Route Infrastructure and the Risk of Injuries to Bicyclists: A Case-Crossover Study

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Objectives. We compared cycling injury risks of 14 route types and other route infrastructure features.

Methods. We recruited 690 city residents injured while cycling in Toronto or Vancouver, Canada. A case-crossover design compared route infrastructure at each injury site to that of a randomly selected control site from the same trip.

Results. Of 14 route types, cycle tracks had the lowest risk (adjusted odds ratio [OR] = 0.11; 95% confidence interval [CI] = 0.02, 0.54), about one ninth the risk of the reference: major streets with parked cars and no bike infrastructure. Risks on major streets were lower without parked cars (adjusted OR = 0.63; 95% CI = 0.41, 0.96) and with bike lanes (adjusted OR = 0.54; 95% CI = 0.29, 1.01). Local streets also had lower risks (adjusted OR = 0.51; 95% CI = 0.31, 0.84). Other infrastructure characteristics were associated with increased risks: streetcar or train tracks (adjusted OR = 3.0; 95% CI = 1.8, 5.1), downhill grades (adjusted OR = 2.3; 95% CI = 1.7, 3.1), and construction (adjusted OR = 1.9; 95% CI = 1.3, 2.9).

Conclusions. The lower risks on quiet streets and with bike-specific infrastructure along busy streets support the route-design approach used in many northern European countries. Transportation infrastructure with lower bicycling injury risks merits public health support to reduce injuries and promote cycling. (*Am J Public Health.* 2012;102:2336–2343. doi:10.2105/AJPH.2012.300762)

Bicycling is an active mode of transportation with a range of individual and public health benefits.[1–5] However, bicycling is underused for transportation in Australia, Canada, Ireland, the United States, and the United Kingdom, constituting an estimated 1% to 3% of trips, compared with 10% to 27% of trips in Denmark, Germany, Finland, the Netherlands, and Sweden.[6–8] The reasons for low bicycle share of trips are multifaceted, but safety is one of the most frequently cited deterrents.[9–11] These concerns are well founded: bicycling injury rates are higher in countries where cycling for transportation is less common.[8,12,13]

To reduce bicycling injuries, the first step is to understand the determinants of risk. Studies in many English-speaking countries have focused on head injury reductions afforded by helmets.[14–17] However, helmet use cannot explain the risk difference because helmets are rarely used in the European countries with lower injury rates.[8,18,19] Typical route infrastructure (physical transportation structures and facilities) in countries with low bicycle share of trips differs from that in countries with high trip shares. In Germany, Denmark, and the Netherlands, bicycle-specific infrastructure is frequently available,[20] so this is a promising avenue for investigating injury risks. In a review of route infrastructure and injury risk,[21] we found some evidence that bicycle-specific infrastructure was associated with reduced risk. However, the studies reviewed had problems that have compromised confidence in the results: grouping of route categories that may have different risks, unclear definitions of route infrastructure, and difficulty controlling for characteristics of cyclists and for exposure to various route types. Debates continue about the contribution of route design to safety and about the safety of various route types.[12,13,20,21]

Here we present a study designed to overcome these limitations.[22] We examined injury risk of 14 route types using a case-crossover design in which injured participants served as their own controls. The design compared route characteristics at the location where the injury event occurred to those at a randomly selected point on the same trip route where no injury occurred. By randomly selecting the control site in this way, the probability that a specific infrastructure type would be chosen was proportional to its relative length on the trip (e.g., on a 4-km trip, there would be a 25% chance of selecting a control site on a 1-km section that was on a bike path). Because comparisons were within-trip, personal characteristics such as age, gender, and propensity for risk-taking behavior were matched, as were trip conditions such as bicycle type, clothing visibility, helmet use, weather, and time of day. This allowed the comparisons to focus on between-site infrastructure differences.

METHODS

The study was conducted in the cities of Toronto and Vancouver, Canada. At the time of the study, Toronto had a population of about 2.5 million, 1.7% of trips by bicycle, 11 kilometers of bike lanes and paths per 100 000 population, snowy winter weather, and warm summer weather. Vancouver had a population of about 0.6 million, 3.7% of trips by bicycle, 26 kilometers of bike lanes and paths per 100 000 population, rainy winter weather, and mild summer weather.[7] Although they do not cover the entire range of cycling infrastructure, together they include most route designs available in North America.

Participant Selection

The study population consisted of adults (≥ 19 years) who were injured during bicycle riding and treated within 24 hours in the emergency departments of the following hospitals between May 18, 2008 and November 30, 2009: St. Paul's or Vancouver General in Vancouver; St. Michael's, Toronto General, or Toronto Western in Toronto. All are teaching hospitals based either in the downtown core or a major business district; 1 hospital in each city was also a regional trauma center.

