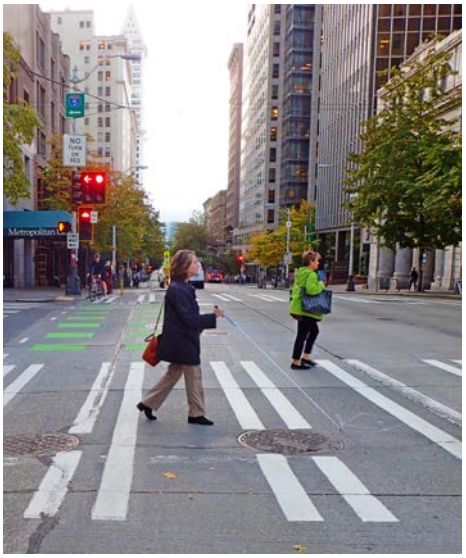
- Regardless of the disability and the mobility technology that people use, all groups in one study reported having to plan routes for outings, to alter planned routes, to go more slowly than planned, or to wait for a different time (Kirchner et al., 2008).
- Pedestrian-oriented environmental characteristics such as curb cuts, smooth pavement and clear sidewalks can reduce mobility disability and promote independence in adults at greatest risk, such as those with underlying weakness in movement-related functions and balance (Clarke et al., 2008).

Poor street conditions negatively affect the accessibility of people with disabilities, although the impact varies by individual and nearby context.

- Adults with visual and motor disabilities using different assistive mobility technologies in New York highlight problems; sidewalk pavement and puddles/poor drainage were the most frequently mentioned environmental barriers by 90% and 80%, respectively. More than 60% identified problems with construction, snow removal, and curb cuts. About 50% experienced narrow sidewalks, public attitudes, scaffolding, and crosswalks as environmental barriers (Kirchner et al., 2008).
- A study among adults over 45 years old in Chicago found that street conditions did not affect outdoor mobility among adults with only mild or no physical impairment. However, among adults with more severe impairment in neuromuscular and movement-related functions, the difference in the odds ratios for reporting severe mobility disability was over four times greater when at least one street was in fair or poor condition (characterized by cracks, potholes, or broken curbs). When all streets were in good condition, the odds of reporting mobility disability were attenuated in those with lower extremity impairment (Clarke et al., 2008).

Planning for pedestrians with disabilities is still a major challenge.

- Disability empowerment emphasizes the need for involvement of people with disabilities in any planning and design efforts (Eisenberg et al., 2020; Elliott et al., 2017; Kirchner et al., 2008).
- Literature on implementation of barrier removal requirements at the city and state level suggest numerous challenges to implementation including insufficient training; lack of ADA knowledge among municipal workers; poor staffing and resources to foreword implementation; underutilization and vastly different expertise of ADA coordinators; and limited understanding of how the built environment affects participation of people with disabilities (Eisenberg et al., 2020).
- While many curb ramps and other facilities have to be upgraded to be in compliance with the ADA, states and local governments have varying approaches to prioritizing improvements, with states being more likely to focus on meeting standards and citizen requests, and local agencies focusing more on demand and trip generators, such as transit (MacKnight et al., 2021).



Street conditions can negatively affect the accessibility of people with disabilities, including visual disabilities (Photo: Toole Design Group)

- U.S. communities have not developed ADA transition plans for pedestrian infrastructure or have developed low-quality plans. A review found that among 401 government entities reviewed, only 13% had ADA transition plans readily available and just seven of the 54 plans acquired met all the minimum criteria in a quality appraisal review (Eisenberg et al., 2020).
- Implementation of national policies at the local level is lagging and removal of barriers for the public right-of-way has still not commonly been addressed through local plans (Eisenberg et al., 2020).
- A white paper on inclusive planning in tribal communities notes that although American Indian and Alaska Native people suffer the highest rate of disability (30%), and many reservations lack basic pedestrian or bicycle infrastructure, people with disabilities are rarely intentionally involved or advocated on behalf of in planning activities in those communities (Aguilar & Thomas, 2020).

Roundabouts and channelized turn lanes (CTLs) represent challenges for pedestrians with vision disabilities.

- The challenges are numerous. Drivers are unlikely to yield to blind pedestrians, naturally occurring gaps may be rare, and many roundabouts – in particular, multilane roundabouts – with pedestrian facilities, do not provide cues that enable pedestrians who rely on traffic sounds to reliably detect gaps that result when drivers yield to them (Inman et al., 2007; B. Schroeder et al., 2016). Visually impaired pedestrians face the multiple challenges of finding the crosswalk, aligning to cross, deciding when it is safe to cross, and maintaining alignment during the crossing in roundabouts and CTLs (B. Schroeder et al., 2016).
- Roundabouts with multiple lanes have been shown to be particularly problematic. Although, under high-volume and high-speed conditions, single-lane roundabouts can exhibit accessibility difficulties (Inman et al., 2007; B. Schroeder et al., 2016).
- Driver yielding to blind pedestrians at roundabouts is poor. At a roundabout entrance, yielding to an apparently blind pedestrian decreases dramatically at modestly higher speeds. At an entrance with measured speeds near 10 mph, nearly all drivers yielded to a pedestrian with one foot into the street and carrying a long cane; however, at 20 mph yielding was less than 15 percent (Inman et al., 2007).
- Factors that can influence motorists' yielding rate are location in the roundabout (entrance), lower speeds, greater aggressiveness of the pedestrian, and an encounter with a pedestrian with a long cane or guide dog. Additional regulatory signage had only a small effect on driver yielding. (Inman et al., 2007).

There is growing evidence on crossing solutions at roundabouts and CTLs for pedestrians with vision disabilities. Accessibility for these pedestrians can be enhanced as multiple methods are combined to achieve even better results (Apardian & Alam, 2015).

- Accessible traffic signals would seem to be a logical alternative as these can reasonably be expected to (1) reliably stop most traffic and (2) provide notice to the pedestrian of when it is appropriate to cross (Inman et al., 2007).
- From the NCHRP 674 report, two treatments emerged that showed particular promise: the Pedestrian Hybrid Beacon (PHB, also known as a HAWK signal or HAWK beacon) and a raised pedestrian crosswalk (B. Schroeder et al., 2016).
- An accessible crossing environment may be established by the Rectangular Rapid-Flashing Beacon (RRFB) treatment only if combined with high driver yielding and roundabout geometry that promotes low vehicle speeds (B. Schroeder et al., 2016).
- A review of methods of crossing at roundabouts for visually impaired pedestrians found that at a low vehicle volume and low pedestrian volume roundabout, a distal or zig-zag crosswalk design may be the best fit; at a moderate-high vehicle and pedestrian volume roundabout, a HAWK signalized crossing with audible signal would be the best fit (Apardian & Alam, 2015).

Raised pedestrian crosswalk at a channelized turn lane. (Photo: Dan Burden, pedbikeimages.org)

Design and characteristics of shared streets can influence safety and accessibility for pedestrians with vision disabilities.

- There is evidence that shared streets, which mix pedestrians, bicyclists and motor vehicles, can result in an ambiguous, highly variable, and potentially difficult experience for pedestrians with vision disabilities (Karndacharuk et al., 2014). Potential navigational challenges for disabled people include: safe space, rules of the road, patterns of use orientation and wayfinding cues, surfacing and defined crossings (Elliott et al., 2017).
- A review of the evolution of shared streets highlights the importance of achieving a low-speed environment via design with a provision of safe zones for those who are reluctant to share the space with motor vehicles, such as people with visual or mobility disabilities, the elderly and young children (Elliott et al., 2017; Karndacharuk et al., 2014).

The design and width of detectable warning surfaces can determine their capacity to serve as a hazard warning effectively.

- Research indicates that many visually impaired pedestrians struggle to establish accurate headings on the basis of detectable warnings (Elliott et al., 2017).
- For a surface to be useful in providing warning to blind individuals, the surface must be both consistently detectable and identifiable (Elliott et al., 2017; B. Schroeder et al., 2016).
- The truncated dome detectable warning surface was found to be detected by most participants on most trials (approximately 90% of trials across multiple experiments) in an extensive study to identify walking surfaces used to alert people with vision disabilities to the presence of hazards (Elliott et al., 2017).
- Another consideration is that detectable warning surfaces, while beneficial for people with vision disabilities, may be a mobility and safety hindrance to people with mobility disabilities (MacKnight et al., 2021)

The needs of disabled cyclists are increasingly being considered in infrastructure design guidance, although today, cycling is still inaccessible to many disabled people (Clayton et al., 2017).

- The primary reported barriers to disabled cycling are infrastructure, social conflict, costs of adapted cycles, risk of loss, and breakdown risk.
- United States data from 2006 reveal that disabled cyclists were five times more likely to have been hit by a motor vehicle than non-disabled cyclists.
- There is the need for detailed and specific guidance in the consideration of adapted cycle dimensions in the construction of the specific infrastructure and support needs which relate either solely or principally to disabled users.

What are the research gaps?

A literature review found that transportation was among the top five ADA research topics. Although there is a considerable amount of ADA research, scholars argue that much of it is not utilized, and policy stakeholders cannot fully assess the ADA's impact (Harris et al., 2014).

There are several gaps related to different types and levels of disabilities, as well as different contexts.

- As noted above, while there is some data on the safety disparities experienced by wheelchair pedestrians (e.g. Kraemer and Connor, 2015), there is limited information on traffic safety disparities for other types of disabilities.
- Much of the existing research on transportation needs of people with disabilities has focused on people with vision impairment. While this reflects their unique challenge in navigating road safety hazards, it also leaves a gap in attaining a fuller understanding of the transportation needs of people with mobility, hearing, and cognitive disabilities, as well as the many people who experience multiple types of disabilities (Prescott et al., 2020).
- Relatively little work has examined the effect of the built environment on mobility disability, particularly across those with different levels and types of physical impairment including individuals with intellectual, psychological and cognitive impairments. Few studies examine more than one physical disability (Clarke et al., 2008; Gamache et al., 2019).
- Studies need to be replicated in different types of communities to evaluate generalizability and identify barriers specific to community types (Kirchner et al., 2008).
- Most current sources do not account for the differences in the roadway environments, including urban, suburban, or rural contexts (Clarke et al., 2008), or different weather conditions (Gamache et al., 2019).
- Research from North America on children with disabilities and active transportation is very sparse, particularly related to Safe Routes to School programs.

Further research may be needed to assess adequate accommodation for pedestrians with disabilities, including:

- Ability of people with visual impairments in finding crosswalks, aligning to cross, and maintaining alignment while crossing at roundabouts and CTLs (B. Schroeder et al., 2016).
- Characteristics of curb ramps (Gamache et al., 2019); accessible features for controlled pedestrian crossings (Gamache et al., 2019; B. Schroeder et al., 2016); and effectiveness, standardization and guidelines for selection of TWSIs in the U.S (Elliott et al., 2017; Gamache et al., 2019; B. Schroeder et al., 2016).
- Ex-post evaluation of TWSI effectiveness, in absolute and cost-benefit terms (Lauria, 2017).
- Accessible roundabouts: effectiveness, location, and number of signal faces (mounted at the roadside) required to achieve high driver compliance, and potential pitfalls and best practices of signals to provide access at roundabout crossings to persons with visual or other disabilities (Gamache et al., 2019; Inman et al., 2007).
- Long-term performance of pedestrian hybrid beacons at roundabouts (B. Schroeder et al., 2016).
- Ways to improve accessibility at single-lane, channelized turn lanes (B. Schroeder et al., 2016).
- There is limited data on infrastructure and asset management, such as inventories of accessible sidewalks or other pedestrian infrastructure, to inform the scale of the accessible pedestrian infrastructure problem and provide insight to current efforts and possible solutions (Eisenberg et al., 2020).
- While there is some research on the construction of accessible pedestrian infrastructure, we found little to no research on the role of maintenance and upkeep of infrastructure in maintaining accessibility.

Planning process gaps have been identified (Eisenberg et al., 2020; Harris et al., 2014; B. J. Schroeder et al., 2009).

- Gaps between national policy and local-level implementation of barrier removal.
- Why state DOTs are not developing ADA transition plans.
- The extent to which people with disabilities have been involved and engaged in planning efforts.

There is little research on understanding the experiences of disabled cyclists and, hence, there is a knowledge gap concerning the efficacy of current design guidance.

- Further research is needed to understand the range of different contexts in which disabled people are cycling, particularly for transport purposes, and what the specific requirements might be (Clayton et al., 2017).
- There is limited evidence on the effects of the various accessibility treatments on other modes of transportations as bikes (B. Schroeder et al., 2016).

How is research on this topic done?

Studies assessing pedestrian infrastructure and accessibility make up a large subset of research on accessibility and disability: bus stops, curb ramps, lighting, pedestrian crossings, ramps, roundabouts, shared spaces, sidewalks, steps, etc. (Gamache et al., 2019).

Several factors make research on accessibility for people with disabilities challenging:

- Few recommendations have been compared. Most studies have been performed in different environments and sometimes lack conclusive evidence (Gamache et al., 2019).
- The methods used varied greatly from one study to the next, making it difficult to compare findings and recommend design solutions. The level of evidence provided in reviewed literature is judged as low (e.g., qualitative studies – expert opinion, case series; quantitative studies – case series) (Gamache et al., 2019).
- Lack of systematic data collection and longitudinal data enables assessing the impact of ADA policy and accessibility intervention (Harris et al., 2014).
- Common administrative definitions of "neighborhoods" (e.g., census tracts) are often too large to meaningfully capture the physical environments faced by individuals when they walk (Clarke et al., 2008). New data collection methods that incorporate geographic information systems (GIS) and other technologies may provide better data on built environment characteristics and barriers (Eisenberg et al., 2020). However, information on these aspects of the built environment are not always publicly available or cataloged in GIS format. Direct observation of built environment features by using an audit instrument allows researchers to capture relevant structural characteristics currently unavailable (Clarke et al., 2008). However, these methods can be resource-intensive.

Current research

Sponsor	Project Information	Status
Transit Cooperative Research Program (TCRP) B-46 https://rip.trb.org/View/1510258	**Tactile Wayfinding in Transportation Settings for Travelers Who Are Blind or Visually Impaired** The objective of this research is to produce guidance for transportation planners, engineers, and orientation and mobility specialists that will provide for consistency in the design, installation, and usability of TWSIs in multimodal transportation in the United States. There will be two products: (1) A Guide to Tactile Wayfinding in Transportation Settings for Travelers Who Are Blind or Visually Impaired, and (2) a final report that includes a review of U.S. and international research and practice, as well as the methods and results of human factors research conducted under this project. The proposed research is focused on determining optimal technical specifications for selection, usability, installation, and maintenance of TWSIs in multimodal environments. All tasks should be coordinated with ongoing related research.	Expected completion date: 8/25/21
Pacific Northwest Transportation Consortium (UTC) https://rip.trb.org/view/1669421	**Combining Crowdsourcing and Machine Learning to Collect Sidewalk Accessibility Data at Scale** Sidewalks significantly impact the mobility and quality of life of millions of Americans. This research described new, scalable methods for collecting data on sidewalk accessibility using machine learning, crowdsourcing, and online map imagery as well as new interactive visualizations aimed at providing novel insights into urban accessibility. The team will work closely with key stakeholders, including local governments and transit departments, mobility-impaired individuals and caretakers, and walkability advocates to help shape and evaluate the design of the team's tools.	Expected completion date: 9/15/21
Mobility21 UTC for Mobility of Goods and People (UTC) https://rip.trb.org/View/1705668	**Safe Intersection Crossing for Pedestrians with Disabilities** This project aims to address the key remaining obstacles to general deployment of PedPal, a mobile app that assists pedestrians with disabilities in safely crossing signalized intersections. Tasks include developing sufficiently accurate localization to enable active monitoring of progress during crossing, generalizing the app to accommodate complex intersections, developing an Apple Watch interface for wheelchair users, and alerting the presence of disabled pedestrians to approaching vehicles.	Expected completion date: 6/30/21

Relevant guidance documents

- The US DOT released a draft Strategic Plan on Accessible Transportation in early 2021, outlining an approach to make transportation more accessible for all travelers (US DOT, 2021). Goal #3 is to “Enhance opportunities for people with disabilities to walk, roll, cycle, and use micromobility services and other innovative mobility technologies to the greatest extent possible.”
- Proposed *Accessibility Guidelines for Pedestrian Facilities in the Public Right-of-Way* (Proposed PROWAG) provides detailed guidance on accessible pedestrian signals, detectable warning surfaces, curb ramps, protruding objects, pedestrian crossing islands, sidewalks, shared use paths, and roundabouts.

- *The Manual on Uniform Traffic Control Devices (MUTCD)* provides detailed regulations and recommendations regarding pedestrian signs, crosswalk markings, accessible pedestrian signals, and bicycle facility pavement markings, signs, and signals.
- The *AASHTO Guide for the Planning, Design, and Operation of Pedestrian Facilities* provides a general description of the characteristics and needs of pedestrians with vision disabilities and includes guidance on crosswalks, curb ramps, midblock crossings, and roundabouts.
- *NCHRP 672* provides guidance about the design of bike ramps at roundabouts and recommendations related to pedestrian refuge islands and median cut-through design, some of which have been further investigated and changed as a result of *NCHRP 834*.
- *NCHRP 834* addresses navigational issues for pedestrians who are blind at roundabouts and channelized turn lanes (CTLs), with a chapter discussing issues and photos of potential solutions. *NCHRP 834* also includes a chapter of design checks related to wayfinding, some of which is transferable to other types of complex intersections.
- *TCRP 175* includes a case study on how to accommodate pedestrians with vision disabilities when designing transit platforms that are in the middle of the street. This information may also be helpful in considering the design of floating bus islands.
- Other guidance documents, such as FHWA's Separated Bike Lane Guide and NACTO's Urban Street Design Guide include considerations for pedestrians with vision disabilities.

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Most common TRID index terms

Accessibility
Pedestrians
Roundabouts
Blind persons
Crosswalks
Urban design

Autonomous and connected vehicles

Autonomous vehicles (AVs) and related technology innovations are reshaping the ways in which people travel. As vehicle technologies become more automated and connected, navigation around and interactions with pedestrians and bicyclists need to be integrated in complex multimodal travel environments (PBIC, 2017). This review focuses on the interactions between AVs and connected vehicles (CVs) and pedestrians and bicyclists.

What do we know?

Although safety improvements are a primary reason for adopting CAVs, questions remain around the safety effects related to active transportation.

- Automation promises mobility and safety gains for vulnerable road users (VRUs) — particularly special populations that are currently underserved, such as children, older adults, and people with disabilities. (Shay et al., 2018).
- A key potential CAV benefit is fewer collisions owing to human error (Shay et al., 2018; Vissers et al., 2016). However, despite general consensus on net fewer crashes, CAVs do not promise zero risk to travelers (Shay et al., 2018). One study reconstructed over 3,000 preventable pedestrian fatality crashes from 2015, and found that automated vehicle technologies would help prevent between 30% and 90% of these crashes, with camera-based systems performing on the low end, and LIDAR (Light Detection and Ranging) and combined sensor technologies, which would be very expensive, performing on the higher end (Combs et al., 2019).
- As CAVs penetrate the market, there is the concern of a proper accommodation of other road users and how these rules will be determined and regulated (Shay et al., 2018). In addition, there is uncertainty with more ADAS-equipped vehicles on the roadway what will be the resulting safety benefits and the change of social norms if the vehicles must adhere to posted speeds and yield to VRUs (PBIC, 2017).

Key definitions

Automated driving systems refer to a vehicle that uses the automated controls. The Society of Automotive Engineers International (SAE) has defined six levels of automation, ranging from Level 0 (no automation) through to Level 5 (fully automated systems). Interim levels provide various levels of automated system assistance and driving functions. The National Highway Traffic Safety Administration (NHTSA) has adopted these definitions.

Advanced Driver-assistance Systems (ADAS) assist drivers in driving and parking functions, including use of automated technology such as sensors and cameras, to navigate and detect nearby obstacles.

Autonomous Vehicles (AVs) typically refers to vehicles that are capable of full self-driving without driver input (Level 4 & 5).

Connected Vehicles (CVs) use short-range wireless ***Vehicle-to-Vehicle (V2V)*** communication to exchange position and speed information with surrounding vehicles, infrastructure, and other road users such as pedestrians and bicyclists.

CAV is a term often used to describe vehicles that are both connected and automated.

Vehicle-to-X (V2X) describes wireless communications between vehicles and other road users and infrastructure. This is also referred to as Vehicle-to-Pedestrian (V2P), Vehicle-to-Infrastructure (V2I) and Pedestrian-to-Infrastructure (P2I) communications.

Sources: SAE, 2018; NHTSA, 2017; PBIC, 2017

Much of the research related to active transportation interactions with AVs and CVs is about the evolution of the different types of detection systems.

- Research has studied the performance and improvement of automated systems' ability to help vehicles and AVs detect mainly pedestrians. Overall, there has been increased attention on detecting VRUs (MacArthur et al., 2019).
- Researchers and industry have focused heavily on the analysis of onboard systems such as Autonomous Emergency Braking Systems and Blind Spot Detection applications, and the evaluation of available technologies such as camera-based machine vision systems, LIDAR, V2X communications, and beacons, among others (MacArthur et al., 2019; Harris, 2015; Hsu, 2016; Siemens, n.d.; Ross, 2017; Navarro et at., 2016; USDOT, n.d.-b.; Volpe, 2017).
- Conditions that present significant challenges to human drivers' ability to detect pedestrians and bicyclists, such as low light or glare, adverse weather conditions, road curvature and other impediments to sight distances, present similar challenges for machine-based systems (PBIC, 2017).
- Separated bike lanes, improvements in lighting, pedestrian crossing islands, and gateway treatments could serve as a contextual warning for AVs to detect or predict the presence of pedestrians and bicycles (Pedestrian and Bicycle Information Center, 2017).
- One study found that road infrastructure features, such as road width, and the presence or absence of zebra crossings had an effect on road users' interaction while approaching an AV (Madigan et al., 2019). Where possible, pedestrians and cyclists appeared to leave as much space as possible between their trajectories and that of the AV minibus. The types of interaction varied considerably across sociodemographic groups, with females and older users more likely to show cautionary behavior around the AVs than males or younger road users. Overall, the results highlight the importance of ensuring that the behavior of the AV matches other road users' expectations as closely as possible in order to avoid traffic conflicts.

While most of the research has focused on motor vehicle technology, there is a growing amount of research on smart technologies for bicycles and pedestrians.

- Sensors on bicycles, scooters, mobile phones, and other wearables are being developed (MacArthur et al., 2019). These sensors or devices would integrate into the connected environment with V2X technology. There are efforts to create industry standard Basic Safety Messages (BSMs) and Personal Safety Messages (PSMs) from sensors on bicycles, scooters and users' accessories over Bluetooth 5, dedicated short-range communications (DSRC) or cellular vehicle-to-everything (C-V2X) (Tome Software, 2019).
- Efforts to add technology to bicycles had focused on monitoring systems (Lee & Jeong, 2018); detection systems (Blankenau et al., 2018; Jeon et al., 2018; Jeon & Rajamani, 2018); and integrated bike navigation systems (Fredriksson et al., 2015). Additional research explores technologies such as audio-navigation systems (He & Zhao, 2020); blind spot warnings (De Raeve et al., 2020; Engbers et al., 2018); and green light optimized speed advice (Fickas et al., 2019).
- Connected technologies can be used to provide timely navigation information to pedestrians and bicyclists, including helping those with disabilities. For example, an app was developed in Minnesota to provide signal geometry and timing information to visually impaired pedestrians as they arrive at intersections, and was found to provide accurate information about 95% of the time in testing (Liao, 2020).

Human-machine interface is a key consideration for CAV safety.

- The value of CAVs for pedestrians and cyclists assumes clear and consistent communication between VRUs and vehicles, making all parties more aware of each other's behavior and better able to predict and negotiate conflict points (Shay et al., 2018; MacArthur et al., 2019). Communication of intent must be clear to make other road users comfortable around autonomous vehicles (Stanciu et al., 2018). One main area of research is the pedestrian crossing behavior with the use of external Human-Machine-Interface (HMI), mainly in virtual reality environments. Research has been done trying to understand the type (non-textual, textual, light-based, etc.) and characteristics of the messages of external HMI in order to make it more persuasive for road users and design guidelines to improve pedestrian safety (Bazilinskyy et al., 2019; Faas & Baumann, 2019; de Clercq et al., 2019).
- Autonomous vehicles will need to be able to detect *and* accurately interpret the variety of communication strategies used by all road users. They will also need to replicate or substitute for the variety of nonverbal communication strategies that are commonly employed by drivers, pedestrians, and bicyclists, ranging from formal, technology-based strategies (such as turn-signal use) to informal strategies (such as hand gestures or eye contact) to communicate to drivers their intent to cross a roadway. Additional complexities are added with people with disabilities. Comprehension of messages is influenced by factors such as culture, language, context, and experience in which messaging takes place (Stanciu et al., 2017; Stanciu et al., 2018).
- Until driverless vehicles are able to provide universally understood messages during interactions with other road users, they are likely to contribute to confusing and conflicting interactions between these users, especially in a shared space setting, which may reduce efficient traffic flow and increase conflicts (Merat et al., 2018).
- Aside from detecting active transportation road users, CAVs will need to be able to anticipate road users' movements and behavior. Predicting pedestrian movement and intention are essential to improving safety (Fang et al., 2017; Kotte et al., 2017).

There are important policy, legal, and regulatory issues for agencies to address.

- Federal and state governments will play a role in ensuring that CAVs operate safely, but local governments will ultimately determine how AVs are integrated into the transportation network and how AVs would affect the safety and health of motorists, cyclists, and pedestrians (Botello et al., 2019). Local governments are struggling to keep pace with the quickly evolving technology and the resources to deploy these technologies (MacArthur et al., 2019).
- Without standardization, tech companies and automobile manufactures will have to navigate the variety of local and state laws and decide how to adapt vehicles when ordinance boundaries are crossed (Pedestrian and Bicycle Information Center, 2017).

These technologies will affect travel behavior, though exactly how is not clear.

- Experts predict that AVs will allow more efficient use of roadways, narrower car-travel lanes, and less on-street parking, which may open up more space for bicycle and pedestrian infrastructure (Botello et al., 2019). Alternatively, if AVs make longer automobile trips more acceptable, that may lead to more suburban sprawl, with trip distances too long to cover by active travel, and to CAVs replacing trips previously taken by foot, bike, or transit (Cavoli et al., 2017; Shay et al., 2018; Botello et al., 2019).
- As stated above, the increase in safety benefits could have significant influence on the number of people willing to walk and bike (MacArthur et al., 2019).

- One review of research suggested that physical activity will be affected in a negative way, with less walking and more sedentary behavior (e.g., sitting) as AVs become available (Spence et al., 2020).

There is some research that assesses how people walking and cycling perceive AVs and how that may affect their behavior in the future.

- Confidence in AVs may influence active transportation users' preference for active transportation infrastructure. Survey-based research found that individuals who are more familiar with the concept of driverless vehicles are less likely to opt for protected facilities compared to those who are unfamiliar (Blau et al., 2018). Penmetsa et al. (2019) found that people's interactive experience positively affects their perceptions and interest in adoption of AV technology.
- At the same time, one study found that people living in neighborhoods with more pedestrian-friendly and mixed-use streets are more likely to express higher levels of concern about AVs' capabilities to react to the environment (Wang & Akar, 2019). At the same time, people in areas with more separated bicycle and pedestrian facilities felt more comfortable with AVs (Wang & Akar, 2019; Blau et al., 2018).
- One study found that cyclists and pedestrians may trust CAVs more than they trust human drivers, as long as CAVs are reliable and programmed to behave safely (Cavoli et al., 2017).

What are the research gaps?

In general, the potential negative effects of CAVs on pedestrian and bicycle safety are understudied. Further research is needed to determine the potential for reducing injuries and fatalities under varying automation scenarios (Shay et al., 2018).

- Evaluation of the pedestrian and bicycle detection capabilities of different ADAS sensor systems under various conditions (e.g., low light, glare, adverse weather conditions, visually cluttered landscapes, crowded streets, amid horizontal and vertical curves, with obstacles such as parked cars, etc.), in different environments, and in detecting people with diverse geometric shapes (e.g., people in wheelchairs, different types of bicycles, etc.) and different appearances, including darker skin (PBIC, 2017).
- Roadway design enhancements that can provide additional contextual warnings to improve detection of pedestrians and bicyclists (PBIC, 2017).
- Needs, desires, comfort level and safety of pedestrians and bicyclists in relation to traveling around and communicating with CAVs (PBIC, 2017; Shay et al., 2018), including pedestrian crossing behavior (Stanciu et al., 2018).
- Safety issues that arise with pick-up/drop-off, particularly for children or people with disabilities who may be using AVs for independent transportation (PBIC, 2017).
- Research is needed into the equity implications CAVs' interactions with pedestrians and bicyclists, including what equipment or infrastructure is needed to safely interact in a CAV environment, and how it is distributed. Further research is also needed into how CAVs will affect pedestrians with disabilities, including vision disabilities.

There are methodological gaps related to pedestrian or bicycle movement and behavior around CAVs.

- Studies to model or predict both crowd and individual behavior based on observable characteristics (such as body posture, travel speed, and direction) could be useful in ADAS development (PBIC, 2017).
- The literature on HMI is sparse relating to VRUs. To develop effective ways for AVs to detect, receive, and properly interpret interpersonal communication on the roadway, there is a critical need to better understand how people do this effectively and when this communication fails (Stanciu et al., 2018).

Other research gaps exist around how AVs may change overall travel behavior, including walking and cycling.

- Future research is needed on how AV penetration will influence active transportation behavior, including scenarios with shared AVs. For example, will this make the ability to walk or bike less or more valued (Shay et al., 2018)?
- As noted above, as CAVs become more common, research is needed to understand how they may change social norms related to vehicle speed and yielding behaviors (PBIC, 2017).
- How might AVs change the mix and character of trips for utilitarian and recreational purposes? Will general and special (underserved) populations increase walking trips to access CAV services, or might a door-to-door model dampen walking-for-access (Shay et al., 2018)?
- How will AV freight delivery, including small vehicles using sidewalks, impact the walking and biking environments?
- The availability and practicality of V2X technologies for all types of pedestrians and bicyclists should be evaluated to ensure that the benefits of these technologies are equitably distributed (i.e., to people of all ages, incomes, educational levels, physical abilities, etc.) (PBIC, 2017).
- While autonomous vehicles, included shared vehicles schemes, may reduce private vehicle ownership and change road space needs and usage patterns, research is needed into how jurisdictions can ensure that active transportation is promoted when making infrastructure and road space decisions (Pettigrew et al., 2020).

The technology of CAVs and smart technologies for pedestrians and bicycles is evolving extremely quickly (MacArthur et al., 2019).

- Communication standards and technologies are developing for CAVs to communicate with VRUs, particularly BSMs/PSMs. Bluetooth 5, C-V2X, and DSRC are still being explored and tested for VRUs. There is currently not clear consensus which wireless communication framework will be used for certain applications.
- ITS and CV applications will need to be developed for use cases that improve safety outcomes for VRUs and enhance the travel experience for these users.
- The growth in electric bicycles (e-bike) and electric scooters has provided an opportunity for industry to start developing smart technologies and sensors that can be integrated into the devices.

How is research on this topic done?

Research on CAVs is ongoing and rapidly changing and speculative. Most studies are cross-sectional or employ simulation modeling. Given the subject, there are few experimental studies and no longitudinal research. US DOT

has two deployment pilot projects ongoing in New York City and Tampa, FL, that are testing connected vehicle applications, of which some applications are focused on pedestrian safety (US DOT, 2020).

Most of the research about how pedestrians and cyclists may react to CAVs is based on surveys with questions about hypothetical situations. These survey respondents may not have a clear understanding of CAVs (Botello et al., 2019).

The increased use of open data, GPS and smartphone information has made evident the challenges related to data privacy and inaccuracies of localization, which would affect predictions of CAVs interacting with pedestrians and cyclists (Kotte et al., 2017).

