Not all protected bike lanes are the same: infrastructure and risk of cyclist collisions and falls leading to emergency department visits in three U.S. cities

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Jessica B. Cicchino
Insurance Institute for Highway Safety

Melissa L. McCarthy
George Washington University Milken Institute School of Public Health

Craig D. Newgard
Center for Policy and Research in Emergency Medicine, Department of Emergency Medicine, Oregon Health & Science University

Stephen P. Wall
Ronald O. Perelman Department of Emergency Medicine, Department of Population Health, New York University School of Medicine

Charles J. DiMaggio
Department of Surgery, Division of Trauma and Critical Care, New York University School of Medicine

Paige E. Kulie
Department of Emergency Medicine, George Washington University Medical Center

Brittney N. Arnold
Center for Policy and Research in Emergency Medicine, Department of Emergency Medicine, Oregon Health & Science University

David S. Zuby
Insurance Institute for Highway Safety

1005 N. Glebe Road, Suite 800
Arlington, VA 22201
+1 703 247 1500

iihs.org

ABSTRACT

Objective: Protected bike lanes separated from the roadway by physical barriers are relatively new in the United States. This study examined the risk of collisions or falls leading to emergency department visits associated with bicycle facilities (e.g., protected bike lanes, conventional bike lanes demarcated by painted lines, sharrows) and other roadway characteristics in three U.S. cities.

Methods: We prospectively recruited 604 patients from emergency departments in Washington, DC; New York City; and Portland, Oregon during 2015–2017 who fell or crashed while cycling. We used a case-crossover design and conditional logistic regression to compare each fall or crash site with a randomly selected control location along the route leading to the incident. We validated the presence of site characteristics described by participants using Google Street View and city GIS inventories of bicycle facilities and other roadway features.

Results: Compared with cycling on lanes of major roads without bicycle facilities, the risk of crashing or falling was lower on conventional bike lanes (adjusted OR=0.53; 95% CI=0.33, 0.86) and local roads with (adjusted OR=0.31; 95% CI=0.13, 0.75) or without bicycle facilities or traffic calming (adjusted OR=0.39; 95% CI=0.23, 0.65). Risk on one-way protected bike lanes did not differ from that on major roads (adjusted OR=1.19; 95% CI=0.46, 3.10). Two-way protected bike lanes were associated with higher risk than major roads when they were at street level (adjusted OR=11.38; 95% CI=1.40, 92.57), but lower risk when raised from the roadway or on bridges (adjusted OR=0.10; 95% CI=0.01, 0.95). Risk also increased in the presence of streetcar or train tracks relative to their absence (adjusted OR=26.65; 95% CI=3.23, 220.17), on downhill relative to flat grades (adjusted OR=1.92; 95% CI=1.38, 2.66), and when temporary features like construction or parked cars blocked the cyclist's path relative to when they did not (adjusted OR=2.23; 95% CI=1.46, 3.39).

Conclusions: Certain bicycle facilities are safer for cyclists than riding on major roads. Protected bike lanes vary in how well they shield riders from crashes and falls. Less frequent intersections with roads and driveways, more continuous separation, and less complexity for turning drivers crossing them appear to contribute to reduced risk in protected bike lanes. Planners should minimize conflict points

when choosing where to place protected bike lanes and should implement countermeasures to increase visibility at these locations when they are unavoidable.

1. Introduction

Bicycling popularity in urban areas has increased in the United States during the 21st century. U.S. workers who reported commuting to work by bicycle increased more than 60% from 2000 to 2008–12, and the proportion of adults who cycle to work nearly doubled during this period in the largest 50 U.S. cities (McKenzie, 2014). With this increase in cycling exposure has come an increase in fatalities and injuries among adult bicyclists. The number of bicyclists age 20 and older fatally injured in U.S. crashes with motor vehicles increased by nearly 50% during 2000–2017 (Insurance Institute for Highway Safety, 2018). Age-adjusted emergency department visit rates for bicycling-related injuries in the United States have similarly risen in recent years (Sanford, McCulloch, Callcut, Carroll, & Breyer, 2015).

Growing cycling popularity and rising cycling-related injuries and deaths have encouraged U.S. cities to install infrastructure for bicyclists along more of their roads. Conventional bike lanes demarcated by painted lines have long existed in the United States, and over the past decade U.S. cities have begun to incorporate protected bike lanes. Protected bike lanes, also called cycle tracks or separated bike lanes, are bicycle facilities separated from motor vehicle traffic by a physical barrier such as parked cars, curb, grade, landscaping, posts, or a combination of these or other features. Protected bike lane mileage in the United States increased from about 40 miles in 2008 to about 400 miles in 2018 (People for Bikes, 2018).

Recent North American evaluations of the effects of conventional bike lanes have had inconsistent results, with some finding them to be associated with fewer bicyclist crashes or injuries overall (Bhatia et al., 2016; Hamann & Peek-Asa, 2013; Park, Abdel-Aty, Lee, & Lee, 2015; Pulugurtha & Thakur, 2015; Teschke et al., 2012; Wall et al., 2016) or in specific circumstances (Kondo, Morrison, Guerra, Kaufman, & Wiebe, 2018), and others reporting no change in crashes or increases associated with them (Chen et al., 2012; Raihan, Alluri, Wu, & Gan, 2019; Wei & Lovegrove, 2013). Different findings in part reflect disparities in how evaluations were conducted. For example, studies of bike lane efficacy vary in how and if cycling exposure was accounted for, which is important given that constructing facilities for cyclists can increase ridership (Buehler & Pucher, 2012; Dill & Carr, 2003).

Research on the effects of protected bike lanes on bicyclist crashes and injuries in North America is sparser than that for conventional bike lanes. Teschke et al. (2012) used a case-crossover design to compare infrastructure at locations where cyclists treated in Toronto and Vancouver, Canada emergency departments were injured with infrastructure at randomly selected locations along the routes cyclists took prior to their injuries, and found that injury risk in protected bike lanes was one tenth of that on major roads with parked cars. Bicyclist injury rates per kilometer traveled were 28% lower on Montreal protected bike lanes compared with similar nearby streets without cycling infrastructure (Lusk et al., 2011). A later Montreal study found that injury rates were lower in protected bike lane segments than on comparison streets but were not always lower at intersections, with effects varying among the lanes examined (Nosal & Miranda-Moreno, 2012).

In the United States, an evaluation in New York City reported that bicyclist injury rates in crashes with motor vehicles were 23% lower on roads with protected bike lanes compared with roads without cycling infrastructure using pedestrian activity as a proxy for bicyclist exposure, although the finding was not statistically significant (Wall et al., 2016). However, severity was higher for injuries sustained in protected bike lanes than those sustained on roads without cycling facilities. Simple before-after examinations of police-reported bicyclist-motor vehicle crash rates in protected bike lanes in New York City and Washington, DC, that accounted for exposure but did not use controls have produced mixed findings, with decreases at New York intersections after the installation of protected bike lanes and increases along the initial lanes constructed in Washington (Goodno, McNeil, Parks, & Dock, 2013; Sundstrom, Quinn, & Weld, 2019). A cross-sectional study examining data from 12 U.S. cities found that the density of protected bike lanes at the city and block level, but not of conventional bike lanes, was associated with fewer police-reported fatalities and serious injuries to all road users (Marshall & Ferenchak, 2019).

With their growing prevalence, more needs to be known about the safety of protected bike lanes in the United States. Existing U.S. evaluations have focused on crashes involving motor vehicles, but other incidents such as falls or collisions with pedestrians or other cyclists cause many cyclist injuries treated in emergency departments (e.g., Beck et al., 2016; de Rome et al., 2014; Schepers et al., 2015; Stutts & Hunter, 1999; Teschke et al., 2012).