Research staff at each hospital identified injured cyclists and provided contact information to study coordinators in each city. The coordinator sent an introductory letter to each potential participant, conducted a screening phone interview for eligibility 1 to 2 weeks later, and arranged an interview if the individual was eligible and willing to participate. Eligibility criteria were designed primarily to ensure that participants could retrace their injury trip, and that they were riding in the city using a cycling mode for which urban cycling infrastructure is designed. They excluded the following: those who lived or were injured outside of Toronto or Vancouver or who had no known address or phone number; those who were fatally injured, unable to communicate either because of their injuries or because of language difficulties, or unable to remember the injury trip; those injured riding on private property or during a trip in which they were trick riding, racing, mountain biking, or participating in a critical mass ride; those who were riding a motorized bike, unicycle, or tandem bike; and those who had already participated in the study after an earlier injury.

Study candidates who were not contacted and recruited within 3 months of the injury event were not included in the study. This criterion reinforced the likelihood that participants could accurately retrace their injury trip, but to provide a conservative estimate of the participation rate, injured cyclists not included for this reason were not counted as ineligible.

Interviews

Participants were interviewed as soon as possible after the injury incident to maximize recall (50% completed within 4.9 weeks, 75% within 7.7). Trained interviewers, using a structured questionnaire that took 25 to 45 minutes to complete, conducted in-person interviews. The questionnaire (http://cyclingincities.spph.ubc.ca/files/2011/10/InterviewFormFinal.pdf) was pretested on 22 cyclists to ensure that the questions were clearly worded, respondents exhibited willingness to answer them, and trip routes could be mapped to locate injury and control sites for subsequent observations.

The primary purpose of the interview was to trace the route of the injury trip on a city map (scale 1:31 250) and note the injury site. Distance traveled was measured using a digital map wheel (Calculated Industries ScaleMaster 6020 Classic, Carson City, NV). A control site on the same route was identified by multiplying a randomly generated proportion by the trip distance, and then tracing the resulting distance along the route using the map wheel. The interviews queried the following: where the participant was riding at the injury and control

TABLE 1—Definitions of the 14 route types

Route type	Definition
Major street,[a] with parked cars	Paved city street with at least 2 demarcated moving lanes of motor vehicle traffic, with parked cars on the cyclist's side of the street
No bike infrastructure	No bicycle markings on street surface, bike signage on posts may be present
Shared lane	Markings on street surface indicating shared bike-HOV lane, shared bike-bus lane, or sharrows indicating bikes and motor vehicles share space
Bike lane	Bike-only lane marked with solid or dotted lines on street surface
Major street,[a] no parked cars	Paved city street with at least 2 demarcated moving lanes of motor vehicle traffic, no parked cars
No bike infrastructure	No bicycle markings on the street surface, bike signage on posts may be present
Shared lane	Markings on street surface indicating shared bike-HOV lane, shared bike-bus lane or sharrows indicating bikes and motor vehicles share space
Bike lane	Bike-only lane marked with solid or dotted lines on street surface
Local street[b]	Paved city street with no demarcated lanes of motor vehicle traffic; car parking may be allowed or not
No bike infrastructure	No bike signage or markings on the street surface
Designated bike route	Bike signage on the street surface or on posts, indicating designated bike route; may have bicyclist operated traffic signals at intersections with major streets
Designated bike route with traffic calming	Bike signage on the street surface or on posts, indicating designated bike route; may have bicyclist operated traffic signals at intersections with major streets; traffic calming measures may include speed humps or bumps, traffic circles, traffic diverters, medians, or street width restrictions via corner bulges or planters
Off-street route	Route that is physically separated from traffic, at least on straightaways between intersections
Sidewalk or other pedestrian path	Paved path meant for pedestrian use, either alongside city streets or away from streets (e.g., in parks)
Multiuse path, paved	Paved path meant for nonmotorized use by pedestrians, cyclists, skaters and others, either alongside city streets or away from streets (e.g., in parks)
Multiuse path, unpaved	Unpaved path meant for nonmotorized use by pedestrians, cyclists, skaters and others, either alongside city streets or away from streets (e.g., in parks)
Bike path	Paved path meant for cyclist use away from streets, (e.g., in parks)
Cycle track	Paved path meant for cyclist use alongside major streets, separated by a physical barrier (e.g., a curb or bollards)

Note. HOV = high occupancy vehicle.

[a] Major streets included the following street types based on transportation engineering nomenclature: arterials (most with > 2 demarcated lanes); and collectors (most with 2 demarcated lanes).

[b] In this study, most local streets were in residential areas.

sites (e.g., street or sidewalk); temporary features (e.g., construction) at each site; characteristics of the trip (e.g., time of day and circumstances of the injury event); and personal characteristics (e.g., age, gender, education, household income, cycling frequency).