Current research

Sponsor	Project Information	Status
National Cooperative Highway Research Program (NCHRP) 20-102(26) https://rip.trb.org/View/1657856	**Dynamic Curbside Management in the Era of CAVs, SAVs, Scooters, Transportation Network Companies (TNCs), and Traditional Vehicles** The objective of this research is to develop a guidebook for state, regional, and local transportation agencies on developing and implementing a dynamic curbside management program.	Expected completion date: 5/15/22
National Cooperative Highway Research Program (NCHRP) 20-102(33) https://rip.trb.org/View/1745953	**Safety of Vulnerable Road Users in a C/AV Future** This project will explore how VRUs could be protected by C/AV and infrastructure technologies in the absence of user-carried smartphone or wearables (e.g., audio, external vehicle displays). The research team will explore and summarize types of on-vehicle and on-street technologies that help protect pedestrians, cyclists and other VRUs sharing the road with C/AVs. This assessment will also provide recommendations for prioritization of technologies to be implemented by OEMs or by local/state/federal agencies such that they are provided a plan of action towards implementation of testing and pilot projects to demonstrate feasibility of technologies.	Start date: 10/19/20
Center for Connected and Automated Transportation (UTC) https://rip.trb.org/View/1715290	**DeepScenario: City-Scale Scenario Generation for Automated Driving System Testing & Evaluation** This project will build a city-scale scenario generation and simulation platform for ADS testing and evaluation. Under different routes and environmental conditions, the simulation platform can generate testing scenarios dynamically along the route to interact with the CAV and systematically evaluate its performance. Meanwhile, a set of corner cases regarding vulnerable road users (VRUs) will be identified and added to the generated scenario library.	Expected completion date: 02/28/22
Pacific Northwest Transportation Consortium (Pactrans) (UTC) https://rip.trb.org/View/1669412	**Managing Increased Demand for Curb Space in the City of the Future** The research findings will improve mobility by increasing our understanding of existing curb usage and provide new solutions to city officials, planners, and engineers responsible for managing this scarce resource in the future. This research will allow for the development of innovative curb space designs and ensure that our urban street system may operate more efficiently, safely, and reliably for both goods and people.	Expected completion date: 09/15/21

Sponsor	Project Information	Status
Center for Advanced Infrastructure and Transportation (CAIT) (UTC) https://rip.trb.org/View/1666414	**The Development of a Smart Intersection Mobility Testbed (SIMT)** The primary goal of this proposal is to establish the pilot Smart Intersection Mobility (SIMO) testbed in downtown New Brunswick. The testbed will be equipped with AV-grade LIDAR and computer vision sensors to collect real-time vehicle, pedestrian, and infrastructure change data. Data sharing and testing platforms will be built for testing and evaluating different mobility, safety, environmental, and energy applications. The intended outcome of the project will be a prototype testbed with components including roadside units, communication units, central computing units, and the visualization center.	Expected completion date: 09/30/20
Small Business Innovation Research (SBIR), Small Business Administration https://www.cra.com/work/case-studies/main-st	**The Multimodal Alerting Interface with Short-Range Transmissions (MAIN-ST)** The project is to develop hardware and software to bring bicycles onto connected vehicle networks and to provide safety information related to possible hazards to the bicyclist. The project developed prototype Dedicated Short Range Communication (DSRC) capability using commercially available hardware, as well as a software hazard detection and notification system that will work with any connected vehicle hardware transport mechanism (potentially including 5G or Bluetooth). The project also developed a virtual reality bicycle simulator and supporting software that has been installed at the Turner-Fairbank Highway Research Center (TFHRC) and that interoperates with the existing driving simulator.	Phase 1: 2016 Phase 2: 2017 Phase 3: 2020
FHWA https://rip.trb.org/View/1662704	**Planning Multimodal Networks in a Connected and Automated Vehicle Future** The objectives of this requirement are to: (1) Synthesize existing research and information related to nonmotorized users in connected vehicle/automated vehicle (CV/AV) environments, with a focus on how the issues and challenges around nonmotorized users have been accounted for thus far in CV/AV development. (2) Based on this synthesis, identify knowledge gaps and critical issues. (3) With a focus on planning objectives to provide safe, comfortable, and connected multimodal networks, convene a workshop and interview stakeholders to help describe likely deployment scenarios of how CV/AV networks will interact with nonmotorized users. (4) Create a final report describing all of the above.	Expected completion date: 10/20/20
North Carolina DOT https://rip.trb.org/View/1723547	**Enhancing AV Traffic Safety through Pedestrian Detection, Classification, and Communication** EcoPRT will employ small autonomous vehicles that will enhance user access and mobility options for navigating the NCSU campus in an efficient and relatively inexpensive manner. Researchers will refine the system for accurate identification of obstacles and humans utilizing vision-based classification via deep learning neural networks. This project will focus on developing AV communication with pedestrians and explore the considerations and potential for doing so with bicyclists.	Expected completion date: 7/31/20

Sponsor	Project Information	Status
Center for Advanced Multimodal Mobility Solutions and Education (UTC) https://rip.trb.org/view/1745751	**Pedestrian Behavior and Interaction with Autonomous Vehicles** This study proposes the use of virtual reality (VR) as a means to overcome the safety challenges inherent in studying pedestrian-vehicle interactions and will focus on identifying any differences in pedestrian behavior when CAVs are introduced to the traffic stream. The central research question of this proposal is: Are there significant behavioral changes in the way pedestrians interact with vehicles at a crossing when a portion of the vehicles is autonomous?	Expected completion date: 9/30/21

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Most common TRID index terms	
Pedestrians	Bicycles
Cyclists	Behavior
Intelligent vehicles	Vulnerable road users
Autonomous vehicles	Connected vehicles
Highway safety	Crash avoidance systems
Traffic safety	

Bicycle and pedestrian data: Emerging user-based data

Crowdsourced and passive data sources, including data collected through smartphone GPS data, provide an opportunity to develop a fuller understanding of walking and bicycling activity and exposure throughout networks. Location-based counts, including from manual and automated counters, as well as survey data, lack extensive spatial and temporal information that can be used for understanding walking and bicycling activity (Boss et al., 2018). The lack of disaggregated travel information forces a reliance among travel modelers on estimated and extrapolated travel information that "that may not reliably reflect movement or agents within the system as a whole" (Harrison et al., 2020). This review covers emerging data sources, primarily for understanding active transportation volume and activity, while touching on crowdsourced infrastructure and related route sources.

Related review topics

- More traditional pedestrian and bicycling count data are covered in *Bicycle and pedestrian data: Location-based counts*.
- Research on pedestrian and bicyclist safety data is covered in *Bicycle and pedestrian data: Safety*.

Key definitions

Crowdsourced data is user-generated data, usually through interaction with an app or web interface.

Passive data is automatically collected data, often by an app running in the background on a smartphone, without needing the user to initiate a trip or activity.

Mode-specified data is travel data where the user indicates their travel mode, removing the need to impute travel mode.

What do we know?

User-based or crowdsourced data can be divided into three types: opt-in and mode-specific sources; passive mode-unspecified sources; and other user-input based sources.

- "Opt-in" datasets include those that users choose to record their trip information, and include bicycle or fitness tracking apps like CycleTracks, Strava, MapMyRide, etc. These are generally "mode-specified" datasets, in which the user specifies that they are making a trip via walking or biking (Lee & Sener, 2020).
- Lee and Sener distinguish regional activity tracking apps like CycleTracks, developed by the San Francisco County Transportation Authority (SFTCA) and adapted by other regions, which are expressly deployed to improve planning for active transportation, from fitness tracking apps like Strava, which sells access to its walking and bicycle data, and others like FitBit and Garmin which do not (Lee & Sener, 2020).
- A challenge for opt-in apps, in terms of being able to passively detect trips, is the issue of battery drain; however, some advancements (e.g., Google's Android Activity Transition Application Programming Interface (API)) have allowed improved passive detection with limited battery drain (Barbeau and Cetin, 2021).
- Another source of mode-specified, active transportation dataset is area bike share data (Lee & Sener, 2020).
- "Track and trace" datasets are passively acquired data, usually from smartphones, pulling location data from cell phone towers, wi-fi connections, or GPS, including apps with location-based services, or other

GPS units, that "capture highly grained mobility content and can be linked to the phone owner/user behavioral choices and other individual context" (Harrison et al., 2020). These are often mode-unspecified data sources, and require imputation to identify mode (Lee & Sener, 2020). Examples of commercial services that provide such data are StreetLight and Cuebiq.

- User feedback and input databases are more consistent with the conventional understanding of "crowdsourced" data, and engage residents to upload information about streets (e.g., OpenStreetMap), and existing or under-development applications include sidewalk inventories or bicycle crash locations (Lee & Sener, 2020).

Passive and crowdsourced data offer the potential to understand the travel characteristics and patterns of active transportation users more fully. They provide broad coverage and contain information on trip types and locations missing from conventional data sources.

- Mode-specified emerging data sources can be used for travel pattern identification (when and where people go by walking and biking); route choice modeling (including facility preferences); travel demand prediction (including understanding volume estimates across a network); crash and air pollution exposure information; infrastructure evaluations (including before-and-after volumes); bike share pattern analysis; and community needs detection (Lee & Sener, 2020).
- Controlling for facility and surrounding contextual factors, third-party (mainly Strava) data has consistently been found to improve estimates of bicycle volumes and safety performance models (Dadashova et al., 2018; Roll et al., 2018; Sanders et al., 2017; Strauss et al., 2015; Wang et al., 2016).
- A study in Ottawa employed Strava data to assist in assessing the impact of bicycle infrastructure changes on ridership at multiple locations around the city (Boss et al., 2018).
- A study in Miami-Dade County found that "Strava data, due to its high spatial and temporal resolution and coverage, can identify how the influence of explanatory variables on estimated bicycle trip volume varies between different trip purposes and days of the week" (Hochmair et al., 2019).
- A 2019 study found that Strava data, when adjusted for population and field observation, was useful for providing exposure information for an intersection crash study (Saad et al., 2019).
- A 2017 study noted that, in a case study in Seattle, Strava in addition to existing count data improved the explanatory power of a bicycle exposure model (Sanders et al., 2017), suggesting a more affordable approach for exposure estimates than developing robust counting programs.
- A 2017 study in Glasgow used Strava trip data to estimate bicyclist and pedestrian air pollution inhalation (Sun et al., 2017).

One concern is whether these data accurately represent all active transportation users. Current research using these data is focused on bicycle travel.

- App users typically make up only a fraction of cyclists (Strava ~2%-10%) at a specific location and sampling ratios can vary significantly even within the same region (Conrow et al., 2018; Griffin & Jiao, 2015; Heesch & Langdon, 2016; Hochmair et al., 2019; Jestico et al., 2016).
- Mobile phone and app users may be more likely to be young and tech savvy (Lee & Sener, 2020), while fitness app (such as Strava) users have been found in multiple studies to be more likely to be young and male (Boss et al., 2018; Lee & Sener, 2020).

- A 2019 study surveyed 95 bicyclists in the Atlanta, GA, area, and asked about their use of smartphone apps and ridership habits and preferences. “App users rode more frequently, self-classified as stronger riders, and rode proportionately more for leisure. Although groups had similar infrastructure preferences at the person level, differences appeared at the level of the estimated ride, where, for example, the proportion of ridership captured by an app on protected bike lanes was lower than the overall proportion of ridership captured” (Garber et al., 2019).
- Sampling rates (the share of cyclists using or recorded by the app) vary by bicycle facility types and surrounding context (Conrow et al., 2018; Dadashova et al., 2018; Hochmair et al., 2019). For example, Hochmair et al. noted sampling rates more than six times higher on streets relative to trails in Miami, while Conrow et al. found Strava sampling rates higher in areas with few bike lanes and in areas of higher socioeconomic status (Conrow et al., 2018; Hochmair et al., 2019). Dadashova also suggests the need to adjust Strava sampling rates by road class and surrounding households with higher incomes (Dadashova et al., 2018).

Data fusion is an emerging trend to mitigate representation bias.

- Fusing crowdsource data with traditional data can help develop new insights on travel analysis methods that scale beyond current approaches (Romanillos et al., 2016).
- Several studies combined or “fused” data with third-party counts to model observed bicycle volumes. One study added segment functional classifications and adjacent numbers of upper-income households (>$200k/yr) (Dadashova et al., 2018). Another study included segment slope, speed limit, on-street parking presence, and a seasonal adjustment along with Strava counts (Jestico et al., 2016). Proulx & Pozdnukhov (2017) used travel demand model derived bicycle volume estimates and bike share counts alongside Strava data. Roll combined Strava counts with segment functional class, bicycle facility types, local accessibility and design measures, and a measure of network centrality (Roll, 2018). Sanders et al. (2017) included number of bike lanes and proximity to the university alongside Strava count data.
- Research has found that fusing together Strava data, which primarily represents recreational trips, with bike share data, which provides more utilitarian trips, can provide a fuller picture of bicycle use and exposure (Proulx & Pozdnukhov, 2017).

Strava, which is the most studied of crowdsourced data, generally correlates well with known count data, particularly in areas with high bicycle volumes.

- In Ottawa, linear correlations between Strava ridership and counts at 11 city locations ranged between .76 and .96. After a campaign to encourage the public to log rides on Strava, correlations improved (to, at worst, .86), suggesting that the potential Strava bias toward certain types of bicyclists could be overcome (Boss et al., 2018).
- A study in Glasgow, Scotland, found that Strava data was correlated with manual cordon counts, and that model adjustments made the data appropriate for estimating magnitudes of bicycling, but that the relationships between Strava and count data varied over time and space, presenting a caution for predicting volumes at locations too far from known data (Livingston et al., 2020).
- Correlation does not necessarily track sampling ratio (Turner et al., 2019) and Strava correlation varies by bicycling volume (Conrow et al., 2018). For example, in Austin, despite a much lower sampling ratio, Ride Report (r=0.61) had a slightly stronger association with observed counts than Strava (0.59) (Turner et al., 2019). Livingston et al. (2020) also noted that predictions based on high Strava cycling counts are more accurate than those based on low counts, which were not recommended for use in planning.
- High overall correlation may mask poor performance such as large site ranking errors (i.e., correlation does not necessarily line up with error) (Turner et al., 2019; Conrow et al., 2018), and can vary widely

across sites in the same region (Conrow et al., 2018). Areas of low correlation may be spatially correlated, with similar values being found more often in areas with lower population density, greater social disadvantage and lower ridership overall (Conrow et al., 2018).

Passive and crowdsourced datasets often require additional expertise to use and raise additional concerns.

- Passive and crowdsource data cannot be used out of the box, and need to be assessed for their appropriateness/fitness and quality for the intended application, including time and computational resource intensive data cleaning and structuring (Harrison et al., 2020).
- Garber et al. (2019) note that representativeness issues associated with smartphone app-generated data can be corrected if bias can be accurately measured (Garber et al., 2019).
- The very characteristics that make passive and crowdsources datasets valuable – their ability to provide person-level trip data – also provides concerns in the areas of privacy, anonymity and the frequent lack of informed consent (Harrison et al., 2020).

What are the research gaps?

- Most of the research on these data sources is on bicycle travel. The use of passive and crowdsourced data to understand pedestrian travel is a gap.
- Representativeness of the data (discussed above) point to some concerns about the validity of crowdsourced data and highlight the need to understand the sample and any related issues.
- Research on accuracy, reliability, and coverage of the continuously emerging new data sources would improve the ability to use the data for planning and engineering.
- One specific such gap is how the change in the share of bicyclists using crowdsourcing apps affects model accuracy over time (Dadashova et al., 2020).
- There are gaps related to using mode-unspecified GPS data. These data must first have travel mode imputed, which can present challenges when attempting to differentiate walking, and especially bicycling, from slow moving vehicles like stop-and-go motor vehicle traffic. In addition, challenges of identifying trip starts and stops may result in missing short trips (Lee & Sener, 2020).
- Strava was by far the most common data source used in the research reviewed, with other sources, including StreetLight and CycleTracks, receiving considerably less assessment.
- Additional research and guidance are necessary on how to fuse emerging data sources with conventional count data to obtain network bicycle volume estimates. This includes comparing different modeling structures for data fusion, and considering what standards or practices are needed to make emerging and more traditional data sources comparable.
- Route planning requests in mapping applications and websites could be an additional data source for active transportation planning. Research would be necessary to understand the usefulness of these data.

Current research

Sponsor	Project Information	Status
National Cooperative Highway Research Program (NCHRP) 07-31 https://rip.trb.org/View/1707202	**State DOT Usage of Bicycle and Pedestrian Data: Practices, Sources, Needs, and Gaps** The objectives of this research are to determine how state DOTs are using data and to identify data sources, gaps, and recommendations on the next steps to develop the data and tools state DOTs need.	Anticipated, 2021 FY
North Carolina DOT NC 2020-43 https://rip.trb.org/View/1672460	**Bicycle Volume: Counting Machine Validation & Correction, Estimating & Forecasting, and Analysis of Injury Risk** This project has four objectives. First, how frequently routine validation should be performed to account for potential machine drift over time and at what level the correction factor should be applied. Second, the programmatic cost associated with calibrating systems at varying frequencies over time. Third, after correcting the automated bicycle count data from the continuous count sites, the crowdsourced data collected from Strava application is used. A bicycle volume prediction model will be developed. A bicycle ridership map will be generated based on the modeling results. Fourth, the bicycle crash data will be collected and combined with the existed crowdsourced bicycle data. Locations that are associated with high crash frequency will be identified and an injury risk model will be developed to analyze the factors that affect the cyclist injury frequency.	Expected completion date: 7/31/21
National Institute for Transportation & Communities (UTC) https://rip.trb.org/View/1575786	**Exploring Data Fusion Techniques to Derive Bicycle Volumes on a Network** The research proposed here would develop a method for evaluating and integrating emerging sources of bicycle activity data with conventional demand data and methods, and then apply the results to several locations to predict network-wide bicycle volumes.	Expected completion date: 6/20/21

Research reviews

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Most common TRID index terms

Crowdsourcing
Bicycling
Cyclists
Global Positioning System
Mobile applications
Smartphones
Bicycle counts
Pedestrians
Data analysis
Travel patterns

Bicycle and pedestrian data: Location-based counts

With the increased focus on bicycle and pedestrian trips in the U.S. over the last decade, many agencies have started count programs to gather active transportation volume data. These data are useful for planning and designing new facilities, in safety analyses, and for quantifying economic impacts. Most of the research to date has focused on bicycle counting. This review covers location-based counts – data collected at fixed locations, either by people (aka "manual counts") or technology (e.g., "automatic counters"). This is in contrast to user-based count data, which comes from people walking and bicycling, such as through an app (e.g., Strava) or other GPS-based technology (e.g., mobile phones).

Related review topics

- There is a separate review of research on *Bicycle and Pedestrian Data: Emerging User-based Counts* that includes topics such as crowdsourced and GPS-based passive data.
- There is also a separate review on *Bicycle and pedestrian data: Safety*.

What do we know?

A counting program should include permanent and short-duration sites that represent travel patterns for all factor groups (e.g., commute, recreational, mixed, etc.) (Jackson et al., 2015).

- Continuous count programs consist of the following steps – reviewing existing programs; developing an inventory of available continuous monitoring sites and equipment; determining traffic patterns to be monitored; establishing seasonal pattern groups; determining appropriate number of continuous count sites; computing monthly factors; and developing seasonal factors (Lindsey et al., 2014).
- Short-duration count programs consist of the following steps – selecting count locations (random or non-random); selecting type of counts (segment or intersection); determining duration of counts; determining the method of counting (automated or manual); determining number of counts; and evaluating counts and applying factors (occlusion, time of day, day of week, monthly, seasonal) (Lindsey et al., 2014).
- Although progress has been made by departments of transportation in establishing counting programs, progress is lagging in programs that monitor or characterize pedestrian travel, particularly in comparison to bicycle travel (Lindsey et al., 2014).
- There is research with recommendations about the minimum number of counters per factor group (Johnstone et al., 2017; Nordback et al., 2019).
- Limiting count sites to locations that are convenient, have the highest volumes or greatest increases in bicycling and walking does not produce a representative sample and may lead to errors during extrapolation (Federal Highway Administration, 2016; Ryus et al., 2014).

Pedestrian and bicycle data collection programs often use more than one type of counting technology (Ryus et al., 2014).

- The choice of counting technology depends on the purpose (why data is being collected); type of data collected (bicycles, pedestrians or both); how long the data is being collected for (permanent, temporary, mid-range); and available resources (cost, staff time) (Federal Highway Administration, 2016).
- Manual counts provide behavior and other attributes (approximate age, apparent gender, helmet use, and use of assistive devices) and can be conducted in the field or by reviewing video (Ryus et al., 2014).
- Counting equipment must be regularly maintained to ensure accurate consistent counts (Ryus et al., 2014).
- Applying a correction factor produces a better estimate of the true count of pedestrians or bicyclists who passed through the counter's detection zone (Ryus et al., 2014).
- Sources of automated counter errors include occlusion (users being obstructed by other users when side by side, for example); environmental conditions (temperature, precipitation, and lighting); counter bypassing; and mixed-traffic effects (Ryus et al., 2014).

People bicycling across a bridge in Portland, OR, are counted when they cross the tube, with the count displayed on a sign at the end of the bridge. (Photo: Jennifer Dill)

- Artificial intelligence, machine learning and computer vision approaches are making it increasingly possible to automatically monitor, track and count pedestrians and bicyclists through video recordings or feeds, providing new sources of location-based counting (Pourhomayoun, 2020).
- LIDAR systems have been shown to be highly accurate at counting pedestrians in areas with high flows (Lesani et al., 2020).
- Although still seldom employed, pedestrian push button or call data from traffic signals can be used to estimate pedestrians with relatively strong accuracy (Singleton and Runa, 2021).

Data quality and standard data formats for count data are emerging.

- Data quality principles must be included in the data collection practices, and both accuracy and validity of the data are important (Turner & Lasley, 2013).
- Recent efforts have focused on standardizing data formats and coding, with the development of the *Traffic Monitoring Guide* (TMG) format that allows count data to be submitted to the traffic monitoring analysis system (TMAS) (Laustsen et al., 2016).
- Adding bicycle and pedestrian counts to an existing database used for motor vehicle monitoring can ease reporting requirements (Nordback et al., 2018).

Annual average daily nonmotorized traffic (AADNT) estimation error is dependent on when short-duration counts are conducted, for how long, and the type of factors used.

For bicycle counts

- Conduct short-duration counts during months with higher traffic volumes (e.g., April – October) to reduce estimation error (El Esawey, 2014).
- At short-duration count sites, count for at least seven days (El Esawey et al., 2013; Nordback et al., 2013).
- Count on Tuesday through Thursday, even for sites with high weekend volumes, except for pedestrian-only counts (Nordback et al., 2019).
- Error is lower for commuter traffic than weekly or weekend multipurpose traffic (Nordback et al., 2019).
- Error is lower for bicycle-only and undifferentiated, mixed-mode counts (Nordback et al., 2019).
- Research supports using monthly factors rather than seasonal factors (El Esawey, 2014; El Esawey & Mosa, 2015); daily factors disaggregated by weather (El Esawey et al., 2013); and day-of-year factors rather than traditional factors (El Esawey, 2016; Hankey et al., 2014; Nosal et al., 2014).
- Research also supports imputing missing values using methods that account for weather and information from similar sites (El Esawey, 2017, 2018a, 2018b).

For pedestrian counts

- Peak period counts generally produced weekly volume estimates with lower error than off-peak counts (Griswold et al., 2018).
- Weekly volume estimates based on 12-hour counts were more accurate than those based on two-hour counts (Griswold et al., 2018).
- Land use and empirical clustering approaches provided better weekly pedestrian volume estimates than the single-factor approach of taking the average of all locations (Griswold et al., 2018).

Modeling pedestrian and bicycle exposure can be done using various count inputs and exposure variables.

- Short-term counts, ranging from several hours to several weeks, can be extrapolated into average annual daily bicyclist or pedestrian volume (AADB, AADP). Permanent counters can be used to calculate AADB or AADP as well. These variables can be used or adapted to assess bicycle or pedestrian exposure (Jahangiri et al., 2019).
- Direct-demand models can be used to estimate pedestrian activity and exposure from a limited set of short-term counts, although separate models likely need to be run for high- and low-volume sites, as well as in different urban/rural contexts (Le et al., 2020).

Direct-demand models have been used to correlate observed counts with sociodemographic, built environment, infrastructure-related, weather and temporal variables.

- Sociodemographic variables used in such models include age, income, education, gender and race (Hankey et al., 2012; Lindsey et al., 2007).

- Built environment variables that have been used in direct demand models include mixed land use, greater street connectivity, higher density at the origins and destinations of trips, and the attractiveness of the environment (Hankey et al., 2012; Haynes & Andrzejewski, 2010; Jones et al., 2010). Other variables, such as the availability of marked crossings, may influence demand but are usually not included in such models because of the lack of accurate data.
- Infrastructure-related variables that significantly affect bicycle volumes include bike lanes and proximity to paved, multi-use trails (Jones et al., 2010; J. Wang et al., 2016).
- Streets with higher transit frequencies were observed to have higher pedestrian volumes (Haynes & Andrzejewski, 2010).
- Higher bicycle and pedestrian traffic volumes were associated with warmer temperatures; both rain and snow were associated with lower volumes, and the effect of precipitation seemed to be greater than temperature (Schneider et al., 2009; J. Wang et al., 2016).
- Temporal variables include time of day, the day of the week, and the month (Hankey et al., 2016).

Aside from count data, better data on pedestrian infrastructure is needed.

- A survey of 40 state DOTs found that, while most collect some form of data on the types or locations of pedestrian facilities, there is not a standard for how to collect the data, what facilities to document, and how to store the data (Louch et al., 2020).

What are the research gaps?

Overall

- Separate data quality checks for low-volume and high-volume count sites (Nordback et al., 2016).
- Clearly defined, robust methods for assigning short-duration count locations to factor groups.
- Methods for optimizing the number and type of counts to conduct to develop an accurate estimate of travel patterns.
- Consistent data collection and management practices and standards are needed for regional, statewide, or national comparison and analysis (Lagerwey et al., 2015).

Pedestrian

Overall, more research is needed on understanding pedestrian travel (Nordback et al., 2016). Some ways to achieve that include the following:

- Guidance on where to locate continuous and short-duration count sites and strategically place counters to get the needed data (Nordback et al., 2016).
- Need to identify pedestrian-specific pattern groups and develop factors (Nordback et al., 2016).
- Guidance on estimating expansion factors to adjust short-duration counts (Nordback et al., 2016).
- Continuing research on appropriate technology to count pedestrians, especially at high-volume locations, and in crosswalks (Nordback et al., 2016).
- Counts of midblock crossings, particularly for safety analysis of exposure to midblock crashes.

Bicycle

- Most of the research needs in the literature are about emerging data sources including the accuracy, reliability, representativeness, and coverage of such data, as well as data fusion. These research gaps are discussed in more detail in the *Bicycle and Pedestrian Data: Emerging User-based Counts* summary.

How is research on this topic done?

- Studies comparing automated counts to manual counts and those that have compared various factors to estimate volumes have used average percentage error and mean average percentage error (MAPE) to determine accuracy (El Esawey et al., 2013; Nordback et al., 2013, 2019; Nordback & Janson, 2010).
- Grouping sites into factor groups were based on visually identifying travel patterns (Nordback et al., 2013); identifying travel patterns using morning-to-afternoon count ratio or weekend-to-weekday count ratio (Miranda-Moreno et al., 2013); or land use and empirical clustering approaches (Griswold et al., 2018).
- Direct-demand models estimated to model counts have largely used multiple regression techniques to model counts. Some studies estimated linear ordinary least square models (Haynes & Andrzejewski, 2010; Liu & Griswold, 2009; Schneider et al., 2009) while others have used log-linear models (Jones et al., 2010; Schneider et al., 2012). Some studies have also concluded that negative binomial models produce more accurate estimation of volumes (Hankey et al., 2012; X. Wang et al., 2014).
- Data fusion modeling approaches to date have include regression, Poisson regression, and mixed effects (Dadashova & Griffin, 2020; Roll et al., 2018; Roy et al., 2019; Sanders et al., 2017).

Current research

Sponsor	Project Information	Status
National Cooperative Highway Research Program (NCHRP) 07-31 https://rip.trb.org/View/1707202	**State DOT Usage of Bicycle and Pedestrian Data: Practices, Sources, Needs, and Gaps** The objectives of this research are to determine how state DOTs are using data to identify data sources, gaps, and recommendations on the next steps to develop the data and tools state DOTs need.	Anticipated, 2021 FY
North Carolina DOT NC 2020-43 https://rip.trb.org/View/1672460	**Bicycle Volume: Counting Machine Validation & Correction, Estimating & Forecasting, and Analysis of Injury Risk** This project has four objectives. First, how frequently routine validation should be performed to account for potential machine drift over time and at what level the correction factor should be applied. Second, the programmatic cost associated with calibrating systems at varying frequencies over time will be determined. Third, after correcting the automated bicycle count data from the continuous count sites, the crowdsourced data collected from Strava application is used. Based on both the manual count data and the corrected continuous count data, as well as the crowdsourced bicycle data, a bicycle volume prediction model will be developed. A bicycle ridership map will be generated based on the modeling results. Fourth, the bicycle crash data will be collected and combined with the existing crowdsourced bicycle data. Locations that are	Expected completion date: 7/31/21

Sponsor	Project Information	Status
	associated with high crash frequency will be identified and an injury risk model will be developed.	
North Carolina DOT NC 2020-39 https://rip.trb.org/View/1672456	**State of the Art Approaches to Bicycle and Pedestrian Counters** The objective of this project is to determine the state of practice for bicycle and pedestrian counting technologies to inform the enhancement and future growth of the North Carolina's Non-Motorized Volume Monitoring Program (NC NMVDP).	Expected completion date: 3/31/21
South Carolina DOT SPR742 https://rip.trb.org/View/1691991	**Automatic Extraction of Vehicle, Motorcycle, Bicycle, and Pedestrian Traffic from Video Data** The objective of this research is to develop image processing algorithms to automatically extract vehicle counts and classifications, as well as counts of motorcycles, bicycles, and pedestrians from real-time and offline videos.	Expected completion date: 12/31/21
Minnesota DOT 99008 https://rip.trb.org/View/1579263	**Understanding Pedestrian Travel Behavior and Safety in Rural Settings** The Minnesota Department of Transportation (MnDOT) has worked to create a methodology for counting people walking and bicycling through manual and automated counts. The purpose of this research is to further the understanding of walking behavior and safety. In rural communities, this is where people may not consistently pass a screen line and behavior is undercounted. With the first Minnesota Statewide Pedestrian System plan currently underway, this research would inform the direction for pedestrian counts and inform the plan's performance measures with the ultimate goal to improve safety and better inform MnDOT's future investment opportunities around pedestrian facilities. The research would also explore additional counting methods such as technology or survey data and how rural communities can support safer walking along and across state facilities.	Expected completion date: 1/31/21
National Institute for Transportation & Communities (UTC) https://rip.trb.org/View/1575786	**Exploring Data Fusion Techniques to Derive Bicycle Volumes on a Network** The research would develop a method for evaluating and integrating emerging sources of bicycle activity data with conventional demand data and methods, and then apply the results to several locations to predict network-wide bicycle volumes.	Expected completion date: 6/30/21

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Most common TRID index terms
Pedestrian counts
Bicycle counts
Nonmotorized transportation
Annual average daily traffic
Data collection
Traffic estimation
Cyclists
Traffic volume
Traffic surveillance
Bicycles
Pedestrians
Bicycle travel
Traffic counts

Bicycle and pedestrian data: Safety

Sufficient and appropriate data is necessary to accurately identify safety concerns and prioritize and evaluate pedestrian and bicycle infrastructure (Sanders et al., 2020). This brief focuses on crash data and other surrogate safety data, although exposure and infrastructure data are also important inputs to many crash analyses.

Related review topics

- Research related to bicycle and pedestrian counts is covered in *Bicycle and Pedestrian Data: Location-based Counts*
- Research related to crowdsourced and passive pedestrian and bicycle activity data is covered in *Bicycle and Pedestrian data: Emerging User-based Data*

Definitions

Surrogate safety measures are measures of activity that are alternatives to or complement crash data, including measures of conflicts or near-crashes.

Post-encroachment time (PET) is a measure of the time between two road users passing the same location in their paths.

Time to collision (TTC) is a measure of the time until a collision occurs given current trajectories.

What do we know?

Crash-related traffic incidents can range from conflicts that do not result in a crash to fatal crashes, with key data sources including police crash records and post-crash data such as emergency response data and health outcomes (Cherry et al., 2018). Self-reported information on collision and near misses also offers the potential to fill in some safety data gaps that arise from underreporting in official crash data (Branion-Calles et al., 2017).

Police Crash Data

Police crash data, from either city, county or state crash databases, crash records, or the Fatality Analysis Reporting System (FARS) are commonly used to understand pedestrian and bicycle safety.

- Police crash report data is generally moving towards consistency across the U.S. based on the Model Minimum Uniform Crash Criteria (MMUCC). Fatal crash data is reported to the Fatality Analysis Reporting System (FARS) database, which provides a consistent dataset across the country (Cherry et al., 2018), although it does not include non-motor vehicle crashes such as solo bike crashes, slips, trips or falls, or bicycle-pedestrian crashes.
- For pedestrian and bicycle crash analysis, crash data would ideally consist of geolocated reports with data systems that support a bicycle- and pedestrian-specific crash typology, such as that described in the Pedestrian and Bicycle Crash Analysis Tool (PBCAT) (a tool that helps agencies to develop a local crash database focused on pedestrian and bicycle crash types – more information at http://www.pedbikeinfo.org/pbcat_us/) (Sanders et al., 2020).

Crash data and analyses typically are differentiated by severity.

- Many states use a crash injury classification that breaks crash severity into five categories. Known by the acronym “KABCO,” the severity levels are: K for Fatal; A for Suspected serious injury (previously incapacitating injury); B for Suspected minor injury (previously non-incapacitating injury); C for Possible injury; and, O for No injury. First responders usually assign these severity levels and often did not make accurate “estimations [of] the injured body part(s) and the scale of the injury severity” (Cherry et al., 2018). The replacement of incapacitating and non-incapacitating injury definitions with suspected serious

or minor injury definitions are an effort to clarify these assignments (Federal Highway Administration, 2012). Injury severity data from a hospital often uses the Abbreviated Injury Scale (AIS), a separate severity scale, which is a clinical scale based on threat to survivability and is assigned by medical personnel rather than police (Cherry et al., 2018). AIS ratings have been found to be more consistent across states than KABCO ratings (Burch et al., 2014).

Multiple studies have found that police crash data miss many crashes and may be incomplete and inaccurate.

- There are a number of reasons why crashes may not be recorded in a crash database, including police not being notified, which is more likely to occur with less severe crashes, while a large number of minor or property damage-only crashes are not reported (Imprialou & Quddus, 2019). For example, pedestrians hit while crossing a road are likely to appear in a police record, while those walking next to or outside of a roadway are less likely to appear in police records (Tarko & Azam, 2011). This may be related to crossing injuries generally being more severe due to higher impact speeds.
- Crashes not involving motor vehicles, including pedestrian slips, trips or falls, solo bicycle crashes, bicycle-pedestrian crashes and bicycle-bicycle crashes, are underreported in crash data (Doggett et al., 2018; Medury et al., 2019).
- Some demographic groups appear to be more likely to be underreported. There is evidence that Black men are likely underreported in police records, which may be related to a wariness with engaging law enforcement (Sciortino et al., 2005). Research found that providing driver's licenses to unauthorized immigrants was associated with a decrease in hit and run crashes (Lueders, Hainmueller, & Lawrence, 2017). These findings imply that fear of immigration enforcement may suppress crash reporting.
- Crash data relies on police to accurately and completely fill in crash characteristics, and has been shown to regularly have missing or wrong information, including crash severity, time, locations, contributing factors, and individuals involved (Imprialou & Quddus, 2017). Noland et al. note that police reports are "often incomplete and inconsistent," partially due to police officers not receiving training in investigating and reporting of traffic casualties (Noland et al., 2017). Windshield bias, or the fact that most crash reporters (police officers) are generally driving cars rather than walking or bicycling, merits further consideration as an influence on reported crash data.

Fatality records, including definitions of pedestrians, are inconsistent between data sources.

- A study of the accuracy of state pedestrian fatality data in New Jersey found that 20% of pedestrian deaths reported in 2012 were classified as pedestrians even though they might not have been walking, including people who fell out of or exited vehicles, were outside of the roadway and not walking, among other factors, suggesting that definitions of pedestrians, particularly in FARS data, should be revisited (Noland et al., 2017). Further, about a fifth of pedestrian death records (37 out of 156 to 157) could not be matched between state records and FARS data.

Emergency response and hospital records

These sources may capture pedestrian and bicycle crashes not found in police data and may include more information about health outcomes.

- Post-crash data consists of a number of official and hospital databases with demographic, geographic and cause-of-death mortality data, hospital billing and ambulatory care records with information on the source of injury, health outcomes, insurance information, trauma center data, and emergency medical system (EMS) data (Cherry et al., 2018).