The current study examined the risks associated with infrastructure characteristics, including protected bike lanes, of bicyclist crashes or falls leading to emergency department visits in the U.S. cities of Washington, DC; New York City; and Portland, Oregon. There were approximately 5 miles of protected bike lanes in use in Portland, 10 miles in Washington, and 100 miles in New York by the end of 2018 (People for Bikes, 2018). During 2017, 6.3% of adult workers in Portland, 5.0% in Washington, and 1.3% in New York biked to work (United States Census Bureau, 2018). We used a case-crossover design similar to Teschke et al. (2012). Infrastructure characteristics at the location where adult cyclists crashed or fell were compared with those at a randomly selected location along the route leading to their incidents. Because cyclists served as their own controls and comparisons made between case and control sites were within trip, the design accounts for exposure to roadway features while matching rider and general trip (e.g., weather) characteristics between sites.

2. Methods

2.1 Patients

We enrolled 604 adults who sought treatment after falling or crashing while riding a bicycle at the emergency departments of George Washington University Hospital in Washington, Oregon Health and Sciences University in Portland, and Bellevue Hospital and the Ronald O. Perelman Center for Emergency Services of NYU Langone Medical Center in New York City. Bellevue and the Washington and Oregon hospitals are Level 1 trauma centers, and NYU Langone is a university-based quaternary hospital juxtaposed to Bellevue Hospital. Trained research staff interviewed patients in the emergency department. The research teams enrolled patients during set hours (9 a.m. – 10 p.m. in Washington, 8 a.m. – 11 p.m. in Portland, 8 a.m. – midnight in New York); patients who visited the emergency department outside of coverage hours were not enrolled. Data collection began in different months in each city (March 2015 in Washington, November 2015 in Portland, April 2016 in New York) and lasted through

September 2017. The final sample included 354 patients from Washington, 131 from Portland, and 119 from New York. The protocol was approved by each hospital's institutional review board.

Adult cycling patients were eligible if they crashed or fell while riding a bike; could remember the route leading to their incidents, understand consent, and communicate with emergency department staff (in English in Washington and Portland and in English or Spanish in New York); and if their incident occurred within a week of the interview; their trip was 0.10 mile or longer and was within the hospital's catchment area; and they were not trick riding, racing, or riding with more than one person on a bicycle during their trip. There were 982 adult cyclists who presented to the emergency departments in Washington and Portland during coverage hours in the study period. Of these, 676 (69%) were eligible, 254 (26%) were ineligible, and 52 (5%) left the emergency department before research assistants could screen them. The research assistants enrolled 485 patients in Washington and Portland, which was 72% of the eligible screened patients in those cities. The most common reasons for being ineligible in Washington and Portland were being unable to remember their route (44 cyclists) and being injured outside of the hospital's catchment area (40 cyclists). Data on cycling patients not enrolled were not collected consistently in New York.

2.2 Interview and injury coding

Research staff used a structured questionnaire to interview participants. The primary purpose of the interview was to record the route the participant took during the trip leading to their crash or fall and collect information that could not be obtained from site inspections. The research assistant mapped each participant's route electronically using the website www.mapmyride.com and selected a control site along the route by multiplying a random proportion between 0.01–0.99 by the length of the entire route and placing the control site at the resulting distance from the start of the trip. For instance, if the trip was 7.5 miles and the random proportion was 0.61, the control location was marked 4.58 miles (7.5x0.61) from the trip's starting point. We adapted additional interview questions from Teschke et al. (2012) to assess circumstances leading to the incident, trip purpose, personal characteristics, what type of route the cyclist was riding at the case and control sites, which lane of the roadway the cyclist was in if they were riding on the road, and temporary site characteristics blocking the cyclist's path such as construction or parked cars. The research assistants showed the participants a Google Street View image of the case and control sites as they answered questions about them.

Following emergency department or hospital discharge, one research assistant at each site reviewed the medical record of each subject and coded each injury sustained using the Abbreviated Injury Scale (Gennarelli & Wodzin, 2008). The AIS score ranges from 0 to 6, with 0 representing no injury and 6 representing nonsurvivable injuries. A score of 2 indicates a "moderate" injury and 3 or greater indicates a "serious" injury.

2.3 Site feature identification

We characterized route types at the case and control locations into one of the 10 following categories. If a site was an intersection, characteristics were recorded for the route type the cyclist was riding on prior to reaching the intersection. We considered three categories of protected bike lanes based on their location, type of separation used, and direction of travel.

- *Major road*: Arterial or collector roads as classified by the functional class system, where cyclists were not in a conventional or protected bike lane or lane with shared lane markings. Following Teschke et al. (2012), who found that injury risks were higher on major roads with parked cars than on other route types, major roads were the reference in analyses.
- *Bike lane on major road*: Conventional bike lanes with painted separation from moving motor vehicles on arterial or collector roads. This classification includes bike lanes with buffers (i.e., painted space between bike lane and road) if there was not also vertical physical separation. (Figure 1a)
- *Sharrows on major road*: Shared lane markings on arterial or collector roads. (Figure 1b)
- *Local road*: Local roads as classified by the functional class system, driveways, and parking lots, without traffic calming and where cyclists were not in lanes with bicycle facilities. Few (3%) sites identified as local roads were on private property.

- *Local road with bike lane, sharrows, or traffic calming:* Local roads that had traffic calming or where cyclists were riding in bike lanes or lanes with sharrows. Traffic calming included nearby speed bumps and Portland's neighborhood greenways, which are local roads that give priority to bicyclists and pedestrians through speed bumps, traffic diverters, and sharrows.
- *Sidewalk*: Paths next to roadways designed for pedestrian use.
- *Off-road/trail*: Off-road areas other than sidewalks with mixed use, such as multiuse trails or roadways shut down to motor vehicle traffic.
- *One-way protected bike lane*: One-way bike lanes physically separated from moving motor vehicles with vertical barriers. All protected bike lanes in this study were on major roads, and those that were one way were separated by barriers such as parked cars, posts, or curbs. None were on bridges or separated by tall, continuous barriers such as bridge rails or concrete walls. (Figure 1c)
- *Two-way protected bike lane at street level:* Two-way bike lanes on the roadway separated from moving motor vehicles by a transient (parked cars), noncontinuous (posts, parking curb), or short (continuous curb) vertical barrier. (Figure 1d)
- *Two-way protected bike lane raised from road or on bridge:* Two-way bike protected lanes separated from moving motor vehicles vertically by grade (e.g., within the sidewalk; Figure 1e) or along bridges (Figure 1f). Lanes on bridges were separated from traffic by tall, continuous barriers (bridge rails, concrete barriers or walls).

We classified route types based on a combination of patient reports and site reviews. The research assistants asked the participants if the routes they were riding on at the case and control sites were roads, bike lanes, sidewalks, or off-road locations. We cross-referenced participants' reports with Google Street View and GIS inventories of cycling facilities maintained by the study cities to validate that the named route types were present at the sites. Off-road sites that were not viewable on Google Street View were visually assessed using Google Earth satellite view. New York's GIS inventory of cycling facilities included facility installation date, and Washington and Portland's included installation year. When it was ambiguous if a facility was installed before or after a trip from the main data sources, we consulted installation dates of new facilities obtained from the city (Washington) or from publicly available information (New York, Portland). We further broke down route types from the initial four categories using these tools and roadway functional class maps maintained by states and the District of Columbia. If bike lanes or sharrows were present, we determined from questionnaire responses if participants were riding in a lane with these markings, another lane, or other route type (e.g., sidewalk) without special markings for bicyclists.

The named route type was not present at 10% of locations. The participant misnamed the route type (e.g., called a multiuse trail or road with sharrows a bike lane) in more than half of these. At most remaining locations, the participant named the route type they were approaching rather than the route type they came from at an intersection (13 sites), or said they were in a bike lane when none was present (26 sites). If the patient said they were in a bike lane when none was present, we assumed they were riding in the road. There were no locations where a participant said they were riding on a sidewalk at a site without one. However, there was one location where sharrows were present but the cyclist said they were traveling in an unmarked lane.

