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Severity of urban cycling injuries and their relationship with personal, trip, route and crash characteristics: Experience in two Canadian cities over a 1.5 year period

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4 **Severity of urban cycling injuries and their relationship with personal, trip, route and crash**
5 **characteristics: Experience in two Canadian cities over a 1.5 year period**
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ABSTRACT

Objective: To examine the relationship between cycling injury severity and personal, trip, route and crash characteristics.

Methods: Data from a study of adults injured in Toronto or Vancouver, Canada, were used to classify injury severity using four metrics: 1) did not continue trip by bike; 2) transported to hospital by ambulance; 3) admitted to hospital; 4) Canadian Triage and Acuity Scale (CTAS). Multiple logistic regression was used to examine associations with personal, trip, route and crash characteristics.

Results: Of 683 participants, 528 did not continue their trip by bike, 251 were transported by ambulance, and 60 were admitted to hospital for further treatment. Treatment urgencies included 75 as CTAS=1 or 2 (most medically urgent), 284 as CTAS=3, and 320 as CTAS=4 or 5 (least medically urgent). Older age and collision with a motor vehicle were each significantly associated with increased severity in three metrics. Factors significantly associated with more severe injuries in one metric included female sex; more frequent cycling; and crashes on multi-use paths, sidewalks or local streets, at non-intersection locations, on downhill grades, and at locations with higher motor vehicle speeds.

Conclusions: In two of Canada's largest cities, about one-third of the bicycle crashes were collisions with motor vehicles and the resulting injuries were more severe than in other crash circumstances, underscoring the importance of separating cyclists from motor vehicle traffic. Our results also suggest that facilities that do not mix cyclists with pedestrians and that minimize slopes would reduce both bicycling injury severity and crash risk.

Strengths and Limitations of this Study

- This study is one of few to examine the relationship between route characteristics and severity of bicycling injuries. Its major strength was use of data from a study of bicycling injury crash risk. This made it possible to consider whether route characteristics that increased crash risk were similar to or different from those that increased bicycling injury severity.
- The results show that bike facilities that separate cyclists from motor vehicle traffic, that do not mix cyclists with pedestrians, and that minimize slopes would reduce both injury severity after a crash and reduce crash risk.
- The analyses examined four metrics covering different aspects of injury severity (not able to continue the trip by bike, transport to hospital by ambulance, admission to hospital, and treatment urgency) and identified factors that were consistently associated with increased risk: increased age and collision with a motor vehicle.
- The study included a range of injury severities resulting in emergency treatment at a hospital but did not include those so severely injured they could not remember their trip, nor those with such minor injuries that emergency treatment was not required.
- The influence of route characteristics on severity was adjusted for potential confounding by personal and trip characteristics in the regression models, but the potential for uncontrolled confounding by unmeasured characteristics remains.

INTRODUCTION

Cycling is used for transportation and is a popular recreational activity. Its health benefits are clear, [1,2] in contrast to motor vehicle travel. Transportation cycling has risks in the same order of magnitude as driving and walking in the US and Canada.[3,4] However it is not nearly as safe as in some European countries where cycling participation is much higher.[5-8]

In 2010, there were 618 cyclist traffic deaths in the United States and 60 in Canada.[9,10] Broader data (including bicycling sports such as mountain biking) indicate that about 27,800 Americans and 4,300 Canadians were hospitalized for cycling injuries in 2009.[11,12] Although bicycling injuries are a small proportion of all traffic injuries and deaths in North America (~2 to 4%),[9,10] reducing their incidence is important because of the direct harm that they do and because they deter potential cyclists.[13-15]

The reason postulated for the inversion of cycling activity and injury risk between North America and Europe is the well-designed bicycle-specific infrastructure in Europe *vs.* its relative paucity in North America. We reviewed published studies and found that bicycle-specific infrastructure was associated with decreased injury risk, but a small range of infrastructure had been studied, often with uncertain control of exposure to risk.[16] We subsequently conducted a case-crossover study of the association between route infrastructure and crash risk in Vancouver and Toronto.[17,18]

Infrastructure that was bicycle-specific (e.g., cycle tracks separated from traffic, bike lanes) or “bicycle-friendly” (e.g., local streets with traffic diversion) had considerably lower risk. Other features were found to increase risk: streetcar or train tracks, downhill grades, construction, major street intersections, and traffic circles at local street intersections. This work was designed to estimate associations with injury risk, with a no-injury control.