Site Observations

Data about route infrastructure at the injury and control sites were collected during structured site observations (http://cyclingincities.spph.ubc.ca/files/2011/10/SiteObservationFormFinal.pdf) by trained personnel blinded to site status. Observations were conducted at a time that conformed as closely as possible to the time of the injury trip (i.e., season; weekday vs weekend; morning rush, midday, afternoon rush, evening, night). The following details were recorded: type of street or path; whether the site was at an intersection; presence of junctions, street lighting, or streetcar or train tracks; slope of the surface (measured using a Suunto PM-5 clinometer, Vantaa, Finland); distance visible along the direction of travel (measured using a Rolatape Measure Master MM-12 trundle wheel, Watseka, IL); counts of cyclist and motor vehicle or pedestrian traffic volume in 5 minutes; and average motor vehicle traffic speed (5 vehicles measured at normal traffic speeds, using a Bushnell Velocity Speed Gun, Overland Park, KS). The site observation method underwent pretesting and revision at 16 sites, then reliability testing at 25 sites by 3 observers. Variables presented in this analysis had raw agreements (all 3 observers) of 0.74 to 1.0 and Fleiss' κ[23] for agreement beyond chance of 0.73 to 1.0.

Data Analysis

We used inferential analyses (SAS version 9.2; SAS Institute, Cary, NC) to examine associations between the cycling environment and the binary dependent variable (1 = injury site or 0 = control site), using the following logistic regression model:

$$\log\left[\pi_{ij}/(1-\pi_{ij})\right] = \alpha_i + x_{ij1}\beta_1 + x_{ij2}\beta_2 + \ldots + x_{ijp}\beta_p, \tag{1}$$

where π_{ij} is the probability of injury for i^{th} individual and j^{th} site, given the covariates $x_{ij1}, x_{ij2}, \ldots, x_{ijp}$. $i = 1, \ldots, N$; $j = 1$ for injury site, $j = 0$ for control site. N is the number of individuals and p is the number of covariates. The conditional likelihood method in Proc Logistic was used to estimate parameters $\beta_1, \ldots, \beta_p$.

TABLE 2—Characteristics of the Study Participants and the Bicycling Trips During Which They Were Injured: Vancouver and Toronto, Canada; 2008–2009

	No. (%)
Participant characteristics	
Male	410 (59.4)
Female	280 (40.6)
Age, y (n = 685)	
19–29	250 (36.5)
30–39	177 (25.8)
40–49	108 (15.8)
50–59	91 (13.3)
60–69	49 (7.2)
≥ 70	10 (1.5%)
Regular cyclist (cycled ≥ 52 times/y)	608 (88.1)
Completed postsecondary diploma or degree	518 (75.1)
Employed	546 (79.1)
Income > $50 000 (n = 610)	341 (55.9)
Trip characteristics	
Purpose	
To/from work/school	287 (41.6)
Exercise or recreation	177 (25.7)
Social reasons (e.g., movies, visit friends)	159 (23.0)
Personal business (e.g., shopping, doctor's visit)	126 (18.3)
During work	17 (2.5)
Timing	
Weekday	531 (77.0)
Daylight hours (i.e., not dawn, dusk, or night)	535 (77.5)
Rainy or snowy weather	52 (7.5)
Distance, km	
< 2	249 (36.1)
2–< 5	221 (32.0)
5–< 10	138 (20.0)
10–< 20	48 (7.0)
≥ 20	34 (4.9)
Protective gear used	
Helmet	478 (69.3)
High visibility clothing on torso	273 (39.6)
Injury event involved	
Collision with motor vehicle	231 (33.5)
Collision with surface feature (e.g., streetcar or train tracks, pothole, rock)	170 (24.6)
Collision with route infrastructure (e.g., post, curb, planter, lane divider)	50 (7.2)
Collision with other person or animal (i.e., cyclist, pedestrian, skater, dog)	46 (6.7)
Fall while trying to avoid a collision	60 (8.7)
Fall in other circumstances	133 (19.3)

Note. The sample size was n = 690 (participants and injury trips).

The primary analysis examined the association of injuries with route type. Site observations were used to classify routes into 14 categories corresponding to those used in a survey of route preferences conducted in Metro Vancouver in 2006.[24] Table 1 provides the definitions of each route type, determined with input from city bicycle transportation engineers and bicycling advocates. Secondary analyses examined associations with other infrastructure features. Each was initially examined separately then offered in a single model with route type. Based on results of the Wald test for each variable, the variable with the highest nonsignificant P value was removed and the model refit with the remaining variables until all variables in the model were significant ($P < .05$).

RESULTS

Of 2335 injured cyclists who attended 1 of the 5 hospital emergency departments during the 18-month study period, 927 were ineligible, 741 were eligible, and 690 agreed to participate (93.1% of known eligible), 414 from Vancouver and 276 from Toronto (Figure A, available as a supplement to the online version of this article at http://www.ajph.org). There were 667 with unknown eligibility. Assuming that the proportion eligible in this group was the same as among those with known eligibility, we estimated the participation rate as 66.5% (Figure A). The mean ages of participants, the ineligible, those who could not be contacted, and those who refused were very similar (36, 36, 35, and 37 years old, respectively), but the gender distributions differed (59%, 73%, 71%, and 66% male, respectively). The ineligible and those who could not be contacted had similar high proportions of men.