Other features identified from site review included grade and the presence of streetcar (tram) or train tracks. Grade was determined through measuring elevation in Google Earth at the case or control site and 0.05 miles before the site and calculating the rise over run. Elevation could not be measured on bridges and overpasses, and grade for sites with these elements was unknown. Grades greater than 1% were considered uphill, less than −1% downhill, and between −1% and 1% flat. Intersections were defined as locations where two or more roads meet; junctions with alleys, driveways, or entrance/exit ramps were not considered intersections.

2.4 Analyses

In the primary analysis, we used conditional logistic regression to examine the association between environmental characteristics and site type, with a binary indicator for site type (1=case, 0=control) as the dependent variable. Independent variables included route type, grade, and the presence of streetcar or train tracks and temporary features that blocked the cyclist's path. Results are presented unadjusted by individual variable and adjusted with all covariates included. Unadjusted results were produced using conditional logistic regression models with a single predictor; the result is also known as a matched-pair odds ratio. We also present results from adjusted models that examine each city separately, and a sensitivity analysis where we excluded patients from the adjusted model who reported riding on a route type at the case or control site that was not observed to be present upon site inspection.

An additional conditional logistic regression model was constructed that included intersection presence and interaction terms between intersection and independent variables from the primary model (route type, grade, streetcar or train tracks, temporary features). This allowed the crash or fall risk associated with various characteristics to be computed separately at intersections and away from intersections. Because crashes and falls leading to emergency department visits are rare events, odds ratios are good approximations of relative risks and so results from logistic regression models are interpreted as changes in risk.

We classified circumstances leading to crashes and falls based on responses to an open-ended question asking patients to describe the circumstances of their accident and forced-choice questions asking what, if anything, they collided with or fell to avoid colliding with. We categorized the proportion of incident circumstances occurring on each route type as collisions with or falls to avoid moving motor vehicles (cars, SUVs, pickups, motorcycles, trucks, buses), stopped or parked motor vehicles (including doors), other cyclists, pedestrians, infrastructure (e.g., curb, pole, fence), or surface features (e.g., potholes, uneven pavement, streetcar tracks); falls due to other causes (e.g., slippery surface, avoiding adverse surface conditions, clothing caught in chain), or other/unknown causes. We computed relative proportions and associated 95% confidence intervals to assess the rate of each circumstance on each route type relative to the rate for the reference category of major roads. Only case sites (and not control sites) were included in these analyses. For relative proportions including a route type where a type of circumstance never occurred, exact 95% confidence intervals were computed that could handle zero values using the Farrington-Manning relative risk score statistic (Chan & Zhang, 1999).

3. Results

3.1 Cyclist, trip, and injury characteristics

Table 1 summarizes the cycling and trip characteristics of the study sample. Participants were mostly male, and about half were under age 40. More than 80% were regular cyclists who reported biking on most days during the months of the year when they ride. Two thirds of trips were shorter than 3 miles, about half were commuting trips, and most occurred on weekdays, with clear conditions, and during daylight. Most cyclists (96.9%) presenting at an emergency department were injured (Table 2), but fewer than half sustained at least one moderate or severe (AIS 2+) injury. Among the 254 participants with AIS 2+ injuries, almost 70% sustained injuries to the extremities.

3.2 Risk of crashing or falling

Table 3 displays results of the unadjusted and adjusted conditional logistic regression models comparing characteristics at case locations to those at control locations. Relative to major roads, risks of crashing or falling were significantly lower on local roads with and without bike infrastructure or traffic calming, bike lanes, and two-way protected bike lanes raised from the road or on bridges in both models, and on off-road locations in the unadjusted model only. Risks were significantly higher in both models on street-level two-way protected bike lanes relative to major roads, on downhill grades relative to flat grades, when temporary features were blocking the path relative to when they were not present, and when streetcar or train tracks were present relative to when they were absent.

Most incidents occurred away from intersections, but risks were higher at intersections (unadjusted OR=5.17; 95% CI=3.60, 7.43). Table 4 describes the risks of crashing or falling associated with various route types and other characteristics at intersections and away from intersections. Risks by roadway segment type were similar to those observed in the primary analysis. At intersections, however, risk was higher on bike lanes relative to major roads (p=0.0535). Interactions between intersection presence and route type indicated that cyclists were significantly more likely to crash or fall at intersections on bike lanes (*p*=0.0018) and on local roads with bike lanes, sharrows, or traffic calming (*p*=0.0098) than at nonintersections on these facilities relative to major roads. Similarly, an interaction between intersection presence and grade indicated that cyclists were more likely to crash or fall at nonintersections than intersections when grade was unknown relative to when it was flat (*p*=0.0402); this effect likely reflects the types of sites where grade could not be measured (bridges, overpasses). No other interactions were significant. Risk was higher for two-way protected bike lanes at street level relative to major roads at both intersections (*p*=0.0731) and nonintersections (*p*=0.0921).

3.3 Incident circumstances

Table 5 summarizes the circumstances of crash or fall incidents by route type. Overall, about half (52.3%) of cyclists collided with or fell to avoid motor vehicles that were moving (40.2%) or stopped or parked (12.1%).

Circumstances varied by the type of route where the incident occurred. Table 6 presents the relative proportions of incident circumstances by route type compared with the proportion that occurred on major roads. A smaller proportion of cyclists crashed with or fell to avoid moving motor vehicles at off-road locations than on major roads, but the proportion involved in motor vehicle crashes on other route types didn't differ significantly from major roads. Collisions with or falls to avoid stopped or parked vehicles were less likely on off-road locations, sidewalks, or local roads without bike infrastructure or traffic calming. The proportion of cyclists who collided with or fell to avoid other cyclists was higher at off-road locations and on both types of two-way protected bike lanes than on major roads, and the proportion who collided with or fell to avoid pedestrians was higher at off-road locations and on street-level one- and two-way protected bike lanes. Relative to major roads, collisions with or falls to avoid infrastructure and other falls were more likely at off-road locations and on sidewalks; collisions with or falls to avoid infrastructure were additionally more likely on two-way protected bike lanes raised from the road or on bridges.

The majority of cyclists who collided with or fell to avoid moving vehicles did so at intersections (58.9%). The definition of intersection in this study did not include junctions with driveways, alleys, or exit/entrance ramps, and crashes or falls in protected bike lanes were reviewed to determine if they occurred at these additional junction types. In protected bike lanes, 60.0% of incidents involving moving vehicles occurred at intersections, 26.7% at junctions with driveways or alleys, 6.7% at junctions with exit ramps, and 6.7% at midblock (not at junctions). Most incidents involving pedestrians in protected bike lanes occurred midblock (66.7%) and those involving other cyclists were evenly distributed between intersections and nonintersections; none of these incidents occurred at junctions with driveways, alleys, or exit ramps.

3.4 Regional results

The main analyses examining crash or fall risk by route type were conducted separately by city and are presented in Tables A1–A3 in the Appendix. Patterns of results for conventional bike lanes, local roads, downhill grades, and temporary features were consistent across cities, although sample sizes were small in New York and Portland, which limited the power to achieve statistical significance. However, we observed some differences among cities. For example, riding on sidewalks was associated with a significantly lower risk in Portland relative to major roads, while it was associated with an elevated risk in New York. The direction of effects for one-way protected bike lanes differed in Washington and New York, and were associated with increased risk in Washington and decreased risk in New York relative to major roads, but neither effect was statistically significant. Most sites with streetcar or train tracks were located in Portland.