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3 An alternative line of inquiry is what factors are associated with injury severity, among those who
4 have been injured. Many studies have found that collisions with motor vehicles increase cyclist injury
5 severity.[11,19-22] However few authors have examined severity with respect to route
6 infrastructure.[23-25] Higher severity has been found with grades, higher speed roads, and crashes in
7 traffic or on shared paths.[23-25] Although these results suggest that predictors of cycling injury risk
8 may be similar to predictors of injury severity, this is not established, and our study offers the
9 opportunity to examine both sets of outcomes, adding a level of context for policy makers,
10 infrastructure designers and other stakeholders. In our opinion, injury severity, not just the fact of
11 an injury, is a second and equally important criterion used by the lay public to evaluate the apparent
12 safety of cycling.
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17 Therefore we examined the relationship between injury severity and personal, trip, route and crash
18 characteristics using data from our study of cyclists injured in two of Canada's largest cities, Toronto
19 and Vancouver.
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27 28 29 30 31 32 33 34 35 36 37 **METHODS**

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40 Methods of study conduct and reliability testing have been described in detail elsewhere.[17,26] The
41 study population consisted of adult (≥ 19 years) residents of Toronto and Vancouver who were
42 injured while riding a bicycle in the city and treated within 24 hours in the emergency departments
43 of the following hospitals between May 18, 2008 and November 30, 2009: St. Paul's or Vancouver
44 General in Vancouver; St. Michael's, Toronto General or Toronto Western in Toronto. Those who
45 were fatally injured or so severely injured that they were unable to remember their trip were not
46 eligible to participate.
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3 Data on characteristics related to severity were abstracted from emergency department records. In
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5 addition, eligible participants were interviewed in person by trained interviewers about personal
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7 characteristics, trip characteristics, and crash circumstances, using a structured questionnaire
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10 (<http://cyclingingcities.spph.ubc.ca/files/2011/10/InterviewFormFinal.pdf>).
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13 The study was not designed to focus on severity, so the data did not include classical severity scoring
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15 using the Abbreviated Injury Scale. However we did have access to four other indicators of severity:
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18 1. Whether the subject continued their trip by bicycle (self-reported in the interview), no vs. yes
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20 2. Whether the subject was transported by ambulance (hospital data), yes vs. no
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22 3. Whether the subject was admitted to hospital (hospital data), yes vs. no
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24 4. Canadian Triage and Acuity Scale (CTAS) (hospital data), levels 1 to 5, defined as
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26 follows:[27,28]

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29 • 1 – Resuscitation; need to be seen immediately
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31 • 2 – Emergent; need to be seen within 15 minutes
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33 • 3 – Urgent; need to be seen within 30 minutes
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35 • 4 – Less urgent; need to be seen within 60 minutes
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37 • 5 – Non urgent, need to be seen within 120 minutes
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43 Site observations were made to document characteristics of crash and control sites, and allow route
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45 infrastructure classification.[17,18] The observations were made blind to whether an injury took
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47 place at the site or not. In the current analysis, only the crash site data was used.
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50 Unconditional logistic regression was used to examine associations of each of the following
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52 independent variables with each severity outcome metric:
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- personal characteristics: sex; age; how frequently he/she cycled; whether the cyclist considered himself/herself experienced, had taken a cycling training course, had a driver's license
- trip characteristics: time of day; weather; helmet use; use of visible clothing on the trunk; use of bike lights; alcohol and drug use in the 6 hours prior
- crash circumstances: collision (with a motor vehicle, obstacle, surface feature, cyclist, pedestrian, or animal) vs. fall; collision with a motor vehicle vs. not; motor vehicle "involvement" (i.e., both direct collisions with vehicles and crashes resulting from motor vehicle avoidance manoeuvres) vs. not
- route characteristics at the injury crash site: type of route; intersection location; presence of bike signage; junctions; construction; streetcar tracks; grade; average vehicle speed; distance visible along route.

All independent variables significant in simple logistic regression (unadjusted analysis) were included in multiple regression models for all four severity metrics. The rationale for this broad inclusion of variables in the final models was to maximize control of potential confounding by personal and trip characteristics and to allow readers to compare results across severity metrics.