Table 2 lists participant and trip characteristics. Most participants were men, younger than 40 years, well-educated, employed, regular cyclists, and earned more than $50 000 a year. Most of the injury trips were utilitarian in nature, on weekdays, during daylight hours, and short (< 5 km). Most cyclists wore helmets on the trip, although the proportions varied by city, reflecting provincial legislation that requires adults to wear helmets in Vancouver (76%) but not Toronto (59%). Less than half wore high-visibility clothing on their torso. Most of the injury events were collisions (72%). About one third of all events involved direct collisions with motor vehicles; another 14% involved motor vehicles indirectly (e.g., avoidance maneuvers; data not shown).

Route Types

Table 3 outlines behavioral and physical characteristics related to the 14 route types (defined in Table 1). Median motor vehicle speeds and traffic counts on major streets were higher than on local streets. Median bike traffic counts were highest on cycle tracks, bike lanes, and paved multiuse paths. Designated bike routes on local streets and shared lanes on major streets were rarely flat. Streetcar or train tracks were most frequently located on major streets without bike infrastructure; almost all were in Toronto (98%). Construction was somewhat more frequent on shared lanes, multiuse paths, and bike paths.

TABLE 3—Characteristics of the 14 Route Types at Randomly Selected Control Sites Along Injury Trip Routes: Vancouver and Toronto, Canada; 2008–2009

Route type	Observed Sites, No.	Motor Vehicle Speed (km/h), Median (25th-75th Percentile)	Motor Vehicle Traffic Count (per h), Median (25th-75th Percentile)	Cyclist Traffic Count (per h), Median (25th-75th Percentile)	Pedestrian Traffic Count (per h), Median (25th-75th Percentile)	Flat Grade (0°), %	Streetcar or Train Tracks Present, %	Construction Under Way, %
Major street, with parked cars								
No bike infrastructure	114	38 (31–44)	816 (528–1044)	24 (12–60)	. . .	56.1	40.4	1.8
Shared lane	7	44 (38–48)	1584 (1092–2160)	24 (12–48)	. . .	14.3	0.0	14.3
Bike lane	28	38 (33–43)	708 (426–1026)	60 (6–168)	. . .	60.7	7.1	3.6
Major street, no parked cars					. . .			
No bike infrastructure	118	40 (34–46)	912 (552–1152)	24 (0–72)	. . .	47.5	35.6	6.8
Shared lane	12	40 (35–44)	1068 (702–1272)	48 (12–114)	. . .	25.0	25.0	25.0
Bike lane	46	42 (37–53)	942 (648–1524)	78 (12–156)	. . .	54.4	2.2	6.5
Local street					. . .			
No bike infrastructure	116	31 (25–34)	48 (12–114)	0 (0–12)	. . .	34.5	1.7	4.3
Designated bike route	57	32 (29–35)	72 (36–132)	36 (12–108)	. . .	17.5	1.8	7.0
Designated bike route with traffic calming	47	29 (28–35)	48 (36–84)	48 (24–96)	. . .	17.0	0.0	6.4
Off-street route								
Sidewalk or other pedestrian path	47	. . .	. . .	0 (0–0)	60 (12–132)	53.2	0.0	8.5
Multiuse path, paved	56	. . .	. . .	72 (24–168)	54 (0–132)	64.3	1.8	16.1
Multiuse path, unpaved	11	. . .	. . .	0 (0–24)	12 (0–24)	54.6	0.0	0.0
Bike path	21	. . .	. . .	48 (12–96)	0 (0–12)	81.0	0.0	14.3
Cycle track	10	. . .	. . .	114 (72–156)	24 (0–48)	40.0	0.0	0.0

Note. Ellipses indicate motor vehicle speeds and counts not measured on off-street route types or pedestrian counts not measured on streets. The sample size was n = 690 injury trips.

TABLE 4—Comparison of Route Types and Other Infrastructure Characteristics of the Injury Sites to Randomly Selected Control Sites Within the Same Trip Routes: Vancouver and Toronto, Canada; 2008–2009