Characteristics of the protected bike lanes that served as case and control sites and their locations are described in Table 7. Nearly all incidents on street-level two-way protected bike lanes occurred in Washington, while all but one two-way protected bike lane site raised from the road or on a bridge were in New York. An approximately 0.67-mile section of protected bike lane along two-way vehicle traffic on 15th Street NW in Washington between Massachusetts Avenue and Pennsylvania Avenue stood out as particularly risky, accounting for 10 of the 21 crashes or falls on street-level two-way protected bike lanes in the study and only one control site. On average, one-way and two-way protected bike lanes at street level each were crossed by driveways, alleys, exit ramps, or intersecting roads about 19 times per mile, although the nature of these crossings varied by city; lanes in Washington were crossed more often by driveways and alleys than those in New York, and those in New York were crossed by intersecting roads more often than lanes in Washington. Two-way protected bike lanes raised from the road were crossed by driveways, alleys, exit ramps, or intersecting roads an average of 6 times per mile, and those on bridges an average of twice per mile.

The characteristics of incidents on street-level protected bike lanes appeared to differ between Washington and New York, although the number of incidents was small in each city. Table 8 summarizes the circumstances and relation to junction of incidents on the type of street-level protected bike lane, broken down by city, direction of travel of the bike lane (one or two way), and proximity to the curb (curbside or in the center of the road). More than half of incidents in curbside lanes in Washington occurred at junctions with intersecting roads or driveways/alleys and nearly half involved moving vehicles. In New York, about a quarter occurred at junctions and less than a quarter involved moving vehicles. About a quarter of incidents in curbside lanes in Washington occurred at junctions with driveways or alleys, while less than 10% did in New York.

4. Discussion

Protected bike lanes are the facility most preferred by cyclists (Winters & Teschke, 2010), with some reporting that they feel safer riding in them than on other types of infrastructure (Monsere et al., 2014; Winters et al., 2012). Cycling levels increased in cities that have built them (Buehler & Dill, 2016). Their rising popularity in North America has led to increased interest in knowing if they live up to expectations and protect cyclists more than other infrastructure types. This study demonstrates that risks of crashes or falls leading to emergency department visits can vary widely among protected bike lanes with different designs, with lower risks seen on two-way protected bike lanes that were raised from the road or on bridges and higher risks seen on those at street level.

Most fatal bicycle-motor vehicle crashes occur midblock away from intersections (Insurance Institute for Highway Safety, 2018), and protected bike lanes are built primarily to shield cyclists from this dangerous crash type. While midblock crashes with or falls due to vehicles that were unrelated to junctions were rare in the current study, those at intersections or junctions with driveways or alleys were not. This was especially the case in Washington, DC, where curbside protected bike lanes were more frequently intersected by driveways and alleys. Crashes with vehicles in protected bike lanes occurred less often in New York, where there were no alleys and most lanes were seldom intersected by driveways. Increased density of junctions increase the risk of bicyclist-motor vehicle crashes because they introduce additional opportunities for conflict (Li, Graham, & Liu, 2017; Pulugurtha & Thakur, 2015; Siddiqui, Abdel-Aty, & Choi, 2012; Vandenbulcke, Thomas, & Panis, 2014; Wei & Lovegrove, 2013). Two-way protected bike lanes raised from the road and on bridges in this study had fewer junctions than those that were street level, which likely contributed to their lower risk.

Intersections and other junctions can be particularly challenging for vehicles turning across contraflow or two-way protected bike lanes, because drivers look most frequently in the direction of traffic and thus may be less likely detect cyclists approaching from the opposing direction (Räsänen & Summala, 1998; Schepers, Kroeze, Sweers, & Wüst, 2011; Summala, Pasanen, Räsänen, & Sievänen, 1996). Two-way protected bike lanes alongside two-way vehicle traffic add additional complexity as turning drivers need to monitor both oncoming vehicle traffic and two-way bicycle traffic in the bike lane. The riskiest protected bike lane segment in this study was a two-way lane at street level along a two-way street.

Cities should consider the density of driveways and other junctions when choosing where to place protected bike lanes (Federal Highway Administration, 2015; National Association of City Transportation Officials, 2014). Raised cycle crossings that lower vehicle speeds have been effective treatments at European intersections with protected bike lanes (Gårder, Leden, & Pulkkinen, 1998; Schepers et al., 2011) and are recommended for consideration in the Massachusetts Department of Transportation's Separated Bike Lane Planning and Design Guide (2015) at driveways and local street crossings. In 2011, the U.S. Federal Highway Administration issued interim approval for the use of green pavement in bike lanes, their extension through intersections, and other conflict areas. Evidence on the effectiveness of colored bike lanes through intersections has been mixed (Hunter, Harkey, Stewart, & Birk, 2000; Jensen, 2008b; Schepers et al., 2011), with a simulator study suggesting that extending bike lanes with white dotted lines through intersections better captures drivers' attention than green coloring (Warner, Hurwitz, Monsere, & Fleskes, 2017). Design guides for protected bike lanes recommend using high-visibility markings at junctions with driveways, as well as restricting parking 20–30 feet prior to the driveways and using signage to alert drivers exiting driveways of potential conflicts (Federal Highway Administration, 2015; Massachusetts Department of Transportation, 2015; National Association of City Transportation Officials, 2014).

Additional countermeasures have been recommended at intersections with protected bike lanes. Dedicated cyclist signals with a leading or partially protected phase and bike boxes can reduce conflicts at intersections (Dill, Monsere, & McNeil, 2012; Ledezma-Navarro, Stipancic, Andreoli, & Miranda-Moreno, 2018). Two-stage turn queue boxes that allow for left turns from the rightmost lane without merging with traffic and lateral shifting of lanes at intersections to allow turning traffic to cross the bike lane are featured in design guides (Federal Highway Administration, 2015; Massachusetts Department of Transportation, 2015; National Association of City Transportation Officials, 2014) but have not been formally evaluated. Yield to cyclist signage, smaller curb radii, and protected intersection designs with islands also showed promise at improving driver behavior around cyclists at intersections in a simulator study (Warner et al., 2017). Some of these countermeasures are used by the study cities.

Vehicles were not the only hazards leading to crashes or falls. Pedestrians were involved in nearly a quarter of incidents in street-level protected bike lanes in the current study but were not involved in many incidents on roads or conventional bike lanes. Surveys, observational studies, and naturalistic cycling studies have noted that pedestrians can be frequent obstacles in protected bike lanes (Basch, Ethan, & Basch, 2018; Conway, Cheng, Peters, & Lownes, 2013; Goodno et al., 2013; Schleinitz, Petzoldt, Franke-Bartholdt, Krems, & Gehlert, 2015; van der Horst, de Goede, de Hair-Buijssen, & Methorst, 2014). For example, Basch et al. (2018) observed about two pedestrians obstructing Manhattan, New York City, protected bike lanes per mile, including one pedestrian about every 2 miles pushing an object or walking a dog in the protected bike lane, and more than half of cyclists who use Washington's

Pennsylvania Avenue protected bike lane surveyed by Goodno et al. (2013) reported near-crashes with pedestrians in that facility. Other cyclists were also involved in incidents in two-way protected bike lanes, and two-cyclist conflicts have similarly been observed in other two-way protected bike lanes involving head-on, same-direction, and crossing configurations (Schleinitz et al., 2015; van der Horst et al., 2014).

Most incidents in protected bike lanes involving pedestrians in this study occurred midblock, which can result from pedestrians using the lane for travel, crossing midblock, exiting a vehicle parked adjacent to it, or waiting for a taxi or other vehicle. It is unclear why protected bike lanes may be more susceptible to pedestrian obstructions than conventional bike lanes, but possibilities include that they can stand between pedestrians exiting parked cars and the sidewalk (Vandenbulcke et al., 2014) or that some pedestrians treat protected bike lanes as sidewalks because they are buffered from traffic. There were no crashes or falls due to pedestrians on the two-way protected bike lanes that were raised or on bridges, and the more substantial barriers and fewer intersections on these facilities likely gave pedestrians fewer openings to enter and cross them. Countermeasures to deter pedestrians from using protected bike lanes need to be developed. These results also highlight the risk of comingling cyclist and pedestrian routes when protected bike lanes are altered for construction or other purposes, and of blocking access to sidewalks that run adjacent to protected bike lanes. Data collection for this study concluded before the arrival of shared e-scooters, and future work should monitor if safety problems arise from these road users sharing protected bike lanes with cyclists.