- A study of bicycle and pedestrian crashes in New York, California, and North Carolina found that only 43% to 67% of bicycle-motor vehicle crashes identified in hospital emergency data were identified in state crash data, while 45% to 68% of pedestrian-motor vehicle crashes were identified (Stutts & Hunter, 1999). A more recent study examining hospital records of traffic crash victims in New York City found similar results: only 50% of pedestrians and 45% of cyclist crash victims could be linked to police crash records, compared to 63% of drivers (Conderino et al., 2017). A study of bicycle-related injuries at San Francisco General Hospital found that, from 2000 to 2009, of 2,504 patients treated for bicycle-related injuries, 54.5% were not associated with a police report (Lopez et al., 2012).
- In various studies looking at pedestrian and bicyclist crashes involving children, 20% of such crashes that required hospital admittance were not captured in a police database, and that 10% to 20% of such cases were underreported (Cherry et al., 2018).

Linking crash data to medical data is important to better understand the severity and outcomes of crashes, risk factors and potential interventions (Cherry et al., 2018).

- Linkages can be done in real time, such as via scanning a government ID or medical ID number, using a direct identifier to link databases after the fact, by a deterministic linkage based on unique identifiers in various datasets, by a probabilistic linkage using judgement for match quality, or by spatial join (Cherry et al., 2018).
- Connecting hospital records with police crash data raises the potential of bias in terms of which records may match. If no police record exists, it cannot be matched to a hospital or emergency response record. Similarly, if a crash victim dies at the scene, there may not be a hospital record (Tarko & Azam, 2011).

Applications of hospital data for engineering guidance and crash modification factors may be limited due to data limitations.

- Due to HIPAA, it can be difficult to get hospital injury data at a sufficiently disaggregate level or with sufficient geolocation and crash type data, particularly for practitioners, to be used for selecting safety treatments.

Surrogate safety measures

- Surrogate safety measures, which do not rely on crash records, can help fill in some gaps in safety data records, particularly providing more context for relatively rare events, such as crashes at a specific location and vulnerable road users where underreporting varies by severity and user type (Johnsson et al., 2018).
- Common surrogate safety measures include time to collision (TTC), or the time until a collision occurs given current trajectories; post-encroachment time (PET), or the time between two road users passing the same location in their paths; and documenting deceleration or other evasive measures (Johnsson et al., 2018). These types of measures can be derived from video data collection, either manually or using computer vision algorithms. Although most computer conflict detection algorithms have required manual annotation or other setup, some newer applications can be placed at random locations and accurately identify conflicts (Maddox et al., 2021).
- The validity of surrogate measures is difficult to appraise because methods vary widely, though most studies found a significant correlation between their measure and crashes. In terms of reliability, the key concern is human judgment and the potential subjectiveness of some surrogate measures (Johnsson et al., 2018). Further, no single measure can tell the full picture; for example, very low TTC or PET measures may not be dangerous if speeds are very low.

- Microsimulation software is frequently used to assess motor vehicle interactions, and offers a potential tool to assess motor vehicle-bicycle interactions; however, default driving behavior parameters appear to underestimate vehicle-bicycle conflicts (Lemcke et al., 2021).

Exposure and other data

Understanding pedestrian and bicycle traffic volumes or exposure data are an important factor in understanding crash risk when analyzing crash data.

- If many people are walking or biking in an area, or if walking and biking numbers increase in response to infrastructure improvements, higher crash numbers in these areas do not necessarily indicate higher crash risk (Sanders et al., 2020).
- Pedestrian or bicycle count data, transit boarding and alighting, GPS smartphone data, and signal call data are among exposure data sources that can be used for pedestrian and bicycle crash analysis (Sanders et al., 2020).
- Roadway and land use characteristics, including road types, volumes, speeds, area populations, and other data, can be important factors in understanding pedestrian and bicycle risk (Thomas et al., 2018).
- There is research-based guidance on methodologies for assessing pedestrian and bicycle crash risk based on analysis goals (specific intersection or segment-based vs network-wide); risk definition (crashes or surrogate measures); exposure measures; and analysis approach (Turner et al., 2018).

What are the research gaps?

- Imprialou and Quddus (2019) note a number of areas for further research, including the effect of incorrect crash locations, times, and severity on crash analyses, an evaluation of accuracy of crash database attributes, and the development of more advanced and accurate reporting systems.
- A research problem statement developed as part of NCHRP's 2019 *A Research Roadmap for Transportation and Public Health* noted that the inconsistency around collection of non-fatal injuries from road interactions needs to be addressed to better understand transportation safety and health impacts for pedestrians and bicyclists (Sandt et al., 2019).
- Improved methods to connecting police crash data with hospital records, including the addition of unique identifiers, could reduce bias and improve analyses. In the meantime, further research is needed on how which populations are most affected by bias when matching crash and hospital data (Doggett et al., 2018).
- There should be further research with regard to the validity and transferability of surrogate safety measures for vulnerable road users (Johnsson et al., 2018).
- Among nighttime pedestrian fatalities, many police reports note that pedestrians were wearing dark clothing; however, there is no systematic way to document pedestrian clothing which would be needed to put this information into context (Noland et al., 2017).

Current research

Sponsor	Project Information	Status
National Cooperative Highway Research Program (NCHRP) 07-31 https://rip.trb.org/View/1707202	**State DOT Usage of Bicycle and Pedestrian Data: Practices, Sources, Needs, and Gaps** The objectives of this research are to determine how state DOTs are using data and to identify data sources, gaps, and recommendations on the next steps to develop the data and tools state DOTS need.	Anticipated, FY 2021
Texas DOT https://rip.trb.org/View/1716491	**Identify Risk Factors that Lead to Increase in Fatal Pedestrian Crashes and Develop Countermeasures to Reverse Trend** The research team will assemble a suite of relevant datasets across the state to deliver both aggregate and highly disaggregate analyses of pedestrian crash data, reflecting exposure pattern variations by site and city, county and region, roadway and intersection design decisions, local economic and demographic conditions, climate and context. Using traditional econometric and artificial intelligence methods, the team will anticipate which factors are at play in fatal and severe pedestrian crashes and identify all factors that increase such risks, to deliver a suite of cost-effective countermeasures and treatments.	Expected completion date: 8/31/21

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Most common TRID index terms
Pedestrian safety Pedestrians Pedestrian-vehicle crashes Traffic safety Crash injuries Crash data Bicycle crashes Cyclists Risk assessment Crowdsourcing Police reports

Bicycle and pedestrian data: Surveys

Surveys are one of the most common data collection methods for understanding active transportation. Travel surveys, which usually collect data on all trips made by household members on a single day, are used for many transportation planning purposes, including estimating travel demand models. The National Household Transportation Survey (NHTS) is one such travel survey. Other surveys, such as the American Community Survey (ACS) conducted by the U.S. Census Bureau, provide limited data on active travel, such as usual commute mode. The advantage, however, is that the ACS is conducted regularly across the country, allowing agencies to use the data for performance measure and benchmarking. Some large-scale health surveys also have data on walking and bicycling activity, though usually reported in time spent, rather than trips. Agencies and researchers often conduct special surveys to answer particular questions or for other focused projects, including for collecting public input.

Related review topics

- Other types of nonmotorized travel data are discussed in the research reviews for *Bicycle and Pedestrian Data: Emerging User-based Data* and *Bicycle and Pedestrian Data: Location-based Counts*
- *Modeling and traffic impact studies*

What do we know?

New and different survey methods are necessary to capture active transportation behavior more accurately.

Common survey methods are often inadequate for understanding active travel.

- Walk and bicycle trips are often undercounted in traditional travel diary surveys because respondents often forget to report them and because the modes, particularly walking, are often used as part of multimodal trips (Clifton & Muhs, 2012; Giaimo et al., 2010; Wolf, Oliveira, & Thompson, 2003).
- In addition, because bicycling is a rarely used mode in most U.S. cities, one-day travel diary surveys often do not have enough bicycle trips reported to use the data for modeling or forecasting (Edwards et al., 2012; Forsyth, Agrawal, and Krizek, 2012).
- Large-scale travel and other surveys usually do not collect data on personal factors that may influence active travel, such as attitudes and barriers.
- Travel surveys also may not accurately represent underserved populations, particularly Black, Indigenous and people of color (BIPOC) households (Lubitow et al., 2019).

An intercept survey for bicyclists. (Photo: Nathan McNeil)

Different survey methods may address these limitations.

- There is research showing that GPS-assisted travel surveys may reduce the underreporting of active transportation trips significantly (Safi et al., 2017).

- Surveys that ask about activity over the past seven days (rather than a single day) are more likely to capture active transportation trips, which are rare for most people (Chen et al., 2017).
- A rolling sample survey design may be more effective at collecting data on active transportation (Chen et al., 2017). This approach involves smaller sample surveys on a regular basis rather than a large survey every seven to 10 years. This is the approach used by the ACS.
- Oversampling or cluster sampling may provide better samples of active travel behavior (Chen et al., 2017; Edwards et al., 2012; Forsyth, Krizek, & Agrawal, 2010).

Qualitative methods may be useful in addressing particular research questions.

- Qualitative research, including focus groups, has been particularly useful in understanding the experience of BIPOC pedestrians and bicyclists, their barriers to active transportation, and the types of actions that might help overcome those barriers (e.g., Brown et al., 2021).
- Mobility biographies are a method that help explain how people's daily mobility may change throughout the course of their lives, including the role of habits and the impact of key events or life transitions (Müggenburg et al., 2015; Scheiner, 2017). The approach has been used in some active transportation research (Thigpen, 2019; Underwood et al., 2014).

What are the research gaps?

- Lack of more detailed travel behavior data (e.g., from surveys) and built environment data is perceived as a key barrier to including walking in travel models, while finer-scale forecasting of these variables would help make the models more applicable for understanding future scenarios (Clifton et al., 2016; De Gruyter, 2019).
- One study found that, while attitudes and perceptions of walking and biking can be particularly important to nonmotorized travel decision-making, there is limited data available and collecting it (e.g., through surveys) is challenging (RSG & RAND Corporation, 2019). Research to develop survey questions that accurately and reliably measure attitudes, perceptions, and preferences could be useful in helping standardize survey instruments. This would allow more comparisons across geographies and time. Results of such research may also help in incorporating such factors into demand models.
- We only identified one study that examined the accuracy of retrospective reporting of active travel (Thigpen, 2019). Because active travel is not common, asking people to recall their behavior for a longer period of time (e.g., the past week or month) is a common approach to a single-day diary. Research on recall accuracy, including recommendations for the appropriate time period for recall, would be useful.

Current research

No current research projects were found related to this topic.

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Most common TRID index terms
Bicycling
Pedestrians
Travel surveys
Surveys
Data collection
Attitudes
Travel demand

Bicycles at intersections: Design and safety

Intersections are locations where bicyclists often have to navigate with other modes and conflicting traffic, whether it involves motorists turning across bicycle paths, cross-traffic, or pedestrians. In urban locations, intersections are the most likely place for crashes to occur (Schultheiss et al., 2018), and account for over a third of bicyclist fatalities (Poole et al., 2017). This review covers safety research about standard intersection characteristics (e.g., number of approaches, width, signals, etc.), as well as bicycle-specific elements such as separated bike lanes (also called cycle tracks or protected bike lanes).

Related review topics

- The effects of intersections on ridership and route choice is covered in *Bikeways: Ridership and demand*. That review also includes research on the effects of perceptions of safety on ridership.
- Research on safety and design related to bikeways is covered in *Bikeways: Safety and design*.

What do we know?

The number, speed, position and type of motor vehicles and bicycles are related to safety.

- Research using bicycle crash data at intersections from Boulder, CO (Nordback et al., 2014) and Minneapolis, MN (Carlson et al., 2019) found that the rate of bicycle crashes decreases as the bicycle volume increases, indicating that the safety-in-numbers phenomenon applies to intersections. Relatedly, a video study of cyclist and motorist interactions found that cyclists arriving at an intersection in a group were less likely to be involved in a dangerous conflict (Zangenehpour et al., 2015).
- Higher numbers of turning motor vehicles are associated with higher risk of dangerous conflict for cyclists (Nordback et al., 2014; Strauss et al., 2013; Zangenehpour et al., 2015).
- Motorists may pay more attention to bicyclists positioned in front of them (Hurwitz et al., 2015), so designs that promote visibility of the cyclists (and of potential conflict) to the motorist are important (Schultheiss et al., 2018).
- Intersections with downhill approaches and right-turning vehicles are at higher risk for right-hook crash types (Hurwitz et al., 2015).
- A major safety threat to cyclists involves turning movements for large vehicles at intersections (Federal Highway Administration et al., 2015; National Transportation Safety Board, 2019).

Certain intersection types and geometries are associated with greater risk for bicyclists.

- Non-orthogonal intersections (Asgarzadeh et al., 2017) and wider cross streets (Sundstrom et al., 2019) are associated with higher crash risk for bicyclists.
- Intersections of major streets and more lanes are more dangerous than local streets (Harris et al., 2013).

- A study using crowdsourced app data (STRAVA) to help estimate exposure when developing SPFs at intersections (Chen et al., 2020) found that a greater number of intersection lanes and legs are associated with an increased risk of bicycle crashes.
- Several studies found that roundabouts with a single travel lane may offer safety benefits for cyclists, although multilane roundabouts, including roundabouts with one general traffic and one bicycle lane, have been found to increase crash risk to cyclists (DiGioia et al., 2017; Reynolds et al., 2009). A literature review of 49 studies relating to bicycles and roundabouts found that higher speed, multiple lanes were associated with increased crash risk for bicyclists, and that the strategy of "taking the lane" also increased crash risk for bicyclists (Poudel & Singleton, 2021). The same literature review noted that separated bicycle paths through roundabouts may be a lower-risk design approach if yielding locations are handled carefully.
- Alternative intersections and interchanges (AII), including Diverging Diamond Interchange (DDI), Restricted Crossing U-Turn (RCUT), Median U-Turn (MUT), and Displaced Left-Turn (DLT), are generally designed and implemented with motorized traffic flow and safety in mind, while bicycle safety at such intersections has traditionally been an afterthought (NASEM, 2021). NCHRP Research Report 948 provides guidance for pedestrian and bicycle safety at AIIs.

Characteristics of the approach segments also factor into bicyclist safety at intersections.

- One study found that bike lanes reduce crashes at four-exit intersections, as well as at one- and two-way stop signs (Kondo et al., 2018), although not at other types of intersections. Other studies have found that the presence of typical bike lanes may increase crash risk (Chen et al., 2020), pointing to the need to assess specific location characteristics when considering bike lanes.
- A video study of cyclists and motorist interactions in Montreal, Canada, found that intersections with right-side cycle tracks were safer than those with no cycle track, though the same was not true for left-side cycle tracks (Zangenehpour et al., 2015).

Research on intersection designs and countermeasures point to some promising approaches to improving bicyclists' safety.

Research has focused on the areas at the intersection where bike lane traffic may conflict with motor vehicles.

- Bike lanes used in right-turn lanes, or mixing/shift areas with a marked bicycle location on the left side of the lane, encourage cyclists to move left and reduce confusion for motorists and bicyclists (C. M. Monsere et al., 2015).
- A study of crashes at intersections along single-direction, protected bike lanes found that, in comparison to split signal phases, short mixing zones were associated with lower crash risk at crossing locations with high right-turn volumes, while split phases were associated with lower crash risk at wider crossings (Sundstrom et al., 2019).
- Mixing zones are "associated with an increase in motorist yielding, improvements in turning movements, and a reduction in vehicle-bicycle conflicts" (Sanders et al., 2020). However, recent research suggests that many bicyclists do not feel less comfortable with mixing with motor vehicles in mixing zones (C. M. Monsere et al., 2020).

Bike lane extension through an intersection. (Photo: Nathan McNeil)

- For mixing zones or lateral shift designs, having restricted-entry demarcations can promote compliance with intended lane use by right turning vehicles and bicyclists (C. M. Monsere et al., 2015).
- Bike lane extensions through intersection: "when used to highlight key conflict points this treatment may improve bicyclist safety via increased motorist yielding, reduced conflicts with turning vehicles, and increased predictability of bicyclist location" (Sanders et al., 2020).
- A simulator study of driver yielding behavior in right-hook situations found that four different treatments offered potential safety improvements, including regulatory signage, which increased visual scanning for bicyclists; reduced curb radii, which slowed turning speeds and reduced high-risk conflicts; intersection pavement markings, which were noted to improve driver behaviors; and protected intersection designs, which also reduced vehicle turning speeds (Warner et al., 2017).

There are some findings related to separated bike lanes and intersections.

- Early findings from protected or offset intersections show mixed results, with some improved behaviors, such as increased two-stage turning by bicyclists, but decreased signal compliance by bicyclists and pedestrians, along with less yielding by drivers making left turn maneuvers (Sanders et al., 2020). In addition, protected intersections were found to be among the most comfortable intersection designs for both current and potential cyclists (C. M. Monsere et al., 2020). A study by NYCDOT that included pilot designs of offset intersections found promising conflict rates, but also found that motorists continued to turn faster than desired and bicyclists increased yielding to cars, possibly due to lack of clarity on who should yield. Cyclist-perceived safety, however, was high (Sundstrom et al., 2018).
- If using two-way cycle tracks, placement of two-way separated bike lanes to the right of general traffic lanes, designs that slow turning traffic (such as raised crossings) and increase visibility (such as offset/deflected crossings), can reduce conflicts at intersections (Harris et al., 2013). One Swedish study found that raised crossings reduced crashes (Gårder et al., 1998), while a Canadian study found the same for raised medians (Strauss et al., 2013).
- Bicyclists in separated bike lanes are particularly vulnerable to left-turning traffic across oncoming traffic lanes, with observed driver yielding rates of 37% or below (Saeidi and Furth, 2021).

There is some research on the effects of other design elements at intersections.

- A driver simulation study found that wider corner refuge islands and presence of crossing cyclists were associated with slow turning speeds (Deliali et al., 2020).
- A review of literature on safety impacts of various bicycle infrastructure elements (DiGioia et al., 2017) found that neighborhood traffic circles resulted in a significant increase in injury crash risk.
- Evidence on bike boxes' effect on conflicts is mixed, with at least two studies showing a reduction and two with little change (DiGioia et al., 2017). Evidence suggests that bike boxes can "improve bicyclist safety through improved visibility of bicyclists, increased awareness of bicyclists by motorists, increased motorist yielding, and a reduction in right-hook conflicts" (Sanders et al., 2020).

Intersection with bike signal and phasing. (Photo: Christopher Monsere)

- Bike-specific phases and signals may decrease bicycle-vehicle conflicts and crash risk (Pucher et al., 2010; Sanders et al., 2020).

- A scan of agencies with bicycle signal implementations found few reports of motorist confusion with regard to bicycle signals (C. M. Monsere et al., 2020).
- Bike crossings of railways pose a danger to bicyclists due to slippery rail surfaces and flange gaps; crossing angles of greater than 30 degrees reduced crash risk and greater than 60 nearly eliminates crash risk, suggesting bike lane realignment could help in some cases (Ling et al., 2017).

What are the research gaps?

There are several design-related gaps, particularly research that will produce CMFs for countermeasures.

- Few of the studies we reviewed examined how different intersection designs work for particular subgroups that might warrant special consideration, such as children or older adults.
- Countermeasures without CMFs identified for bicyclists include: bike lane extensions through intersections, bicycle signals, bike boxes, leading bicycle intervals, mini traffic circles, mixing zone treatments, passive bicycle signal detection, protected intersections, two-stage bicycle turn boxes (Sanders et al., 2020).
- Countermeasures with CMFs for pedestrians but not bicyclists include: advanced stop or yield lines, protected phases, grade-separated crossings, high-visibility crosswalk markings, parking restrictions near intersection for visibility improvement, protected phases, rectangular rapid flashing beacons (RRFB), and signal timing (Sanders et al., 2020).
- Countermeasures designed for pedestrians, but that might have some benefit to bicyclist safety, and without CMFs identified include: active warning beacons, crossing barriers, curb extensions, curb radius reductions, gateway treatments, and, in-street pedestrian crossing signs (Sanders et al., 2020).

A study of bicycle signals (C. M. Monsere et al., 2020, p. 47) found a need for more research in the areas of:

- "Optimal methods to communicate allowable, protected, or permissive movements to bicyclists at signalized intersections.
- Evaluation of size, placement, and orientation of bicycle signal faces on bicyclist and driver comprehension and compliance.
- Guidance on visibility and detection of bicycle symbols in signal faces by lens size and distance."

Overall, there needs to be improved methodological rigor and consistency when evaluating bicycle infrastructure projects for safety.

- A review of safety impacts of bicycle infrastructure found that safety studies were inconsistent in terms of methodology, including standardizing exposure, controls, and gaps in crash reporting procedures that made safety analysis very challenging (DiGioia et al., 2017).
- Conflict path analysis of bicycles at intersections (or other conflict points) has been inconsistent in terms of methods and the connection to safety outcomes (e.g., crashes) is not well known, limiting attempts to extract measured conflicts to information (Federal Highway Administration et al., 2015).
- There were relatively few before-and-after or controlled studies for many of the design elements.

- Bicycle level-of-service assessments in the Highway Capacity Manual do not currently account for bicycle delay or exposure to motorized vehicle exposure, which could negatively affect the quality of intersections that are approved and implemented (Fournier et al., 2021).

How is research on this topic done?

Research methods vary across studies, ranging from spatial analysis of crash records with intersection characteristics, video conflict and compliance analysis, surveys and more.

- Using police crash records and roadways characteristics and conducting analysis with GIS to understand the relationship between crashes and various intersection and other roadway characteristics (Asgarzadeh et al., 2017; Burbidge et al., 2012; Carlson et al., 2019; Saad et al., 2019).
- Another approach is to conduct before-and-after analyses of intersection designs, assessing crash data at numerous locations, corresponding to several broad design types across a city (Sundstrom et al., 2019).
- Several studies used video review of motorist and bicycle interactions at varying intersection-type locations, including comparing compliance across a variety of designs (Madsen & Lahrmann, 2017; C. M. Monsere et al., 2015) or using a control-case study approach to compare intersections with and without cycle tracks (Zangenehpour et al., 2015).
- Some analyses strive to put crash numbers into context by providing exposure estimates, such as by estimating daily bicycle traffic through a city count program (Carlson et al., 2019; Sundstrom et al., 2019), app-based data collection such as STRAVA (Chen et al., 2020; Saad et al., 2019).
- Studies looking at cyclists' perceptions of safety and comfort tended to rely on surveys presenting respondents with riding scenarios (C. M. Monsere et al., 2015, 2020; Wang & Akar, 2018). Less common were studies that actually monitored bicyclist physiological reactions as they rode through intersections (Caviedes & Figliozzi, 2018).
- Simulators allow researchers to study specific designs, including hypothetical designs, and control experimental conditions (Deliali et al., 2020; Hurwitz et al., 2015; Hurwitz & Ghodrat Abadi, 2016).

Current research

Sponsor	Project Information	Status
National Cooperative Highway Research Program (NCHRP) 15-73 https://rip.trb.org/View/1628615	**Design Options to Reduce Turning Motor Vehicle-Bicycle Conflicts at Controlled Intersections** The objective of this research is to develop guidance and tools for transportation practitioners to use to reduce turning conflicts between motor vehicles and bicycles at controlled intersections.	Expected completion date: 10/2/23
National Cooperative Highway Research Program (NCHRP) 17-84 https://rip.trb.org/View/1407195	**Pedestrian and Bicycle Safety Performance Functions for the Highway Safety Manual** The objective of this research is to develop pedestrian and bicycle safety performance functions (SPFs) using risk-based or predictive methods, for transportation practitioners at all levels to better inform planning, design, and operations decisions. The results	Expected completion date: 2021

Sponsor	Project Information	Status
	of the research will be used to update the Highway Safety Manual (HSM) and associated tools.	
Federal Highway Administration (FHWA)	**Evaluations of Innovative Intersection Designs for Pedestrian and Bicyclists** This project investigating innovative intersection designs (also known as protected intersection designs) will include before-and-after analysis of 15 intersection locations to assess safety for pedestrians and bicyclists.	Expected completion date: 9/2022
Oregon DOT SPR 833 https://rip.trb.org/View/1672694	**Impacts of Intersection Treatments and Traffic Characteristics on Bicyclist Safety** The primary research objectives are: (1) Determine which factors affect the frequency and/or severity of bicycle-vehicle conflicts at intersections with different bicycle-related treatments such as mixing zones, leading bike interval (LBI), split LBI, as well as those traditional bicycle lanes and with no treatments, and others; (2) Provide data-driven guidance as to the efficacy of certain intersection treatments in mitigating vehicle-bicycle conflicts; (3) Develop a countermeasure selection "toolbox." A desired outcome of this research will be determination of threshold bicycle and vehicle volumes where specific levels of treatments should be considered over others.	Expected completion date: 6/30/21
Mountain Plains Consortium (UTC) MPC-603 https://rip.trb.org/View/1638269	**Investigating Bicyclist Safety Perceptions and Behaviors at Roundabouts** The primary objective of this research is to characterize and evaluate how bicyclists perceive the safety of roundabouts overall, and of specific design and operational characteristics of roundabouts.	Expected completion date: 7/31/22
District of Columbia DOT https://rip.trb.org/View/1745985	**Pedestrian and Cyclist Intersection Safety Sandbox** The District Department of Transportation (DDOT) intends to implement one or more pilot or demonstration projects that use emerging technology solutions to improve pedestrian and/or cyclist safety in intersections. This project will designate a "sandbox" of a single intersection or corridor within the District to be used to safely pilot new technologies and evaluate the outcomes.	Expected completion date: 6/28/22

Research reviews

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Most common TRID index terms
Bicycle crashes
Intersections
Bicycling
Highway safety
Bicycle lanes
Traffic safety
Cyclists
Signalized intersections
Highway design
Crash causes
Bicycle facilities
Case studies
Traffic conflicts

Bike share

Bike share systems have grown dramatically over the past decade, serving 240 cities in North America in 2019 (North American Bike Share Association & North American Bike Share Association, 2020). Bike share offers the potential to provide improved mobility and physical activity to users. Research has also examined its potential to reduce greenhouse gas emissions through shifting modes of users, as well as operational challenges (e.g., rebalancing). Other areas of research have included assessing the equity of bike share and the changing models of bike shares, including dockless and e-bikes, as well as other shared micromobility, such as e-scooters.

Related review topics

- Research on non-bicycle shared mobility is covered in the research brief on *Micromobility, including e-scooters.*

What do we know?

Several factors help determine bike share use.

Features of the environment, particularly density and infrastructure, help determine bike share demand.

- In general, higher densities of population, jobs and retail, more park area, school and universities, and water features such as lakes or rivers, along with improved bicycle infrastructure, are associated with increased bike share demand (Eren & Uz, 2020).
- A study in Minneapolis of station trips generated found that proximity to the CBD, college campuses, parks, water bodies, and off-street trails were positively associated with bike share trips (Wang et al., 2016).
- A study in New York found that stations near areas of higher job and residential density, as well as busy subway stations and bicycle facilities, were associated with more station trips. Dense residential areas saw particularly disproportionate usage on non-working days (Noland et al., 2016).
- Farther distances to transit features such as bus and metro stops is negatively correlated with bike share use, while the number of stops or stations in the vicinity is positively correlated with use (Eren & Uz, 2020).
- Bike share stations with more docks and capacity are correlated with increased bike share use (Eren & Uz, 2020). Proximity to a bike share station is also an important determinant of use. One study found that "every additional meter of walking to a station decreases a user's likelihood of using a bike from that station by 0.194% (±0.0693%), and an even more significant reduction at higher distances (>300 m)." The study found that 80% of the station's users would come from within 300 meters (Kabra et al., 2019).
- Steep slopes, particularly above 4 degrees, are associated with decreased bike share usage (Eren & Uz, 2020).
- In a review of factors affecting bike share demand, Eren and Uz (2020) found that demand increases as temperature increases up to 68 degrees Fahrenheit, and that 68 to 86 is a maximum demand zone, with precipitation adversely affecting demand most at low temperatures. Wind speed and relative humidity are also generally found to be negatively correlated with bike share demand.

Convenience and the ability to get around faster and more easily is often cited as a top reason to use bike share among riders, while saving money has also been found to be an important reason to use bike share (Fishman, 2016).

- A study of Capital Bikeshare users in Washington, D.C., found that 73% of users were riding because of the travel time savings, while 25% were saving travel costs by using bike share (Buehler & Hamre, 2015).
- Members are more likely to use bike share for work-related trips such as commuting, while casual users are more likely to use bike share for fun or recreation (Fishman, 2016).
- Many bike share members are infrequent riders, with nearly half of participants in several studies saying that had not taken a ride in the past month (Fishman, 2016).

Bike share use varies among different groups.

In the U.S., bike share users do not represent the population with respect to gender, age, education, income, and race, though there is some evidence that may change.

- Most studies have found that bike share users are more likely to be male, disproportionately young, and educated (Dill & McNeil, 2021; Eren & Uz, 2020). A number of studies have found that bike share users are disproportionately white, and tend to have higher incomes (Dill & McNeil, 2021; Fishman, 2016; McNeil et al., 2018).
- Bike share usage in disadvantaged neighborhoods has been found to be lower than in other areas, although higher rates of employment appear to be associated with increased levels of bike share use in disadvantaged areas (Qian & Jaller, 2020).
- There is some evidence suggesting that lower-income users may be more likely to become frequent users. A Vancouver, B.C., study examining people who made 20 or more trips per month found that these "super-users" were more likely to be young, male, have incomes below $75,000, have stations near their home and place of work, and were less likely to own their own bike or have a car share membership (Winters et al., 2019). A study in New York City found that people who went from not bicycling in the year before signing up for Citi Bike to being a frequent rider were more likely to be men, have lower incomes, no car, and were primarily motivated to join by the appeal of getting around town faster and cheaper (Reilly et al., 2020).

A bike share station in Brooklyn, NY. (Photo: Nathan McNeil)

- Some research has found that bike share users are more likely than regular cyclists to be women (Buck et al., 2013).

Top barriers to bike share include cost and knowledge about how to use the system, along with concerns about riding in traffic (Fishman, 2016; McNeil et al., 2018).

- Programs to promote bike share, particularly among underserved populations, are becoming increasingly common, with one recent study finding that 60% of all bike share programs, and nearly 80% of large systems (750 or more bikes), have programs designed to encourage use among low-income and unbanked individuals, underserved neighborhoods, BIPOC residents, and people with disabilities (McNeil et al., 2019).

Most bike share trips are shifted from walking or transit trips, although some car trips are replaced.

- A 2020 industry report noted that, based on user surveys, bike share trips were replacing walk trips (37% of trips), transit trips (20%), taxi and ridehail (18%), personal car trips (11%), personal bike trips (5%), and other trip types (5%), while 4% were trips that would not have taken place otherwise. Bike share trips were less likely than scooter trips to replace taxi or ridehail trips, and more likely than e-scooters to replace transit trips (North American Bike Share Association & North American Bike Share Association, 2020).
- A 2016 literature review also noted that most studies found bike share trips were primarily replacing transit and walk trips, although three out of five studies also showed that about 20% of trips were replacing car trips (Fishman, 2016).
- A 2014 study found that in most cities, bike share led to a reduction in vehicle miles travelled, with one exception being London, which had only a 2% mode shift from car to bike share, and for which bicycle balancing and maintenance outweighed that shift (Fishman, Washington, & Haworth, 2014).
- Some research has examined whether bike share complements or substitutes for transit use. One study found that the relationship varies by geography, with people in dense urban cores potentially shifting away from public transit, while those on urban peripheries or less dense urban areas shifted toward more transit use (Martin & Shaheen, 2014). In contrast, a study using data from four large US cities found that the time of the trip and whether the rider was a subscriber was more important the geography in predicting whether the bike share trip substituted for transit or was used to access transit (Kong, Jin & Sui, 2020). They estimated that 35-55% of the bike share trips made by subscribers were to access transit. Another study found that transit fares may be a significant factor in whether a bike share trip substitutes for transit (Welch, Gehrke & Widita, 2020), Bike share's impact on health includes considerations of physical activity, crashes, and air pollution.
- A 2020 study using a difference in differences approach across eight Canadian and American cities found that implementing bike share did not result in an increase in bicycle crashes. Cities that had bike share for longer periods of time actually saw decreases in reported bike crashes (Branion-Calles et al., 2020).
- A number of studies have found that bike share users are less likely than other cyclists to wear helmets (Eren & Uz, 2020; Fishman, 2016), with some indication that helmet requirements for bike share use reduced demand (Fishman, 2016; Fishman, Washington, Haworth et al., 2014). There is also evidence than longer-term riders may be more likely to wear a helmet (Buck et al., 2013).
- Several studies have found increases in physical activity associated with bike share use, with related benefits including potential reduction in heart disease and reductions in depression (Fishman, 2016). A 2015 study found that 60% of bike share trips replace sedentary modes of transport (Fishman et al., 2015).
- A study of the effect of bike share on greenhouse gas levels found that emission reductions are relatively consistent per mile traveled, ranging from 286 to 353 grams of CO^2, but that larger systems, and particularly those with more daily trips per station and per bike, were able to realize much higher reduction per bike and overall (Kou et al., 2020).

Bike share has the potential to bring economic benefits to cities, ranging from increased spending to time savings and health benefits for users.

- A study in Dublin found that the economic benefit from bike share, when taking into account time savings, health benefits, and more conventional economic metrics, has a "combined benefit-cost ratio of 12.3:1" (Bullock et al., 2017).

- A 2015 study of Capital Bikeshare users found that 16% of riders said they were making more trips because of bike share, and 23% indicated they were spending more at businesses because of it (Buehler & Hamre, 2015).
- In a survey of businesses in near proximity (1/10 of a mile) to bike share stations, 20% indicated that bike share helped their business in terms of sales, while 61% were positive or neutral to replacing parking with bike share in front of their store (Buehler & Hamre, 2015).

Some research focused on how to plan and operate bike share systems.

Major bike share system challenges include determining station (or bike) density and service area, and maintaining bicycle balancing and maintenance.

- A major challenge for bike share systems involves a major shift of bikes from one area to another, such as shifting from residential areas to the city center during morning commute hours, leaving some stations or areas empty and others full. Research on the topic includes attempts to understand the reasons and factors influencing station usage, programs designed to encourage users to redistribute bikes through incentives, and how to efficiently use trucks to redistribute bikes (Fishman, 2016).
- A study of bike share station placement and distribution in Phoenix to be both spatially optimized, in terms of station density and utility, and optimized for social equity, found that balancing these goals to provide coverage for the entire city was not feasible, and that trade-offs are needed that balance these goals (Conrow et al., 2018).

The bike share landscape is changing rapidly, with dockless bike share, e-bikes, and competition from scooter share.