For dichotomous severity metrics (did not continue by bike, ambulance transport, hospital admission), traditional logistic regression was used. For CTAS, ordinal logistic regression modeled the odds of a more severe CTAS group, after verifying that the proportional odds assumption was valid. CTAS categories were grouped as follows: most severe, levels 1 or 2; moderate severity, 3; least severe, 4 or 5.

RESULTS

The study included 690 injured cyclists (414 in Vancouver, 276 in Toronto). Seven were unable to recall their crash circumstances, so were removed from analyses; none of these continued by bike, six were transported by ambulance, their CTAS scores were either 1 or 2, and one was admitted to hospital. After these subjects were excluded, 683 subjects remained for most analyses, though four additional subjects did not have information on CTAS or ambulance transport.

Most participants were men (59%), younger than 40 years (63%), regular cyclists (88% cycled \geq 52 times per year), and had a drivers' license (90%), but few had taken a cycling training course (6%).

On the trip when the injury occurred, 69% were wearing a helmet, 33% were wearing bright clothing on their torso, 19% were using bike lights, and 10% had consumed alcohol and 11% had consumed drugs in the previous 6 hours. Most of the trips were on weekdays (77%), during daylight hours (78%), and in clear weather (70%). Most of the injury sites were on streets with no cycling infrastructure (42% on major streets, 27% on local streets) *vs.* 8% on sidewalks, 11% on multi-use paths, and 12% on bicycle-specific infrastructure (bike lanes, cycle tracks, off-street bike paths).

Other conditions at the injury sites included the following: 31% were at intersections, 38% were on downhill grades, 12% had construction present, and 87% had junctions in the last 100 meters.

Most of the crashes were collisions (74% $n=506$; with motor vehicles, $n=231$; cyclists, pedestrians or animals, $n=40$; obstacles, $n=69$; streetcar tracks, $n=97$; and other surface features, $n=69$) rather than falls (26%, $n=177$). Crashes "involving" motor vehicles (48%, $n=330$) included direct collisions, as well as crashes to avoid collisions ($n=99$).

Figure 1 shows the distribution of subjects by the four severity metrics. Figure 2 shows the severity metrics against crash circumstances, classified three ways. Collisions tended to be more severe than falls, and crashes "involving" motor vehicles tended to be more severe than those not. Direct

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3 collisions with motor vehicles had the highest proportion in the more severe category of every
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5 metric except admitted to hospital. In unadjusted analyses, collision (of any type) and motor vehicle
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7 “involvement” both had elevated odds ratios for the same severity metrics as motor vehicle collision
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9 (data not shown), but the odds ratios were lower, indicating that it was direct collision with a motor
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11 vehicle that led to increased severity. Only the motor vehicle collision variable was included in
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13 multiple regression models.
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18 Table 1 shows the results of the multiple logistic regression models for each severity metric,
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20 including all independent variables statistically significant in at least one unadjusted analysis. Four
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22 personal characteristic variables were included: age, sex, cycling experience, and cycling frequency.
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24 Age showed consistent associations across all severity metrics; older age groups had more severe
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26 injuries, significantly so for ambulance transport, admission to hospital and CTAS. Women were
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28 significantly more likely to stop their trip by bike than men. There was a tendency for more
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30 experienced and more regular cyclists to have higher injury severity, though only one association was
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32 statistically significant in multiple regression.
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36 Cyclists whose crash was a direct collision with a motor vehicle had elevated odds ratios for all
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38 severity metrics, statistically significant for not continuing by bike, being transported by ambulance
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40 and more urgent triage score (CTAS). Those whose crash sites were on multi-use paths, sidewalks
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42 and local streets tended to have more severe injuries than those who crashed on major streets;
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44 significant associations were observed for certain associations with ambulance transport and hospital
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46 admission. Crashes at intersections had inconsistent results; the only significant odds ratio indicated
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48 that those injured at an intersection were less likely to stop their trip by bike. Downhill grades were
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50 consistently related to greater injury severity, significantly so for transportation by ambulance. The
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52 same pattern was observed for higher average motor vehicle speeds at the crash location. Time of
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day and presence of streetcar tracks were both significant in some unadjusted analyses, but did not remain so in multiple regression.

Table 1. Odds ratios (OR) and 95% confidence intervals (CI) for associations between metrics of injury severity and personal, trip, crash circumstance, and route characteristics (N=683). Multiple logistic regression models; all independent variables significant in at least one unadjusted analysis included.