Marshall and Ferenchak (2019) reported that a higher density of protected bike lanes is associated with fewer fatalities and serious injuries to all road users. That finding is not necessarily at odds with the current results. Most injuries in this study were minor and we were not able to investigate risk by injury severity. Research from Copenhagen has reported that protected bike lanes change the distribution of crash types, with the frequency of some types increasing (e.g., crashes involving pedestrians, two bicyclists, turning vehicles) and others decreasing (e.g., rear-ends by motor vehicles, crashes with parked cars) when protected bike lanes are built (Jensen, 2008a). The crash and fall types seen on protected bike lanes in this study demonstrate a similar pattern. While there were crashes and falls involving pedestrians, other cyclists, and vehicles at junctions, there were few involving vehicles at nonjunctions, which is the scenario leading to the majority of bicyclist fatalities. Thus, it seems plausible that some protected bike lanes could both carry a higher risk of injury in general while reducing risk of the most serious injuries.

Conventional bike lanes were associated with lower risks than major roads overall and at nonintersections, but intersections were problematic for these facilities. Bike lanes to the right of travel lanes make cyclists susceptible to right-hook crashes, where a vehicle turns right in front of cyclist traveling straight (Hurwitz, Jannat, Warner, Monsere, & Razmpa, 2015). Many of the treatments recommended for use with protected bike lanes at intersections also apply to conventional bike lanes.

Results for some other infrastructure characteristics support findings from Teschke et al. (2012) and elsewhere. Local streets with and without bicycle facilities or traffic calming were associated with low crash or fall risks (Aldred, Goodman, Gulliver, & Woodcock, 2018; Minikel, 2012), and downhill grade increased risk (Allen-Munley, Daniel, & Dhar, 2004; Klop & Khattak, 1999), likely because it increased cyclist speed. Streetcar or train tracks increased risk substantially, which is consistent with findings from Toronto, Vancouver, and Brussels (Teschke, Dennis, Reynolds, Winters, & Harris, 2016; Vandenbulcke et al., 2014) and should be a consideration for cities expanding or implementing a streetcar network.

Findings for other infrastructure characteristics were consistent with Teschke et al. (2012) but differ with other previous research. In the current study and Teschke et al. (2012) risks associated with sharrows and multiuse trails or off-road locations were lower than those for major roads, although not always significantly so. Sharrows have been associated with positive changes in driver and cyclist behavior (Furth, Dulaski, Bergenthal, & Brown, 2011; Hunter, Thomas, Srinivasan, & Martell, 2010) but with increases in injury severity or crash rates in prior studies (Ferenchak & Marshall, 2016; Wall et al., 2016). Others have reported increased risks associated with multiuse trails and other off-road locations (Aultman-Hall & Hall, 1998; de Rome et al., 2014; Moritz, 1998; Reynolds, Harris, Teschke, Cripton, & Winters, 2009).

4.1 Limitations

While a case-crossover design evaluates the relative risks associated with infrastructure at a point in time, it cannot explain if the installation of a protected bike lane made a roadway safer or less safe. Protected bike lanes are typically installed on major thoroughfares where more protection for cyclists is warranted. It is crucial that controlled before-after studies of protected bike lanes are performed in the United States to inform policy decisions of if these lanes should be built. Similarly, while the case-crossover design accounted for cyclist activity, the current study did not incorporate motor vehicle and pedestrian volumes because they were not consistently available. Higher motor vehicle and pedestrian volumes would make crashes with these road users more likely and having this information could better elucidate why crash types occurred at particular sites. Patients who died or who could not remember their route due to head injuries were excluded, so by design we did not include the most severely injured patients.

There were some regional differences among the three cities studied, and effects may not generalize to all environments. For example, sidewalks were associated with low risk in Portland and high risk in New York City, which might reflect relative congestion of the sidewalks in those cities. Data on street-level two-way protected bike lanes came mostly from Washington, with one two-way lane/two-way road section of 15th Street a risky standout, and two-way protected bike lanes raised from the road and on bridges were mainly in New York. Different implementations of two-way protected bike lanes may not perform similarly in other locations.

A cyclist's recollections of characteristics of their route may not have always been correct. The primary analysis was repeated excluding the 46 patients who reported being in a route type that was not present at the case or control site where the lapse could not be explained by misnaming (e.g., calling sharrows or a multiuse trail a bike lane), and results stayed the same (Table A4). Although Google Street View has been validated as a reliable alternative to in-person site visits for determining infrastructure features (Mooney et al., 2016; Nesoff et al., 2018), our method was not able to capture temporary alterations to facilities, such as changes due to construction, that may have happened between the Google Street View capture and the trip dates.

4.2 Conclusions

Protected bike lanes increase ridership, but designs vary in the amount of potential conflict points and complexity for crossing vehicles to navigate. Some designs may introduce new hazards that increase the risk of a crash or fall resulting in emergency department attendance without eliminating crashes with motor vehicles. Planners should consider the number of intersections with roads, driveways, and alleys when choosing where to place protected bike lanes and should implement countermeasures to maximize the visibility of cyclists at these conflict points when they are unavoidable. Designs with continuous separation and few conflict points appear to diminish hazards and carry a low risk of crashes or falls, while the riskiest protected bike lane segment in this study required turning drivers to cross multiple directions of vehicle and bicycle traffic. Future work should more systematically examine the features that lead to higher and lower risk to guide design.

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Table 1. Characteristics of cyclists and their trips (unknown values excluded, total sample N=604)

Characteristic	Number of cyclists with nonmissing values	Percent
Male	604	72.3
Age	603	
18–29		33.3
30–39		29.0
40–49		16.3
50–59		14.3
60–69		5.3
70+		1.8
Regular cyclist	601	82.0
Completed college degree or higher	599	68.9
Income >= $50,000	495	66.7
Race/ethnicity		
White, non-Hispanic	597	66.2
Hispanic		13.9
Black, non-Hispanic		11.4
Asian/Pacific Islander		4.2
Other		4.4
Trip purpose	603	
To/from work/school		54.4
Exercise or recreation		19.4
Personal business (e.g., errands)		10.1
Social reasons (e.g., movies, visit friends)		10.0
During work		5.3
Other		0.8
Weekday	604	82.1
Daylight	604	84.4
Clear weather	597	88.1
Trip distance	604	
<1 mile		33.8
1 to <3 miles		32.8
3 to <5 miles		11.1
5 to <10 miles		13.3
10+ miles		9.1
Helmet used	603	62.5
Shared or rental bike	602	7.3

Table 2. Injury severity among all cyclists and injured body regions of cyclists with moderate or severe (AIS 2+) injuries

Injury characteristic	Percent
Maximum injury severity (AIS)	N=604
AIS 0	3.2
AIS 1	54.8
AIS 2	34.8
AIS 3+	7.3
Injured body regions with AIS 2+ injuries, among cyclists with at least one AIS 2+ injury	N=254
Head	14.6
Face	7.5
Neck	0.4
Thorax	11.0
Abdomen	2.4
Spine	7.9
Extremities	69.7

Note: Some of the 254 cyclists sustained multiple AIS 2+ injuries.