- As of 2019, 72% of the North American cities with systems only had pedal bikes, while 28% of systems included e-bikes (North American Bike Share Association & North American Bike Share Association, 2020).
- A study of e-bikes in Zurich, Switzerland, found that e-bikes are one of the faster urban travel options, and that trip distances had considerable overlap with transit and taxi trip distances (Guidon et al., 2019).
- As of 2019, 42% of North American cities with bike share systems had docked systems, 23% had dockless systems, 26% had hybrid systems, and 9% had multiple system types (North American Bike Share Association & North American Bike Share Association, 2020).
- Dockless bike share offers the potential for widespread equitable bike availability (Mooney et al., 2019; Qian et al., 2020), though in practice one study found that more bikes were ending up in, and therefore more frequently available in, areas with higher income and higher education levels (Mooney et al., 2019).
- A study in China found that when both docked and dockless bike share options are available, dockless bikes tend to be used more frequently, but for short trips (Ma et al., 2020).
- Comparison to scooter usage: A study looking at bike share and scooter share trip making in Washington, D.C., found that scooter share users behaved more similarly to bike share non-members than to bike share members (Younes et al., 2020). The study also found that station-based bike share was more affected by poor weather than scooter share was, perhaps because the station-based system is not door-to-door (Younes et al., 2020).

What are the research gaps?

Gaps described in the literature include questions around bike share data, financial sustainability, and usage.

- Research is needed to understand how to best collect and utilize bike share user and trip data to better serve customers and cities, along with data standards and applications merits further research (Hirsch et al., 2019). For programs designed to improve bike share equity, current data collection and metrics often do not produce meaningful evidence of program outcomes (McNeil et al., 2019).
- There are gaps related to financial sustainability and models of bike share systems, including station-based and dockless systems, including the role of sponsorships, public funding and user fees (Hirsch et al., 2019).
- Researchers note that it is very difficult to confirm causal links between bike share systems and city or regional bicycling increases, as well as connections to physical activity levels (Bauman et al., 2017).
- Most research looking at bike share members assumes that all trips taken under one membership are taken by the member, but the extent to which two or more people share memberships is unclear (Reilly et al., 2020).

More recent bike share systems and technologies, including dockless and e-bikes, are little studied.

- There are research needs to understand usage of dockless and e-bike bike share as distinct from station-based bike share, including if different users are attracted to the system, if they take longer trips, use the bikes for different types of trips, can have a more widespread impact on physical activity levels, and can result in more equitable access and use (Hirsch et al., 2019). Barriers to bike share usage for dockless and e-bike systems have been little studied, and so it is not clear if or how the cost, technology, and other barriers associated with station-based systems would apply (Mooney et al., 2019).
- Little is known about the interactions of multiple shared mobility systems in a city or region, and how they serve customers and integrate service areas, fares and other features (Hirsch et al., 2019). There is also little research on how better integration of transit and bike share (e.g. fare payment systems and trips planning) could affect bike share use.

How is research on this topic done?

- Many of the studies on bike share trips are based on station-to-station trip data and API data from venders. Station trip data has been used to assess the draw of stations, including nearby attractors. These studies do not include much, if any detailed information about the demographics of the users.
- Research on mode shift has been primarily done through survey data. Surveys are often focused on members or casual users who have provided usable contact information.
- Many of the studies focused on single cities and systems, which limits the ability to extrapolate findings to other locations.

Current research

Sponsor	Project Information	Status
Transit Cooperative Research Program (TCRP) J-11/Task 37 https://rip.trb.org/View/1584713	**Transit and Micromobility (Bike share, Scooter share, etc.)** The proposed research has four key objectives: (1) Identify the impact of micromobility on bus and rail transit ridership. (2) Identify the economic impacts of micromobility for the community and the transit agency. (3) Identify the impacts on the built environment (i.e., bike lanes, parking spaces, etc.) on the implementation of micromobility. (4) Identify ways to strengthen the relations between micromobility and transit to maximize sustainable trip modes.	Start date : 9/10/19
National Cooperative Highway Research Program (NCHRP) Synthesis 20-05/Topic 52-13 https://rip.trb.org/View/1707243	**Shared Micromobility Policies, Permits, and Practices** The objective of this synthesis is to document state department of transportation (DOT) policies, permits, and practices with regard to shared micromobility services.	In progress, FY 2021
National Institute for Transportation and Communities (UTC) https://rip.trb.org/View/1724591	**Mobility for the People: Evaluating Equity Requirements in Shared Mobility Programs** This project will answer the following four research questions: 1) What cities incorporate equity requirements into shared mobility agreements or partnerships and how are they monitored? 2) How can we systematically evaluate success of equity programs across modes and cities? 3) How effective are equity requirements at increasing shared mobility adoption among target populations? And 4) how do equity programs and program efficacy vary by mode?	Expected completion date: 12/1/21
National Center for Sustainable Transportation (UTC) https://rip.trb.org/View/1652757	**Dock-based and Dockless Bikesharing Systems: Analysis of Equitable Access for Disadvantaged Communities** The objectives of this project are to expand the previous work to evaluate the potential benefits of dockless systems to improve accessibility to disadvantaged communities, and to compare them with dock-based systems. Specifically, the project will analyze the difference in service levels among dock-based and dockless systems. Quantitatively, the team will study the trip patterns and user characteristics under dockless and dock-based systems.	Expected completion date: 6/30/21

Sponsor	Project Information	Status
Southeastern Transportation Research, Innovation, Development and Education Center (UTC) https://rip.trb.org/View/1682038	**Evaluation of Transportation Network Infrastructure, Safety, and Travel Route Characteristics of Bike Share, Electric-Powered Pedal-Assist Bike Share, and Electric Scooter System Operation** Using global positioning system (GPS) tracking data, user demographic information, transportation network conditions, and traffic operations data, a comparative Geographic Information System (GIS) research investigation will be conducted, in cooperation with private mobility as a service (MaaS) partners, focusing on the following objectives: (1) Establish a better understanding of these travel modes to accommodate shared mobility demand; (2) Identify operational patterns of use of the transportation network infrastructure; (3) Catalogue critical elements of system implementation to be addressed by local jurisdictions; and (4) Evaluate potential for serving as an effective countermeasure to urban network congestion for mid-size cities.	Expected completion date: 6/30/21
Center for Transportation Equity, Decisions & Dollars (UTC) https://rip.trb.org/View/1676641	**E-bike sharing and the infrastructure implications and environmental impacts of new technology in transportation systems** This work will use a survey approach to gather data as to who the users of the e-bike share are and the types of trips which they are making with the e-bikes. This will be utilized to build a mode choice model which includes e-bike sharing. The environmental and economic impacts of e-bike sharing programs will be evaluated in order to generate insight into this mode of transportation.	Expected completion date: 8/31/21
Center for Teaching Old Models New Tricks (UTC) https://rip.trb.org/view/1746168	**Consumer Attitudes and Behavioral Implications in the New Era of Shared Mobility** The main objectives of the research are to: (1) Understand the perceptions, attitudes, and user's mobility choices toward dockless bike-sharing services; (2) Develop advanced analytics and machine learning algorithms to uncover patterns associated with mobility choice, activity travel, and additional spending; and (3) Empirically evaluate if and how the introduction of the dockless bike-sharing services influences public transit ridership and business sales.	Expected completion date: 10/1/21
National Center for Sustainable Transportation (UTC) https://rip.trb.org/View/1708101	**Examining Market Segmentation to Increase Bike-share Use: The Case of the Greater Sacramento Region** This project will focus on better understanding the market segments for bike share through multivariable models of the survey data. Market segmentation is an important first step for targeting growth of any service or product.	Expected completion date: 9/30/21

Research reviews

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Most common TRID index terms
Vehicle sharing
Bicycles
Bicycling
Spatial analysis
Bicycle sharing stations

Bikeways: Safety and design

The most common, fatal bicycle crash type, vehicle overtaking bicyclist (28% of all fatalities), occurs on midblock segments between intersections (L. Thomas et al., 2019). In these crashes, a bicyclist is nearly twice as likely to sustain a fatal or serious injury, controlling for the posted speed limit and urban-rural land use (National Transportation Safety Board, 2019).

Evidence is accumulating that purpose-built, bicycle-specific facilities reduce crashes and injuries among cyclists, providing the basis for transportation engineering guidance (Marshall & Ferenchak, 2019). This review focuses on the safety and design research related to bikeways, defined as "a facility intended for bicycle travel which designates space for bicyclists distinct from motor vehicle traffic" (Schultheiss et al., 2019). The different types of bikeways are described in the box (Dickman et al., 2016; Schultheiss et al., 2019).

Related review topics

- The effects of bikeways on ridership and route choice is covered in *Bikeways: Ridership and demand.* This includes research on the effects of perceptions of safety on ridership.
- Research on safety and design related to intersections, including bicycle-specific infrastructure, is covered in *Bicycles and intersections: Safety and design.*

What do we know?

Research generally supports the safety benefits of on-street bike lanes.

Two reviews of safety research found that, overall, on-road striped bike lanes have positive safety benefits, though some individual studies had mixed or insignificant effects (DiGioia et al., 2017; Reynolds et al., 2009). Positive benefits were found in additional studies of urban arterials in Florida (Park et al., 2015) and roads in metropolitan Melbourne, Australia (Morrison et al., 2019; Smith et al., 2019). The Florida study found that the bike lanes were associated with a reduction in both bike crashes and all crashes, though the reduction in bike crashes was greater. A study using hospital data in New Orleans concluded that on-street bikeways, which included striped and separated lanes, improved bicyclist safety.

Bikeway definitions

Bicycle boulevards are low-stress bikeways primarily located on low-volume, low-speed local streets with treatments such as shared lane markings, wayfinding signs, traffic calming, and improved crossings with higher-volume roadways.

Advisory bike lanes demarcate a preferred space for bicyclists and motorists to operate on narrow streets that would otherwise be shared lanes. Unlike dedicated bicycle lanes, motor vehicle use is not prohibited in the advisory bike lane and is expected on occasion.

Bike lanes designate an exclusive space for bicyclists to operate one-way on the roadway through striping.

Research shows that continuous paved **shoulders** and bicycle lanes act essentially the same in terms of operations as bike lanes.

Buffered bike lanes use additional markings to increase the space between the lanes for bicyclists and motor vehicles.

Separated bike lanes are physically separated from adjacent travel lanes with a vertical element, such as a curb, flex posts, or on-street parking. These can be two-way or one-way.

Sidepaths are two-way separated bike paths immediately adjacent and parallel to a roadway.

Shared use paths provide a travel area separated from roadways for bicyclists and other users (e.g., pedestrians, skaters, joggers, etc.) and are usually two-way.

Shared lanes are travel lanes shared between motor vehicles and bicycles, with no dedicated space for the bicycle.

The safety benefits of on-street lanes vary by context and design.

- Crash modification factors (CMFs) for bike lanes on urban arterials vary across the sites with different roadway characteristics, including annual average daily traffic (AADT), number of lanes, AADT per lane, median width, bike lane width, and lane width are significant characteristics that affect the variation in safety effects of adding a bike lane (Park et al., 2015).
- There is evidence that the safety benefits are greater when general traffic lanes are narrower (Morrison et al., 2019; Park et al., 2015).
- The Melbourne study found that the safety benefits of on-road bicycle lanes are generally most effective where speeds are greater and bus routes and tram stops are present. Exclusive bike lanes with the more physical separation provided the greatest safety benefits (Morrison et al., 2019).
- Research in Europe found that drivers gave more distance when passing cyclists with children on their bike (in a seat or trailer), though 25% still passed too close.

The width and design of the bike lane or shoulder can influence safety.

- A systematic review of 42 papers found that increased road width was associated with greater lateral passing distance (LPD). Higher speed limits were also associated with greater LPD, though the increase may not be enough to make cyclists more comfortable or safe. Normal bike lanes, without physical separation, were not associated with greater LPD (Rubie et al., 2020).
- Data from several cities indicates that dooring crashes account for 12-27% of all bicycle-motor vehicle crashes. Research found that with standard 5-foot bike lanes next to parking, nearly all cyclists rode in the door zone, likely increasing risk of dooring crashes (Schimek, 2018).
- When motor vehicle traffic volumes are higher and/or as the truck percentage in the vehicle mix increases, bicyclists ride closer to parked vehicles or the curb. When there is curbside parking, a buffer between the parked cars and the bike lane may be safer than a wider bike lane without a buffer (Torbic et al., 2014).
- In rural areas, general traffic lane width, type of lane marking and the presence of a centerline rumble strip influence the lateral distance that drivers overtake bicycles (Feng et al., 2018; Kay et al., 2014). Vehicle speed and size in addition to the lateral passing distance influence perceived comfort (Llorca et al., 2017).

A striped bike lane in Portland, OR, with a buffer for the door zone. (Photo: Jennifer Dill)

- Shoulder rumble strips can present a hazard to bicycles (Torbic et al., 2009).

There is growing evidence supporting the safety benefits of *separated bike lanes*.

Early reviews found some evidence of crash reduction, though there were limitations in the research at the time, including the number and design of the studies. A more recent review also found a reduction in crash rates (DiGioia et al., 2017).

- A 2013 review found that separated bike lanes exhibit crash reductions when compared with similar streets without bicycle infrastructure. Although, it has not been found to increase crash incidence compared with roads with bike lanes (University of North Carolina et al., 2013).
- Another review published that same year concluded that when controlling for exposure and including all collision types, building one-way separated lanes reduces injury risk (B. Thomas & DeRobertis, 2013).
- Those reviews indicate that separated bike lanes may be effective at reducing certain crash types, including vehicle overtaking crashes and dooring crashes.
- More recent research using data from 12 large U.S. cities found fewer crashes and injuries in areas with a higher density of protected/separated bike facilities (Marshall & Ferenchak, 2019).
- Research on high-speed roads finds that increased separation is necessary to avoid serious risks when speeds are 45 mph and above (National Transportation Safety Board, 2019; Schonfeld et al., 2016).
- A review of research on lateral passing distance (LPD) research suggested that bollards or other physical separation is correlated with greater LPD (Rubie et al., 2020).

As with striped bike lanes, the design and characteristics of a separated lane will affect safety, including one-way vs two-way and intersection design.

- There is some evidence that bidirectional separated bike lanes exhibit higher crash rates, potentially as drivers are unaccustomed to yielding to two directions of traffic (University of North Carolina et al., 2013).
- There is research indicating that one-way separated bike lanes are safer than two-way, particularly at intersections, though the research is not consistent. Some research indicates that the safety risks of two-way lanes can be mitigated (Schultheiss et al., 2018; B. Thomas & DeRobertis, 2013a).
- One multisite, before-and-after study found when they compared intersection vs midblock crashes, the percentage of crashes that occurred at an intersection went up, for both bicycle crashes and those not involving a bicycle. However, the study was not able to control for changes in bicycle volumes for the before-and-after periods, and the number of crashes was small (Rothenberg et al., 2016).

Shared-use paths safety issues are mostly with other path users.

- Safety studies of multiuse paths have mixed findings (DiGioia et al., 2017; Reynolds et al., 2009). The inconsistent findings stem from different methodologies, mixes of users (e.g., pedestrians, pets, etc.), and designs (e.g., paved or unpaved).
- Research suggests that riders adjust their speeds to accommodate pedestrians and path conditions. Path characteristics that support separation from pedestrians may allow relatively higher speeds, without substantial loss of safety and higher confidence and safety perception (Boufous et al., 2018; Nazemi et al., 2019).

A shared-use path crossing in Minneapolis. (Photo: Jennifer Dill)

- Crashes at trail crossings of roads have been found to be associated with trail volume, cross vehicle volume, three-way intersections with trails crossing perpendicular to the main road, and crossing length (Schneider et al., 2021).

There is some evidence about the safety benefits of other types of bikeways.

- Some studies have found safety benefits of bicycle boulevards (DiGioia et al., 2017).

- Studies of shared lane markings, or sharrows, indicate that they may influence cyclists' position on the road, but there is no evidence of a reduction in crashes or injuries (DiGioia et al., 2017). A more recent study found an increase in injury and crash rates in places with *only* sharrows as bicycle infrastructure (Ferenchak & Marshall, 2019). A review of research on the effect of sharrows on lateral passing distance found mixed results (Rubie et al., 2020).
- The findings on the safety effects of colored bike lanes are mixed (DiGioia et al., 2017).

What are the research gaps?

There are several gaps related to separated bike lanes (Monsere et al., 2014, 2019; B. Thomas & DeRobertis, 2013; University of North Carolina et al., 2013).

- Appropriate locations based on preferred speed and volume thresholds.
- Preferred widths to accommodate a specified bicycle design vehicle and side-by-side riding.
- Safety and operational effect of height of bikeway relative to the roadway and sidewalk.
- Types of buffers, including effectiveness at keeping drivers from entering the separated bike lanes.
- Appropriate signing and marking.
- Specifics on traffic controls.
- Effects of on-street parking.
- Effects on the types of crashes and crash and injury severity.
- Operational and design features for intersection safety, including with different traffic volumes and using crash data.
- Best practice for the horizontal alignment at intersections.
- Safety performance of one-way vs bidirectional lanes.

A two-way seaparated lane in downtown Seattle with green paint at a driveway. (Photo: Jennifer Dill)

NCHRP 766 report included several remaining research gaps on bike lane widths (Torbic et al., 2014).

- Recommended bicycle lane widths based on vehicle speeds (or posted speed limits) and grade.
- Wider range of buffered bicycle lane designs, including with buffers on both sides, for reducing threat of passing vehicles and dooring from parked vehicles.
- Relationship between effective bike lane widths, the physical and operational widths of bicyclists, and bicycle crashes, including bicycle crashes in the presence of passing vehicles and parked vehicles.
- Design guidance for bicycle lane widths in rural areas.

There are research gaps regarding other types of bikeways and designs.

- There is very limited and inconclusive safety research regarding buffered bike lanes, colored bike lanes, and advisory bike lanes (DiGioia et al., 2017; Schultheiss et al., 2018).

- More evidence is needed regarding the safety of bicycle boulevards relative to arterials (Minikel, 2012).
- Research on shoulder width and specific designs of shoulder rumble strips is required to safely accommodate bicycles while maintaining the effectiveness in reducing lane departures (Torbic et al., 2009).

Additional research gaps include:

- The full extent of the dooring problem, since most data sources exclude this type of incident by definition (Schimek, 2018).
- Few studies have examined drivers' design preferences (Sanders & Judelman, 2018).
- There is limited evidence of bicyclist safety on high-speed roadways, including different design alternatives (Schonfeld et al., 2016).
- Very few studies on the safety of bikeways examined particular population groups, such as children, older adults, or other demographics.
- Most current sources do not account for the differences of the roadway environments, including urban, suburban, or rural contexts (Schultheiss et al., 2018). Much of the research in the U.S. on new types of facilities is from large cities.
- There are mixed findings in research on whether vehicle type influences lateral passing distance, except that research has shown that buses pass closer to cyclists. There is also a lack of research on the effects of minimum passing distance laws (Rubie et al., 2020).
- Bicycle facility designs that work well for non-traditional bicycles, including adaptive bikes, trikes, cargo bikes.

How is research on this topic done?

There are several factors that make research on the safety of new types of bikeways challenging. These factors should be considered when designing new research projects.

- Too few studies control for exposure to risk, often because of the lack of count data.
- There is increasing evidence of a period of adjustment in terms of safety and ridership after the installation of the bike facility. A study in New Zealand shows how there is no consistent "step" increase in cycling numbers immediately following installation of cycle lanes. Changes on cycling growth rates were more positive, although it is clear that other wider trends such as motor traffic growth are having an effect (Koorey et al., 2016).
- The relative newness of separated bike lanes and the rarity of bicycle collisions contribute to small sample sizes when analyzing crash data (University of North Carolina et al., 2013). When there are a small number of bicycle crashes at a study site, a change of one or two crashes yields a very large percentage change (Rothenberg et al., 2016).
- Another challenge is that some studies do not define the terminology used to describe the bicycle infrastructure, or they grouped facilities that may have different injury risks (Reynolds et al., 2009).
- Instrumented bicycles, equipped with devices such as cameras and sonar detectors, have been used to measure bikeway experience characteristics, including factors such as passing distance (e.g., Louro et al., 2021).

Current research

Sponsor	Project Information	Status
National Cooperative Highway Research Program (NCHRP) 15-74 https://rip.trb.org/View/1652757	**Safety Evaluation of On-Street Bicycle Facility Design Features** The objective of this research is to provide practitioners at state DOTs and other transportation agencies with data-driven guidelines for selecting context-appropriate design features for safety improvements to existing separated and non-separated, on-street bicycle facilities and for the planning of new facilities. The guidelines will be based on an up-to-date, quantitative analysis of crash patterns as well as an evaluation of the roadway characteristics, land use patterns, human factors that increase conflicts, and the risk and severity of midblock crashes that involve bicyclists.	Expected completion date: 8/31/23
National Cooperative Highway Research Program (NCHRP) 08-149 https://rip.trb.org/View/1842753	**Impacts of Active Transportation Network Gaps** The objective of this research is to understand the causes and impacts of gaps in the urban and rural active transportation network that exist, efforts and barriers in reducing gaps, and designs and/or policies have been used to address the difference between various active transportation users.	Anticipated start: 2021
Federal Highway Administration (FHWA)	**Development of Crash Modification Factors for Different Separated Bike Lane Configurations** The goal of this project is to evaluate the safety of SBL facilities and to develop associated crash modification factors. This project assesses SBLs in multiple geographic locations and with varying midblock and intersection configurations. The outcomes of this project are envisioned to help FHWA develop guidance on the safety merits and predicted safety performance of SBL facilities.	Expected completion date: 8/2022
Texas DOT https://rip.trb.org/View/1716486	**Addressing Bicyclist Safety through the Development of Crash Modification Factors for Bikeway Facilities** In this project, the research team will develop crash reduction factors for bikeway facilities implemented on Texas roadways to assess their safety and economic effectiveness. Bikeway facilities include, but are not limited to, bike lanes, buffered bike lanes, advisory bike lanes, through bike lanes, sharrows (shared bike lanes), two-way cycle tracks, protected bike lanes and so on. This research will address the development of crash reduction factors for target crash types where sufficient bicycle facility information and crash information is available.	Expected completion date: 4/30/22
North Carolina DOT https://rip.trb.org/View/1672442	**Assessment of Separated Bike Lane (SBL) Applications in North Carolina** The objective is to assess the state of the practice with respect to SBL planning and design, and conduct research on the performance of SBL applications in North Carolina. The team will be able to document their impacts on safety, bicyclist volumes, motor vehicle volumes, speed, and other outcomes.	Expected completion date: 7/31/21

Sponsor	Project Information	Status
Urban Mobility and Equity Center (UTC) https://rip.trb.org/View/1562252	**Shared Bus/Bike Lane Safety Analysis: Assessing Multimodal Access and Conflicts** Using video observation and survey data, the aim of this study is to analyze cyclist safety on SBBLs as a function of geometric configuration, bus frequency and level of service. The safety of cyclists on SBBLs will be compared with separated bike facilities with adjacent bus routes.	Expected completion date: 9/30/20

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Most common TRID index terms

Bicycle lanes	Bicycle safety
Traffic safety	Intersections
Bicycling	Bikeways
Bicycle crashes	Safety
Highway safety	Drivers
Cyclists	Passing

Bikeways: Ridership and demand

This review focuses on the relationship between bicycle infrastructure and ridership, also known as demand. The focus is on bikeways, defined as "a facility intended for bicycle travel which designates space for bicyclists distinct from motor vehicle traffic" (Schultheiss et al., 2019) as well as bicycle-specific infrastructure at intersections. Relevant definitions are described in the box in the *Bikeways: Safety and Design* summary.

Related review topics

- The effects of bikeways on safety and design are covered in *Bikeways: Safety and design.*
- Research on safety and design related to intersections, including bicycle-specific infrastructure, covered in *Bicycles at intersections: Design and safety.*

What do we know?

Research generally finds a significant, positive relationship between cycling facilities and cycling levels, though the effects vary by facility type and design features.

Several reviews of existing research document the positive relationships found between more bikeways and higher ridership (Buehler & Dill, 2016; Pucher et al., 2010; L. Wang & Wen, 2017; Yang et al., 2019). Some of the specific findings are highlighted here.

- Several studies provide evidence that increased street connectivity (regardless of cycling infrastructure) is associated with higher amounts of cycling, particularly for transportation and commuting (L. Wang & Wen, 2017; Yang et al., 2019). A review of the most recent research found positive associations between bikeways and cycling generally and commuting by bicycle, but was inconclusive about recreational cycling (Yang et al., 2019).
- Several studies find that people cycling prefer roads with fewer general traffic lanes, slower and fewer motor vehicles, and without on-street parking (Buehler & Dill, 2016).
- Most aggregate-level studies (e.g., city-level) have found positive and statistically significant relationships between on-street bike lanes and levels of bicycling, while the findings from individual-level studies are mixed. Studies that ask people about their preferences usually find a preference for on-street lanes vs no bikeway (Buehler & Dill, 2016; Pucher et al., 2010). Overall, the research indicates that striped bike lanes may be better than no bikeways, but that they are unlikely to increase overall levels significantly by inducing people who currently do not ride to start riding.
- There is conflicting evidence on whether on-street striped bike lanes or off-street paths have greater effects on cycling levels. Some stated preference studies find that experienced cyclists may prefer on-street lanes to bike paths, but that may be because of perceived trade-offs in travel time (Buehler & Dill, 2016). Research using GPS data from regular cyclists found a preference for paths and bicycle boulevards over striped bike lanes (Broach et al., 2012).
- When riding on roadways with motorized traffic, cyclists seem to prefer traffic-calmed residential neighborhood streets (aka bicycle boulevards), lower car traffic volumes, slower car traffic speeds, and roadways without car parking (Buehler & Dill, 2016).

- There is no strong evidence that shared lane markings (aka sharrows) alone, particularly on busy streets, increase comfort levels or cycling volumes (Buehler & Dill, 2016; Ferenchak & Marshall, 2016; Schultheiss et al., 2018; Winters & Teschke, 2010).
- Curbside parking appears to be a major deterrent, particularly for less experienced, utilitarian cyclists (Watkins et al., 2020).
- There is limited research on how a network of bikeways influences ridership. One study indicates that densifying the bikeway network may be most effective (Schoner et al., 2015). This is consistent with another study that found that, after controlling for slope, land use and roadway characteristics, the total length of bikeways in a zone was associated with more biking (Osama et al., 2017).
- A small but growing number of studies are using the Level of Traffic Stress (LTS) system of categorizing cycling infrastructure, which emphasizes the role of the "weakest link" in a network and the different levels of comfort people have cycling in different environments (Mekuria et al., 2012). The few studies linking LTS to bicycling behavior show mixed results, with a recent study in Ohio finding a relationship between LTS 2 (but not LTS 1) and bike commuting (K. Wang et al., 2020).

A growing body of research finds a preference for physically separated facilities (Schultheiss et al., 2018).

- A recent NCHRP study found that people (cyclists and non-cyclists) rated facilities with more separation from motor vehicles higher, particularly protected or separated bike lanes and paths (Watkins et al., 2020). This is consistent with an earlier study of current and potential cyclists, who preferred off-street paths, followed by protected bike lanes and then residential routes (Winters & Teschke, 2010).
- A major reason behind these preferences is the perceived risk of collisions with motor vehicles. Separated bike lanes with a physical barrier can offset the negative effects of the roadway, such as the number of traffic lanes (Watkins et al., 2020).
- Studies find that the preference for separation is even stronger among certain groups, including people cycling with children (Sanders & Judelman, 2018); women (Aldred et al., 2017); non-transport cyclists (Sanders & Judelman, 2018); and those who are more risk-averse (Clark et al., 2021).
- Physical barriers, such as bollards or planters can increase comfort levels substantially (Watkins et al., 2020). Another study also found that bike lane buffers with some sort of vertical separation, even just a plastic flexpost, increased perceived comfort for potential cyclists (McNeil et al., 2015).

A parking-protected bike lane in Chicago, IL. (Photo: Nathan McNeil)

Some research finds inconsistencies between objective measures of bikeways and people's perceptions.

- Research on the effects of bikeways on bicycling behavior have measured bikeways in two ways: (1) objective measures using GIS data representing infrastructure on the ground; and (2) survey respondents' self-reported perceptions of the presence and/or quality of bike infrastructure (Yang et al., 2019).
- A review of several studies that included both types of measures of active transportation infrastructure found that the correlation between perceived and objective measures varied a lot, from low to high agreement. The authors concluded that perceptions cannot substitute for objective measures and that

the two measure different things. In 16% of the studies, the perception measure was correlated with activity, in 13% the objective measures were, and in 3% both were (Orstad et al., 2017).

- A study from Portland, OR, found that perceptions and objective measures of the cycling environment had different effects on cycling behavior. After controlling for attitudes, objective measures had a stronger effect on the likelihood of bicycling at all for transportation. Perceptions had an effect on predicting the frequency of cycling (Ma et al., 2015).

Intersection characteristics can influence route choice and, perhaps, cycling demand.

- The research on intersections does not make a direct link to ridership. Rather, some research has found that bike-specific features at intersections (e.g., bike boxes and bike signals) may improve the comfort of people cycling. Studies have documented that people cycling prefer to avoid intersections that cause delay (e.g., stop signs), but that they may seek out signalized intersections if they need to cross busy streets (Buehler & Dill, 2016).
- A study of different designs for intersections with protected bike lanes found that people rated the designs that minimized interactions with motor vehicles most comfortable. This included fully separated signal phases and protected intersections. Comfort levels dropped off significantly with less separation, particularly for less confident cyclists. This supports the notion that more separation is necessary to increase cycling rates (C. Monsere et al., 2019).

Some research finds that motor vehicle drivers prefer separated cycling infrastructure.

- A survey of Michigan adults found that they preferred driving on roadways with increased separation from bicyclists (Sanders & Judelman, 2018).
- A study of protected bike lanes in five U.S. cities found that a majority of drivers (53%) living nearby felt that bicyclists were more predictable and riding more safely since the lanes were built. About 30-40% indicated some negative impacts on driving, such as congestion or finding parking, though this varied significantly by city (C. Monsere et al., 2014).
- A survey of motorists in Portland, OR, found that half of those who did not cycle themselves felt that a new parking-protected bike lane made driving on the street safer, while 23% disagreed (C. M. Monsere et al., 2012).

The concept of a “design user” or “cyclist type” can be used to make design decisions for ensuring comfort of riders.

- Over the years, research and practice related to user types have evolved. The most common approaches today focus on a person’s comfort level or tolerance for riding with motor vehicle traffic (Schultheiss et al., 2018). The FHWA *Bikeway Selection Guide* uses three types: highly confident, somewhat confident, and interested but concerned (Schultheiss et al., 2019).
- A review of research on cyclist typologies found that three groups often emerges: current cyclists, potential cyclists, and non-cyclists. The authors concluded that dividing potential cyclists into different categories could inform planning and infrastructure development (Félix et al., 2017).
- A commonly used typology developed by the City of Portland’s bicycle coordinator, Roger Geller, includes four types: the Strong and Fearless, Enthused and Confident, Interested but Concerned, and No Way No How. These types are largely based on comfort levels and have been used in numerous bicycling planning efforts, with a focus on targeting the Interested by Concerned adults. One study applying the typology to urban areas in the U.S. estimated that 51% of adults fall into that group, with 37% in the No Way No How

group, often because of physical limitations (Dill & McNeil, 2016). Other studies have aimed to improve and refine that typology. One resulted in three types: Uncomfortable or Uninterested, Cautious Majority, and Very Comfortable Cyclists (Cabral & Kim, 2020).

- Comfort levels are often correlated with demographics. Several studies have found that women feel less comfortable than men in many cycling environments, including two very recent national studies (Monsere et al., 2019; Watkins et al., 2020). Those studies also found lower levels of comfort or willingness to ride among people of color or African Americans. Among those who did not already cycle, age was also negatively associated with comfort (Watkins et al., 2020).

What are the research gaps?

- While the evidence is pretty clear that cycling infrastructure is associated with more cycling, and that people prefer more infrastructure with more separation from motor vehicles, the research has not provided the types of quantitative estimates often needed for accurately predicting future demand given different infrastructure scenarios.
- Most of the existing research uses cross-sectional data (one point in time), making conclusions about cause and effect difficult. Longitudinal studies, ideally with controls (also known as natural experiments), can better examine causal relationships (Buehler & Dill, 2016; Yang et al., 2019). This is particularly necessary for newer or less common types of infrastructure, such as separated or protected bike lanes, bicycle boulevards, and advisory bike lanes.
- More research on the effect of networks of infrastructure (rather than just a single facility) could help inform planning decisions (e.g., on whether to concentrate investments in subareas).
- A growing number of agencies are using the Level of Traffic Stress (LTS) typology of infrastructure for planning, yet few empirical studies have validated the correlation between LTS and ridership.
- It is unclear whether there would be ridership differences for separated lanes at the sidewalk versus street level. One study in Chile found a preference for the road level (Rossetti et al., 2019), though that may be influenced by high pedestrian volumes on sidewalks in dense urban areas.
- Most current sources of guidance do not account for the differences of the roadway environments when planning in an urban, suburban, or rural context, and may therefore not be as applicable as they could be to all practitioners in the United States (Schultheiss et al., 2018).
- There is limited evidence on the effects of car-free zones, home zones, and shared streets (Pucher et al., 2010).
- Few studies have examined drivers' design preferences (Sanders & Judelman, 2018).
- Research connecting people's perceptions of the cycling environment to objective measures of the environment may help inform practice. For example, in an area with good infrastructure, what would change perceptions, if that is what influences behavior?

How is research on this topic done?

While some studies rely on descriptive case studies, historical analysis, or discourse analysis, the vast majority of studies in this area use quantitative techniques to investigate the relationship between bikeway networks and cycling levels (Buehler & Dill, 2016). Revealed or stated preference surveys are used in much of the research. These are almost always cross-sectional, thus limiting inferences about changes over time. Surveys are also subject to sampling and other types of response errors. GPS-based studies allow for more objective measures of behavior, including route choice, but are challenging to implement. New "big data" sources (e.g., mobile phone

data) may provide opportunities, but questions remain about mode imputation and representation of those samples. Some studies use cycling volumes before and after the installation of specific facilities, providing simple time-series evidence. However, these studies do not always control for other factors affecting cycling levels, and without controls it is difficult to know if increases in volumes are due to new cyclists or route changes of existing cyclists. With the increase in count data collected in some cities, a few studies are able to look at changes longitudinally over larger geographies and controlling for more factors.

The existing research uses a variety of bicycling outcomes, which can explain inconsistent findings. At an individual level, this can include whether a person bicycles at all, how often or far they bicycle, and/or the purposes for which they bicycle (e.g., utility vs recreation). At the aggregate level, the analyses can be done at the city-level or smaller geographies (e.g., Census tract), which can also affect findings. Studies also define or characterize bikeways in different ways. Some lump all types of bikeways into a single category, which does not provide the evidence needed for most practitioners trying to recommend specific types of infrastructure (with varying costs) for investments.