	Descriptive statistics	Did not continue by bike N=528 (77%) OR (95% CI)	Transported to hospital by ambulance N=251 (37%) OR (95% CI)	Admitted to hospital N=60 (8.8%) OR (95% CI)	CTAS † 1 or 2, N=75 (11%) 3, N=284 (42%) 4 or 5, N=320 (47%) OR (95% CI)
Sex					
Male	404 (59%)	1 (reference)	1 (reference)	1 (reference)	1 (reference)
Female	279 (41%)	1.91 (1.26 – 2.92)	1.34 (0.93 – 1.93)	1.07 (0.59 – 1.94)	0.98 (0.71 – 1.35)
Age					
19 to 29	262 (39%)	1 (reference)	1 (reference)	1 (reference)	1 (reference)
30 to 39	167 (25%)	1.15 (0.70 – 1.88)	1.18 (0.75 – 1.85)	1.18 (0.54 – 2.61)	1.29 (0.87 – 1.91)
40 to 49	115 (17%)	1.22 (0.70 – 2.14)	1.40 (0.83 – 2.34)	1.96 (0.89 – 4.33)	2.07 (1.33 – 3.23)
50 to 59	81 (12%)	1.50 (0.77 – 2.95)	1.04 (0.57 – 1.91)	1.02 (0.35 – 2.97)	1.57 (0.95 – 2.62)
≥ 60	55 (8%)	1.33 (0.63 – 2.82)	2.57 (1.31 – 5.05)	3.52 (1.37 – 9.04)	1.42 (0.78 – 2.60)
Considered themselves an experienced cyclist					
No	46 (7%)	1 (reference)	1 (reference)	1 (reference)	1 (reference)
Yes	637 (93%)	1.36 (0.63 – 2.95)	2.16 (0.97 – 4.83)	1.03 (0.28 – 3.84)	1.52 (0.78 – 2.95)
Cycling frequency ° (trips/year)					
	mean = 152 SD = 81	1.00 (0.78 – 1.76)	0.92 (0.72 – 1.08)	1.18 (0.85 – 1.50)	1.18 (1.00 – 1.38)
Time of day					
Day	530 (78%)	1 (reference)	1 (reference)	1 (reference)	1 (reference)
Dusk or dawn	50 (7%)	0.65 (0.33 – 1.29)	0.53 (0.24 – 1.13)	0.75 (0.21 – 2.62)	0.72 (0.39 – 1.30)
Night	103 (15%)	0.90 (0.53 – 1.54)	1.16 (0.71 – 1.90)	1.87 (0.90 – 3.86)	0.90 (0.58 – 1.40)
Motor vehicle collision					
No	452 (66%)	1 (reference)	1 (reference)	1 (reference)	1 (reference)
Yes	231 (34%)	3.46 (2.07 – 5.76)	3.66 (2.44 – 5.48)	1.27 (0.63 – 2.54)	2.03 (1.41 – 2.90)
Route type *					
Major street	288 (42%)	1 (reference)	1 (reference)	1 (reference)	1 (reference)
Local street	187 (27%)	1.08 (0.61 – 1.92)	1.44 (0.86 – 2.39)	2.76 (1.15 – 6.62)	1.18 (0.75 – 1.84)
Sidewalk	52 (8%)	1.15 (0.42 – 3.19)	3.72 (1.37 – 10.1)	3.26 (0.51 – 20.7)	1.31 (0.56 – 3.06)
Multi-use path	74 (11%)	1.33 (0.52 – 3.44)	2.18 (0.83 – 5.77)	7.56 (1.43 – 40.0)	1.22 (0.55 – 2.68)
Bicycle-specific infrastructure	82 (12%)	0.98 (0.50 – 1.94)	1.02 (0.55 – 1.89)	0.89 (0.27 – 2.99)	1.27 (0.74 – 2.18)
Intersection					