Table 3. Comparison of route types and other characteristics at case and control sites and associated crash/fall risk estimates (N=604)

Characteristic	# of case sites/ # of control sites	Unadjusted OR (95% CI)		Adjusted OR (95% CI)	
Route type					
Major road (ref)	244/187	1.00		1.00	
Bike lane on major road	92/109	0.52*	(0.33, 0.82)	0.53*	(0.33, 0.86)
Sharrows on major road	16/17	0.68	(0.29, 1.61)	0.57	(0.23, 1.43)
Local road, no bike infrastructure/traffic calming	50/79	0.37*	(0.23, 0.61)	0.39*	(0.23, 0.65)
Local road with bike lane, sharrows, or traffic calming	17/27	0.28*	(0.12, 0.67)	0.31*	(0.13, 0.75)
Sidewalk	60/61	0.61	(0.36, 1.05)	0.70	(0.40, 1.22)
Off-road/trail	83/93	0.49*	(0.29, 0.83)	0.60	(0.35, 1.04)
One-way protected bike lane	18/13	1.07	(0.42, 2.72)	1.19	(0.46, 3.10)
Two-way protected bike lane at street level	21/9	8.40*	(1.08, 65.53)	11.38*	(1.40, 92.57)
Two-way protected bike lane raised or on bridge	3/9	0.08*	(0.01, 0.73)	0.10*	(0.01, 0.95)
Grade					
Flat (ref)	277/309	1.00	1.00	1.00	
Downhill	225/167	1.66*	(1.24, 2.23)	1.92*	(1.38, 2.66)
Uphill	75/103	0.82	(0.57, 1.18)	0.81	(0.55, 1.19)
Unknown	27/25	1.27	(0.68, 2.36)	1.50	(0.77, 2.89)
Temporary features					
No (ref)	483/520	1.00		1.00	
Yes	114/75	1.94*	(1.33, 2.84)	2.23*	(1.46, 3.39)
Unknown	7/9	0.88	(0.28, 2.83)	0.73	(0.20, 2.63)
Streetcar or train tracks					
No (ref)	582/600	1.00		1.00	
Yes	22/4	19.00*	(2.54, 141.93)	26.65*	(3.23, 220.17)

Note: Adjusted model included variables listed in table as covariates (route type, grade, temporary features, streetcar or train tracks). OR=odds ratio; CI=confidence interval; *p<0.05.

Table 4. Comparison of route types and other characteristics at case and control sites at intersections and nonintersections and associated crash/fall risk estimates (N=604)

Characteristic	Nonintersection			Intersection		
	# of case sites/ # of control sites	Adjusted OR (95% CI)		# of case sites/ # of control sites	Adjusted OR (95% CI)	
Route type						
Major road (ref)	168/157	1.00		76/30	1.00	
Bike lane on major road	49/102	0.39*	(0.21, 0.72)	43/7	3.87	(0.98, 15.32)
Sharrows on major road	8/16	0.45	(0.14, 1.46)	8/1	6.37	(0.52, 78.41)
Local road	28/68	0.30*	(0.15, 0.58)	22/11	0.59	(0.21, 1.65)
Local road with bike lane, sharrows, or traffic calming	4/24	0.07*	(0.01, 0.34)	13/3	9.09	(0.32, 260.81)
Sidewalk	36/53	0.48*	(0.24, 0.97)	24/8	1.20	(0.41, 3.53)
Off-road/trail	74/90	0.66	(0.35, 1.23)	9/3	1.24	(0.21, 7.16)
One-way cycle track	13/12	1.19	(0.36, 3.91)	5/1	++	
Two-way protected bike lane at street level	11/8	7.80	(0.71, 85.17)	10/1	13.38	(0.78, 228.26)
Two-way protected bike lane raised or on bridge	2/9	0.04*	(0.00, 0.55)	1/0	++	
Grade						
Flat (ref)	188/280	1.00		89/29	1.00	
Downhill	129/147	1.74*	(1.16, 2.61)	96/20	2.17	(0.93, 5.07)
Uphill	51/91	1.00	(0.61, 1.63)	24/12	0.39	(0.14, 1.10)
Unknown	25/21	1.92	(0.92, 4,00)	2/4	0.21	(0.03, 1.60)
Temporary features						
No (ref)	312/466	1.00		171/54	1.00	
Yes	77/65	3.40*	(2.00, 5.78)	37/10	1.38	(0.50, 3.78)
Unknown	4/8	0.89	(0.17, 4.65)	3/1	0.45	(0.03, 6.11)
Streetcar or train tracks						
No (ref)	381/536	1.00		201/64	1.00	
Yes	12/3	10.00*	(1.16, 86.28)	10/1	++	

Note: Adjusted model included variables listed in table as covariates (route type, grade, temporary features, streetcar or train tracks) and the interactions between these and the intersection indicator. OR=odds ratio; CI=confidence interval; *p<0.05; ++model could not produce reliable estimates.

Table 5. Fall or crash circumstances by route type (percent, N=604)

	Crash with or fall to avoid								
Facility type	Moving vehicle	Stopped/ parked vehicle	Other cyclist	Pedestrian	Infrastructure	Surface feature	Other fall	Other/ specifics unknown	Total
Major road (n=244)	45.5	18.0	2.5	0.8	2.9	18.4	10.3	1.6	100
Bike lane on major road (n=92)	50.0	21.7	3.3	2.2	1.1	10.9	8.7	2.2	100
Sharrows on major road (n=16)	43.8	18.8	0	0	0	25.0	12.5	0	100
Local road (n=50)	44.0	4.0	8.0	2.0	8.0	22.0	10.0	2.0	100
Local road with bike lane, sharrows, or traffic calming (n=17)	52.9	0	0	0	5.9	29.4	11.8	0	100
Sidewalk (n=60)	40.0	1.7	1.7	3.3	13.3	11.7	26.7	1.7	100
Off-road/trail (n=83)	10.8	0	19.3	10.8	13.3	14.5	30.1	1.2	100
One-way protected bike lane (n=18)	38.9	11.1	0	22.2	5.6	11.1	11.1	0	100
Two-way protected bike lane at street level (n=21)	33.3	4.8	14.3	23.8	9.5	4.8	9.5	0	100
Two-way protected bike lane raised or on bridge (n=3)	33.3	0	33.3	0	33.3	0	0	0	100
All (n=604)	40.2	12.1	5.6	4.1	6.0	16.1	14.4	1.5	100

Table 6. Fall or crash circumstances, relative to major road, and 95% confidence intervals by route type (N=604)

Route type	Collision with moving vehicle	Collision with stopped/ parked vehicle	Collision with cyclist/ fall to avoid cyclist	Collision with pedestrian/ fall to avoid pedestrian	Collision with infrastructure	Other fall
Major road (ref)	1.00	1.00	1.00	1.00	1.00	1.00
Bike lane on major road	1.10 (0.86, 1.41)	1.21 (0.75, 1.93)	1.33 (0.34, 5.19)	2.65 (0.38, 18.55)	0.38 (0.05, 3.04)	0.85 (0.40, 1.81)
Sharrows on major road	0.96 (0.54, 1.70)	1.04 (0.36, 2.98)	0 (0.00, 9.80)	0 (0.00, 39.53)	0 (0.00, 8.35)	1.22 (0.32, 4.70)
Local road	0.97 (0.69, 1.36)	0.22* (0.06, 0.89)	3.25 (0.95, 11.11)	2.44 (0.23, 26.39)	2.79 (0.85, 9.17)	0.87 (0.39, 2.43)
Local road with bike lane, sharrows, or traffic calming	1.16 (0.73, 1.86)	0 (0.00, 1.26)	0 (0.00, 9.17)	0 (0.00, 37.32)	2.05 (0.27, 15.72)	1.15 (0.30, 4.45)
Sidewalk	0.88 (0.63, 1.23)	0.09* (0.01, 0.66)	0.68 (0.08, 5.52)	4.07 (0.58, 28.29)	4.65* (1.75, 12.31)	2.60* (1.49, 4.56)
Off-road/trail	0.23* (0.13, 0.45)	0* (0.00, 0.25)	7.84* (3.17, 19.37)	13.23* (2.92, 59.99)	4.62* (1.85, 11.53)	2.94* (1.79, 4.82)
One-way cycle track	0.85 (0.47, 1.55)	0.62 (0.16, 2.34)	0 (0.00, 8.88)	27.11* (5.32, 138.16)	1.94 (0.25, 14.89)	1.08 (0.28, 4.22)
Two-way protected bike lane at street level	0.73 (0.39, 1.36)	0.26 (0.04, 1.82)	5.81* (1.56, 21.58)	29.05* (5.99, 140.76)	3.20 (0.74, 14.98)	0.93 (0.24, 3.66)
Two-way protected bike lane raised or on bridge	0.73 (0.15, 3.65)	0 (0.00, 3.84)	13.56* (2.28, 80.77)	0 (0.00, 175.75)	11.62* (2.00, 67.47)	0 (0.00, 6.92)

Note: *$p<0.05$. Circumstances where no route types differed from major roads (surface feature, other/specifics unknown) do not appear in table.