Current research

Sponsor	Project Information	Status
Center for Advance Multimodal Mobility Solutions and Education (UTC) https://rip.trb.org/View/1669762	**Bicycle Network Connectivity and Accessibility: A Study on the Effects of Bike Infrastructures on Bicycle Sharing System Demand** The proposed project is a longitudinal analysis to study the effects of bike infrastructures, particularly bike lanes and bike paths, on bicycle sharing system demand.	Expected completion date: 9/30/21
National Highway Traffic Safety Administration (NHTSA) https://rip.trb.org/View/1656362	**Understanding and Using New Pedestrian and Bicycle Facilities** The objective of this project is to identify discrepancies between how pedestrian and bicycle facilities were designed to be used versus actual behaviors and knowledge of pedestrians, bicyclists, and motorists; examine knowledge of proper facility use and enforcement by law enforcement; and document available educational resources and initiatives. Facilities such as sharrows, bike lanes, green lanes, HAWKs, shared right turns, leading pedestrian intervals (LPIs), and pedestrian hybrid beacons will be investigated.	Expected completion date: 9/30/22
North Carolina DOT https://rip.trb.org/View/1672442	**Assessment of Separated Bike Lane (SBL) Applications in North Carolina** The objective is to assess the state of the practice with respect to SBL planning and design, and conduct research on the performance of SBL applications in North Carolina. The team will be able to document their impacts on safety, bicyclist volumes, motor vehicle volumes, speed, and other outcomes.	Expected completion date: 7/31/21
National Cooperative Highway Research Program (NCHRP) 08-149 https://rip.trb.org/View/1842753	**Impacts of Active Transportation Network Gaps** The objective of this research is to understand the causes and impacts of gaps in the urban and rural active transportation network that exist, efforts and barriers in reducing gaps, and designs and/or policies that have been used to address the difference between various active transportation users.	Anticipated start: 2021

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Most common TRID index terms
Bicycle lanes
Bicycle facilities
Cyclists
Bicycling
Highway design
Highway safety
Bicycle travel
Attitudes
Traffic safety
Surveys
Built environment
Comfort

Distraction and impairment: Effects on pedestrian and bicyclist safety

Distraction, particularly from mobile electronic devices, and impairment, particularly from alcohol, are responsible for nearly a quarter of motorist-caused pedestrian and bicyclist fatalities. There is also some evidence that distraction by pedestrians and bicyclists may result in reduced awareness and safety. Alcohol-impairment of the pedestrian is involved in about thirty-five percent of fatalities; a lower share of bicyclists are impaired in fatalities (twenty-one percent). This review covers research related to distraction and impairment as it relates to pedestrian and bicyclist safety.

What do we know?

Distracted and alcohol-impaired drivers are connected with nearly one-quarter of pedestrian and bicyclist (or other non-vehicle occupant) traffic fatalities.

- In 2018, 506 non-occupants, including pedestrians and bicyclists, were killed by distracted drivers, which accounted for 18% of the 2,841 total deaths attributable to distracted drivers, and 7% of the 7,354 "non-occupant" fatalities (NHTSA, 2019a, 2020). A recent study of pedestrian fatalities noted that 9.4% of pedestrians killed between 2012 and 2016 were hit by drivers with a noted distraction, and notes they believe this to be an underestimate (Schneider, 2020).
- In 2018, 1,178 non-occupants, including pedestrians and bicyclists, were killed in crashes with alcohol-impaired drivers, accounting for 11% of alcohol-related motor vehicle crash fatalities and 16% of the 7,354 "non-occupant" fatalities. (NHTSA, 2019a, 2019b). A study of pedestrian fatalities trends noted that the percentage of pedestrian fatalities due to drivers who had been drinking was consistently around 18% from 1977 to 2016 (Schneider, 2020).

Distracted driving, including talking on a cell phone and texting, is an increasing safety risk that puts pedestrians and bicyclists at risk.

- The annual National Occupant Protection Use Survey (NOPUS) found that an average of 3.2% of drivers were talking on a handheld cell phone (at any given time) in 2018, which is up slightly from 2.9% in 2017 but down from a high of 5.2% in 2012. An additional 2.1% were visibly manipulating a handheld device (e.g., dialing or texting), which is a similar level to the 2.2% peak reached in 2014 (NHTSA, 2019c). Further, a 2011 report noted that 77% of drivers indicated that they answer phone calls while driving, and 41% indicated that they make phone calls while driving (Tison et al., 2011).
- Driving studies agree that distraction increases the risk of driver error and crash risk, with using and dialing a cell phone being a top risk (Scopatz & Zhou, 2016).
- Multiple studies have found that drivers reacted slower to pedestrians entering a crosswalk in a simulated environment when talking on a handheld or hands-free cell phone (M. M. Haque & Washington, 2013; Laberge et al., 2004), as well as cause drivers to miss exits or turns and neglect mirror checks (Stavrinos et al., 2018).
- A simulated driving study comparing cell phone use to alcohol intoxication found that drivers had slower reaction times when using the cell phones than when using alcohol (Burns et al., 2002).
- Texting was found to be particularly detrimental in terms of drivers moving laterally and leaving their travel lanes (Stavrinos et al., 2018).

- Cognitive distraction, such as being focused on a conversation or other task, has also been linked in simulator studies to drivers spending less time looking at potential hazards such as areas where bicyclists may appear (Ebadi et al., 2020).

Young people may be more likely to be distracted, with more substantial impact on their safety, than other drivers and pedestrians.

- Young people, particularly in the 20 to 29 age group, make up a disproportionate percentage of distracted drivers involved in fatal crashes. Twenty-five percent of distracted drivers involved in fatal crashes in 2018 were 20 to 29 years old, and 34% of distracted drivers involved in fatal crashes while using a cell phone were in this age group (NHTSA, 2020).
- Studies have also found that beginning drivers are also much more likely to deviate from their lanes when interacting with a phone (Stavrinos et al., 2018).
- A meta-analysis found that, for youth pedestrians and young drivers, interacting with a phone (e.g., texting) was a greater safety threat than talking on the phone (Stavrinos et al., 2018).

Pedestrian distraction may increase pedestrian crash risk, although the risk to other road-users is low and a focus on pedestrian distraction can itself distract from more important contributors to pedestrian crashes.

Some studies have found that distracted pedestrians may walk more slowly or unevenly, exhibit inattention blindness and exhibit other behaviors that could compromise safety (Osborne et al., 2020; Scopatz & Zhou, 2016).

- An observational study in New York City and Flagstaff, AZ, found that 14% of 3,038 observed pedestrians crossing at major intersections were “distracted” in some way, including 2.9% talking on cell phones, 5.7% texting, 3.7% listening to headphones, and 1.2% engaged in other distracted behavior (Russo et al., 2018). The study did not find that people talking on or texting on mobile phones crossed more slowly than non-distracted pedestrians, and actually found that people listening to headphones crossed faster. People texting while crossing were found to be more likely to cross outside of the marked crosswalk area.
- Some studies have found that pedestrians using cell phones are less likely to notice unusual or out-of-place objects (inattention blindness), and behave in a less safe manner (Scopatz & Zhou, 2016). Whether talking on a cell phone or looking at a phone (e.g. texting), pedestrians on average wait longer to cross, are more likely to miss safe openings to cross, and cross more slowly (Stavrinos et al., 2018).
- Simulation-based studies have found that pedestrians who are engaging with electronic devices, particularly texting or talking on a cell phone, were more likely to be struck by a car in a simulation-based environment, while findings related to listening to music while walking are mixed in terms of safety effects (J. Mwakalonge et al., 2015).
- A literature review on distracted walking noted that “experimental-based and observational-based studies clearly showed that distracted walking can have a detrimental safety impact on pedestrians. It was found that texting pedestrians were 3.9 times more prone to exhibit at least one dangerous crossing behavior compared to undistracted pedestrians” (J. Mwakalonge et al., 2015).
- A meta-analysis of 17 pedestrian distraction experiments found that texting was associated with a moderate increase in pedestrian crashes and near misses, talking on the phone was associated with a small increase in risk, and that listening to headphones was not associated with increased risk (Simmons et al., 2020).

- The actual contribution of distraction to pedestrian deaths and injuries is poorly understood due to limited and inconsistent data, but estimates range from less than 1% to as high as 21.5% (Ralph & Girardeau, 2020). They also note that pedestrian injuries have not been increasing as quickly among younger people, or in areas with younger populations, contrary to what would be expected if this highly smartphone-use segment of the population were taking on extra risk through that activity.
- However, a study of observed conflicts between pedestrians and bicyclists at pedestrian crossings in Montreal and Vancouver, Canada, found that pedestrians on cell phones or wearing headphones were not more likely to be involved in an interaction (Hosford et al., 2020).

While factors such as roadway speeds, intoxication, and driver distraction are known to be responsible for considerable portions of pedestrian crashes and factors, efforts to reduce speeds, improve enforcement measures or change roadway design are more expensive and politically fraught than pedestrian distraction (Ralph & Girardeau, 2020).

- A survey of transportation practitioners found that most overestimated the contribution of pedestrian distraction to pedestrian death, which was then linked to a preference for education-based pedestrian safety solutions rather than efforts to reduce speeds or find design solutions (Ralph & Girardeau, 2020). The study also found that transportation practitioners who travel primarily by car, or spend less time in pedestrian-oriented areas, were more inclined to view pedestrian distraction as a major concern.

There are few studies of distracted bicycling, with limited findings on safety impacts.

- Mwakalonge et al. (2014) point out that "while distracted drivers endanger themselves and other, distracted bikers, in general present more risk to themselves than to others."
- Studies of distracted bicycling have found that many bicyclists have used their portable electronic devices while riding, ranging from around 17-23% using devices all the time or during an observation period, and another portion (up to 55%) reported using devices sometimes (J. L. Mwakalonge et al., 2014).
- Safety effects of using electronic devices or engaging in secondary activities while bicycling are unclear, although there is some evidence that using such devices is associated with increased crash risk for cyclists younger than 35 (Goldenbeld et al., 2012). One study found that using two earbud-style headphones reduced reaction time for cyclists, while wearing only one headphone did not affect reaction time (de Waard et al., 2011).
- Several studies have found that bicyclists, including teens and young adults, use compensatory strategies, such as stopping or slowing their speed, in order to engage in more visually demanding activities such as texting (Stavrinos et al., 2018).

Alcohol is a factor in many pedestrian fatalities (35% in 2014) and a considerable share of bicyclist fatalities (21%).

- A study examining crash fatality trends of pedestrians and bicyclists with high blood alcohol content (BAC >=.08) found that, between 1982 and 2014, the percentage of fatally injured pedestrians with high BAC dropped from 45% to 35%, while the percentage of fatally injured bicyclists dropped from 28% to 21% (Eichelberger et al., 2018).
- Fatally injured pedestrians who had BAC greater or equal to 0.08 were more likely to have had prior alcohol-related offenses on their driving records, suggesting that people with patterns of alcohol abuse may be at greater risk for being killed as high-BAC pedestrians (Blomberg et al., 2019).

- A study in Tennessee found that intoxicated pedestrians were overrepresented among pedestrian fatalities, with 22% of pedestrian killed in crashes having alcohol in their system, compared to only 7% of pedestrians involved in any type of crash (Hezaveh & Cherry, 2018). A study in Australia found that 45% of pedestrians killed were intoxicated (R. Haque et al., 2012).
- A 2020 study in Louisiana found that crashes involving intoxicated pedestrians are associated with areas with limited lighting, country roadways, and midblock locations (Das et al., 2020).
- One study found that in many cases, particularly late-night fatal crashes, both pedestrians or cyclists and motorists have BAC greater than 0.08 – 16% of fatally injured pedestrians and bicyclists with BAC >=.08 were involved with similarly impaired drivers (Eichelberger et al., 2018).

What are the research gaps?

- While four states have laws against bicycling under the influence, and 21 states allow charges to be brought against cyclists under general impaired driving laws, there is not good information about how the laws are applied or their effectiveness in deterring impaired cycling (Eichelberger et al., 2018).
- A meta-analysis of distracted road behavior and youth only identified one study looking at distracted bicycling, and pointed to mixed findings on the safety implications of distracted bicycling (Stavrinos et al., 2018).
- Distracted bicycling awareness programs exist, but little is known about their effectiveness (J. L. Mwakalonge et al., 2014).
- A meta-analysis of studies looking at distraction and youth walking, bicycling and driving found that small sample sizes and inconsistent methods were a limiting factor (Stavrinos et al., 2018).
- Stavrinos et al. (2018) noted that, “No published work examines how texting may impact pedestrian safety in young children”, and that there is little research available on distraction and youth bicycling.”
- Many studies collapse age and experience groups in a way that makes it difficult to identify whether age or experience have an impact on distraction risk (Stavrinos et al., 2018).
- Data quality/underreporting: We don’t know very well overall exposure (how many intoxicated peds/bicycles) and how many crashes are distraction-related but not coded as such (only if a person admits to distraction in lower-severity crashes).
- Observational studies of pedestrian or bicyclist distraction may attribute certain behaviors to distraction but often lack a control group, so the relationship between distraction and safety behavior merits further study (Ralph & Girardeau, 2020).
- Much of the pedestrian distraction research has focused on who got hit (the pedestrian) as opposed to who did the hitting (generally motorists). More research on the latter could yield more effective safety solutions for pedestrians (Ralph & Girardeau, 2020).
- Research is needed to better understand how often drivers in fatal pedestrian or bicycles crashes are intoxicated, as not all drivers in serious pedestrian or bicycle injury crashes are tested for alcohol impairment, including instances of hit-and-run.
- Research should examine whether a resilient pedestrian environment, such as that which would accommodate pedestrians with vision or mobility disabilities, would likely safety accommodate distracted or impaired pedestrians.

How is research on this topic done?

- A number of studies have used naturalistic observation of pedestrians to assess distraction behaviors, either in real time or via recorded video, to view pedestrians in public, often as they crossed streets or navigated sidewalks. Often cell phone use has been examined as it relates to pedestrians' observations of unusual or out-of-place objects (Scopatz & Zhou, 2016).
- Naturalistic observation of drivers can be done through instrumented vehicles (Scopatz & Zhou, 2016).
- Simulation or laboratory studies have been used to assign research participants with tasks and varying types of distraction, which can minimize participant risk (Scopatz & Zhou, 2016).
- Most distracted bicycling studies have been conducted in the Netherlands, and have focused on technology-based distractions (J. L. Mwakalonge et al., 2014).
- FARS data includes blood alcohol levels (BACs) from alcohol tests and imputed BACs when test are not reported, and is available for motorists, pedestrians and bicyclists (Eichelberger et al., 2018). FARS also reports on whether a crash is "distraction-affected" or if a cell phone was in use at the time of the crash (NHTSA, 2020). Data on distraction for bicyclists and pedestrians is often derived from surveys or observational data (J. L. Mwakalonge et al., 2014).

Current research

Sponsor	Project Information	Status
Florida DOT https://rip.trb.org/View/1677589	**Determining Sample Measures of Distracted Driving, Distracted Pedestrian Activities and Impacts of Such Behavior on Traffic Operations at Signalized Intersections** The proposed project aims to measure different distraction types for both motorists and pedestrians to determine the impact of such behavior on traffic operations at signalized intersections.	Expected completion date: 9/30/21
Safety Research Using Simulation (SAFER-SIM) (UTC) https://rip.trb.org/View/1705304	**Impact of Road Information Assistive Systems on Pedestrian Crossing Safety** The objective of this research is to study the impact of Road Information Assistive Systems (RIAS) on the ability of a pedestrian to cross the roadway. This project will use virtual reality equipment to study the effect on pedestrians' decisions in roadway crossing maneuvers when having an active RIAS in a simulated smartphone or tablet. The intent is to simulate as if the pedestrian is operating in a P2I environment, and the connected device is giving information about the road and traffic conditions to assist the pedestrian in making the crossing maneuver safely. The study will analyze the performance of at-risk and vulnerable pedestrian populations, such as older adults and persons with functional diversity.	Start date: 6/01/20
Center for Advanced Transportation Mobility (UTC) https://rip.trb.org/View/1706841	**Acoustic Situation Awareness and Its Effects on Pedestrian Safety within a Virtual Environment** Due to the excessive use of personal listening devices (PLDs), vulnerable road users have begun subjecting themselves to reduced levels of achievable situation awareness resulting in risky street crossings. The current research seeks to investigate the effects of acoustic situation awareness and the use of PLDs on pedestrian safety by allowing pedestrians to make "safe" vs "unsafe" street crossings within a simulated virtual environment.	Expected completion date: 8/31/21

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Most common TRID index terms

Pedestrians
Distraction
Fatalities
Pedestrian safety
Traffic safety
Literature reviews
Walking
Cellular telephones
Bicycling
Behavior
Risk assessment
Crash characteristics
Alcohol use
Pedestrian vehicle crashes

Economic benefits of walking and bicycling

Walking and bicycling offer economic benefit to individuals in the form of the value of their trips as transportation and recreation endeavors. Walking and bicycling infrastructure may promote activity and, in turn, help businesses. Downstream benefits of walking and bicycling include improved health and decreased morbidity and mortality due to increased physical activity, which can bring economic benefits in terms of decreased health care costs and increased productivity and longevity. Other benefits include reducing fossil fuel consumption and vehicle use. Efforts to understand the economic impact of these various benefits are discussed in this brief.

What do we know?

Studies looking at business impacts of walking and bicycling find generally positive impact.

A number of studies document the economic impact of the bicycling industry, including bicycle production, sales, maintenance, employment and tourism.

- Studies in several states have found that bicycle-related purchases and services added considerable amounts to their economies annually, including from $556 million to $924 million in Wisconsin; more than $400 million in Iowa; around $261 million in Minnesota; $1 billion in Colorado; and over $500 million in Vermont (Flusche et al., 2012). A study in Nebraska finds that recreational bicycling was likely responsible for over $228 million in output, $31 million in tax revenue, and over 2,000 jobs (Arroyo et al., 2020).

People arriving at businesses by walking or bicycling spend as much or more than those arriving by car.

- Although people who arrive at a business by driving may spend more per visit, evidence suggests that people who arrive by walking, bicycle or transit visit stores more frequently, and may spend more over time at local businesses. For example, a study of visitors to downtown San Francisco found that travelers arriving on foot or by transit, on average, spend more per month at area businesses than those arriving by car, due to more frequent visits (Bent & Singa, 2009).
- A study in Portland found similar results, with pedestrians, cyclists and transit users visiting businesses, including restaurants, drinking places and conveniences stores, more frequently than car drivers and spend more, on average, over a month at those businesses (Clifton et al., 2013).
- One review found that in six of eight North American studies there was evidence that people arriving on bicycles or walking spent more per month than people driving, though the differences were not always statistically significant. Findings on spending per trip were mixed (Volker and Handy, 2021).
- A study in Montana found that, from 2011 to 2013, touring bicyclists spent between $75 and $102 per bicyclist per day (Nickerson et al., 2013). A

An on-street bike parking corral outside of a restaurant (Photo: Jennifer Dill)

Washington study estimated that recreational trail users spent $8.4 billion annually in the state on items such as food, lodging, entrance fees, travel, and equipment (ECONorthwest, 2019).

Businesses facing streets with improved walking and bicycling infrastructure often see increased economic indicators, such as employment or sales.

- A review of 15 North American studies found "positive effects for the vast majority of active travel facilities" (Volker and Handy, 2021, p. 19). That review included a study of seven corridors (in four cities) with bicycle and pedestrian improvements implemented and looked at several sources of employment and sales data. It found that such street improvements had "either positive impacts on corridor economic and business performance or nonsignificant impacts," with the food service industry benefiting the most, followed by the retail industry (Liu & Shi, 2020).
- A study in New York City examining sales tax data before and after street projects involving walking and bicycling infrastructure found that storefronts in these areas generally outpaced comparable areas and corridors in terms of sales (New York City Department of Transportation, 2013).
- A study looking at the impact of bicycle and pedestrian infrastructure spending on employment in 11 U.S. cities found that of 58 such projects, an average of nine jobs were created per million dollars spent, including direct jobs via engineering and construction and indirect jobs in the supply chain (Garrett-Peltier, 2011).

Findings are mixed on the impact of walking and bicycling facilities on real estate values, although some studies show a positive impact.

- A study in Portland found that proximity to bicycle boulevards and separated bike lanes was associated with increasing residential property values, as was access to a denser and more extensive bicycle network (Liu & Shi, 2017).
- Other studies looking at the relationship between walking and bicycling facilities and property values have found mixed results, including one study finding a positive relationship between off-street trails and home values (Welch et al., 2016), and another finding a negative relationship, particularly in suburban locations (Krizek, 2006). The former also found that on-street bicycle facilities (generally bike lanes) were negatively associated with home values.

Active transportation provides health, environment, congestion and employment benefits that results in additional economic value.

Walking and bicycling offer the potential to provide direct economic benefit to the participant/user.

- Walking and bicycling offer a mobility benefit, a recreational benefit and a health benefit, each of which can be quantified, including by looking at what people would spend or how much they might save through the activity (Krizek et al., 2007). Safe infrastructure may offer a safety benefit to the user, which has an economic value to both the user and society.
- Benefits of walking and bicycling facilities are likely different depending on the facility and location. For example, a recreationally focused trail might yield physical and mental health benefits, while a commute-focused facility may also yield benefits related to congestion reducing and reduced need for parking (Krizek et al., 2007). In either case, quantifying the benefits from an economic perspective is a further challenge.

- Active transportation's economic value can also be considered in terms of cost savings compared to travel by other modes. As of 2018, the average household spent $9,761 per year on transportation (BTS, 2020), primarily for car ownership and upkeep.

A number of benefits of walking and bicycling have indirect economic value, including the potential to increase physical activity and reduce mortality and morbidity, improve the environment, reduce congestion, relieve parking needs, and more.

- One study looked at how cities went about appraising the value of livability transportation policies in the areas of trip quality, time use in transport, place quality, time use in places, personal security, visual blight, community severance, equity/social inclusion, and health/wellbeing (Anciaes & Jones, 2019). It found that new appraisal methods are needed for measuring monetized values of such policies, including time use in transport and visual blight.
- A meta-analysis of cost-benefit studies of active transport investments that included health-related effects of physical activity found that 26 of 32 studies found a higher than one-to-one return on investment (Brown et al., 2016).
- The economic value of the environmental benefits of active transportation depends largely on the extent to which active travel is substituting for motorized travel, which produces more pollutants. Accurately estimating such effects is challenging (Piatkowshi, Krizek, & Handy, 2015). One study found that CO_2 reduction benefits, using a cost of $125 per ton of CO_2, offset walking and bicycling infrastructure costs by about 15% to 17% (Chapman et al., 2018).

A review of studies looking at the health impacts of active transportation found that health benefits, primarily from increased physical activity, outweigh health risks such as traffic injury and exposure to air pollution (Mueller et al., 2015).

- A study in Portland estimated economic benefits in the form of health care cost savings, fuel savings, and reduced mortality based upon building out the planned city bicycle infrastructure plan. A range of investment levels, from $138 to $605 million were estimated to "result in health care cost savings of $388 to $594 million, fuel savings of $143 to $218 million, and savings in value of statistical lives of $7 to $12 billion" (Gotschi, 2011).
- A study in New Zealand quantified health benefits by considering the increased likelihood that people would walk or bike given investments in related infrastructure, and the resulting increase in disability-adjusted life years (a measure of avoided loss of life, injury and disease) primarily due to reduced cardiovascular disease, diabetes, depression, cancer, respiratory diseases and injuries. They found that the health benefit economic value outweighed the infrastructure cost by over 10 to 1 (Chapman et al., 2018). Another New Zealand study estimated that a 5% increase in bicycle trips of seven kilometers or less would reduce the nation's annual health budget by 1.6% (Giles-Corti et al., 2010).

Active transportation infrastructure can lead to health benefits from increased walking and bicycling (Photo: Jennifer Dill)

- Another study found that a more walkable urban development area would provide residents with more physical activity and reduced incidence of inactivity-related chronic diseases than residents in a low-density suburban neighborhood, with potential economic

benefits due to health-adjusted life expectancy of $94 million Australian dollars for a community with a population of 21,000 (Zapata-Diomedi et al., 2019).

- Other studies have found high returns on investment from walking and bicycling investment in Portugal (Rodrigues et al., 2020), Canada (Whitehurst et al., 2021), and Denmark (Rich et al., 2021).

Active transportation projects provide among the highest number of jobs per dollar spent

- Transportation Enhancements projects, which include relatively labor-intensive projects delivering walking and bicycling projects, were found to provide the highest number of jobs per dollar spent of any type of project implemented under the ARRA, producing over 17 jobs per million dollars spent (Dowell and Petraglia, 2012).

What are the research gaps?

- Most of the North American studies on the economic impacts of active transportation facilities on businesses examined bicycle infrastructure, with only a few focused on pedestrian improvements. In addition, the contexts of the studies varied, preventing the estimation of an average effect that could be applied for planning purposed (Volker and Handy, 2021).
- Much of the observed research on the secondary or co-benefits of walking and bicycling came from outside the United States, including Australia, New Zealand and Europe.
- There is a need for a better understanding of the impact of bicycle and pedestrian facilities on home values and rents, including differences between types of facilities and location types, potential links to gentrification and displacement, and effectiveness of anti-displacement strategies.
- Methodologies to assess the social economic benefit of major road and transit transportation investments are established, but evaluation of the economic impact of walking and bicycling infrastructure are less established (Krizek et al., 2007).

Research on the economic impacts of pedestrian improvements is less common (Photo: Jennifer Dill)

How is research on this topic done?

Studies examining the economic impacts of active transportation infrastructure on businesses use a variety of existing data sources and different statistical methods. Some studies use control locations and most studies look at changes over time, before and after construction. A study looking at various data sources to analyze the economic impact of bicycle and pedestrian improvement compared the value of Longitudinal Employer-Household Dynamics (LEHD) employment data, Quarterly Census of Employment and Wages (QCEW) employment and wage data, retail sales tax data, and National Establishment Time Series (NETS) employment and sales data. The study found that NETS and sales tax data allows for the finest geographic scale analysis (Liu & Shi, 2020). The project also produced a guide to conducting corridor economic analyses based on bicycle and pedestrian improvements (PeopleForBikes, 2020). Studies of the impacts of infrastructure on property values use well-established hedonic modeling techniques and existing data sources.

Research estimating the economic value of the direct economic benefits to users (e.g., health) and co-benefits (e.g., pollution reduction) often use findings from other research. A commonly used assessment framework and tool is the health economic assessment tool "HEAT" for walking and for cycling (Kahlmeier et al., 2011).

Current research

Sponsor	Project Information	Status
Georgia DOT https://rip.trb.org/View/1522835	**Economic Impact of Bicycling in Georgia** The primary objective of this research is to analyze how bicycling and related activities benefit Georgia's economy, providing a consistent framework to evaluate costs and benefits of proposed bicycle projects.	Expected completion: 3/6/21

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Most common TRID index terms
Bicycle facilities Economic impacts Bicycling Cyclists Cities Neighborhoods Modal shift Health Benefit cost analysis

Equity and bicycling

Bicycling is not a one-size-fits-all proposition. People have different needs based on identity, social interactions, and neighborhood of residence (Barajas, 2019). Many people in the U.S., in particular traditionally underserved populations, suffer from problems associated with inactivity, many of which could be addressed through improved access to safe walking and wheeling facilities (Sandt et al., 2016). Research indicates that enhancing the ability of traditionally underserved populations to travel via active transportation modes can potentially lead to improved outcomes in public health, safety, and economic development.

Related review topics

- For findings on the topic of underserved populations and walking as a mode, see *Equity and pedestrian travel*.
- Research on impact of fear of harassment and violence in reducing active transportation use among BIPOC pedestrians and bicyclists is covered in *Equity and personal safety*.
- Research on pedestrian and bicycle safety and crash data is covered in *Bicycle and pedestrian data: Safety*.
- For more detailed information on pedestrian safety at street crossings, see *Pedestrian crossings: Design and safety*.

What do we know?

Rates of cycling vary by socioeconomic group.

- Data from the 2017 National Household Travel Survey (NHTS) show that females are less likely than males to bicycle at least 10 minutes a day and that non-Hispanic whites are more likely to do so, relative to all others. Difference by income group is small or non-existent. When the rates are analyzed controlling for residential density and car ownership, it is found that men are nearly three times as likely than women to bike 10 or more minutes a day and non-Hispanic white adults are over twice as likely as adults of color to do so (Buehler et al., 2020). However, people in households with no cars are much more likely to ride, indicating that lower incomes are associated with cycling.
- There is mixed evidence as to whether rates of cycling among people of color is growing. The national data from 2001 to 2017 did not show an increase (Buehler et al., 2020). A longitudinal analysis in New York City found that people of color represented the largest source of growth in the bike commuting population between 2000 and 2009 (Rebentisch et al., 2019).
- Rates of cycling among women in countries with high overall rates of cycling (such as Denmark and the Netherlands) are equivalent to those of men (Garrard et al., 2012), indicating that the gender gap in the U.S. could be closed. The national data from 2001 to 2017 did not show an increase in women's cycling (Buehler et al., 2020). The cycling gender gap in the U.S. is starker for Latinos and Latinas due to cultural norms that particularly discouraged women from cycling, according to results of 23 in-depth interviews with low-income Latino immigrants in the San Francisco Bay Area (Barajas, 2020).
- Immigrants, particularly new immigrants, are more likely to travel by bicycle than native born U.S. adults, even after controlling for income, age, car ownership, and neighborhood characteristics (Smart, 2010). Some research from the San Francisco Bay Area starts to explain this pattern. It found that immigrants who cycled were more likely to know other cyclists and they perceived the mode as convenient. Immigrants were more likely to substitute cycling for another mode (particularly walking), while for non-

immigrants cycling was more likely to be a complementary travel mode, such as for access to transit (Barajas, 2019). Immigrants who live in immigrant neighborhoods are more likely to bicycle because of stronger social ties with the neighborhood's cyclists, while non-immigrants in the same neighborhoods who cycle less may be dissuaded from bicycling because they view the activity as something "other people" do (Barajas, 2020).

There is some evidence of demographic disparities in bicyclist safety.

- The rate of bicyclist traffic deaths (per 100,000 population) from 2015-2019 was higher for American Indian/Alaska Native (2.1) and Black cyclists (1.5) than for Hispanic (1.2), white (1.2), Asian (0.6), and Native Hawaiian/other Pacific Islander cyclists (GHSA, 2021). In 2010, Hispanics were involved in 38% of bicyclist fatalities, though they were 16% of the population (Barajas, 2018).
- Some studies linking crash rates and neighborhood socioeconomic characteristics have found higher rates of bicycle crashes in areas with greater shares of Hispanic or non-white residents and lower incomes, though others have not (Barajas, 2018; Lindsey et al., 2019).

The rate of bicyclist traffic deaths vary by race and are higher among Black people (Photo: Toole Design Group)

- A study using crash data from the San Francisco Bay Area estimated that Blacks had the highest crash rate per distance cycled, about three times that of the next racial/ethnic group (Hispanics) and over seven times that for whites. When analyzed geographically, risks of crashes were higher in areas with more poverty and even more so for Black cyclists (Barajas, 2018).
- Analysis of crash data in New York City found that cyclist crash rates were highest in the lower-income neighborhoods (outside of Manhattan) (Rebentisch et al., 2019), while an analysis in Minneapolis that controlled for exposure, infrastructure, and the built environment did not find neighborhood poverty to be associated with bicycle crashes (Lindsey et al., 2019).
- Some have argued that new immigrants are particularly susceptible to bicycle crash risks because of cultural and language barriers (Barajas, 2016).
- Cyclist fatality rates are about eight times higher for males than females (National Center for Statistics and Analysis, 2019), which is higher than the differences in rates of cycling. This indicates that males may be engaging in riskier behavior while cycling (Behnood & Mannering, 2017; Kim et al., 2007). There is mixed evidence on whether drivers behave differently towards cyclists based on gender (Haworth et al., 2018; Rubie et al., 2020; Walker, 2007).

Low-income and BIPOC populations face a disproportionate lack of access to quality infrastructure, which may affect cycling rates.

- A study of bike lane access and area-level sociodemographic characteristics in 22 large U.S. cities found that, after adjusting for indicators of cycling demand, access to bike lanes is lower in areas with lower educational attainment, higher proportions of Hispanic residents, and lower socioeconomic status (Braun, 2018). Other studies have found that bicycle infrastructure investments tend to benefit advantaged or gentrifying neighborhoods, including providing better access to key destinations such as jobs, stores or schools, for more advantaged populations (Jahanshahi et al., 2021).

- Investing in bicycle infrastructure in low-income and/or BIPOC neighborhoods may lower risk of collisions (Barajas, 2016; Rebentisch et al., 2019).
- There is evidence that women and minorities feel significantly less safe traveling by bicycle than white males in the U.S. A majority of women and minorities agreed or strongly agreed that, given more supportive infrastructure (e.g., sidewalks, bike lanes, and separated facilities), they would be much more likely to try using a bicycle for transportation (League of American Bicyclists & Sierra Club, 2013).
- Safety considerations affect women's choice of whether to cycle and where to cycle (Garrard et al., 2012). Consistent with gender differences in risk aversion and greater concerns about safety in public spaces (Brown & Sinclair, 2017; Loukaitou-Sideris, 2014), women express stronger preferences and more positive associations for greater segregation from motor vehicles than men (Aldred et al., 2017; Blickstein & Brown, 2017; Garrard et al., 2012).

While infrastructure improvements are often enough to encourage more walking, the same is not always true for encouraging more bicycling. Additional barriers exist for underserved populations.

- Research from three large U.S. cities found that both people of color and lower-income residents face more barriers to bicycling generally than higher-income white residents, on top of traffic safety issues which are barriers for all groups (McNeil et al., 2018).
- Barriers that are more prevalent for people of color include fear of being harassed or a victim of crime and police attention, particularly for lower-income people of color (Lubitow, 2017; McNeil et al., 2018).
- Barriers particularly prevalent for lower-income people include those related to the cost of bicycling (e.g., buying a quality bicycle and the right gear) (McNeil et al., 2018).
- A study in Portland found that women and minorities faced a range of challenges incorporating cycling into their everyday routines, including concerns or experiences with sexism (gender expectations for women's appearance); racism in public spaces; and concerns about safety in relation to infrastructure or a lack of time or gear to make cycling accessible (Lubitow, 2017).
- In one study, lower-income people of color were more likely to rate physical limitations as a big barrier for cycling, including carrying things on a bike, being too out of shape or too old, or having personal health issues. They were also less likely to have a place to store a bicycle at home (McNeil et al., 2018).
- Studies have found that parenting and household labor are barriers to biking for women (Garrard et al., 2012; Lubitow, 2017; Barajas, 2019). An U.S. survey of women cyclists found that 19% of women cited the inability to carry children or other passengers as a factor that discouraged them from cycling for transportation, compared to only 7% of men (Scheider, 2010).
- "Soft" policies, such as outreach and educational programs, may be needed in order to counteract negative attitudes or cultural experiences that are barriers to increasing rates of bicycling (Blickstein & Brown, 2017). Organizations that provide social resources and support are a critical form of human infrastructure as a supplement to physical infrastructure that is often missing in historically marginalized communities (Barajas, 2020). Such programs, including individualized marketing and public events that get people bicycling in fun and comfortable environments, may be particularly important for women and older adults (Blickstein & Brown, 2017; Buehler & Dill, 2016; Dill et al., 2015).
- Bicycle infrastructure can also be seen as a symbol of, or contributor to, gentrification, as well as being viewed as catering to white bicyclists in BIPOC communities (Hoffman, 2016).