Variable	No. Injury Sites/No. Control Sites	Unadjusted OR (95% CI)	Adjusted OR (95% CI)
Major street route, parked cars[a]			
No bike infrastructure	155/114	1.00 (Ref)	1.00 (Ref)
Shared lane	9/7	0.78 (0.25, 2.41)	0.71 (0.21, 2.45)
Bike lane	25/28	0.53 (0.26, 1.07)	0.69 (0.32, 1.48)
Major street route, no parked cars			
No bike infrastructure	112/118	0.65* (0.44, 0.97)	0.63* (0.41, 0.96)
Shared lane	13/12	0.66 (0.24, 1.82)	0.60 (0.21, 1.72)
Bike lane	35/46	0.47* (0.26, 0.83)	0.54 (0.29, 1.01)
Local street route			
No bike infrastructure	89/116	0.44* (0.28, 0.70)	0.51* (0.31, 0.84)
Designated bike route	52/57	0.53* (0.30, 0.94)	0.49* (0.26, 0.90)
Designated bike route with traffic calming	49/47	0.59 (0.32, 1.07)	0.66 (0.35, 1.26)
Off-street route			
Sidewalk or other pedestrian path	52/47	0.73 (0.42, 1.28)	0.87 (0.47, 1.58)
Multiuse path, paved	64/56	0.75 (0.42, 1.34)	0.79 (0.43, 1.48)
Multiuse path, unpaved	12/11	0.63 (0.21, 1.85)	0.73 (0.23, 2.28)
Bike path	21/21	0.54 (0.20, 1.45)	0.59 (0.20, 1.76)
Cycle track	2/10	0.12* (0.03, 0.60)	0.11* (0.02, 0.54)
Grade, degree			
0 (flat)	245/312	1.00 (Ref)	1.00 (Ref)
< 0 (downhill)	333/231	2.13* (1.61, 2.81)	2.32* (1.72, 3.13)
> 0 (uphill)	112/147	1.07 (0.76, 1.50)	1.13 (0.79, 1.63)
Streetcar or train tracks			
No	540/592	1.00 (Ref)	1.00 (Ref)
Yes	150/98	3.48* (2.14, 5.65)	3.04* (1.80, 5.11)
Construction			
No	605/644	1.00 (Ref)	1.00 (Ref)
Yes	85/46	2.05* (1.39, 3.04)	1.93* (1.27, 2.94)

Note. CI = confidence interval; OR = odds ratio. Analysis was performed via logistic regression, conditional on participant injury trip, for each variable separately and in a multiple logistic regression model.
[a] Parked cars on the cyclist's side of the street.
**P* <.05.

Injury Risks and Infrastructure

Table 4 lists the odds ratios (ORs) comparing injury sites to randomly selected control sites within the same trips, for all characteristics that were statistically significant in unadjusted or adjusted analyses. We designated the most frequently observed route type as the reference category: major streets with parked cars and no bike infrastructure. All other route types had lower injury ORs. The following 5 route types had significantly lower risks in the unadjusted analysis: major streets without parked cars and with no bike infrastructure, major streets without parked cars and with bike lanes, local streets with no bike infrastructure, local streets designated as bike routes, and cycle tracks. Three other infrastructure characteristics were significantly associated with increased injury ORs in unadjusted analyses: downhill grades, streetcar or train tracks, and construction. ORs in the multiple logistic regression model were very similar to the unadjusted estimates.

The following infrastructure elements were not significantly associated with injury risk: site at an intersection (OR = 0.96; 95% confidence interval [CI] = 0.76, 1.2); presence of junctions (e.g., driveways, lanes) in the previous 100 meters (OR = 1.2; 95% CI = 0.86, 1.6); presence of bike signage on major streets (OR = 0.80; 95% CI = 0.55, 1.2); number of marked traffic lanes, compared with none (2 lanes: OR = 1.2; 95% CI = 0.79, 1.8; >2 lanes: OR = 1.4; 95% CI = 0.97, 1.9); and distance visible along the route, compared with 20 meters or greater (<20 m: OR = 1.20; 95% CI = 0.52, 2.8). Note that these variables were not included in the final model, so these ORs are unadjusted.

DISCUSSION

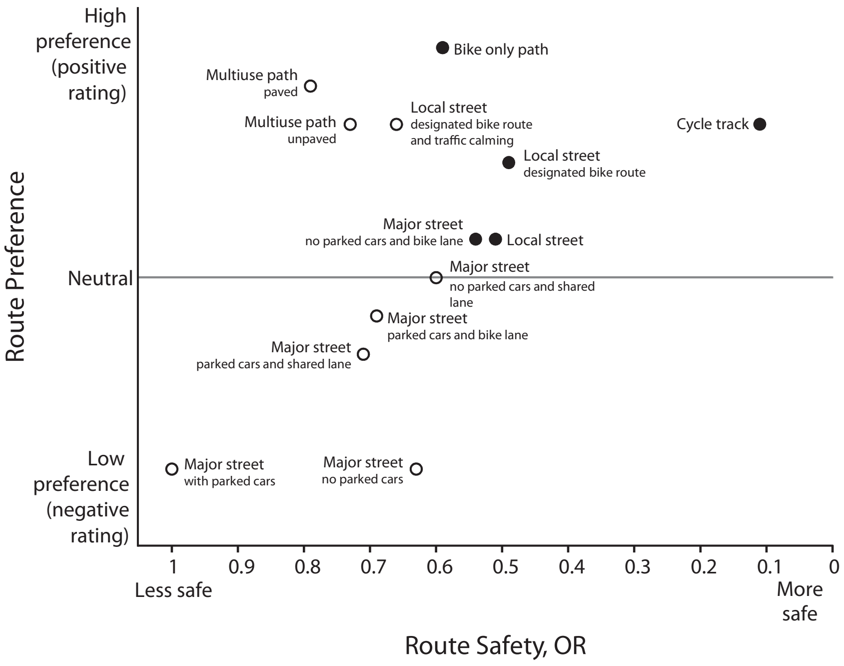
In this study, route type was associated with injury risk. Cycle tracks had the lowest injury risk, about one ninth the risk of the reference route type. Bike lanes on major streets with no parked cars and off-street bike paths had nearly half the risk of the reference. Route characteristics other than bike infrastructure were also associated with risk reductions: quiet streets (i.e., local streets); and no car parking on major streets. Shared bike infrastructure (shared lanes, multiuse paths) and pedestrian infrastructure had small risk reductions, and none were significant.