No	472 (69%)	1 (reference)	1 (reference)	1 (reference)	1 (reference)
Yes	211 (31%)	0.57 (0.36 – 0.88)	1.44 (0.98– 2.13)	1.04 (0.53 – 2.04)	0.89 (0.63 – 1.26)
Streetcar or train tracks					
No	534 (78%)	1 (reference)	1 (reference)	1 (reference)	1 (reference)
Yes	149 (22%)	1.11 (0.65 – 1.91)	1.03 (0.63 – 1.70)	0.98 (0.39 – 2.47)	1.36 (0.88 – 2.10)
Grade					
Flat or uphill	354 (52%)	1 (reference)	1 (reference)	1 (reference)	1 (reference)
Downhill	329 (48%)	1.32 (0.89 – 1.96)	1.62 (1.14 – 2.32)	1.23 (0.68 – 2.22)	1.31 (0.96 – 1.79)
Motor vehicle speed [°] β (km/h)	mean = 36 SD = 9.5	1.05 (0.89 – 1.24)	1.21 (1.01 – 1.43)	1.24 (0.91 – 1.69)	1.08 (0.94 – 1.24)

† CTAS = Canadian Triage and Acuity Scale, grouped into 3 categories for analysis using ordinal logistic regression; the odds ratio represents the comparison of categories 1 & 2 vs. 3, 4 & 5 and categories 1, 2 & 3 vs. 4 & 5 under the proportional odds assumption

* Major streets included arterials and collectors with no bicycle infrastructure or shared lanes;

Local streets were mainly residential and included those designated as bikeways;

Multi-use paths were paths designated for pedestrian and bicyclists;

Bicycle-specific infrastructure included bike lanes on major streets, cycle tracks (separated bike lanes) alongside major streets, and off-street bike paths.

° Odds ratios and confidence intervals for continuous variables calculated for a one standard deviation increase

β Average motor vehicle speed at the crash site, measured 5 times during site observations using a Bushnell Velocity Speed Gun (Overland Park, KS)

The following independent variables were not associated with any of the injury severity metrics in unadjusted analyses and were not included in multiple regression: whether the participant had taken a cycling training course or had a driver's license; weather; use of a helmet, visible clothing on the trunk, or bike lights; alcohol or drug use in the 6 hours prior to the trip; presence of bike signage, junctions, or construction; and distance visible along the route.

DISCUSSION

In this study, using four severity metrics that spanned rider self-evaluation (unable to continue by bike) to clinical-practitioner evaluation (CTAS), we found that the following characteristics were associated with more severe injuries: older age; female sex; more experience and frequency of cycling; collision with a motor vehicle; crash on a multi-use path, sidewalk or local street, at non-intersection location, on a downhill grade, and at locations with higher motor vehicle speeds.

Personal Characteristics

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3 Older age has frequently been associated with more severe injuries in bicycling crashes.[19-22, 29-33]
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5 We observed the same for all metrics, though the odds ratio was not always statistically significant.
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8 This pattern is attributed to increasing frailty with age and has been observed for all vulnerable road
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10 users.[32]

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13 Although sex has frequently been associated with bicycling injury severity, the evidence does not
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15 show a clear pattern. We found that women were less likely to continue their trip by bicycle and had
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17 a non-significant increased chance of ambulance transport. Moore *et al.* found women to have more
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19 severe injuries,[31] but others have found higher severities in men.[19,22,32] Theories for each of
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21 these results are available. The smaller average size of women may make them more vulnerable and
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23 men may be more comfortable handling minor injuries without help. A greater propensity for risk-
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25 taking and speed may provide opportunities for men to have higher impact crashes.[34-36]
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29 We found that experienced cyclists and those cycled more frequently had greater injury severity
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31 (more likely to need ambulance transport, or to have a more urgent triage score, respectively).
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34 Similarly Heesh *et al.* found that frequent and experienced cyclists had more severe injuries.[21]
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36 These cyclists may travel at higher speeds and incur higher impact forces in a crash.
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39 **Crash Circumstances**

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42 About a third of the injuries were collisions with motor vehicles. These were strongly associated
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44 with three of our four injury severity metrics. In other research, collisions with motor vehicles have
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46 consistently been associated with increased severity.[11,19-22] Collisions with larger vehicles have
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48 resulted in more severe injuries and fatalities.[29,31,33,37]
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52 Previous analyses showed that collisions with motor vehicles were associated with route type in our
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54 study.[38] They never occurred on off-street bike paths or on cycle tracks (separated bike lanes), and
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56 were over-represented on major streets with parked cars and no bike infrastructure. We considered
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3 whether route type confounded the association between collision with a motor vehicle and severity
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5 (and vice versa), but this was not the case, nor was there interaction between the two variables (data
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7 not shown).
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10 The severity of direct collisions with motor vehicles provides clear rationale for transportation
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12 planners to minimize interactions between cyclists and vehicles. This planning approach is
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14 supported by the results of our earlier analyses of injury crash risk: cycle tracks (bike lanes that
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16 physically separate cyclists and motor vehicle traffic) were associated with 1/9th the risk compared to
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18 streets with no bicycle infrastructure.[17] Separating modes of traffic with large differences in speed
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20 and mass is a principle used by countries such as Sweden, Germany, Denmark and the Netherlands
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22 where bicycling injury risk is much lower than in North America.[6,8]
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27 **Route Characteristics**