What are the research gaps?

More research is necessary to better understand the different rates of bicycling among certain populations.

- Overall, less research has been done to evaluate bicycling inequities outside of the recently growing bike sharing literature (Lee et al., 2017). Further research is required to explore the exact reasons for unequal bicycle usage of different population groups and to discuss policy implications in response to this new knowledge (Jahanshahi et al., 2020).
- Very few studies explore the relationship between race and bicycling, including the intersection of race and other characteristics, including gender, immigrant status, income, age, and disability. Little is understood about how racism and racial bias (of other road users and law enforcement) affects bicycling behavior of BIPOC people.
- For women, the role of infrastructure is fairly well understood, though there are gaps with respect to specific infrastructure designs and on how other design factors, including cycling speed, affect preferences by gender (Aldred et al., 2017). The role of other factors related to gender, including cycling experience, household responsibilities, social norms, the need to carry items, weather, and personal safety concerns are less understood. Studies also need to understand how gender shapes mobility considering how mobility shapes gender (Ravensbergen et al., 2019).
- Even less is known about people and disabilities and bicycling (Clayton et al., 2017; MacArthur et al., 2020; Poonsiri et al., 2018). There is a need to recognize and understand how issues of body size and disability might be at odds with the type of infrastructure available (Lubitow, 2017).
- There is little work that considers how other gender minorities experience mobility in public spaces and explore the unique vulnerabilities that women and minorities may experience (Lubitow, 2017; Lubitow et al., 2020).

There are research gaps regarding safety risks for different populations.

- Only a subset of the active transportation research exploring factors contributing to safety risk includes analyses by demographic groups, and the relationships are not well understood. The research suffers from a lack of data, particularly exposure (bicycle volume or activity) data (Lindsey et al., 2019).
- Future work should investigate the causes of increased crash frequency in areas with higher poverty rates and higher shares of BIPOC people (Barajas, 2016).
- There is growing evidence that driver biases may affect safety-related behaviors around bicyclists (Goddard et al., 2020), though very little is known about how racial, gender, and other biases on the part of drivers may influence bicyclist safety.

There is still a lack of understanding of accessibility.

- More research is needed to understand disparities in bicycle accessibility by demographic groups. This research should consider different measures of accessibility that take into account infrastructure quality and different geographic scales (Braun et al., 2019).

The relationship of bicycling and health disparities should be further explored, including the potential for active transportation to lessen disparities.

- NCHRP Report 932: A Research Roadmap for Transportation and Public Health, notes that there is a need for further research on the health impacts of transportation giving "growing inequities among different sub-populations" (Sandt et al., 2019).

How is research on this topic done?

- Quantitative studies are most common, though focus groups and other qualitative studies may provide useful insights.
- Safety studies often link crash data to characteristics of the location of the crash. However, crash data often do not include detailed demographic data. Therefore, this research sometimes relies on demographic data for the neighborhood where the crash occurred, particularly when considering income. Safety studies also suffer from the lack of exposure data, particularly by demographic group.
- Quantitative studies of bicycling by demographic groups are often limited by sample size. Because cycling is not common, even large-scale surveys may not include enough people who bicycle regularly to examine differences by characteristics such as race.
- Few studies used longitudinal multilevel models to uncover additional relationships between income, injuries, location, and investment in improvements (Rebentisch et al., 2019).
- Scholars have noted that many people of color and lower-income people who cycle may not be captured through traditional data sources, such as the Census, which exclusively tracks commuting, and travel surveys (Brown & Sinclair, 2017; Lubitow et al., 2019).
- The lack of comprehensive bicycle infrastructure data makes it difficult to generate measures of accessibility for active transportation modes (Lee et al., 2017).

Current research

Sponsor	Project Information	Status
National Institute for Transportation and Communities (UTC) https://rip.trb.org/View/1724591	**Mobility for the People: Evaluating Equity Requirements in Shared Mobility Programs** This project will answer the following four research questions: 1) What cities incorporate equity requirements into shared mobility agreements or partnerships and how are they monitored? 2) How can we systematically evaluate success of equity programs across modes and cities? 3) How effective are equity requirements at increasing shared mobility adoption among target populations? And 4) how do equity programs and program efficacy vary by mode? Using project findings, the research team will develop guidelines that practitioners can use to enact strong equity programs to promote greater shared mobility adoption among groups often excluded in transportation planning.	Expected completion date: 12/1/21

Sponsor	Project Information	Status
California DOT https://rip.trb.org/View/1652757	**Dock-based and Dockless Bikesharing Systems: Analysis of Equitable Access for Disadvantaged Communities** This project aims to contribute to the knowledge about how dockless systems can help relieve barriers for disadvantaged populations. This project will use San Francisco as a case study to analyze the spatial distribution of bike share trips and trip usages for dock-based and dockless bike share systems, and the team will quantify the service level (e.g., bike share usage and bike distribution areas) for disadvantaged populations. Comparing the differences in service levels between the systems, the team will study if dockless systems are able to address equity issues. The results will also provide policy insights to local municipalities on how to properly regulate these systems in order to improve equity access.	Expected completion date: 6/30/21
Center for Advanced Multimodal Mobility Solutions and Education (UTC) https://rip.trb.org/view/1669763	**Quantification of Societal Bicycle Impacts (Phase III)** The objective of this project is to contribute to estimated impacts of bicycle facilities on environmental justice. A direct estimation method as well as a two-step estimation procedure are developed to estimate usage of a proposed bicycle facility. The use of zonal socioeconomic characteristics as predictor variables is intended to enable the models to predict bicycle facility usage by population segments. Usage predictions can form the basis for broad spectrum estimates of bicycle facility impacts upon health, food availability, employment access and, ultimately, regional sustainability.	Expected completion date: 09/30/21
Center for Safety Equity in Transportation (UTC) https://rip.trb.org/View/1544255	**Barriers and Opportunities for Using Rail-Trails for Safe Travel in Rural, Isolated, and Tribal Communities** This project aims to create a context-sensitive solution with a cultural safety assessment that would understand the barriers and opportunities for travel in rural, isolated, and tribal communities. As part of the project the team will answer questions such as: Does this trail best serve the transportation needs of the local population? Are there potential safety concerns at certain intersections or highway crossings that prevent wider use? Is the trail alignment matched with the daily commute of residents and of those with more utilitarian travel patterns? Are there physical or policy barriers that restrict snowmobile and ATV travel? Are there new or potential technologies, such as e-bikes, that might make the trails more attractive for long-distance travel between rural and isolated communities?	Expected completion date: 09/30/20

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Most common TRID index terms	
Bicycling	Walking
Cyclists	Accessibility
Equity (justice)	Infrastructure
Demographics	Gender
Bicycle crashes	Low-income groups
Bicycle facilities	Females

Equity and pedestrian travel

Everyone is a pedestrian at one time or another. However, evidence shows some populations are more dependent on walking for transportation, have worse facilities on which to do it, and suffer disproportionately from pedestrian injuries and fatalities. These "underserved populations" are often Black, Indigenous, and people of color (BIPOC) and/or lower income – populations that often suffer from greater health disparities.

Related review topics

- For research related to the impact of fear of harassment and violence on active transportation, see *Equity and personal safety*.
- For findings on the topic of underserved populations and bicycling as a mode, see *Equity and bicycling*.
- Research on pedestrian and bicycle safety and crash data is covered in *Bicycle and pedestrian data: Safety*.
- For more detailed information on pedestrian safety at street crossings, see *Pedestrian crossings: Design and safety*.
- For research on pedestrians and bicyclists with disabilities, see *Accessibility for pedestrians and cyclists with disabilities*.

What do we know?

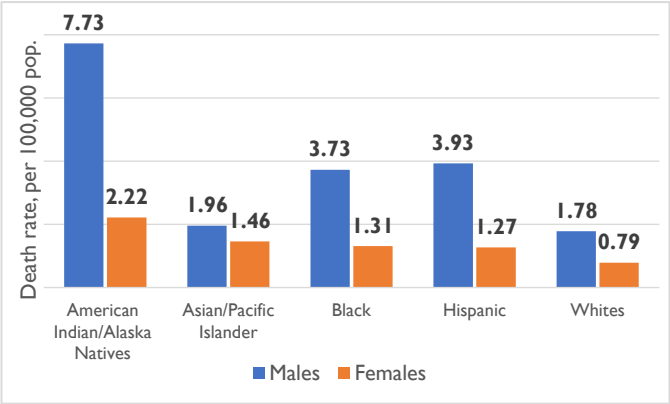
Underserved demographic groups, including BIPOC and low-income people, are more likely to rely on walking for commuting and other purposes.

- Data from the 2017 National Household Travel Survey (NHTS) shows that people in the lowest-income group and people of color (any group other than non-Hispanic whites) were most likely to walk at least 10 minutes a day. Walking rates are about the same for both genders. After controlling for car ownership, density, education, age and gender, non-Hispanic white adults were about 20% more likely to walk 10 minutes daily (Buehler et al., 2020). This likely indicates that non-Hispanic white adults are more likely to walk by choice, rather than necessity.
- A literature review looking at the relationship between the built environment and walking across different socioeconomic contexts noted that low-income people walk more than high-income people, on average, in unsupportive built environments, but, while both groups had higher levels of walking in a supportive built environment, advantaged groups increased their walking much more than disadvantaged groups (Adkins et al., 2017). This illustrates that, for disadvantaged groups, walking is more of a non-choice or captive mode, while for advantaged groups walking is more of a choice mode.
- People who are low-income, BIPOC and/or immigrant are more likely to have non-standard working hours, and thus have to commute at times that may not have good transit service and may be outside of daylight hours (Sandt et al., 2016).
- A study in Austin, Texas, found that poverty rate and percentage of Hispanic population were the strongest factors in determining commuting by walking (Yu, 2014).

Underserved populations, including those who are BIPOC and/or with lower incomes, are more likely to be involved in pedestrian crashes and have more severe injuries.

- Numerous studies have found an inverse relationship between socioeconomic status and injury and fatality risk, and that the risk to children in particular is much higher for those with lower socioeconomic status, ranging from twice as high to up to seven times higher as for children of higher socioeconomic status (Stoker et al., 2015). Research consistently finds that lower-income areas correlate with increases in pedestrian crashes (Chakravarthy et al., 2010; Guerra et al., 2019; Jermprapai & Srinivasan, 2014; Maciag, 2014; Wier et al., 2009).

- Across the U.S., Black or African American pedestrians and American Indian and Alaska Native pedestrians are more likely to be struck and killed while walking, than the overall U.S. rate (Zaccaro et al., 2019). From 2001-2010, the death rates of pedestrians from traffic fatalities by race and gender is shown in the figure. These disparities are similar to those calculated for 2015-2019 where the number of American Indian/Alaska Native pedestrians killed per 100,000 population was 30.7. This was followed by Blacks (15.0), Hispanics (9.8), Native Hawaiian/other Pacific Islanders (7.4), whites (7.2) and Asians (4.6) (GHSA, 2021).



Age-adjusted traffic-related pedestrian death rates, 2001-2010. (data from Centers for Disease Control, 2013)

- A national study of outcomes for vehicle-struck pedestrians revealed that, compared to white pedestrians, African Americans had 22% greater odds of mortality while Hispanics had 33% greater odds of mortality (Maybury et al., 2010). A number of studies have found that areas with a higher proportion of BIPOC residents are associated with increases in pedestrian crashes (Abdel-Aty et al., 2013; Apardian & Smirnov, 2020; Cottrill & Thakuriah, 2010; Guerra et al., 2019; Loukaitou-Sideris et al., 2016).

- A number of studies have also found that higher education attainment, on average, is associated with fewer pedestrian crashes (Chakravarthy et al., 2010; Jermprapai & Srinivasan, 2014; Lin et al., 2019).

- A study of pedestrian crashes in Florida found that as the proportion of people who do not speak English well in census block groups increases, pedestrian crashes increase (Jermprapai & Srinivasan, 2014).

- Young children, older adults, and people with disabilities are overrepresented in traffic deaths and traffic injuries (Stoker et al., 2015).

Areas with high shares of lower-income households, people of color, and other underserved populations often have fewer and more dangerous pedestrian facilities (Sandt et al., 2016).

- One national study found that 89% of streets in high-income areas have sidewalks on one or both sides of the street, while only 59% of streets in middle-income areas do and only 49% of streets in low-income areas do. In addition, streets in high-income areas are much more likely to have marked crosswalks (13% of streets), than middle-income (8%) or low-income (7%) areas (Gibbs et al., 2012). Further, 8% of streets in high-income areas have traffic calming features, compared to 4% in middle-income areas and 3% in

low-income areas, and that 75% of streets in high-income areas have street or sidewalk lighting, while only 51-54% of those in middle- and low-income areas have such lighting (Gibbs et al., 2012).

- A 2016 study of street trees in the pedestrian realm in Spokane noted that areas with lower median income and lower home values had lower street tree canopy coverage, which is significant because trees can provide shade in hot months and protection from rain (Brooks et al., 2016).

Racial bias is affecting the pedestrian experience and likely safety.

- A 2015 study of driver yielding behavior in Portland, OR, found that Black male pedestrians waiting to cross at a marked midblock crosswalk "were passed by twice as many cars and experienced wait times that were 32% longer than white pedestrians" (Goddard et al., 2015).
- A study of driver yielding with four crossing participants (one black male, one white male, one black female and one white female) found that "cars yielded more frequently for females (31%) and whites (31%) compared to males (24%) and non-whites (25%)," while more expensive cars were associated with decreased odds of yielding (Coughenour et al., 2020).
- There is evidence that BIPOC people are more likely than white people to be stopped or ticketed by law enforcement for jaywalking (Sanders et al., 2017; Schmitt, 2020).

Children's use of active transportation has declined over several decades. Recent efforts are attempting to reverse that trend.

- From 1969 to 2009, the share of children 14 years and under who walked or biked to school fell from 42%-49% (depending on age group) to 12-13%. Over 90% of those children were walking (McDonald et al., 2011). While the traffic fatality and injury rates of children 14 and under are lower than the population, 17% of those children who were killed in traffic crashes were pedestrians (NHTSA, 2020).
- Much of the research on children and active transportation has focused on travel to and from school. Distance to school is one of the most important factors in whether children walk or bike to school. Based on data from the National Household Travel Survey, children within a mile of school are more likely to use active transportation to school if they live in a home with no vehicle or less than one vehicle per driver, with higher incomes, and in higher density neighborhoods (Kontou et al., 2020). Other research has found that lower income students are more likely to walk or bike to school (Rothman et al., 2018).
- Studies of Safe Routes to Schools (SRTS) programs have examined programming and infrastructure projects designed to encourage more and safer active transportation among children. A review of 27 studies of interventions found that about half were associated with higher rates of active travel to school, with some indication that interventions that included both educational activities and infrastructure improvements were more effective (Larouche et al. 2018).
- Some SRTS project evaluations have had ambiguous safety findings (e.g. Burbidge, 2020), without identifying any change in crash rates around SRTS infrastructure projects. Other studies have identified modestly positive safety findings, including: some locations had crash reductions (Boarnet et al., 2005); locations with steady crash numbers but increasing active transportation trips revealing crash rate reductions (Ornstein et al., 2007); and finding of infrastructure projects associated with crash reductions, but no effect for noninfrastructure SRTS projects (Lizarazo et al., 2020).
- A national-scale analysis suggested that child pedestrian fatalities are more concentrated around parks than around schools or citywide (Ferenchek and Marshall, 2017).

Pedestrian master plans are starting to include equity.

- A scan of 15 pedestrian master plans found that cities are increasingly acknowledging the need to incorporate equity as a consideration, but that few are laying out accountability measures within their plans (Berg and Newmark, 2020).

What are the research gaps?

- Overall, practice would benefit from a better understanding of the effect of transportation infrastructure and the built environment on the walking behavior and safety of BIPOC, lower-income, and other underserved communities, including the intersectionality of different socioeconomic characteristics.
- Multicollinearity, particularly of socioeconomic variables with each other, and socioeconomic variables with land use or transportation variables, makes it difficult to disentangle the precise reason for higher pedestrian crash rates in lower-income and BIPOC neighborhoods (Loukaitou-Sideris et al., 2016).
- "Exposure" vs "risk" needs to be better understood, in particular for understanding how many people are walking and how that relates to risk (Aldred, 2018).
- The role of driver racial bias in pedestrian safety outcomes, including injuries and fatalities, is unknown.
- The role racial bias in traffic enforcement and its impact on BIPOC communities, including their safety and likelihood of walking, is not well documented.
- Underreporting for non-motor vehicle crashes and for specific populations can affect our understanding of pedestrian equity and safety. For example, one study noted that African-American males are less likely to have a reported injury in the California state crash reporting (Wier et al., 2009), while Aldred (2018) notes that pedestrian falls are not included in road injury statistics in some cases.
- The relationship of walking and health disparities should be further explored, including the potential for active transportation to lessen disparities. NCHRP Report 932: A Research Roadmap for Transportation and Public Health, notes that there is a need for further research on the health impacts of transportation giving "growing inequities among different sub-populations" (Sandt et al., 2019).

How is research on this topic done?

- A number of studies have looked at geographic areas, such as Census tracts, as a means of overlaying sociodemographic data, primarily through Census data and crash data (Chakravarthy et al., 2010; Guerra et al., 2019; Jermprapai & Srinivasan, 2014; Maciag, 2014; Wier et al., 2009).
- Studies may compare the overall number of pedestrian crashes, severe crashes and/or fatalities. Few studies take into account pedestrian volumes or exposure, which may partially account for the common finding that higher-density areas are correlated with more pedestrian crashes.
- Most statewide studies we reviewed use multiple years' worth of crash data in order to have a high enough sample size for analysis.

Current research

Sponsor	Project Information	Status
Transportation Consortium of South-Central States (UTC) https://rip.trb.org/View/1717050	**Equitable Complete Streets: Data and Methods for Optimal Design Implementation** This project analyzes different components of Complete Streets design and use with the goal of creating fast, low-cost, and high impact (transportation) changes in our communities.	Expected completion date: August 2021
Upper Great Plain Transportation Institute (UTC) https://rip.trb.org/View/1574752	**Where the Sidewalk Ends: Equity Disparities with Respect to Municipal Maintenance Policy** This research project will conduct a comprehensive spatial analysis of the sidewalk infrastructure of two cities that take on the responsibility of sidewalks, and two that put that responsibility onto the abutting property owners. The research team will first ask whether variation in sidewalk maintenance policy impacts how sidewalks are being supplied and maintained in cities as well as if there are differences in the provision and condition of sidewalks based on income, race, or ethnicity in neighborhoods across these cities. If the team finds disparities, they will then seek to see if these are related to differences in pedestrian safety outcomes.	Expected completion date: July 2022
Oregon DOT SPR 841 https://rip.trb.org/View/1738059	**Understanding Pedestrian Crash Injury and Social Equity Disparities in Oregon** This research will investigate the underlying infrastructure and behavioral conditions in Oregon that are leading to these disparate outcomes.	Expected completion date: 2022

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Most common TRID index terms
Pedestrian safety Pedestrian-vehicle crashes Demographics Pedestrians Low-income groups Behavior

Equity and personal safety

Underserved populations, including women, Black, Indigenous and people of color (BIPOC), and LGBTQ+ people, face distinctive fears in public spaces. Personal safety concerns affect the way in which these groups engage in travel, including walking and bicycling. Researchers have argued that fear for personal safety can contribute to the social exclusion of certain groups, if it precludes their use of public spaces and/or transport services. This situation may be exacerbated in higher-crime neighborhoods that typically have few transportation options (Loukaitou-Sideris, 2014).

Related review topics

- *Equity and bicycling* reviews research on the rates of bicycling and safety among different population groups, as well as barriers to cycling.
- *Equity and pedestrian travel* covers similar topics for pedestrian travel.

What do we know?

There are different categories of personal safety concerns that affect the use of active transportation for different demographic groups.

- Street harassment includes "unwanted or undesired attention in public including verbal comments or catcalling, physical contact such as groping or touching and non-physical contact such as gesturing or leering" (Flores, 2014). Women, people of color, lower-income people, and persons who identify as lesbian, gay, bisexual, or transgender are disproportionately affected by street harassment overall (Stop Street Harassment, 2014).
- Other types of crimes people may fear and experience while walking or cycling include theft (e.g., pickpocketing), assault, sexual assault, and even homicide. Bicyclists may also be concerned about theft of their bicycle. If a crime is motivated (in whole or part) by the offender's bias against certain groups, including race, religion, disability, sexual orientation, ethnicity, gender, or gender identity, the FBI defines that as a hate crime.
- People may also be concerned about safety threats from law enforcement, including local police and immigration enforcement.

There is ample evidence that personal safety concerns disproportionately negatively affect women's likelihood of walking or bicycling, as well as their experiences while doing so.

- The fear of violence has been demonstrated to greatly influence the travel patterns and mobility of women. One of the biggest hurdles to women's mobility remains the anxiety over possible victimization in public spaces, buses and trains. These fears can lead to women avoiding public space altogether. Conversely, men's lack of fear reinforces the notion that public space is their territory (Loukaitou-Sideris, 2014).
- Nationally, 65% of women reported experiencing at least one type of street harassment in their lifetimes vs 25% of men. For women, anger experienced from harassers is often sexualized (Stop Street Harassment, 2014).

- As a result of these fears, women often adjust their behavior, such as by choosing specific routes, changing travel modes, not walking or cycling alone, avoiding certain settings, avoiding travel in the evening, or not wearing certain types of clothing or jewelry (Loukaitou-Sideris, 2014; Lubitow, 2017; Stop Street Harassment, 2014). Some women cyclists have also reported breaking laws to try to evade harassers when otherwise they would not have (Stop Street Harassment, 2014).
- Women living in neighborhoods with high levels of violence tend to avoid cycling for commuting more than men, according to an analysis of 23 in-depth, semi-structured interviews with low-income Latino immigrants in the San Francisco Bay Area (J. M. Barajas, 2020).
- There is evidence that women in poor neighborhoods and women of color often experience higher levels of fear than white women (C. T. Brown & Sinclair, 2017; Loukaitou-Sideris, 2014).
- In at least two qualitative studies, women report that their cycling routinely elicited catcalls and other forms of harassment from men (drivers, pedestrians, and other bicyclists), though some felt safer from street harassment while on their bicycles compared to walking (Lubitow, 2017; Stop Street Harassment, 2014).

Similar concerns affect LGBT and gender nonconforming people.

- In a national study, people who identified as LGBT experienced higher levels of street harassment than people identifying as heterosexual (Stop Street Harassment, 2014).
- The emerging literature that includes transgender and gender nonconforming people shows that they experience high rates of violence and differential access to public space (Loukaitou-Sideris, 2014).
- Interviews with transgender and gender nonconforming public transit users in Portland, OR, found that they routinely experience harassment and discrimination (Lubitow et al., 2020).
- Lesbian women are often more fearful of assault in public spaces (Loukaitou-Sideris, 2014).

Fear of crime and harassment is also more prevalent for BIPOC people.

- Several studies find that BIPOC people are more concerned than whites about being victims of crime while cycling (Blickstein & Brown, 2017; C. Brown, 2016; C. T. Brown & Sinclair, 2017; McNeil et al., 2018). The fear of being robbed and assaulted while bicycling ranked as the number two barrier to bicycling in a study of bicycle access and usage among Blacks and Hispanics in 34 neighborhoods throughout New Jersey (C. Brown, 2016). People of color in Portland reported feeling anxiety in relation to biking in public spaces. As a result, some individuals reported cycling less (Lubitow, 2017).
- Health researchers pointed to the public murder of Ahmaud Arbery (while running in a public street) and other Black men and women as evidence of the role of racism in health disparities in the U.S. (Boyd et al., 2020).
- Undocumented immigrants highlight the fear of committing a traffic infraction out of ignorance as a way of additional, unwanted opportunities for interacting with law enforcement (J. M. Barajas, 2020).

Fears of law enforcement are a problem.

- Some studies have documented that people of color, particularly Black people, are more concerned about the possibility of being stopped by police while cycling (Lubitow, 2017; McNeil et al., 2018).
- Data from several cities indicates that Black people are more likely to be stopped and/or ticketed by police while walking or cycling (J. Barajas, 2020; Roe, 2020; Sanders et al., 2017).
- There are reasons for people of color to be fearful of encounters with police. Some of these stops escalate to violence and even death, such as the case of Dijon Kizzee in Los Angeles in 2020 (Coulon,

2020; Tchekmedyian, 2020). The *Los Angeles Times* identified 16 incidents since 2005 in which bicyclists had been shot by police after being stopped, often for minor violations such as not having working lights or riding on the wrong side of the road. Eleven of those shooting victims died, and all were either Black or Hispanic (Santa Cruz et al., 2020).

- In the national report on street harassment, several people talked about the police as a problem, too, be it for sexual or racial harassment (Stop Street Harassment, 2014).

What are the research gaps?

Overall, this is a relatively under-researched topic, with several gaps to fill.

- Additional research is needed to understand the magnitude of the problem – how much do personal safety fears reduce levels of walking and cycling among certain populations, particularly in BIPOC communities? How does this vary by different geographies (e.g., core urban areas, suburbs, and rural areas)?
- Among the different groups we examined, there is more research on cisgender women. There were fewer studies that examine the role of personal safety and active transportation for different races and ethnicities, sexual orientations, transgender and gender-non-conforming people, and people with disabilities.
- While there is research on design solutions addressing some of these fears (e.g., better street lighting), there is little or no research that evaluated solutions to other problems such as gender- or race-based street harassment.
- Research on these topics needs to address the intersectionality of the problem, including between race, gender identity, sexual orientation, and disability.
- More research is needed on racial biases in traffic enforcement affecting pedestrians and cyclists, including the extent, causes, and effects of the problem.
- Research is needed on immigration status and pedestrian safety, including underreporting of pedestrian crashes, along with crash victims avoiding hospital or other needed care, due to fear of Immigration and Customs Enforcement.

How is research on this topic done?

- There is more research on personal safety and public transit use compared to walking and cycling, though lessons from the transit research can be relevant.
- Most of the research is from urban areas.
- Both quantitative and qualitative approaches have been used and are necessary to understand this issue.
- There is significant underreporting of sexual harassment in public spaces (Loukaitou-Sideris, 2014).

Current research

Sponsor	Project Information	Status
Behavioral Traffic Safety Cooperative Research Program (BTSCRP) BTS-21 https://rip.trb.org/View/1864198	**Equity in Pedestrian and Bicyclist Mobility, Safety, and Health: The Impact of Racial Bias** The objectives of the research are: (1) Provide evidence of the nature and magnitude of racial disparities in policing with respect to pedestrians, bicyclists, and micromobility users, as well as the impact of such disparities on BIPOC communities; (2) Describe steps communities are taking to consider and address the effects of biased enforcement of pedestrian and bicycle related laws, including alternatives to police enforcement; and (3) Develop and apply a framework to evaluate the impacts and equity outcomes of these approaches and establish guidelines and recommendations for mitigating inequities in the enforcement of traffic laws with respect to pedestrians, bicyclists, and micromobility users.	Anticipated 2021-22 project

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Most common TRID index terms
Bicycling Females Bicycle travel

Micromobility, including e-scooters

Shared micromobility, including docked and dockless bike share and shared e-scooters, have become increasingly common in U.S. cities. The Federal Highway Administration defines micromobility as "any small, low-speed, human or electric-powered transportation device, including bicycles, scooters, electric-assist bicycles (e-bikes), electric scooters (e-scooters), and other small, lightweight, wheeled conveyances" (Federal Highway Administration, n.d.). This brief focuses primarily on e-scooters; bike share is covered in a separate research review (see "related review topics" below). Research related to e-scooter safety, technologies, and policies is discussed below. In addition, while most e-scooters used today in the U.S. are from shared fleets, the research on some aspects may be applicable to vehicles owned by individuals.

Related review topics

- Research specific to bike share is covered in the research brief *Bike share*.

What do we know?

Policies regulating e-scooters and other micromobility devices are varied and evolving.

- A 2018 study noted that specific regulations for personal transportation devices, including e-scooters, skateboards and other mobility devices, vary widely and often are subject to regulations for other devices (Fang et al., 2018).
- Regulations about where e-scooter users can ride vary from state to state, with some like California requiring riders to use the street, or if present, a bike lane, while others like Virginia riders can choose a street or a sidewalk (Fang et al., 2018).
- A guide for helping local governments adapt to new mobility technologies noted that cities should develop policies with mode-agnostic definitions of micromobility; regulate bicycles and micromobility jointly; combine infrastructure such as bike lanes to be inclusive of micromobility; and require permits for micromobility system operators (Schlossberg & Brinton, 2020).
- Data sharing is required of some jurisdictions for operating micromobility systems in their right of way, which can help to identify network or service gaps, system and service equity, and improve real-time information delivery (Shaheen & Cohen, 2019).

Studies are starting to reveal findings about why and where e-scooters and micromobility users travel.

- E-scooters and micromobility help reduce car trips. Surveys exploring mode substitution effects from e-scooters vary by geography, but have tended to find a plurality or even slight majority are substituting for walk trips (30% to 60% in most surveys), and around 10% are substituting for bike trips, with around 25% to 40% of trips coming from car trips, and transit accounting for much of the rest (Wang et al., 2021).

E-scooter riders using active transportation infrastructure. (Photo: Jennifer Dill)

- A review of international studies on micromobility found that users want safe, comfortable and connected networks of dedicated and protected lanes (Oeschger et al., 2020).

Some research examines concerns over shared infrastructure and conflicts with other users.

Concerns about parking, and particularly blocking of sidewalk access, have been prominent among cities and planners, though the relative importance of this problem is not clear.

- A study looking at parking practices of e-scooters, bikes, and other vehicles or objects in five cities found that 1.7% of parked e-scooters and 0.3% of parked dockless bikes were noted to be violating parking codes, either by blocking access to a crosswalk, curb ramp or reducing sidewalk access to less than 32 inches. These violation rates were far lower than observed rates of motor vehicles parked in a way that impeded access, at 24.7%, with a disproportionate share of those violations coming from ridehail, taxi and food delivery vehicles (Brown et al., 2020).
- In some places, personal delivery robots are permitted to operate on sidewalks, although the implications for sidewalk access and safety are not clear (Jennings and Figliozzi, 2019).

Vehicle and system technologies, including geofencing, may help to address some concerns.

- There are several technologies that could potentially be deployed to reduce unwanted rider or parking behaviors, including geofencing, which stops the scooter functionality when ridden outside of a pre-determined zone, or through an exclusion zone such as a park, as well as technology to limit speeds in certain zones (Ciarlo et al., 2020).
- Geofencing has been suggested as an option to limit micromobility devices, particularly shared e-scooters and e-bikes, from riding on certain roads such as access-controlled highways, limiting travel speeds, and restricting parking locations. Of eight jurisdictions surveyed about geofencing in California, Colorado and Texas, all either had experience using or requiring geofencing from vendors, with most using the technology to limit speeds or manage allowable parking locations. About half of the respondents noted some issues with geofencing, primarily around the device not identifying the restricted locations quickly (Caltrans Division of Research, Innovation and System Information, 2020).
- A study of micromobility vehicle speeds found that e-scooters and traditional bicycles travelled at similar average speeds (11.76 mph to 10.55 mph), while electric skateboards averaged 14.93 and skateboards averaged 8.19 (Bell et al., 2020).

There is some evidence related to safety and health and e-scooters.

Helmet usage has been low among e-scooter users.

- A survey of e-scooter riders in Portland in 2019 found that helmet usage was higher for Portlanders, with 20% always wearing a helmet and 10% sometimes wearing a helmet, than for visitors to the city, of whom 9% indicated they always wore a helmet and 6% sometimes (Ciarlo et al., 2020).
- Researchers note that, even with helmet requirements and programs to distribute free helmets to users, e-scooter riders are rarely wearing helmets. They note that e-scooter sharing innovation has surged ahead of policies that could keep riders safe, and urge legislation to keep riders safe (Choron & Sakran, 2019).

Although there are few reported fatalities, there is concern over injuries associated with e-scooters.

- A report from the City of Portland notes that e-scooter riders experienced zero fatalities in over 1.7 million trips in 2019, and had an injury (hospital presentation) rate of 2.5 injuries per 10,000 trips or 2.3 per 10,000 miles (Ciarlo et al., 2020). A study in Auckland, New Zealand, found an injury rate of 60 per 100,000 trips, with hospital presentation rates of 20 per 100,000 trips (Bekhit et al., 2020). These rates appear to be considerably higher than bike share injury rates – about 50 times higher than hospital presentation rates calculated for Capital Bikeshare and Bay Area Bike Share in one study (Martin et al., 2016), and 500 times higher than rates calculated in a study of bike share in Paris and London (Fishman & Schepers, 2018).
- A study in southern California found that, of people presented to two southern California hospitals for injuries related to standing electric scooters over a one-year period in 2017-2018, 94% were treated and released, while 6% were admitted, and less than 1% were admitted to the intensive care unit. Among the frequent types of injury were fractures (32% of those presenting at the hospital), head injury (40%), other injuries (28%) such as contusions, sprains or lacerations (Trivedi et al., 2019).
- A study of patients presented to two southern California hospitals over a one-year period in 2017-2018 found that 21 of 249 patients were non-riders (Trivedi et al., 2019).

What are the research gaps?