These findings reinforce some conclusions of our recent review: that busy streets are associated with higher risks than quiet streets; and that bicycle-specific facilities are associated with lower risks.[21,25–32] Many, though not all, of the previously reviewed studies found higher risks on off-street route types,[27,29–34] but this was not the case in the present study. Our study did not include injury events sustained during mountain biking; this may account for at least some of the difference. Most previous studies grouped off-street routes into only 1 or 2 categories, typically sidewalks and other off-street routes. Our study was able to differentiate within these categories; we found that sidewalks and multiuse paths presented higher risks than bike-only paths and cycle tracks.

The higher risk estimates for undifferentiated off-street routes observed in previous studies have been used to recommend against bike-specific infrastructure in Canada and the United States.[35] This point of view has had a dominant influence on bike transportation facilities in North America for the last 40 years, and has resulted in the very different infrastructure available compared with continental European countries with higher cycling rates.[20,36] Cycle tracks highlight the difference: they are common alongside major city streets in the Netherlands and Denmark, but rare in North America, Australia, and the United Kingdom. Cycle tracks had the lowest risk in this study, statistically significant despite their low prevalence in Toronto and Vancouver. Most studies of cycle tracks elsewhere have shown risk reductions: in Montreal (relative risk = 0.72 vs nearby streets), in Copenhagen (0.59 vs before cycle track installation [our calculation] and 1.10 vs estimates of expected injury rates), and in the Netherlands and Belgium (0.10 and 0.83, respectively, vs roundabout designs without cycle tracks).[25,26,36,37] Relative risk estimates likely vary because of differences in study design (particularly methods of adjusting for traffic volumes and exposure to risk) and differences in comparison infrastructure.

An important issue is whether safer route types are routes that cyclists would prefer to use. Figure 1 presents data on route safety from this study and data from the Metro Vancouver route preference survey that used the same route classification.[24] Many route types with positive preference ratings were also among the safest: cycle tracks; local streets; bike only paths; and major streets with bikes lanes and no parked cars. These provide a range of options with potential to both lower injury rates and increase cycling. This in turn may create a positive feedback cycle because increased ridership has been associated with increased safety.[12,38–40]

In addition to route type, 3 infrastructure components were associated with injury risk: downhill slopes, streetcar or train tracks, and construction. Two studies have shown increased injury severity with increased grades.[41,42] Route grades may not seem modifiable, but bike routes can be located where grades are low (e.g., along abandoned rail beds). This would also improve route preference because steep slopes are a deterrent to cycling.[11] Streetcar or train tracks were found to be particularly hazardous to cyclists, a finding that does not appear to have been reported elsewhere. There is renewed interest in streetcars for urban transportation, so this result deserves consideration in broader transportation planning. The higher risk for construction also has not been reported elsewhere; it suggests that when construction sites impact transportation corridors, safe detours need to be provided for cyclists. Other infrastructure factors examined in this study did not have statistically significant associations with injuries, although most had associations in the expected directions and deserve to be evaluated in future studies.



Source. Route preference data from 2006 Metro Vancouver opinion survey.[24]

Note. OR = odds ratio. Closed circles represent route types with positive preference rating and adjusted injury OR < 0.6 (safest route types). Open circles represent route types with negative or neutral preference rating or adjusted injury OR ≥ 0.6. "Sidewalk or other pedestrian path" was not included because this route type was not queried in the preference survey. ORs for injury risk are plotted in reverse order.

FIGURE 1—Route preference vs route safety of 13 route types: route safety data from the injury study in the cities of Vancouver and Toronto, Canada, 2008–2009.

Strengths and Limitations

A strength of this study is its case-crossover design. It allowed a direct focus on the route environment, by fully controlling for personal characteristics and other factors that are stable within a trip. The design also controlled for exposure to the various types of infrastructure by randomly selecting control sites from each cyclist's route.

