Bicyclists’ Injuries and the Cycling Environment: The impact of route infrastructure


Submission date: July 31, 2012


Word Count: 5,825

Number of Figures: 2

Meghan Winters **Corresponding Author
Faculty of Health Sciences, Simon Fraser University
8888 Blusson Hall, Burnaby, BC, Canada, V5A 1S6
T: 778.782.9325
F: 772.782.5927
mwinters@sfu.ca

Harris, MA
Occupational Cancer Research Centre, Cancer Care Ontario
505 University Avenue, 17th Floor Toronto, Ontario, M5G 1X3 Canada
T: 416-217-1849
Harris.m.anne@gmail.com

Reynolds, CCO
Liu Institute for Global Issues, University of British Columbia
6476 NW Marine Drive Vancouver, BC Canada V6T 1Z2
Fax: 604-822-6966
Conor.reynolds@gmail.com

Cripton, PA
Department of Mechanical Engineering, University of British Columbia
2054-6250 Applied Science Lane Vancouver, B.C., V6T 1Z4
T: 604 822-2781
cripton@ mech. ubc.ca

Chipman, M
Dalla Lana School of Public Health, University of Toronto
155 College Street Health Science Building, 6th floor
Toronto, ON M5T 3M7
mary.chipman@utoronto.ca

Cusimano, MD
Neurosurgery, St. Michael’s Hospital, University of Toronto
30 Bond Street Toronto, Ontario M5B 1W8, Canada
T: 416-360-4000
ABSTRACT

Introduction. Safety concerns have contributed to low bicycling rates in North America. Injury rates are lower and cycling is more common in northern European countries where route infrastructure is designed for cyclists, yet few studies have examined the relationship between the cycling environment and injuries.

Methods. 690 people injured while cycling were recruited via emergency departments in Toronto and Vancouver, Canada. Conditional logistic regression compared route infrastructure at each injury site to that of a randomly selected control site from the same trip. The case-crossover design controlled for exposure to risk and for personal and trip characteristics that are stable within a trip.

Results. Of 15 route types, cycle tracks (physically separated lanes alongside city streets) had the lowest risk, about 9 times lower than the reference (arterials and collectors with parked cars and no bike infrastructure). Bike lanes on arterials and collectors with no parked cars, local streets, and off street bike paths had 2-fold risk reductions. Risks on arterials and collectors were lower when parked cars were not present. Other infrastructure characteristics were associated with increased risks: downhill grades; streetcar or train tracks; and construction.

Conclusions. These results indicate that the design approach used in countries in northern Europe with high cycling rates is effective in North America. The following route types are the best choices for common urban transportation locations and would lower injury risks to cyclists: alongside arterials and collectors – cycle tracks; on local streets – designated bikeways with traffic diversion; and off-street – bike paths.
INTRODUCTION

Bicycling is an active mode of transportation that integrates physical activity into daily life. It has a range of individual and public health benefits, including improved physical and mental health, decreased obesity, reduced risk of cancer, cardiovascular and other diseases, and reduced motor vehicle noise, air pollutants and greenhouse gases (1-5). However, bicycling is underused for transportation in North America, comprising an estimated 1 to 3% of trips, compared to 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 injuries rates in North America are higher than in northern European countries (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, since 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 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. Debate continues about the contribution of route design to safety and about the safety of various route types (12,13,20,21).

We conducted a study designed to overcome these limitations (22). It examined injury risk of 15 route types using a case-crossover design in which injured participants served as their own controls. It 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 (i.e., 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, sex, and propensity for risk-taking behaviour were matched, as were trip conditions such as bicycle, clothing visibility, helmet use, weather, and time of day. This allowed the comparisons to focus on between-site infrastructure differences.

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 km 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 km of bike lanes and paths per 100,000 population, rainy winter weather and mild summer weather (7). Although these cities did not have the entire range of cycling infrastructure in place in European settings, together they included most route designs available in North America at the time.

METHODS

The study population consisted of adults (≥ 19 years) who were injured while riding a bicycle 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; one hospital in each city was also a regional trauma centre. The study methods were reviewed and approved by the human subjects ethics review boards of the University of British Columbia, the University of Toronto, and the participating hospitals.
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 one to two 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 while 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.

Participants were interviewed as soon as possible after the injury incident to maximize recall (50% completed within 4.9 weeks, 75% within 7.7). In-person interviews were conducted by trained interviewers, using a structured questionnaire that took 25 to 45 minutes to complete. The questionnaire was pretested on 22 cyclists to ensure that the questions were clearly worded, respondents were willing 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 travelled 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, 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 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, sex, education, household income, cycling frequency).

Data about route infrastructure at the injury and control sites were collected during structured site observations by trained personnel blinded to site status. Observations were done at a time that conformed as closely as possible to the time of the injury trip (i.e., season; weekday vs. weekend; morning rush, mid-day, 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, 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 motor vehicle, cyclist and/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 three observers) of 0.74 to 1.0 and Fleiss’ kappa (KS). The site observation method underwent pretesting and r

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

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

where $\pi_{ij}$ is the probability of injury for $i^{th}$ subject 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 subjects and p is the number of covariates. The conditional likelihood method in Proc Logistic was used to estimate parameters $\beta_1, \ldots, \beta_p$.