Table 7. Locations and descriptions of protected bike lanes at case and control sites

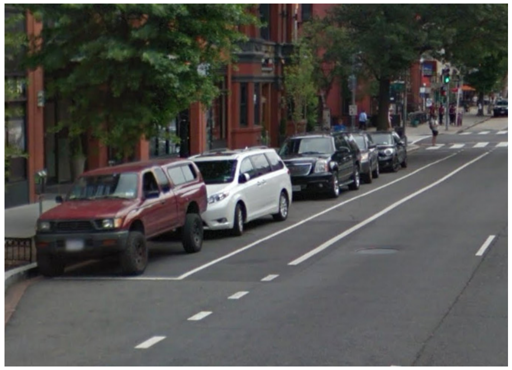
Road	City	Separation	Intersections or ramps crossing lane per mile	Driveways or alleys crossing lane per mile	Painted buffer	Side of street	Direction of adjacent vehicle traffic	# case sites/ # control sites
One way								
L Street NW	DC	Posts, parking curb	11	17	Y	L	One way	2/1
M Street NW	DC	Posts, parked cars	11	13	Y	R	One way	3/1
R Street NE*	DC	Parked cars	17	0	Y	L	One way	0/1
1st Ave	NYC	Parked cars	18	1	Y	L	One way	5/3
2nd Ave	NYC	Parked cars	18	3	Y	L	One way	2/1
6th Ave	NYC	Parked cars	21	0	Y	L	One way	3/2
7th Ave	NYC	Continuous curb, grade	21	0	N	L	One way	1/0
Broadway	NYC	Planters, posts, parked cars	20	2	Y	L	One way	1/1
8th Ave	NYC	Parked cars	20	<1	Y	L	One way	0/1
9th Ave	NYC	Parked cars	20	1	Y	L	One way	0/1
Columbus Ave	NYC	Parked cars	17	0	Y	L	One way	0/1
Hawthorne Blvd	Portland	Posts	13	0	Y	R	One way	1/0
Two way, street level								
15th Street NW	DC	Posts, parked cars	15	14	Y	L	One way	3/4
15th Street NW	DC	Posts, parked cars	7	6	Y	S	Two way	10/1
Pennsylvania Ave NW	DC	Parking curb	12	0	Y	C	Two way	5/2
1st Street NE	DC	Continuous curb, posts, parking curb	7	9	N	S	Two way	1/1
Kent Ave	NYC	Parked cars	10	10	Y	L	One way	2/0
Kent Ave	NYC	Posts	6	14	Y	S	Two way	0/1
Two way, raised or bridge								
Williamsburg Bridge	NYC	Bridge rail	0	0	N	S	Two way	2/3
Manhattan Bridge	NYC	Bridge rail	1	0	N	S	Two way	1/1
Hudson River Greenway	NYC	Grade, trees, landscaping	4	2	N	S	Two way	0/1
Pulaski Bridge	NYC	Concrete barrier topped with rail	4	0	N	S	Two way	0/1
Queens Boulevard	NYC	Concrete barrier topped with rail	8	0	N	S	Two way	0/1
Queensboro Bridge Greenway	NYC	Grade, concrete wall, trees, landscaping	14	0	N	C	Two way	0/1
Southwest Moody Ave	Portland	Grade, railing	8	3	N	S	Two way	0/1

Note: Not all separation types were used concurrently for entire lane. DC=Washington DC; NYC=New York City; L=left, R=right, C=center, S=side of two-way street. *denotes contraflow lane; other lanes on one-way streets followed direction of traffic.

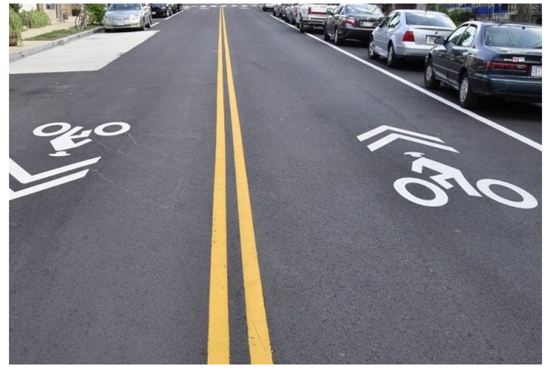
Table 8. Distribution of junction types and incident circumstances by location and type of street-level protected bike lane (percent of each protected bike lane type in parentheses)

City	Type	Junction type				Incident circumstances			
		Intersection	Alley or driveway	Junction with exit ramp	Nonjunction	Moving vehicle	Pedestrian	Other cyclist	Other circumstance
Washington	One way, curbside (N=5)	2 (40.0%)	2 (40.0%)	0	1 (20.0%)	3 (60.0%)	1 (20.0%)	0	1 (20.0%)
	Two way, curbside (N=14)	6 (42.9%)	3 (21.4%)	0	5 (35.7%)	6 (42.9%)	3 (21.4%)	3 (21.4%)	2 (14.3%)
	Two way, center of road (N=5)	4 (80.0%)	0	0	1 (20.0%)	1 (20.0%)	2 (40.0%)	0	2 (40.0%)
New York	One way, curbside (N=12)	3 (25.0%)	0	0	9 (75.0%)	3 (25.0%)	3 (25.0%)	0	6 (50.0%)
	Two way, curbside (N=2)	0	1 (50.0%)	0	1 (50.0%)	0	0	0	2 (100.0%)
Portland	One way, curbside (N=1)	0	0	1 (100.0%)	0	1 (100.0%)	0	0	0

Figure 1. Bike lane (a), sharrows (b), one-way protected bike lane (c, 1st Avenue, New York), two-way protected bike lane at street level (d, 15th Street Northwest, Washington), two-way protected bike lane raised from road (e, Hudson River Greenway in Battery Park, New York), and two-way protected bike lane on bridge (f, Pulaski Bridge, New York)



(a)



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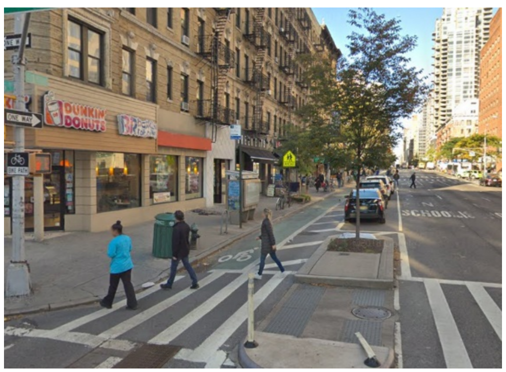

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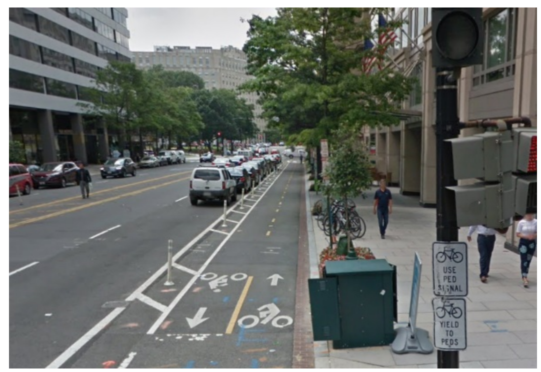