Another feature of the study is that it used detailed and objective site observations to delineate a much wider array of cycling infrastructure than previous injury studies. However, even with 14 route types, there were types not observed in this study (e.g., rural roads), and others that were grouped here, but could be separated into finer categories in cities where they are more common (e.g., bidirectional versus unidirectional cycle tracks). Because the cycling infrastructure was observed after the injury event, we cannot be certain the infrastructure was exactly as occurred on the injury trip. We expect this to most greatly affect the results for temporary features, like construction, and at sites where the infrastructure changed within a short distance (within a block), such that potential errors in site location would be consequential. Because site observations were made in the identical way for injury and control sites and observers were blind to site status, we expect any misclassification to be nondifferential and to be more likely to bias risk estimates to the null.

The results on the 14 well-defined and detailed route types are new and merit investigation in other settings. If confirmed, they should be generalizable to cities with comparable route infrastructure and urban environments. Features of the Toronto and Vancouver cycling environments were described in the Methods section. It should be noted that the infrastructure the injured cyclists encountered was likely weighted toward the urban core of each city because the participating hospitals were in or near downtown. This may explain in part why major streets were so frequently observed, although the range of route types covered was still very broad. One hospital in each city was a regional trauma center, providing a wide geographic reach for the most serious injury events.

The study participants had very similar gender, age, and trip distance distributions to population-based samples of cyclists in the 2 cities and in other North American cities.[7,24,33,43] Our sample had a high proportion of regular cyclists (88%, vs 13% of all cyclists in Vancouver), likely because more frequent cycling provides more opportunity for injury events.[24]

As in all injury studies, only a segment of those injured were included; in this case those whose injuries were serious enough to result in a visit to a hospital emergency department, but not to cause death or a head injury so severe that the trip could not be recalled. Only 2 potential participants were fatally injured and 26 of those contacted could not remember their route; it is possible that others who were not successfully contacted may have been in the latter category. By recruiting injured cyclists from hospital records, we were able to include injuries caused by all kinds of crashes, whether motor vehicles were involved or not, thus encompassing a broad array of injury circumstances faced by cyclists. By excluding mountain biking, racing, and trick riding incidents, the study focused on the utilitarian and recreational cycling for which urban bicycle route infrastructure is designed.

Conclusions

This study strengthens previous evidence that route infrastructure (bike-specific facilities, quiet streets, gentle slopes, absence of streetcar tracks) can be designed for primary prevention of injuries to cyclists. As a public health approach, safer route infrastructure offers many advantages: it is population-based and therefore benefits everyone, it does not require active initiatives by individual cyclists, it does not require repeated reinforcement, and it prevents crashes from occurring rather than preventing injuries after a crash has occurred.[17] ■

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References

1. Frumkin H, Frank L, Jackson R. *Urban Sprawl and Public Health – Designing, Planning, and Building for Healthy Communities.* Washington, DC: Island Press; 2004.

2. Rabin BA, Boehmer TK, Brownson RC. Cross-national comparison of environmental and policy correlates of obesity in Europe. *Eur J Public Health.* 2007;17:53–61.

3. Oja P, Titze S, Bauman A, et al. Health benefits of cycling: a systematic review. *Scand J Med Sci Sports.* 2011; Epub ahead of print.

4. Johan de Hartog J, Boogaard H, Nijland H, Hoek G. Do the health benefits of cycling outweigh the risks? *Environ Health Perspect.* 2010;118:1109–1116.

5. Hamer M, Chida Y. Active commuting and cardiovascular risk: a meta-analytic review. *Prev Med.* 2008;46:9–13.

6. Parkin J. Comparisons of cycle use for the journey to work from the '81, '91 and 2001 censuses. *Traffic Eng Control.* 2003;44:299–302.

7. Pucher J, Buehler R, Seinen M. Bicycling renaissance in North America? An update and reappraisal of cycling trends and policies. *Transport Res A.* 2011; in press.

8. Pucher J, Buehler R. Making cycling irresistible: lessons from the Netherlands, Denmark and Germany. *Transp Rev.* 2008;28:495–528.

9. Ogilvie D, Egan M, Hamilton V, Petticrew M. Promoting walking and cycling as an alternative to using cars: systematic review. *BMJ.* 2004;329:763.

10. Noland RB. Perceived risk and modal choice: risk compensation in transportation systems. *Accid Anal Prev.* 1995;27:503–521.

11. Winters M, Davidson G, Kao D, Teschke K. Motivators and deterrents of bicycling: comparing influences on decisions to ride. *Transportation.* 2011;38:153–168.

12. Jacobsen PL. Safety in numbers: more walkers and bicyclists, safer walking and bicycling. *Inj Prev.* 2003;9:205–209.

13. Pucher J, Buehler R. Why Canadians cycle more than Americans: a comparative analysis of bicycling trends and policies. *Transp Policy.* 2006;13:265–279.