As evidenced by the large number of ongoing research projects (see "Current Research" below), there is a lot of research taking place in this area. Gaps in the research include:

- We do not have a clear understanding of the extent of conflicts and safety impacts on shared infrastructure, including sidewalks, bike lanes, and multiuse trails. This includes parking obstructions and interactions between moving vehicles and pedestrians, particularly people with disabilities. Research is also needed on the effectiveness of various strategies to reduce such conflicts, including infrastructure design and user education.
- More research is needed on the social impacts of micromobility's integration with transit, including the potential for private vehicle reduction, improved mobility and more (Oeschger et al., 2020).
- Understanding of the applicability and efficacy of geofencing technologies, including on the device and on user smartphones, for improving rider safety and achieving local goals relating to usage and parking (Caltrans Division of Research, Innovation and System Information, 2020).
- More information is needed on safe (i.e., non-abrupt) slowing for geofencing applications (Ciarlo et al., 2020).
- Better data collection is needed related to e-scooter rider safety, including which programs and policies can help reduce injury, along with the need for a medical code specific to e-scooter riders (Choron & Sakran, 2019).
- Would behavior be different if users owned the vehicles vs renting from a shared fleet? We found limited literature focused on the role of the sharing model in some of the potential negative findings related to safety and pedestrian access (e.g., helmet use, sidewalk parking, etc.).
- We found limited literature on other powered micromobility modes such as electric skateboards, Segway-type devices, hoverboards, onewheels and more.

How is research on this topic done?

- Some studies used inventory-like street analyses of behavior and activity, such as noting micromobility parking locations and rider locations (Brown et al., 2020).
- Studies on safety included reviews of hospital presentation and admission data (Bekhit et al., 2020) to understand prevalence, severity and cost of micromobility crashes.
- Cities may require vendors to provide information on vehicle usage, such as the City of Portland requiring vendors to provide information on each e-scooter trip and distance (Ciarlo et al., 2020).
- Trips seeking to assess mode shift and trip-chaining, for example to identify the extent to which micromobility is being used as a first- or last-mile connector to transit, have tended to rely on surveys of users, along with GPS-enabled micromobility devices to see if trips start or end adjacent to transit stops (Oeschger et al., 2020).

Current research

Sponsor	Project Information	Status
Behavioral Traffic Safety Cooperative Research Program (BTSCRP) BTS-10 https://rip.trb.org/View/1632551	**E-Scooter Safety: Issues and Solutions** The objective of this research is to identify emerging behavioral safety issues arising from the expanding use of e-scooters, both rental and privately owned, and develop comprehensive guidance to help affected agencies plan for and mitigate related safety problems. The guidance should include tools, policy alternatives, educational materials, institutional requirements, and other relevant techniques to mitigate, if not eliminate, identified risks.	Expected completion date: 12/5/22
National Cooperative Highway Research Program (NCHRP) 20-102(29) https://rip.trb.org/View/1657854	**Incorporating New Mobility Options into Transportation Demand Modeling** The objective of this research is to identify the key transportation demand modeling parameters related to traveler use of the new mobility options, review and summarize traveler behavior studies that could inform selection of those parameters (including factors that positively or negatively affect traveler acceptance), and recommend approaches to track and project changes in traveler acceptance of these mobility options.	RFP anticipated in 2021
National Cooperative Highway Research Program (NCHRP) Synthesis 20-05/52-13 https://rip.trb.org/View/1707243	**Shared Micromobility Policies, Permits, and Practices** The objective of this synthesis is to document state department of transportation (DOT) policies, permits, and practices with regard to shared micromobility services.	Active; FY 2021

Sponsor	Project Information	Status
Transit Research Cooperative Program (TCRP) J-11/Task 37 https://rip.trb.org/View/1584713	**Transit and Micro-Mobility (Bikeshare, Scooter-share, etc.)** The proposed research has four key objectives: (1) Identify the impact of micromobility on bus and rail transit ridership; (2) Identify the economic impacts of micromobility for the community and the transit agency; (3) Identify the impacts on the built environment (i.e., bike lanes, parking spaces, etc.) of the implementation of micromobility; (4) Identify ways to strengthen the relations between micromobility and transit to maximize sustainable trip modes.	In progress
Transit Research Cooperative Program (TCRP) B-47 https://rip.trb.org/View/1577715	**Impact of Transformational Technologies on Underserved Populations** The objective of this project is to develop a playbook with guidance on corrective actions with data, methods, and metrics to achieve inclusive mobility.	Expected completion date: 11/4/21
Safety through Disruption (UTC) https://rip.trb.org/View/1722362	**Micromobility Safety Regulation: Municipal Best Practices Review** This project explores what types of regulations municipalities and regions are imposing in an effort to address the safe deployment of these micromobility options.	Expected completion date: 1/31/22
Safety Research Using Simulation (SAFER-SIM) (UTC) https://rip.trb.org/View/1705865	**Driver Behavior in the Presence of E-Scooters within Varying Infrastructure** The objective of this research is to develop a driving simulator experiment where drivers interact with e-scooter riders to investigate how transportation infrastructure and e-scooter riding behavior affect driver behavior. In addition, the research team proposes to assess whether driver attitudes can be associated with certain driving behaviors.	Expected completion date: 8/31/21
Mobility21 (UTC) https://rip.trb.org/View/1705657	**Analysis of the Potential for Micromobility to Replace Short Car Trips in Urban Areas, And Impacts on Congestion** The purpose of this research is to estimate the number of short-distance POV trips that could be replaced by micromobility options and the resulting environmental benefits, and to develop policy recommendations that could assist policymakers in better understanding where the greatest opportunities for expanding active transportation exist.	Expected completion date: 6/30/21
National Institute for Transportation and Communities (UTC) https://rip.trb.org/View/1667686	**E-Scooters and Public Health: Understanding the Implications of E-Scooters on Chronic Disease** To investigate the chronic disease implications, this project will use the Integrated Transport and Health Impact Model (ITHIM) to perform the first known analysis of e-scooters on a range of morbidity outcomes.	Expected completion date: 7/1/21
Collaborative Sciences Center for Road Safety (UTC) https://rip.trb.org/View/1649131	**Understanding Micromobility Safety Behavior and Standardizing Safety Metrics for Transportation System Integration** The purpose of this study is to accelerate shared learning around micromobility safety impacts and to fast-track improvements to injury surveillance of emerging modes such as e-scooters and related micromobility devices (e-bikes, electric skateboards, hoverboards, etc.) used on and around city streets, etc.	Expected completion date: 6/30/21

Sponsor	Project Information	Status
Center for Advanced Multimodal Mobility Solutions and Education (UTC) https://rip.trb.org/view/1745725	**Impacts of Speed on Dockless Electric Scooter Crashes** The objective of this project is to characterize the impact of mandatory speed reduction on e-scooter crash frequency and injury severity.	Expected completion date: 9/30/21

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Most common TRID index terms
Bicycles Scooters Vehicle sharing Mobility Sidewalks Shared mobility

Modeling and traffic impact analysis

Bicycle and pedestrian travel demand can be important to understand for assisting at the regional planning level, corridor and subarea level, and facility and project development level (Aoun et al., 2015; Kuzmyak et al., 2014). Four-step travel demand models have traditionally focused on motorized transport. However, using the process to better understand bicycle and pedestrian trips can help to understand development impacts, prioritize projects, plan active travel networks, and plan for active transportation user safety (Ewing et al., 2019). Efforts have sought to better incorporate these modes in travel demand models, often used by metropolitan planning organizations (MPOs), and into trip generation analyses that estimate the impact of new development on traffic and parking. The first part of this brief focuses how active transportation modes are or could be incorporated into travel demand modeling. The second part focuses on traffic impact analyses.

Related review topics

- Active transportation travel data is discussed in the research reviews for *Bicycle and pedestrian data: Emerging user-based data* and *Bicycle and pedestrian data: Location-based counts.*

What do we know?

Incorporating bicycles and pedestrians in travel demand modeling.

Agencies have not been quick to incorporate active transportation modes into models.

- Many MPOs do not even consider active transportation modes, and most studies prior to the mid-2000s did not differentiate between walking and bicycling. Of the 25 randomly selected MPOs in one 2018 study, 15 did not have models to predict the share of walk and/or bike mode trips (Ewing et al., 2019). A larger survey of 72 MPOs and 24 state DOTs found that half the MPOs and a quarter of state DOTs model both bicycle and walking trips, although a third of those combined them as nonmotorized trips (RSG & RAND Corporation, 2019).
- The lack of widely available active transportation travel behavior data, relevant built environment data, and the focus on traffic analysis zone (TAZ)-level modeling has been a barrier preventing many planning organizations from incorporating active transportation modes into regional travel models (Clifton et al., 2016).
- About half of agencies (MPOs and DOTs) that model walk and/or bike trips utilized a trip-based model, while the other half use an activity or tour-based model – the latter is more common in agencies with more modelers on staff (RSG & RAND Corporation, 2019).
- A survey of MPOs and state DOTs found that modeling staff time was the biggest impediment to developing or improving active transportation models (RSG & RAND Corporation, 2019).

There is a growing amount of research on how to better incorporate these modes into models. Some of that research focuses on the analysis unit.

- Clifton et al. (2016) proposed a revised spatial unit approach for analyzing walk trips, called the pedestrian analysis zone (PAZ), which is finer-grained than the commonly used traffic analysis zone (TAZ) level, and first filters out walk trips before processing other trips through the four-step model at the TAZ level. They find the approach "improves travel model sensitivity to pedestrian-relevant factors,

yielding results that are more responsive to socioeconomic changes and policy interventions" (Clifton et al., 2016, p. 120).

- For a home-based trip generation model, one study found a road network buffer to more accurately represent the physical environment around the household than a TAZ or circular buffer (Tian & Ewing, 2017).
- Another study found that for both walking and biking, assessing travel environments in buffers around representative routes between two points provided more information pertinent to mode choice decisions than did measuring areas around the trip ends (Broach, 2016).

Direct-demand models can help estimate pedestrian and bicyclist volume based on commonly available datasets.

- Bicycle and pedestrian volumes should be modeled independently, as different variables will be relevant depending on the mode, location, community and other factors. Walking trips are more likely to be influenced by characteristics near the trip origin, such as presence of sidewalks, while bicycling trips are more likely to be influenced by factors beyond the trip origin (Munira & Sener, 2017).

Other research addresses mode choice and the data sources to help estimate that.

- Broach notes that, in order to model active transportation mode choice, it must first be determined which modes are available, with techniques including "universal choice set (all modes always available), rule of thumb distance thresholds, sample-based time/distance thresholds, and tour-based availability," while bicycle availability should be considered for bike trips (Broach, 2016, p. 21).
- Tian and Ewing (2017) utilize a two-step model (a two-stage hurdle model) to first estimate the likelihood of a household generating walk trips, and then estimating the number of walk trips generated.
- Travel survey data is important to walking and bicycling models for model estimation, which requires robust data to inform explanatory variables and choice variables in a model, and model calibration, which does not need as robust data and may be used to adapt a model to local conditions (RSG & RAND Corporation, 2019). Stated preference surveys are less common as actual active transportation behavior is now easier to observe via GPS data, trip diaries, and smartphone-based data.

Traffic impact analysis and trip generation.

Traffic impact analyses estimate the effects of new development on motor vehicle traffic, with a focus on roadway impacts and congestion. The basis for most of these analyses in the U.S. is the Institute of Transportation Engineers (ITE) *Trip Generation Manual*.

- The *Trip Generation Manual* has historically focused on understanding the private motor vehicle trip activity and has not considered the impact of access to transit, bicycle or pedestrian infrastructure on the expected motor vehicle trip rate (Clifton et al., 2015). Recent updates to the *Manual* have started to address this problem.
- Research has raised questions about the quality and applicability of the data in the *Manual.* One study found that the trip estimates are influenced by the year of the underlying data, with rates declining over time. In addition, the data are not transparent, limiting the user's ability to improve their analysis (Currans & Clifton, 2018).
- The data in the *Manual* does not reflect a wide range of geographies and skews towards suburban locations for many land uses. Clifton et al. (2015) found that, for convenience stores and drinking establishments in Portland, vehicle trips decreased as the setting became more urban in terms of density,

access to transit, bike facilities, and other measures. The rates from those more urban locations were significantly lower than the *Manual*.

- A literature review of multimodal trip generation studies found that data collection methods range from manual vehicle counts and automatic vehicles counts, both of which need to be combined with other methods to get at multimodal (non-vehicle) trips; person counts, which may need to be combined with an intercept survey; intercept surveys; household travel surveys; and workplace or school surveys (De Gruyter, 2019).
- Of 153 studies estimating trip generation, 97% estimated vehicle trips, while only 42% estimated transit trips, 37% estimated walk trips, and 35% estimated bike trips, although studies including multimodal trip estimates have increased since 2008 (De Gruyter, 2019).

What are the research gaps?

Data Gaps

- More detailed travel behavior data (e.g., from surveys) and built environment data is perceived as a key barrier to including walking in travel models, while finer-scale forecasting of these variables would help make the models more applicable for understanding future scenarios (Clifton et al., 2016; De Gruyter, 2019).
- One study found that, while attitudes and perceptions of walking and biking can be particularly important to active transportation travel decision-making, there is limited data available and collecting it (e.g., through surveys) is challenging (RSG & RAND Corporation, 2019).
- There needs to be further work to guide the expansion of fine-grained spatial scale analysis into more four-step modeling applications, as well as incorporating the approach into activity-based models (Clifton et al., 2016).

Methods and process gaps

- Further research is needed to refine the ITE *Trip Generation Manual* to consider the impact of walking and bicycling trips in urban contexts (Clifton et al., 2015).
- More data collection standardization and cross-jurisdictional assessments of multimodal trip generation and relevant factors is needed to understand the impact of built environment and other factors on walk and bike trip generation (De Gruyter, 2019).
- While we observed a number of studies on active transportation mode choice modeling, there is more limited research on active transportation route choice modeling, particularly for pedestrians.
- A review of modeling practice found that many techniques employed by researchers are challenging for agency modelers to employ outside the laboratory (RSG & RAND Corporation, 2019). This reveals a need for new research or a technology transfer effort to make the research more accessible to practice.

The Evaluation of Walk and Bicycle Demand Modeling Practice report produced as part of NCHRP 08-36 (RSG & RAND Corporation, 2019) noted the following recommendations for future research:

- Data standards and transferable data and data tools.
- The transferability of walk and bike behavior and models across regions.
- Use of passive “big data” to better impute and expand walk and bike trips.

- The separate effects of aging and generational change (age cohorts) on the propensity of walking and biking.
- Methods to better incorporate latent attitudinal variables.
- A new competing mode: transferability of the methods to shared electric scooters.
- The role of state DOTs in advancing the state of the practice.

How is research on this topic done?

- Direct-demand modeling (DDM) is also sometimes used to forecast travel. The approach seeks to use a one-step equation to estimate a trip based on inputs such as sociodemographic variables, travel times, cost and mode availability (Tian & Ewing, 2017). These might include regressions models to estimate aggregate bicycle or pedestrian demand based on known volume data and attributes such as population or employment density, land use and transportation characteristics (Aoun et al., 2015). Regional travel demand models are more sophisticated models, as described below.
- Nested logit and multinomial logit models are the two most common model forms to predict active transportation trips, which is consistent with mode choice modelling in general (Ewing et al., 2019; Singleton & Clifton, 2013).
- Broach notes that, of seven studies that considered nested logit approaches for mode choice determinations, three rejected that approach for a multinomial logit model, suggesting that "bike and walk modes are not necessarily closer substitutes for one another than for motorized modes" (Broach, 2016, p. 23).

Current research

Sponsor	Project Information	Status
National Cooperative Highway Research Program (NCHRP) 20-101(29) https://rip.trb.org/View/1657854	**Incorporating New Mobility Options into Transportation Demand Modeling** The objective of this research is to identify the key transportation demand modeling parameters related to traveler use of the new mobility options; review and summarize traveler behavior studies that could inform selection of those parameters (including factors that positively or negatively affect traveler acceptance); and recommend approaches to track and project changes in traveler acceptance of these mobility options.	Anticipated RFP in 2021
Maryland DOT https://rip.trb.org/View/1715600	**Evaluating the Effect of Complete Streets on Mode Choice, A Case Study in Baltimore-Washington Area** With the increased attention on pedestrian and bicycle safety, this information is needed for the Travel Forecasting and Analysis Division's statewide regional modeling efforts. Tasks: (1) Develop and administer a survey of travelers. 2) Develop a new mode choice model using the Complete Streets concept. (3) Modify the regional model's mode choice model. (4) Investigate the systemwide effect of Complete Streets on the area (5) Investigate the effects on pedestrian and bicyclists, or other short-distance modes.	Expected completion date: 4/30/21

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Most common TRID index terms
Travel demand Bicycling Walking Pedestrians Built environment Nonmotorized transportation Mode choice Metropolitan planning organizations State of the practice

Pedestrian crossings: Design and safety

Whether to access transit, to complete a commute trip, to access shops, or to take a leisure walk, pedestrians need safe ways to cross streets. Nationally in recent years, 27% of pedestrian traffic fatalities occurred at intersections, with a higher rate of 32% in urban areas (Sanders et al., 2020). This review covers research relating to pedestrian crossings, including risk factors and considerations, crossing locations and types of crossing elements and facilities.

Related review topics

- Research on pedestrian and bicycle safety and crash data is covered in *Bicycle and pedestrian data: Safety*.
- Research related to pedestrian equity, including safety, is covered in *Equity and pedestrian travel.*

What do we know?

Pedestrian risk is associated with certain roadway and intersection characteristics as well as factors related to pedestrians and their behavior.

Several roadway design features are associated with increased or decreased risk, as well as perceptions of safety.

- A literature review found that roadway characteristics associated with increased or more severe pedestrian crash risk include wider roadways, more lanes to cross, presence of bus stops, undivided crossings, and arterials (Ryus et al., 2021b; Stoker et al., 2015). Roadway characteristics associated with decreased risk include the presence of median refuges, marked crosswalks, and sidewalks (Ryus et al., 2021b).
- The vast majority of pedestrian fatalities occur in the roadway (90%), and on streets with speeds of 35 mph or more (70%) (Schneider, 2020). Over time, the percentage of pedestrian fatalities occurring in crosswalks has increased from 7.9% in the five-year period ending 1981 to 10.5% in the five-year period ending 2016 (Schneider, 2020).
- Pedestrian satisfaction with roadway environments is more tied to attributes perceived as impacting safety, such as road width, volume, speed, and lighting than factors impacting comfort or convenience (Ryus et al., 2021b).
- Higher traffic volumes are associated with more frequent pedestrian-involved crashes while higher speeds are associated with more severe pedestrian injuries and fatalities (Stoker et al., 2015).
- Certain intersection characteristics are associated with increased pedestrian crash risk, including longer cycle lengths, number of lanes being crossed, lack of traffic controls, curves or grades on approach, and turn lanes (Ryus et al., 2021b).

Transit crossings, including crossings to get to and from transit, are a pedestrian safety concern.

- Transit stops and corridors are associated with increased pedestrian risk, including from pedestrians rushing to cross streets to board a transit vehicle, or due to higher pedestrian activity along busy corridors (Craig et al., 2019; McNeil et al., 2017).

- *TRCP Reports 175: Guidebook on Pedestrian Crossings of Public Transit Services* notes a number of factors that influence pedestrian safety at rail crossings, including the fact that pedestrians can be inattentive, ignore warnings, and will usually seek as direct a path as possible, all of which require designing rail crossings to make safe crossings obvious and easy (Fitzpatrick et al., 2015). The Guidebook outlines 34 pedestrian crossing treatments.
- While crossings should be located near transit stops to help riders access them, nearside bus stops may increase multiple threat risk by obstructing the view of drivers in other lanes (Craig et al., 2019).
- A study in Minneapolis, MN, found that bus stops near unsignalized, marked crosswalks are associated with lower yielding rates (Craig et al., 2019).
- There is less research focused on pedestrian crossings near school bus stops. While school buses are the safest mode of travel to school, there are particular risks to child pedestrians when loading and unloading from drivers of other vehicles (Katz et al., 2021). Research on this topic has examined improving warnings for drivers approaching school bus stops with devices such as activated beacons and message signs (Katz et al., 2017), and enforcement cameras on school buses (Katz et al., 2021).

When pedestrians travel, their characteristics also influence risk.

- Poor visibility, usually associated with nighttime or low-light conditions, is another major risk factor for pedestrian crashes, including two-thirds of pedestrian fatalities occurring under such conditions (Stoker et al., 2015). Twilight may be most dangerous because visibility is low and pedestrian volumes are still quite high (Griswold et al., 2011).
- A literature review of pedestrian safety and risk factors found that people in a number of sociodemographic and risk-profile groups were more likely to be victims of traffic injuries or fatalities, including young children and older adults, people with disabilities, men, low socioeconomic status, and intoxicated or distracted pedestrians (Stoker et al., 2015). A study of children at crosswalks in school zones in Iran found that boys were nearly twice as likely as girls to put themselves at risk by crossing with a small gap in traffic, and girls crossed about 9% more slowly than boys (Mirbaha et al., 2021).
- Pedestrian crossing speeds are an important consideration because they determine how much time it will take to get safely across the street. The recommended speed calculations in the Manual of Uniform Traffic Control Devices (MUTCD) were reduced from 4 feet per second (ft/sec) to 3.5 ft/sec based on studies finding that older pedestrians (over 65) and young people were slower. Most studies have found older adults crossing speeds of between 2.2 and 3.5 ft/sec (Ryus et al., 2021b). One study recommended a speed of 3 ft/sec for older and less-able pedestrians (Fitzpatrick et al., 2006).

Several intersection design features have been found to reduce risk for pedestrians crossing roadways.

Crosswalks, particularly certain designs, have safety benefits.

- High-visibility crosswalks, including continental or “zebra” crosswalks, which are arranged vertically, have been found to increase yielding, increase pedestrians looking for approaching vehicles and reduce pedestrian crashes (McGrane et al., 2013; Ryus et al., 2021b). A 2011 study found that continental markings were detected by motorists at twice the distance from the crosswalk as transverse crosswalk markings, in both daytime and nighttime conditions (Fitzpatrick et al., 2011). They were found to have crash modification factors (CMFs), compared to standard parallel markings, of 0.52 in urban locations and 0.63 in urban school zones (Feldman et al., 2010; Ryus et al., 2021a).

- A 2013 review of high-visibility crosswalks concluded that "because high-visibility markings are more easily detected by motorists and have been shown to lead to a reduction in pedestrian-vehicle collisions when compared to transverse line crosswalks, transportation agencies should install high-visibility markings at uncontrolled crossing locations whenever a determination is made to provide marked crosswalks" (McGrane et al., 2013).

Other intersection design features that increase visibility and reduce crossing distance also have safety benefits.

- Curb extensions shorten the crossing distance and enhance visibility and have been associated with motorist speed reductions (Ryus et al., 2021a), decreased crash severity, and increased driver yielding (Mead et al., 2014; Ryus et al., 2021b).
- Curb radius reductions can be used to slow motorist turning speeds, which can increase yielding. Mountable truck aprons can achieve effective curb radius reductions while accommodating larger vehicles (Sanders et al., 2020).
- Median refuges have been commonly found to lower pedestrian crash rates, increase yielding, and reduce vehicle speeds. Raised medians have been found to have similar impacts (Mead et al., 2014; Ryus et al., 2020b). Several studies looking at the impact of refuge islands have found CMFs of between 0.54 and 0.68 for pedestrians (Ryus et al., 2021b; C. Zegeer et al., 2017).
- A number of studies have found that signage instructing motorists to yield, stop, not turn on red, etc. are associated with increasing driver yielding and compliance as well as higher likelihood that pedestrians will choose to cross at a treated location (Ryus et al., 2021b).
- Removal of parking near intersections increased visibility, and studies have found that the measure can reduce pedestrian crashes by 30% (Ryus et al., 2021b).
- Several studies have found that overhead lighting placed at crosswalk locations can increase yielding and visibility (Mead et al., 2014).

A crossing in Santa Monica, CA, combined a curb extension and median refuge to shorten the crossing distance (Photo: Nathan McNeil)

The safety benefits of some design features are specific to signalized, unsignalized, or midblock crossings.

At signalized intersections, signal features, including timing and phasing, can improve safety.

- A comprehensive review of existing research found that signal phasing and timing factors have been shown to reduce pedestrian crash risk, including providing an all-red clearance interval, providing an exclusive pedestrian scramble phase (which may reduce pedestrian compliance), and providing a leading pedestrian interval. Pedestrian push buttons, automated pedestrian detection, and pedestrian countdown timers are associated with reductions in pedestrian crashes and/or pedestrian-vehicle conflicts (Ryus et al., 2021b).

- A number of studies have found that leading pedestrian intervals are an effective countermeasure and have been found to reduce conflicts with turning vehicles, as well as reducing pedestrian collisions and severity (Mead et al., 2014).
- A study of four signal-related pedestrian countermeasures in New York City (increasing cycle length, Barnes Dance, split phase timing and adding a signal) found that each tested approach can provide benefits (and drawbacks) under specific circumstances, and that facility selection needs to be catered to the context and objective (Chen et al., 2014).
- Research found that countermeasures in New York City that separate out pedestrian movements were associated with reduced pedestrian crashes, including split phase timing, all pedestrian phases, adding signals and increasing pedestrian crossing time, compared to features such as high-visibility crosswalks and speed reduction signs, which had less of a safety impact (Chen et al., 2013).
- Although exclusive phasing for pedestrians may be perceived as safer for pedestrians, a 2017 study found compliance to be higher at locations with concurrent phasing than at locations with exclusive phasing (Ivan et al., 2017), which may be related to pedestrians being more likely to cross without the walk signal if they have to wait longer (Sanders et al., 2020).
- A study exploring the relative benefits, in terms of pedestrian delay and vehicle operational efficiency, of recall vs push button actuation for pedestrian signals found that actuation should be on recall if the probability of a pedestrian at a given cycle is 0.6 or greater, or if the pedestrian volume per cycle is over 0.9 (Cesme et al., 2021).

At unsignalized intersections, the safety effects of crosswalks depend on the context, while other countermeasures may also improve safety.

- A number of studies published between 1972 and 2000 found that pedestrian crashes were higher in marked than unmarked crosswalks; however, these studies generally did not consider pedestrian or motor vehicle volumes or other factors, such as the number of lanes and presence of medians (Mead et al., 2014).
- A newer study of 2,000 unsignalized intersections showed that at lower volumes, marked crossings did not affect pedestrian crash risk. However, at volumes greater than 12,000 (without a raised median) or 15,000 (with a raised median), a marked crosswalk, absent other improvements, actually increased pedestrian crash risk significantly (C. V. Zegeer et al., 2001). This may be due to older adults being more likely to choose marked crosswalks, as well as to the multiple threat concern of vehicles in lanes beyond the nearest lane to the curb not yielding (Mead et al., 2014; C. V. Zegeer et al., 2001).
- Other research helps explain the mixed findings about marked crosswalks at unsignalized intersections. One study found that pedestrians may be more aggressive in marked crosswalks, starting to cross on shorter gaps than in unmarked crosswalks (Mitman et al., 2008). Marked crosswalks have been connected to reduced vehicle speeds and increased pedestrian volumes (Knoblauch et al., 2001), and increased yielding (Mitman et al., 2008).
- Raised crosswalks or speed tables, often used in two-lane commercial areas, have been found to reduce vehicle speeds (Mead et al., 2014) have a CMF of 0.55 (Ryus et al., 2021a).

A pedestrian-activated rectangular rapid flash beacon at a marked crosswalk. (Photo: Jennifer Dill)

- In roadway "yield to pedestrian" signs requiring drivers to navigate a narrow lane in between as a gateway treatment have been found to increase motorist yielding and may reduce motorist speeds (Ryus et al., 2021a).
- Pedestrian-activated flashing yellow beacons are associated with modest increases in motorist yielding, although the impact on pedestrian-motorist conflicts likely varies by site and implementation factors (Mead et al., 2014).

Midblock crossings, including where trails cross, merit special consideration to make motorists aware of the possibility of pedestrian crossings.

- Pedestrian-activated yellow flashing beacons, usually in combination with high-visibility crossings or advance yield markings, have been found to increase driver yielding rates (Ryus et al., 2021b).
- Rapid rectangular flashing beacons (RRFBs) have been found to increase driver yielding, reduce pedestrian crashes and reduce instances of trapped pedestrians (Fitzpatrick et al., 2011; Ryus et al., 2021b), including being significantly more effective than traditional overhead or side-mounted yellow flashing beacons (Fitzpatrick et al., 2011). They have CMFs of between 0.53 and 0.64 (Monsere et al., 2016; Ryus et al., 2021a; C. Zegeer et al., 2017).
- Pedestrian hybrid beacons are associated with increased yielding and decreased crashes and pedestrian crashes pedestrians (Fitzpatrick et al., 2011; Ryus et al., 2021b), and a CMF of .453 according to one study (C. Zegeer et al., 2017). They have been found to be effective at promoting high yielding rates, even on higher-speed roads of up to 45 or 50 mph (Fitzpatrick et al., 2020).
- Advanced stop markings or signs, often combined with other crossing infrastructure, are found to reduce pedestrian crashes, with one study finding a CMF of .075 (C. Zegeer et al., 2017).
- A 2016 study of pedestrian crossing enhancements at 191 midblock locations in Oregon (most commonly continental crosswalk markings, median islands, curb bulb-outs, flashing beacons, and advanced stop bars), found that pedestrian crash severity was reduced after treatments were added (Monsere et al., 2016).
- At-grade trail crossings are usually either midblock or parallel path crossings (with conflict points shortly after a vehicle turns), and since pedestrians often use multiuse paths, ensuring the safe crossings for pedestrians at these locations is essential. Absent adequate accommodation, trail crossings can present trail users with complex tasks including gap selection, scanning for turning vehicles, considering other trail users, and more (Noyce et al., 2013).

Pedestrian and driver awareness and education campaigns may help improve compliance.

- A study of a "Street Smart" campaign in select New Jersey towns and cities found that driver and pedestrian compliance improved, particularly at busy urban intersections, after a pedestrian safety campaign emphasizing the need for motorists to comply with yielding to pedestrian laws, and for pedestrians to cross with a signal (Jalayer et al., 2021).

What are the research gaps?

- Pedestrian crossing facilities without CMFs for pedestrians include active warning beacons, crossing barriers (restricting crossing at unmarked locations), curb extensions, curb radius reductions, gateway treatments or in-street pedestrian crossing signs, mini traffic circles or roundabouts (Blackburn et al., 2017; Sanders et al., 2020).

- Limited pedestrian exposure data (i.e., volume counts) makes understanding the impacts of crossing improvements and interpreting CMFs challenging (C. Zegeer et al., 2017).
- Most of the crossing elements discussed here are used in combination with other elements (e.g., an RRFB with advanced stop markings or a median island). Therefore, understanding the individual and combined effects of each element is challenging, including how to interpret CMFs when combining elements (C. Zegeer et al., 2017).
- Many CMFs are developed at single locations, or comparable geographies (e.g., within one city or region), and thus the application of the CMF to other contexts and locations is a question (C. Zegeer et al., 2017).
- Research suggests that driver yielding near bus stops may be lower than at other locations, although the reasons for this effect are unclear and warrant further research (Craig et al., 2019).
- For rail-adjacent trails, crossings may include traversing railroad tracks and busy roads at complex intersections, and there is limited guidance for bicycle and pedestrian treatment selection, particularly for paths running next to a railroad (Alligood et al., 2018).
- There are not consistent pedestrian infrastructure data collection processes across agencies or states (Louch et al., 2020).
- There is limited research focusing on the unique contexts of crossings near school bus stops.

How is research on this topic done?

Common research methods used when assessing pedestrian crossings include:

- Pedestrian crashes, injuries and fatalities are identified through police crash records, and may be combined with hospital records for crash and injury analysis, although underreporting is a known issue.
- Before-and-after analyses of driver yielding and crossing behavior is generally collected via observation, including video collection.
- Treatment sites may be compared to sites with no treatment, such as marked vs unmarked locations.
- Exposure data for pedestrian and motor vehicles is important to understand risk. Pedestrian exposures data can come from observations including automated and manual counters, nearby land use and transit data, push button data, or emerging sources such as passive smartphone app data (Sanders et al., 2020).

Current research

Sponsor	Project Information	Status
National Cooperative Highway Research Program (NCHRP) 03-141 https://rip.trb.org/View/1707196	**Midblock Pedestrian Signal Warrants and Operation** The objectives of this research are to (1) document the benefits of the Midblock Pedestrian Signal (MPS) and develop language for a new section of the MUTCD (including definitions for the MPS, warrants, and operations guidance, including at driveways and minor side streets).	Selection and award pending

Sponsor	Project Information	Status
National Cooperative Highway Research Program (NCHRP) 17-97 https://rip.trb.org/View/1707227	**Strategies to Improve Pedestrian Safety at Night** The objective of this research is to identify and evaluate strategies for improving pedestrian safety in the dark.	Selection and award pending
National Cooperative Highway Research Program (NCHRP) 08-149 https://rip.trb.org/View/1842753	**Impacts of Active Transportation Network Gaps** The objective of this research is to understand the causes and impacts of gaps in the urban and rural active transportation network, efforts and barriers in reducing gaps, and designs and/or policies that have been used to address the difference between various active transportation users.	Anticipated start: 2021
Illinois DOT https://rip.trb.org/View/1706845	**Railroad-Highway Crossing (RHC) Safety Improvement Evaluation and Prioritization Tool** Safety performance ranking and prioritization of railroad-highway crossings (RHC) are primarily determined using a United States Department of Transportation (DOT) model to estimate "final accident prediction" at the crossing. The goal is to obtain pedestrian safety prediction factor values and circuitry upgrade prediction factor values that can be used in a modified FRA or Illinois model.	Expected completion 2023
Indiana DOT https://rip.trb.org/View/1646231	**SPR-4437: Effective Design and Operation of Pedestrian Crossings** The proposed study will identify the conditions when the risk of injury and fatality of pedestrians on road crossings is excessive.	Expected completion date: 2021
Indiana DOT https://rip.trb.org/View/1592141	**SPR-4301: Assessment of an Offset Pedestrian Crossing for Multilane Arterials** This study will investigate an innovative crossing solution that offsets pedestrian and bicycle crossings from the intersection, with the hope that it will potentially improve pedestrian safety (due to fewer potential conflicts with turning vehicles) and vehicle service.	Expected completion date: 2021
Urban Mobility & Equity Center (UTC) https://rip.trb.org/View/1715285	**A Comparative Study of Pedestrian Crossing Behavior and Safety in Baltimore and Washington, D.C., Using Video Surveillance** Using video surveillance of locations in Baltimore, MD, and Washington, D.C., this study compares pedestrian-related travel behavior in the two neighboring cities. Statistical analyses will determine which factors – such as land use, infrastructure, and sociodemographic characteristics – contribute to pedestrian travel behavior decisions and safety.	Expected completion date: 8/31/21

Sponsor	Project Information	Status
Maryland DOT https://rip.trb.org/View/1715285	**Design and Demonstration of Pedestrian Waiting Time Countdown at Pedestrian Activated Signals** There is a need to conduct a study that evaluates the effects of a proposed countermeasure (i.e., wait-time countdown) on pedestrian compliance, and designs the wait-time countdown strategies to include countdown numbers on the pedestrian signal, voice broadcast at the intersection, and notification on smartphones. The wait-time countdown signal with different operational strategies would be demonstrated for its performance evaluation. The evaluation results could be used to justify the implementation of wait-time countdown at pedestrian-activated signals. This countermeasure is expected to reduce the percentage of pedestrians who do not push the button or start crossing before the "Walk" phase.	Expected completion date: 3/31/21
Center for Advanced Multimodal Mobility Solutions and Education (UTC) https://rip.trb.org/View/1745749	**Estimation of Pedestrian Compliance at Signalized Intersections Considering Demographic and Geographic Factors** The objective of this project is to estimate models to predict pedestrian compliance at traffic signals as a function of traffic, demographic, geospatial and road design factors. The result will be information about how pedestrian signal compliance relates to pedestrian and vehicle traffic counts over a range of land development, demographic, crosswalk and roadway conditions.	Expected completion date: 9/30/21
Center for Advanced Multimodal Mobility Solutions and Education (UTC) https://rip.trb.org/view/1745729	**Optimizing Type and Location of Pedestrian Crossing Signs at Non-signalized Intersections** The objective of this project is to identify optimal locations for signage at unsignalized pedestrian crossing locations, as well as optimal signage configurations.	Expected completion date: 9/30/21
DC DOT https://rip.trb.org/View/1745985	**Pedestrian and Cyclist Intersection Safety Sandbox** The District Department of Transportation (DDOT) intends to implement one or more pilot or demonstration projects that use emerging technology solutions to improve pedestrian and/or cyclist safety in intersections. This project will designate a “sandbox” of a single intersection or corridor within the District to be used to safely pilot new technologies and evaluate the outcomes.	Start date: 6/28/22
National Institute for Transportation & Communities (UTC) https://rip.trb.org/View/1724535	**Pedestrian Behavior Study to Advance Pedestrian Safety in Smart Transportation Systems using Innovative LIDAR Sensors** The aim of this research is to investigate the pedestrian behavior at signalized intersections using the state-of-the-art LIDAR sensing technologies, and to use this data along with vehicular data to develop a more effective multimodal signal control system.	Expected completion date: 11/30/21

Sponsor	Project Information	Status
North Carolina DOT https://rip.trb.org/View/1723542	**Yielding Compliance at High Visibility Crosswalks** This project seeks to first, verify that HVCs are more effective at inducing driver yielding than other legal crosswalks (unmarked or marked with transverse parallel lines). Second, assuming that they are found to be equally or more effective for the first measure, to determine if increasing the prevalence of HVCs within a given area negatively impacts their effectiveness at inducing driver yielding.	Expected completion date: 5/31/21

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Most common TRID index terms

Pedestrian safety
Crosswalks
Pedestrian movement
Pedestrian-vehicle crashes
Pedestrian-vehicle interface
Pedestrians
Traffic safety
Best practices
Highway safety
Countermeasures
Before-and-after studies
Pedestrian areas
Visibility

Policy, planning and decision-making

Over the past two decades, the volume of research about active transportation has expanded significantly. We now know a lot more about why people do or do not walk or bicycle, what changes can be made to increase active transportation, and how to make it safer. However, implementation is lagging behind this knowledge; we often know what will work, but we cannot get it done. The barriers are often not technical. This topic reviews research that examines planning and decision-making around active transportation.