The primary analysis examined the association of injuries with route type. Site observations were used to classify routes into 15 categories corresponding to those used in a survey of route preferences conducted in Metro Vancouver in 2006 (24). Secondary analyses examined associations with other infrastructure features. Each was initially examined separately then offered in a single model with route
The following route types had injury sites to randomly selected control sites within the same trips, for Figure 1 shows the odds ratios (the estimator of relative risk) and 95% confidence intervals comparing injury sites to randomly selected control sites within the same trips, for the 15 route types, grouped into four categories. We designated the most frequently observed route type as the reference category: arterials and collectors with parked cars and no bike infrastructure. All other route types had lower injury risks. The following route types had statistically significantly lower odds ratios, starting with the lowest risk route type:

- cycle tracks (bike lane alongside arterial or collector, but separated by a curb or other physical barrier);
local street designated bike routes (with bike signage and usually cyclist-operated traffic lights at intersections with arterials and collectors);
local streets with no bike infrastructure;
bike lanes on arterials and collectors with no parked cars; and
arterials and collectors with no parked cars and no bike infrastructure.

Two other route types had notably low risks though not statistically significant:
local street bike routes with traffic diversion had the lowest risk of all local street types; and
bike paths had lower risks than multi-use paths and sidewalks shared with pedestrian.

It is also important to note that local street bike routes with traffic slowing devices (speed bumps, speed humps, traffic circles, corner bulges) were not as safe as other local street route types.

FIGURE 1 Relative risks for 15 route types; adjusted odds ratios and 95% confidence intervals estimated using multiple logistic regression.

Figure 2 shows the odds ratios and 95% confidence intervals for other infrastructure characteristics that were significantly associated with injury risk in the final logistic regression model (with route type). Downhill grades, streetcar or train tracks and construction were all associated with increased risk of injuries. The following infrastructure elements were not significantly associated with injury risk and were not included in the final model: intersection location; presence of junctions (e.g., driveways, lanes) in the previous 100 m; presence of bike signage on arterials and collectors; number of marked traffic lanes; distance visible along the route.
FIGURE 2  Relative risks for other infrastructure components, including grade, rail tracks and construction; adjusted odds ratios and 95% confidence intervals estimated using multiple logistic regression; same model as routes types (results in Figure 1).

DISCUSSION

In this study, bike-specific infrastructure was associated with lower injury risk. Cycle tracks had the lowest injury risk, about one-ninth the risk of the reference route type. Bike lanes on arterials and collectors 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: local streets (except with traffic slowing devices); and no car parking on arterials and collectors. Shared bike infrastructure (shared lanes, multi-use paths) and pedestrian infrastructure had only small risk reductions, and none were significant.

These findings reinforce some conclusions of our prior review of the literature: 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 that occurred while mountain biking; this may account for at least some of the difference.
Most previous studies grouped off-street routes into only one or two categories, typically sidewalks and other off-street routes. Our study was able to differentiate within these categories. In our study, sidewalks and multi-use paths had among the highest risks, but bike-only paths and especially cycle tracks had lower risks.

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 to continental European countries with higher cycling rates (20,36). Cycle tracks highlight the difference: they are common alongside arterials and collectors in the Netherlands and Denmark, but rare in North America, Australia and the UK. Cycle tracks had the lowest risk in this study. Most studies of cycle tracks elsewhere have shown risk reductions: in Montreal (relative risk = 0.72, compared to nearby streets); in Copenhagen (0.59, compared to before cycle track installation (our calculation) and 1.10, compared to estimates of expected injury rates); and in the Netherlands and Belgium (0.10 and 0.83, respectively, compared to 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 question is whether safer route types are routes that cyclists would prefer to use. Many route types with positive preference ratings in our early study of route preferences were also among the safest: cycle tracks; local streets; bike only paths; and arterials and collectors with bikes lanes and no parked cars (24). 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, since increased ridership has been associated with increased safety (12,38-40).

In addition to route type, three 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 routes can be located where grades are low (e.g., along abandoned rail beds). This would also improve route preference, since 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, though most had associations in the expected directions and deserve to be evaluated in future studies.

A strength of this study is its case-crossover design. It allowed a direct focus on the route environment, while 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 15 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 vs. 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 non-differential and to be more...
likely to bias risk estimates to the null.

The results on the 15 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 earlier. The infrastructure that the injured cyclists encountered was weighted towards the urban core of each city, since the participating hospitals were in or near downtown.

The study participants had very similar sex, age, and trip distance distributions to population-based samples of cyclists in the two 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. Two 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 reinforces previous evidence that the cycling environment can be designed for primary prevention of injuries to cyclists. Bike-specific facilities, quiet streets, gentle slopes, and absence of streetcar tracks were all associated with lower risks 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).

ACKNOWLEDGMENTS

We thank the study participants for generously giving their time. We appreciate the many contributions of study staff (Evan Beaupré, Niki Blakely, Jill Dalton, Vartouji Jazmaji, Martin Kang, Kevin McCurley, Andrew Thomas), hospital personnel (Barb Boychuk, Jan Buchanan, Doug Chisholm, Nada Elfeki, Kishore Mulpuri), city personnel (Peter Stary, David Tomlinson, Barbara Wentworth) and community collaborators (Jack Becker, Bonnie Fenton, David Hay, Nancy Smith Lea, Fred Sztabinski). The study was funded by the Heart and Stroke Foundation of Canada and the Canadian Institutes of Health Research (Institute of Musculoskeletal Health and Arthritis, and Institute of Nutrition, Metabolism and Diabetes). J.R. Brubacher, M.A. Harris, and M. Winters were supported by awards from the Michael Smith Foundation for Health Research. M.A. Harris, C.C.O. Reynolds, and M. Winters were supported by awards from the Canadian Institutes of Health Research.
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