14. Attewell RG, Glase K, McFadden M. Bicycle helmet efficacy: a meta-analysis. *Accid Anal Prev.* 2001;33:345–352.

15. Macpherson A, Spinks A. Bicycle helmet legislation for the uptake of helmet use and prevention of head injuries. *Cochrane Database Syst Rev.* 2008; (3):CD005401.

16. Coffman S. Bicycle injuries and safety helmets in children. Review of research. *Orthop Nurs.* 2003;22:9–15.

17. Chipman ML. Hats off (or not?) to helmet legislation. *CMAJ.* 2002;166:602.

18. Ritter N, Vance C. The determinants of bicycle helmet use: evidence from Germany. *Accid Anal Prev.* 2011;43:95–100.

19. Villamor E, Hammer S, Martinez-Olaizola A. Barriers to bicycle helmet use among Dutch paediatricians. *Child Care Health Dev.* 2008;34:743–747.

20. Pucher J, Buehler R. Cycling for everyone: lessons from Europe. *Transp Res Rec.* 2008;2074:58–65.

21. Reynolds CO, Harris MA, Teschke K, Cripton PA, Winters M. The impact of transportation infrastructure on bicycling injuries and crashes: a review of the literature. *Environ Health.* 2009; 8:47(1-19)

22. Harris MA, Reynolds CCO, Winters M, et al. The Bicyclists' Injuries and the Cycling Environment (BICE) study: a protocol to tackle methodological issues facing studies of bicycling safety. *Inj Prev.* 2011; in press.

23. Fleiss JL. Measuring nominal scale agreement among many raters. *Psychol Bull.* 1971;76:378–382.

24. Winters M, Teschke K. Route preferences among adults in the near market for cycling: findings of the Cycling in Cities Study. *Am J Health Promot.* 2010;25:40–47.

25. Schoon C, Van Minnen J. The safety of roundabouts in the Netherlands. *Traffic Eng Control.* 1994;35:142–148.

26. Daniels S, Brijs T, Nuyts E, Wets G. Injury crashes with bicyclists at roundabouts: influence of some location characteristics and the design of cycle facilities. *J Safety Res.* 2009;40:141–148.

27. Kaplan J. *Characteristics of the Regular Adult Bicycle User.* MSc thesis. University of Maryland, Civil Engineering Department. 1975

28. Lott DF, Lott DY. Effect of bike lanes on ten classes of bicycle-automobile accidents in Davis, California. *J Safety Res.* 1976;8:171–179.

29. Tinsworth DK, Cassidy SP, Polen C. Bicycle-related injuries: Injury, hazard, and risk patterns. *Int J Consum Prod Saf.* 1994;1:207–220.

30. Rodgers GB. Factors associated with the crash risk of adult bicyclists. *J Safety Res.* 1997;28:233–241.

31. Moritz WE. Adult bicyclists in the United States: characteristics and riding experience in 1996. *Transp Res Rec.* 1998;1636:1–7.

32. Moritz WE. Survey of North American bicycle commuters: design and aggregate results. *Transp Res Rec.* 1997;1578:91–101.

33. Aultman-Hall L, Kaltenecker MG. Toronto bicycle commuter safety rates. *Accid Anal Prev.* 1999;31:675–686.

34. Aultman-Hall L, Hall FL. Ottawa-carleton commuter cyclist on- and off-road incident rates. *Accid Anal Prev.* 1998;30:29–43.

35. Forester J. *Effective Cycling.* 6th ed. Cambridge, MA: The MIT Press; 1993.

36. Lusk AC, Furth PG, Morency P, Miranda-Moreno LF, Willett WC, Dennerlein JT. Risk of injury for bicycling on cycle tracks versus in the street. *Inj Prev.* 2011;17:131–135.

37. Jensen S. Bicycle tracks and lanes: a before-and-after study. Presented at the Transportation Research Board 87th Annual Meeting; January 13–17, 2008; Washington, DC.

38. Robinson DL. Safety in numbers in Australia: more walkers and bicyclists, safer walking and bicycling. *Health Promot J Austr.* 2005;16:47–51.

39. Vandenbulcke G, Thomas I, de Geus B, et al. Mapping bicycle use and the risk of accidents for commuters who cycle to work in Belgium. *Transp Policy.* 2009;16:77–87.

40. Elvik R. The non-linearity of risk and the promotion of environmentally sustainable transport. *Accid Anal Prev.* 2009;41:849–855.

41. Klop JR, Khattak AJ. Factors influencing bicycle crash severity on two-lane, undivided roadways in North Carolina. *Transp Res Rec.* 1999;1674:78–85

42. Allen-Munley C, Daniel J, Dhar S. Logistic model for rating urban bicycle route safety. *Transp Res Rec.* 2004;1878:107–115

43. Winters M, Brauer M, Setton EM, Teschke K. Built environment influences on healthy transportation choices: bicycling versus driving. *J Urban Health.* 2010;87:969–993.