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29 Our main interest in this analysis was to determine whether route characteristics were associated
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31 with increased or reduced injury severity. Route type, presence of an intersection, grade, and average
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33 motor vehicle speed at the crash location were all associated with injury severity.
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37 In comparison to crashes on major streets without cycling infrastructure, crashes on sidewalks and
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39 multi-use paths had considerably higher odds of ambulance transport (odds ratio for multi-use paths
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41 not significant). Crashes on sidewalks and multi-use paths also had considerably higher odds of
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43 hospital admission (odds ratio for sidewalks not significant). In our earlier analyses of crash risk,
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45 multi-use paths and sidewalks had among the highest, despite being off-street.[17,18] The increased
46
47 severity after a crash adds to concern about these route types. Local streets (mainly residential
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49 streets) were found to be a safe route type in our earlier analyses, with only about half the risk of a
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51 crash.[17] The current analysis indicates that if a crash did occur, there was an increased odds of one
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53 severity measure – hospitalization.
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3 Few studies have examined route type and injury severity. De Rome *et al.* found that more severe
4 injuries were associated with crashes in traffic and on multi-use paths, and less severe with crashes in
5 bike lanes and on sidewalks.[25] Slaughter *et al.* found lower severity in bike lane crashes. In our
6 study, bicycle-specific infrastructure was not associated with severity.[39]
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12 Intersection vs. non-intersection crash locations did not present a clear pattern of association with
13 severity in this study. Moore *et al.* found differing patterns of injury severity at intersections and non-
14 intersections.[31]
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21 Downhill grade was significantly associated with increased severity for all metrics in unadjusted
22 analyses, and remained significant in the final model for ambulance transport. Three previous studies
23 have shown that injury severity is greater with grades.[23,24,31] Downhill grade is likely to be
24 associated with increased cyclist (and motor vehicle) speed, and therefore increased force of impact.
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29 Our earlier analyses found that downhill slopes were associated with higher injury crash risk, and
30 that uphill grades deter cycling.[15,17,18] This suggests that, wherever possible, routing bicycle
31 facilities where slopes are gentle is a good strategy for both reducing injuries and motivating cycling.
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38 Higher average motor vehicle speed was associated with increased severity for all metrics, and
39 remained significant in the final model for ambulance transport. Other studies found higher speed
40 roads to be associated with greater injury severity to cyclists.[23,24,37] Our earlier analyses found
41 that injury crash risk was lower at intersections where motor vehicle speeds were 30 km/h or lower
42 and that routes with high vehicle speeds deter cycling.[15,18] This supports recent changes in some
43 European and North American cities to lower urban speed limits.
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51 **Trip Characteristics**

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54 Only one trip characteristic was associated with injury severity. Time of day (night riding) was
55 associated with a higher odds of hospital admission in unadjusted analyses and was elevated but not
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3 significant in multiple regression. Night-time riding has been associated with increased injury
4 severity in other studies, especially where roadways were not lit.[24,29,32,33]
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8 Although much of the bicycle safety literature focuses on helmets and head injury mitigation,
9 [22,37,40,41,42] helmet use was not associated with any of the severity metrics in this study. Both
10 biomechanical studies[42] and epidemiological studies[22,37,40,41] have demonstrated that helmets
11 can prevent serious skull and brain injuries. This study was not limited to head injuries, likely
12 contributing to our result that helmet use was not associated with injury severity. In one of the
13 largest studies to examine helmets, their use was found to significantly reduce head injuries, but was
14 not associated with serious injury mitigation across all body regions.[22,41] In this context, it is
15 important to recognize that cyclists may sustain injuries, including serious trauma, to any body part,
16 including their thorax, abdomen, neck and extremities.[22] A helmet can do nothing to prevent non-
17 head injuries. Our earlier analyses of crash risk show the potential for all injuries to be significantly
18 decreased for cyclists separated from motor vehicle traffic in a cycle track or a local street with
19 traffic diversion[17,18] and the present results show that injury severity significantly increases in a
20 collision with a motor vehicle. Together these results point to bicycle infrastructure that physically
21 separates cyclists from motor vehicle traffic to prevent trauma to any area of the body.
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41 **Strengths and limitations**