Related review topics

- *Modeling and traffic impact analysis* reviews research on analysis methods used to support planning and decision-making, including travel demand modeling and traffic impact analysis.

What do we know?

There is research that helps explain why active transportation infrastructure and policies are (or are not) widely adopted.

A key factor in success is political leadership, often in conjunction with local advocacy.

- A survey of state DOT staff found that pressure from interest groups had a significant impact on the agency's active transportation policy and planning, second only to the efforts of the DOT bicycle and pedestrian coordinator. The next highest rated factors were improved knowledge and training among the engineering staff and management (Dill et al., 2017).
- A case study of Memphis, TN, pointed to the election of a new mayor who was supportive of bicycling and recruited similarly supportive people into local government as a key reason for that city's growth in active transportation infrastructure. Coupled with this was a network of several advocacy groups that grew in size and effectiveness (Smiley et al., 2016).
- Political leadership was also cited as a key factor in a case study of Toronto, Ontario. However, varied levels of support geographically among city elected officials may result in infrastructure being concentrated where existing demand is already higher (Wilson & Mitra, 2020).
- Advocates and non-government organizations can play important roles through protest, filling gaps in government expertise or resources, and at counteracting path dependence within public agencies (McLeod et al., 2020).

Some motivations and political arguments appear to be more effective than others.

- A 2010 survey of state DOTs found that safety was the top motivation behind adopting active transportation policies, plans, and programs, followed by livability and health/physical activity. Climate change was ranked the lowest. Funding was the largest barrier (Dill et al., 2017).
- Reliance on traditional cost-benefit analysis may not capture all the benefits of active transportation (McLeod et al., 2020).
- In Memphis, TN, the political support for infrastructure was tied in part to an argument that it would help support economic development tied to the creative class. One downside of this can be that projects are more likely to benefit well-off parts of the city (Smiley et al., 2016).

- Planning around bicycle infrastructure is often politicized, most commonly in cases where bicycle infrastructure appears to reduce space for cars and trucks (Wilson & Mitra, 2020). This did not appear in the research as a barrier for pedestrian policy and planning. There is some indication of greater support among state DOT engineers for pedestrian projects relative to bicycle projects (Dill et al., 2017).
- There is strong evidence that policies that discourage private vehicle use, such as road or parking pricing, would be very effective at increasing rates of active transportation. However, most places in the U.S. focus on investments that enable more bicycling and walking, such as infrastructure, with much more modest effects. The main reason often cited is lack of political feasibility (Piatkowski et al., 2017).
- A study of road safety measures in the Netherlands found that a hotspot approach to crash safety had dwindling efficacy over time, and that a systems approach that is proactive in designing safe roads, rather than reactive to safety issues, allowed the country to achieve a traffic safety record that is much better than comparable counties, and without fatality disparities between road users in vehicles, on foot or on bike (Shi et al., 2021).

Examples of success often point to taking advantage of timely opportunities and experiments.

- Success in planning for infrastructure often depends on taking advantage of "windows of opportunity," which can be spatial (e.g.. new infrastructure in places that will yield immediate benefits) or process-focused (e.g., requirements for bike lanes on new roadways) (McLeod et al., 2020).
- Interviews with practitioners and advocates from the four communities that were part of the Non-Motorized Transportation Pilot Program (NTPP) found that the influx of funding provided an opportunity to leverage existing, smaller efforts (which were often focused on recreational use) and institutionalize bicycle and pedestrian planning (Piatkowski et al., 2017).
- There are several examples of cities using "experiments" to test out new infrastructure and then building on that success to grow networks (McLeod et al., 2020; Piatkowski et al., 2017).
- Turnover in state DOT management was cited as an important factor in adopting active transportation policies and plans, as well as changing interests of agency commissions or boards (Dill et al., 2017).

Increased learning and training, including exposure to places with high levels of bicycling and walking, can influence policymakers and practitioners.

- In the survey of state DOT staff about factors that influenced the adoption of active transportation policies and plans, the third- and fourth-ranked factors were improved knowledge and training among the engineering staff and management. The amount or type of technical expertise among staff was ranked second (after funding and tied with support from mid-level management) as a barrier to implementing active transportation projects. The survey also indicated that top management might be more supportive than highway engineering staff (Dill et al., 2017).
- Research based on a survey of over 100 participants in study tours about cycling and 15 in-depth interviews concluded that the tours result in learning transfer, a key component to the policy transfer process. Large majorities of the participants indicated that the tour changed the way they work and influenced projects their organization did. Over half said their organization approached mobility differently because of the tour and about 40% said that their organization set new priorities as a result. One key factor in learning outcomes was the involvement of organizational leaders on the tour, particularly managers and elected officials, along with staff. The research found that the tours were particularly effective in conceptual learning that is more abstract or tacit and which can change people's assumptions, increasing commitment among leadership, and developing a shared understanding among organization members (Glaser et al., 2020).

- A case study of the success in Memphis, TN, noted that the mayor took a group of government officials and local partners to the Netherlands to gain a better understanding of the bicycling culture there (Smiley et al., 2016).

Researchers have proposed frameworks that can be useful in understanding how change happens.

- A growing body of research, drawing from other disciplines, examines the policy process and, in particular, alternatives to the "technical-rational model" that dominates transportation. That model includes problem identification, goals and objectives, data collection, alternative generations, analysis, evaluation, decision-making, implementation, and monitoring. Marsden and Reardon (2017) reviewed transportation policy research and suggest alternatives. One is the multiple streams approach, which argues that when three process "streams" – politics, policy and problem – join together in a "window of opportunity" an issue can gain relevance and, hence, policy change. The theory recognizes that solutions are often not implemented due to non-technical reasons. The advocacy coalition framework focuses on the role of groups of actors (individuals and organizations) who share "policy core beliefs" and coordinate their actions to affect policy change. This framework recognizes that the beliefs of the actors influence whether and how evidence is used to influence policy, as well as how it is acted upon. Decision-makers are not neutral consumers of evidence.
- The review of policy research compared "top-down" and "bottom-up" approaches to understand how policy gets implemented. Both provide insights, though bottom-up approaches recognize the dispersed nature of who controls implementation, including lower-level personnel who have discretion and knowledge of the system (Marsden & Reardon, 2017). The 2010 survey of state DOT staff involved in active transportation revealed that lack of support from mid-level management was tied for the second-highest ranked barrier to implementation (after funding and tied with technical expertise among staff) (Dill et al., 2017).
- Several researchers have examined the concept of "policy transfer" – the transfer of policies from one jurisdiction to another. Some of the constraints of such transfer include policy complexity, past policies, and structural institutional feasibility. The latter might include economic, technical, cultural, and bureaucratic barriers. Policy transfer can happen through communities of practice or more active interventions such as policy networks or best practices guides (Marsden & Stead, 2011).
- A review of research on learning processes aimed to understand how learning happens within organizations, which helps build capacity to effect policy change. They identified four important mechanisms: (1) The strength of relationships (both internally and externally) and the ability to build relationships. (2) Communications systems that are both horizontal and vertical, creating "overlapping knowledge" and group learning. (3) Organizational resources, including dedicating staff to learning and research, communicating support for learning among staff, and rewarding learning. (4) Leadership that is collaborative and distributed (Glaser et al., 2019).
- One set of authors developed a "Planning for Cycling Maturity Model" which could be used for assessing where an agency is and where they might focus efforts to move along five stages of maturity, from a stage where cycling is largely marginalized and ignored to one where cycling is the culture and success is self-sustaining (McLeod et al., 2020).

Equity is not always adequately considered in active transportation policy and planning.

- There is a growing amount of research on equity and active transportation. However, the focus has been on evaluating social and spatial equity in terms of active transportation infrastructure distribution. Other

factors such as project funding, access to employment or activities, or facility quality are typically not considered (Lee et al., 2017).

- A study of pedestrian master plans in the U.S. found that only two-thirds of 15 reviewed plans both acknowledge equity as a key value and provided planned actions to address pedestrian inequity, while only 40% of plans included accountability elements such as establishing equity-related goals (Berg & Newmark, 2020).
- A case study from California demonstrated how the Integrated Transport and Health Impacts Model (ITHIM) could be adapted to present health impacts of active transportation on different demographic groups based on race/ethnicity and income (Wu et al., 2019).
- Procedural equity, or whether transportation decision-making is carried out in a fair and consistent manner, including involvement of diverse stakeholders, low-income and BIPOC communities, is also an important consideration (Bullard, 2003; Schweitzer & Valenzuela, 2004).
- A toolkit and score card was developed to help MPOs consistently incorporate equity into planning and project prioritization.

There are several guidance documents to support active transportation planning and policy.

- *Noteworthy Local Policies That Support Safe and Complete Pedestrian and Bicycle Networks* "provides local and state agencies with the tools to create a solid policy platform to support the creation of multimodal transportation networks for users of all ages and abilities." The resource emphasizes the need for defining visions and goals and setting performance measures, and includes 26 case studies (Louch et al., 2016).
- The *Guidebook for Developing Pedestrian and Bicycle Performance Measures* is designed to help jurisdictions "develop performance measures that can fully integrate pedestrian and bicycle planning in ongoing performance management activities" (Semler et al., 2016).
- *Strategies for Accelerating Multimodal Project Delivery* is a workbook with 13 key strategies and supporting case studies. The resource addresses the following common challenges: programming delays and funding source challenges; difficulties competing for limited funding; inadequate internal and external coordination; inadequate community input; design guidelines insensitive to context; lengthy environmental reviews; and insufficient staff capacity or technical knowledge (Raulerson et al., 2018).
- The NCHRP report *Practical Approaches for Involving Traditionally Underserved Populations in Transportation Decision-making* is a resource to help make planning processes more inclusive (Aimen & Morris, 2012).
- The *Guide to Developing a Vision Zero Plan* draws from dozens of examples to describe best practices for developing a Vision Zero plan, including community engagement (LaJeunesse et al., 2020).

What are the research gaps?

- There are few studies that examine policy transfer in transportation, particularly active transportation. Carefully documented case studies of successes and failures in policy adoption and planning for active transportation can help inform current efforts, but these are rare. The frameworks discussed above can help in conducting such case studies. Comparative studies can help the generalizability of the findings.
- The "bottom-up" approach highlights the role of professional staff who can influence implementation. There is little research on how to effectively change the actions of professionals who can help or hinder implementation of active transportation policies. Additional research on learning transfer may help.

- There is limited understanding of whether and how equity is incorporated in active transportation plans. There is one small-scale study of pedestrian plans (Berg & Newmark, 2020). We did not find any similar research on bicycle plans, and no research on the effectiveness of such efforts.
- There is very limited research evaluating the effectiveness of efforts to have more inclusive processes in active transportation planning and policymaking. Overall, procedural equity has not been a focus of much research (Lee et al., 2017). There are likely lessons that may be applied from efforts in other policy realms.

How is research on this topic done?

Research on these topics is often based on case studies and qualitative methods, such as interviews with people involved in planning and policy. Some research uses surveys of practitioners or decision-makers to draw conclusions. Overall, there is less research on these topics, which are often grounded in disciplines such as public administration, political science, business management, human resources development, and organizational theory. Of the research we found, the focus was more likely to be on bicycling, perhaps because of the greater level of conflict over bicycle infrastructure found in some cities. Because of different political and regulatory contexts, our review primarily draws from research conducted in the U.S. or Canada.

Current research

Sponsor	Project Information	Status
National Cooperative Highway Research Program (NCHRP) 15-78 https://rip.trb.org/View/1628620	**Guidebook for Urban and Suburban Roadway Cross-Sectional Reallocation** The objective of this research is to develop a guidebook and decision-making framework for roadway designers, planners, and others for identifying, comparing, evaluating, and justifying context-based, cross-sectional reallocations of existing urban and suburban roadway space for multimodal safety, access, and mobility.	Active
Mountain-Plains Consortium (UTC) https://rip.trb.org/View/1574752	**Where the Sidewalk Ends: Equity Disparities with Respect to Municipal Maintenance Policy** This research project will conduct a comprehensive spatial analysis of the sidewalk infrastructure of two cities that take on the responsibility of sidewalks, and two that put that responsibility onto the abutting property owners.	Expected completion date: 7/31/22
National Cooperative Highway Research Program (NCHRP) Synthesis https://rip.trb.org/View/1707175	**Measuring Investments and Benefits of Active Transportation Investments When Accomplished as Part of Other Roadway Projects** The objective of this synthesis is to document the methods that DOTs are currently using to track and record their investments in active transportation infrastructure when accomplished as part of other roadway projects.	State date: 5/1/20

Research reviews

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Most common TRID index terms
Pedestrians Transportation planning Bicycling Nonmotorized transportation Policy Equity (justice) Cyclists Decision-making Bicycle travel Urban areas Performance measurement

Rural and small urban areas

Rural areas cover around 81% of the U.S. land area, rural roads make up about 60% of all road miles in the U.S., and about 19% of the population lives in rural areas. While some people in rural areas live long distances from shops and services, many small towns are compact with walkable and bikeable distances (Dickman et al., 2016; Nabors et al., 2012). While there is less walking and bicycling occurring in rural and small urban areas than in more urbanized areas, walking and bicycling is still happening in these less dense areas and presents unique safety and planning challenges.

What do we know?

Levels of walking and bicycling

- A study based on 2009 NHTS data found that, when looking at walking and bicycling rates at finer levels than just urban vs rural, rates were not dramatically different in rural communities compared to large cities. Depending on the type of rural areas, "rural Americans walk at a rate between 58 and 80 percent of the overall national rate, depending on what type of community they live in. For biking, the numbers are even higher—between 74 and 104 percent" (Loh et al., 2012, p. 5).
- One study found that, although more biking occurs in urban than rural locations, women and youth have been found to be more likely to bicycle in rural, small and low-density areas than in urban areas (McAndrews et al., 2017).

Crash characteristics

Crash patterns in rural areas differ from urban areas.

- Active transportation crashes in rural areas tend to be dispersed in time and location, which makes spot or location-based countermeasures more limited in efficacy. Due to this dispersed nature, it is more imperative on states to review crash data and identify factors affecting active transportation user safety that can be addressed systematically (Nabors et al., 2012).
- About one-quarter of pedestrian and bicycle fatal crashes occur on rural highways. Pedestrian and bicycle crashes in rural areas are about half as likely to occur at intersections than crashes in urban areas (Federal Highway Administration, 2010). Rural roads are mostly two-lane roads, which are where most rural bicycle and pedestrian crashes occur (Nabors et al., 2012).
- Pedestrian and bicycle crashes in rural areas usually occur on roads without paved shoulders (71% of pedestrian crashes and 80% of bicycle crashes, compared to 18% and 20% in urban areas, respectively) (Federal Highway Administration, 2010).
- Most rural pedestrian crashes occur during the night (and a disproportionate number compared to urban areas), while most rural bicycle crashes occur in daylight (Carter & Council, 2006; Nabors et al., 2012). In contrast, pedestrian crashes in urban areas are more likely to occur in daylight (Federal Highway Administration, 2010).
- Pedestrian crashes in rural areas are disproportionally likely to be a pedestrian walking along the roadway (Carter & Council, 2006).

Crashes in rural and small urban areas tend to occur at higher speeds and be more severe.

- When they occur, pedestrian crashes in rural areas are twice as likely to result in a fatality, and rural bicycle crashes are three times as likely to result in a fatality, compared to crashes in urban areas (Carter & Council, 2006; Federal Highway Administration, 2010).
- Rural bicycle and pedestrian crashes in North Carolina were more likely to involve higher speeds, with nearly half occurring at speeds of greater than 40 mph, while most bicycle-motorist crashes in urban areas and a plurality of pedestrian-motorist crashes in urban areas occur at speeds less than 20 mph (Carter & Council, 2006).

Overtaking/passing maneuvers and lack of paved shoulders are a particular bicycle safety issue in rural areas.

- Bicycle crashes in rural areas are more likely to involve bicyclists and motorists travelling in the same direction, are more likely to occur in the bike lane or shoulder, and are less likely to occur on a sidewalk or crosswalk than in urban areas (Carter & Council, 2006). Most rural bicycle crashes occurred on roads with unpaved shoulders (80%) and posted speeds greater than 50mph (54%)(Carter & Council, 2006).
- A study in Wisconsin found that drivers in rural areas made frequent unsafe passing maneuvers, including passing outside of designated passing areas. However, drivers usually gave more than the required 3 feet of passing clearance, with an average of 6.2 to 6.3 feet; drivers were four to six times less likely to cross the center line during passing maneuvers when a paved shoulder was available (Chapman & Noyce, 2012).

Pedestrian safety for American Indians on reservations is a particular concern.

- NHTSA FARS data shows that American Indians and Alaska Natives suffer a pedestrian fatality rate of over twice the national rate, with about 30% of those fatalities occurring on reservations (NHTSA, 2020).
- A challenge for safety on reservations safety is that road ownership is often split between reservation, state, county or others, which can make it very difficult to plan and coordinate on traffic safety needs comprehensive safety needs (Quick & Narváez, 2018).

Improved design is part of the solution.

- Although rural areas and small towns may have some walking and biking infrastructure, they often lack networks to help people make complete trips by active transportation modes (Dickman et al., 2016).
- Based on frequency of crashes, two-lane roads have the greatest need for safety improvement and, therefore, “funds for safety research and treatment development would be better spent if focused on this roadway class” (Federal Highway Administration, 2010).
- Along roadways in rural areas, countermeasures may include signage notifying users to share space, or engineering measures that dedicate or reinforce space for bicyclists and pedestrians, including striping wide shoulders or adding rumble strips (Nabors et al., 2012). Other measures could include the targeted addition of sidewalks and paving shoulders, and adding targeted lighting. At intersections, targeted addition of lighting and pedestrian signals could help (Federal Highway Administration, 2010).

Pedestrians using a shoulder along a roadway. (Photo: Dan Burden, pedbikeimages.org)

Programming and education approaches are important since walking and bicycling infrastructure may not be feasible in many areas.

- Because of the dispersed nature of walking and biking crashes in rural and small urban areas, programming and education are viewed as one way to have more of an impact with safety dollars. Educating pedestrians and drivers are important countermeasures, particularly for crossing as opposed to walking-along-the-roadway crashes (Federal Highway Administration, 2010).
- A study of 10 rural, small and low-density communities in Colorado that received grant funding to increase cycling all opted to spend their funds on marketing and public outreach, partially due to lack of public support for cycling infrastructure improvements (McAndrews et al., 2018).

What are the research gaps?

- Limited bicycle and pedestrian volume and exposure data on rural roads makes analyzing risk and treatment potential in rural areas challenging (Federal Highway Administration, 2010).
- Due to the potential lack of public support for cycling infrastructure improvements in some rural or small urban areas, further political or cultural support may be needed to make changes in some communities. This may merit further research into effective means of achieving this upstream change, including approaches which may work for rural or small areas that are distinct from urban areas (McAndrews et al., 2018).

How is research on this topic done?

For many topics, the methods used in rural and small urban areas are similar, though existing data sources may be limited. One study, noting the lack of pedestrian activity and exposure data in rural and small urban areas, found that NHTS data and an area-based analysis approach can be useful to infer walk trips down to a block group level (Jamali & Wang, 2017).

Current research

Sponsor	Project Information	Status
Center for Safety Equity in Transportation (UTC) https://rip.trb.org/View/1733243	**Assessing the Relative Risks of School Travel in Rural Communities** The study examines school travel risk in rural communities, where the roadway environment introduces several safety challenges for school-aged children, parents, the local community, and commuters, particularly during morning arrival and afternoon dismissal periods when pedestrian and vehicular traffic and pedestrian-vehicle interaction are at their highest.	Expected completion date: 7/31/21
Center for Safety Equity in Transportation (UTC) https://rip.trb.org/view/1733244	**Developing Data-Driven Pedestrian Safety Assessment Methods for RITI Communities** This research will address the need in rural, isolated, tribal or indigenous (RITI) communities for systemic and data-driven pedestrian safety assessment methods that provide guidance on the collection and analysis of necessary data, identification and investigation of contributing factors, development of pedestrian safety indices, identification of high-risk roadways and intersections, etc.	Expected completion date: 7/31/22

Sponsor	Project Information	Status
Minnesota DOT https://rip.trb.org/View/1579263	**Understanding Pedestrian Travel Behavior & Safety in Rural Settings** The objectives of this Phase 2 project are to complete field investigations and identify safety concerns at multiple sites on at least four additional reservations; evaluate countermeasures that are being installed at Phase 1 sites in response to previous research; and evaluate countermeasures installed in response to Phase 2 investigations.	Expected completion date: 6/30/23

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Most common TRID index terms

Rural areas
Pedestrian safety
Rural highways
Pedestrians
Bicycling
Bicycle safety

Speed management and active transportation

A recent NCHRP synthesis on speed management noted that "though there are often multiple factors contributing to a pedestrian crash, a consistent factor contributing to pedestrian injury severity is vehicle speed. Research has found unequivocally that higher speeds lead to higher injury severity" (Sanders et al., 2019). This review covers research on speed management measures and their impact on walking and biking safety and demand.

Related review topics

- Research on designs and policies to improve pedestrian and bicycle operations and safety by managing motor vehicle access to arterials and highways is covered in the *Access management and active transportation* review.

What do we know?

Higher vehicle speeds are associated with more severe injuries and fatalities for pedestrian and bicyclists.

A recent literature review noted that "driver speed directly influences not only the injury severity of a pedestrian, but also the likelihood of a collision" (Sanders et al., 2019).

- A range of studies have found that risk of serious injury or fatality for pedestrians increases dramatically as vehicle speed on impact increases, with a roughly 13% change of fatality or severe injury at 20 miles per hour (mph), 40% at 30 mph, and 73% at 40 mph (Sanders et al., 2019; Tefft, 2013). A literature review analyzed 20 studies pertaining to the relationship between vehicle impact speed and pedestrian fatalities, and found that the odds of a pedestrian dying increase 11% for every 1 km increase in impact speed, starting at around 5% fatality for impact speeds of 19 mph, 10% at 23mph, 50% at 37mph and 75% at 43mph (Hussain et al., 2019). The study found that top speeds of 19 to 25 mph are appropriate for streets with high pedestrian activity.
- Studies have found that areas with greater proportions of higher-speed arterials are associated with more and/or more severe pedestrian and bicycle crashes (Guerra et al., 2019; Lin et al., 2019), and that areas with higher average speeds are associated with greater pedestrian injury risk (DiMaggio, 2015; Yu, 2015).
- A study of bicyclist injury severity found that the "largest effect [on the probability of a bicyclist suffering a fatal injury] is caused when estimated vehicle speed prior to impact is great than [50 mph], where the probability of fatal injury increases more than 16-fold" (Kim et al., 2007).
- A key consideration for the relationship between speed and safety is that drivers have less time to react to unexpected situations when travelling at higher speeds, which results in greater breaking distance required and less recovery time for distractions (Boodlal et al., 2015).
- Studies have found that older adults are likely to experience severe injury or fatalities at lower speeds than younger pedestrians (Sanders et al., 2019; Tefft, 2013).

Speeding as a contributing factor to pedestrian and bicycle crashes is underreported in crash reports.

- Speeding is often only recorded as a contributing factor in fatal crashes when there is clear evidence that drivers of involved vehicles were travelling over the speed limit, as opposed to fatal crashes in which the speed of the vehicle was a factor (Neuner et al., 2016).

Common approaches to managing speed for pedestrian and bicyclist safety include physical countermeasures to slow drivers.

Countermeasures that incorporate vertical deflection, such as speed humps or speed tables, are more effective than horizontal deflection countermeasures, such as chicanes, and more effective than enforcement measures (Mountain et al., 2005; Sanders et al., 2019).

- Speed humps (continuous raised areas across a street) and speed lumps (which have a cutout to allow emergency vehicles to pass unimpeded) have been found to reduce speeds in a range of studies, with 85th percentile reductions of 21% to 30%, or 5 to 8 mph (Sanders et al., 2019). They have also been found to reduce crashes, particularly for children, and have a CMF of 0.74 on local roads, and of 0.56 for children ages 0 to 14 (Rothman et al., 2015; Sanders et al., 2019; Tester et al., 2004). FHWA noted pedestrian crash reductions in five out of six studies, ranging from 33% to 48% reductions (Federal Highway Administration, 2014). One study found that speed humps were more effective at reducing pedestrian-motor vehicle crashes for children than for adults (Rothman et al., 2015).
- A study in New York City found that speed humps were effective in reducing pedestrian crashes at segments, but were not effective in reducing bicycle crashes (Chen et al., 2013).
- Speed tables and raised crossings have similar speed reduction benefits as speed humps, and when combined with a marked crosswalk have been found to have CMFs of 0.45 to 0.55 (Federal Highway Administration, 2014; Sanders et al., 2019).

Horizontal deflection elements such as chicanes or traffic circles, require drivers to shift laterally and slow down.

- Chicanes, or bulb-out that require motorists to weave, have been associated speed reductions ranging from 3 mph to 12 mph on several studies, although safety impacts on pedestrian have not been studied (Federal Highway Administration, 2014; Sanders et al., 2019).
- Mini traffic circles on lower speed roads have been associated with speed decreases ranging from about 4 mph to 7 mph (Sanders et al., 2019).

Road design or reconfiguration can also reduce driving speeds by eliminating passing opportunities and narrowing the travel lanes.

- **Road diets** that convert from four travel lanes down to three have been associated with reduced travel speeds of 1 to 7 mph (Sanders et al., 2019). Reductions in pedestrian crashes have been found to be significant, with one study finding a 0.38 CMF for vehicle-pedestrian crashes (Chen et al., 2013).
- **Neckdowns, bulb-outs, curb extensions, and chokers** narrow the roadway for brief stretches, and can be combined with marked crossings to provide shorter crossing distances. Sanders et al. (2019) found few safety studies looking at the efficacy of these features, along with limited but mixed findings on speed impacts of such features.

- **Raised medians or pedestrian islands** can narrow the roadway and have been found to reduce driving speeds from 2 mph to 8 mph, and have CMFs of 0.54 to 0.75 in most cases (Federal Highway Administration, 2014; Sanders et al., 2019).
- **Roadway striping placement** can be used to create the effect of a narrower lane, although the impact of such markings on speeds have been minimal or mixed in studies (Federal Highway Administration, 2014; Sanders et al., 2019).
- **Curb radius reductions** may require motorists to slow when turning, although a literature review did not identify studies demonstrating such a slowing (Sanders et al., 2019). One study did find that conflicts between pedestrians and turning cars were fewer after curb radius reductions were installed at two locations (Zangenehpour et al., 2017).

Curb extensions along a major arterial in Cornelius OR reduces pedestrian crossing distances. (Photo: Jennifer Dill)

In-street and active speed feedback signs have been successful at reducing driver speeds.

- **In-street pedestrian yielding signs** placed in a center median were found to increase speed limit compliance from 31% to 54% and decrease average speeds by 5 mph in one study, and reduce average speeds 1 to 5 mph in another study (Sanders et al., 2019). Another study found the measure only reduced speeds at a low volume site, but not at two higher-volume sites (Sanders et al., 2019).
- **Speed feedback signs** display the travel speed for all vehicles or only those exceeding a certain limit. They have been associated with speed reductions of 4 to 9 mph across several studies, although there is limited information on their effectiveness on pedestrian or bicyclist safety (Sanders et al., 2019).

Automated speed enforcement has been shown to reduce speed and crashes, while high-visibility enforcement does not appear to have lasting effects once the campaign is over.

- **Automated speed enforcement** using fixed or mobile speed cameras have been found to reduce driver speeds and crashes, with reductions in mean speeds and top-end speeds in a number of studies (Sanders et al., 2019). Campaigns in Seattle and New York City have found pedestrian crash reductions of 50% in Seattle and 23% in New York (Sanders et al., 2019).
- **High-visibility enforcement** has not been found to be particularly effective at reducing speeds in the long term (Sanders et al., 2019).

Policies and systematic approaches to reducing speeds, including Vision Zero programs, have been linked to improved pedestrian safety.

- A 2016 study of State Strategic Highway Safety Plans (SHSP) found that seven states had speed management strategies to address pedestrian safety (Neuner et al., 2016).
- A study in New York City found that **posted speed limit reductions** were effective in reducing pedestrian crashes, but were not effective in reducing bicycle crashes (Chen et al., 2013). Studies of citywide speed limit reductions in Boston and Portland found that overall speeds were reduced by 0.3 to 0.37%, significant in both studies, and that the percentage of drivers travelling over 25 mph, 30 mph, or 35 mph were reduced (Anderson et al., 2020; Hu & Cicchino, 2020).
- **Speed reduction zones**, including reducing speed limits around school zones, have been linked to reductions in pedestrian fatalities and injuries in London and the Netherlands (Sanders et al., 2019).

- Although more commonly optimized for throughput, **signal timing** can be adjusted to promote slower speed progression along a corridor (Neuner et al., 2016).

What are the research gaps?

- There are some gaps related to understanding speed and injury or fatality risk for certain populations. Tefft's assessment of severe injury or fatality risk by impact speed did not include children under age 15, who might be more prone to severe injury or death at lower impact speeds (Tefft, 2013). Another study noted that it is important when comparing studies to have consistent measures and definitions of injury severity, as well as understanding population factors that may influence severity (such as older population) (Rosen et al., 2011).
- Although the factors relating to the danger of speed and impact speed for pedestrians will apply to bicyclists in many cases, we noted few studies specifically linking bicyclists' injury or fatality risk and speed.
- Some countermeasures have been found to reduce speed, but the connection to pedestrian or bicyclist safety has not been specifically analyzed, such as chicanes, mini-traffic circles, and speed feedback signs (Sanders et al., 2019).
- Strong speed or safety findings were not identified for curb extensions (Sanders et al., 2019).
- While research generally suggests that slower motor vehicle speeds encourage more walking or cycling, there is limited research that quantifies that relationship.

How is research on this topic done?

A literature review examining countermeasures to reduce the negative safety effects of speed on pedestrians noted that, "Most studies included in this review measure the impact of countermeasures via a before–after or cross-sectional approach; some studies use both to control for general trends that may be occurring throughout a specific area" (Sanders et al., 2019).

There are different ways to quantify speed. Many studies measured mean speeds and 85th percentile speeds, while some also looked at the percentage of drivers speeding by certain amounts (e.g., 5 or 10 mph over the speed limit). Crowdsourced speed data, such as that provided by INRIX, can be helpful in understanding speed in certain contexts, and has been used to supplement pneumatic tube speed data (Fitzpatrick et al., 2019).

Current research

Sponsor	Project Information	Status
NHTSA https://rip.trb.org/View/1678171	**Impact of Lowering Speed on Pedestrian and Bicyclist Safety** The objective of this study is to assess the extent to which vehicle speeds, pedestrian/bicyclist crashes and conflicts, and pedestrian/bicyclist injury severity change as a result of implementation of speed-related programs to improve pedestrian and bicyclist safety.	Estimated completion date: 09/30/23

Sponsor	Project Information	Status
Minnesota DOT https://rip.trb.org/View/1530034	**Guidelines for Safer Pedestrian Crossings: Understanding the Factors that Positively Influence Vehicle Yielding to Pedestrians at Unsignalized Intersections** Approaches to encouraging drivers yielding to pedestrians are typically guided by the posted and operating speeds of a roadway. Stopping sight distance and a driver's ability to perceive a pedestrian are negatively impacted by the speed of the vehicle. An analysis of the relationship between vehicle speed, roadway context, and drivers yielding to pedestrians should be conducted.	Start date: 07/01/20

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Most common TRID index terms
Fatalities
Pedestrian safety
Pedestrian-vehicle crashes
Traffic safety
Pedestrian vehicle interface
Crash analysis
Injury severity
Literature reviews
Speed
Speed control