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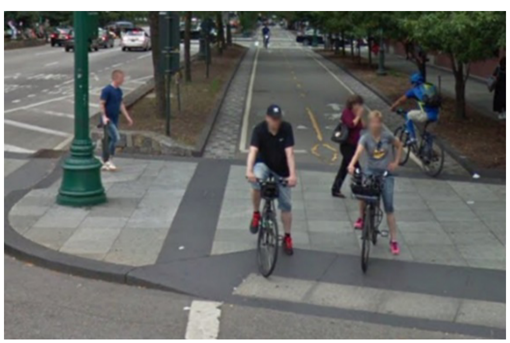

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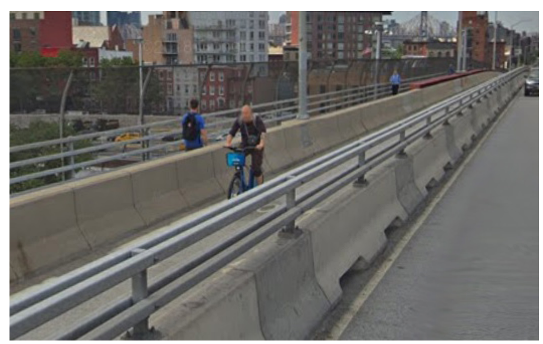

(f)

APPENDIX

Table A1. Comparison of route types and other characteristics at case and control sites in Washington, DC, and associated crash/fall risk estimates (N=354)

Characteristic	# of case sites/ # of control sites	Adjusted OR (95% CI)	
Route type			
Major road (ref)	137/101	1.00	
Bike lane on major road	44/66	0.41*	(0.22, 0.76)
Sharrows on major road	8/9	0.53	(0.16, 1.79)
Local road	32/47	0.49*	(0.26, 0.91)
Local road with bike lane, sharrows, or traffic calming	8/10	0.53	(0.16, 1.73)
Sidewalk	51/60	0.46*	(0.23, 0.92)
Off-road/trail	50/50	0.73	(0.38, 1.41)
One-way cycle track	5/3	1.62	(0.26, 9.96)
Two-way protected bike lane at street level	19/8	9.36*	(1.15, 76.07)
Two-way protected bike lane raised from road or on bridge	0/0	++	
Grade			
Flat (ref)	152/173	1.00	
Downhill	146/111	1.69*	(1.14, 2.49)
Uphill	45/56	0.89	(0.54, 1.47)
Unknown	11/14	0.73	(0.29, 1.89)
Temporary features			
No (ref)	269/289	1.00	
Yes	84/58	1.79*	(1.10, 2.90)
Unknown	1/7	++	
Streetcar or train tracks	1/0	++	

Note: Adjusted model included variables listed in table as covariates (route type, grade, temporary features, streetcar or train tracks). OR=odds ratio; CI=confidence interval; **p*<0.05; ++model could not produce reliable estimates.

Table A2. Comparison of route types and other characteristics at case and control sites in New York City and associated crash/fall risk estimates (N=119)

Characteristic	# of case sites/ # of control sites	Adjusted OR	(95% CI)
Route type			
Major road (ref)	65/56	1.00	
Bike lane on major road	11/15	0.32	(0.06, 1.64)
Sharrows on major road	8/7	0.45	(0.09, 2.32)
Local road	6/9	0.18	(0.03, 1.04)
Local road with bike lane, sharrows, or traffic calming	1/4	0.08	(0.00, 1.75)
Sidewalk	6/8	0.68	(0.12, 3.68)
Off-road/trail	5/1	6.66	(0.56, 78.78)
One-way cycle track	12/10	0.81	(0.22, 2.96)
Two-way protected bike lane at street level	2/1	++	
Two-way protected bike lane raised from road or on bridge	3/8	0.12	(0.01, 1.76)
Grade			
Flat (ref)	82/86	1.00	
Downhill	22/14	2.18	(0.83, 5.73)
Uphill	13/17	0.67	(0.24, 1.85)
Unknown	2/2	0.64	(0.05, 8.12)
Temporary features			
No (ref)	99/112	1.00	
Yes	16/5	5.77*	(1.57, 21.20)
Unknown	4/2	2.38	(0.15, 37.75)
Streetcar or train tracks[a]	0/0		

Note: Adjusted model included variables listed in table as covariates (route type, grade, temporary features, streetcar or train tracks). OR=odds ratio; CI=confidence interval; *$p<0.05$; ++model could not produce reliable estimates. [a]variable not included in model.

Table A3. Comparison of route types and other characteristics at case and control sites in Portland, OR and associated crash/fall risk estimates (N=131)

Characteristic	# of case sites/ # of control sites	Adjusted OR	(95% CI)
Route type			
Major road (ref)	42/30	1.00	
Bike lane on major road	37/28	0.74	(0.20, 2.59)
Sharrows on major road	0/1	++	
Local road	12/23	0.16*	(0.04, 0.64)
Local road with bike lane, sharrows, or traffic calming	8/13	0.13*	(0.02, 0.98)
Sidewalk	26/25	0.66	(0.13, 3.27)
Off-road/trail	5/10	0.14*	(0.02, 1.00)
One-way cycle track	1/0	++	
Two-way protected bike lane at street level	0/0	++	
Two-way protected bike lane raised from road or on bridge	0/1	++	
Grade			
Flat (ref)	43/50	1.00	
Downhill	57/42	3.62*	(1.32, 9.95)
Uphill	17/30	0.53	(0.18, 1.59)
Unknown	14/9	3.22	(0.79, 13.08)
Temporary features			
No (ref)	115/119	1.00	
Yes	14/12	2.47	(0.54, 11.37)
Unknown	2/0	++	
Streetcar or train tracks	21/4	66.44*	(5.06, 872.75)

Note: Adjusted model included variables listed in table as covariates (route type, grade, temporary features, streetcar or train tracks). OR=odds ratio; CI=confidence interval; *p<0.05; ++model could not produce reliable estimates.

Table A4. Comparison of route types and other characteristics at case and control sites and associated crash/fall risk estimates, among patients who reported being in route types that were present at the sites

Characteristic	# of case sites/ # of control sites	Adjusted OR	(95% CI)
Route type			
Major road (ref)	221/168	1.00	
Bike lane on major road	87/101	0.53*	(0.32, 0.89)
Sharrows on major road	14/16	0.51	(0.20, 1.32)
Local road	47/71	0.42*	(0.24, 0.72)
Local road with bike lane, sharrows, or traffic calming	16/26	0.31*	(0.13, 0.75)
Sidewalk	78/90	0.57	(0.32, 1.01)
Off-road/trail	54/55	0.67	(0.37, 1.22)
One-way cycle track	17/13	1.08	(0.40, 2.88)
Two-way protected bike lane at street level	21/9	11.37*	(1.39, 92.68)
Two-way protected bike lane raised from road or on bridge	3/9	0.09*	(0.01, 0.90)
Grade			
Flat (ref)	250/288	1.00	
Downhill	214/155	2.04*	(1.45, 2.88)
Uphill	67/93	0.81	(0.53, 1.22)
Unknown	27/22	1.84	(0.92, 3.68)
Temporary features			
No (ref)	447/478	1.00	
Yes	104/73	2.02*	(1.31, 3.14)
Unknown	7/7	0.97	(0.24, 3.89)
Streetcar or train tracks			
No (ref)	537/554	1.00	
Yes	21/4	25.25*	(3.03, 210.62)

(N=558)

Note: Adjusted model included variables listed in table as covariates (route type, grade, temporary features, streetcar or train tracks). OR=odds ratio; CI=confidence interval; *$p<0.05$.