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44 Strengths of the study include two study cities with differing climates, terrain, cycling mode shares
45 and cycling infrastructure, an urban-only cycling sample, the prospective accrual of subjects,
46 observation of route characteristics blinded to whether the site was an injury site, and the number of
47 clinical and cyclist self-report severity metrics that we used.
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54 Study limitations include a relatively small sample of injured cyclists, restriction to Canadian cities
55 and lack of data on the anatomical location of the injury. As in all injury studies, only a portion of
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3 injured cyclists were included; here, those whose injuries were serious enough to be treated at a
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5 hospital emergency department, but not to cause death or a head injury so severe that the trip could
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7 not be recalled. This reduced the pool of the most severely injured cases: 2 potential participants
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9 were fatally injured, 26 of those contacted could not remember their route, and 7 could not recall
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11 their crash circumstances. An unknown number of cyclists had injuries so minor that no emergency
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13 department visit was made.
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18 Our overall study had a case-crossover design to fully control for differences between individuals
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20 and between trips that could confound the relationship between injury crash risk and infrastructure
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22 (the focus of the main study). To examine severity of injuries in the current analysis, the analysis was
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24 restricted to cases only, introducing the potential for confounding by personal and trip
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26 characteristics. We addressed this via adjustment in our regression models, but the potential for
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28 uncontrolled confounding by unmeasured characteristics remains.
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32 Given that we did not have data on more traditional measures of severity, the Abbreviated Injury
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34 Scale and Injury Severity Score, it is important to consider our outcome metrics, their relationship to
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36 each other and their potential reliability and validity as measures of severity. The four metrics
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38 measured different aspects of severity, as shown by their low correlations (Table 2).
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43 **Table 2.** Pearson correlations between the four metrics of severity used in this study

	Did not continue by bike	Transported to hospital by ambulance	Admitted to hospital	CTAS
Did not continue by bike	1	0.40	0.17	-0.29
Transported to hospital by ambulance	0.40	1	0.24	-0.39
Admitted to hospital	0.17	0.24	1	-0.20
CTAS	-0.29	-0.39	-0.20	1

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53 Note: Correlations with CTAS were all negative because the scale was in the opposite direction, with 1 = most urgent
54 and 5 = least urgent. All the others were assigned 1 = more vs. 0 = less severe.
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3 Hospital admission is based on an in depth medical assessment and should reflect the most severe
4 injuries. There are no standardized decision criteria, and physicians' decisions to admit emergency
5 department patients to hospital have been found to differ substantially.[43] Data from Rivara *et al.*
6 were available to compare hospitalization to Injury Severity Scores above *vs.* below 9.[22]
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12 Hospitalization had high specificity (0.94) but lower sensitivity (0.72), suggesting that few patients
13 with minor injuries are admitted to hospital, but some who are severely injured are not admitted.
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17 This could be because some patients with severe injuries (e.g., some extremity fractures, intra-
18 abdominal trauma) may be treated and stabilized in an emergency department then discharged home,
19 but scheduled for later surgical repair. This may have contributed to our somewhat different results
20 for hospital admission and its lower correlations with the other metrics.
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27 Ambulance transport is based, in part, on whether or not someone at the scene called an ambulance.
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29 It had the strongest correlations with all other outcome metrics. Data from Lang *et al.* were available
30 to compare ambulance transport to Injury Severity Scores above *vs.* below 12.[44] Ambulance
31 transfer had low specificity (0.26) but high sensitivity (0.95), opposite to the pattern for
32 hospitalization. This suggests that most severely injured patients are transported by ambulance, but
33 so are many who are not severely injured.
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41 The CTAS triage scale is based on assessment by a triage nurse of a standardized list of presenting
42 complaints, vital sign modifiers, and pain severity.[27] Certain injury mechanisms, e.g., being hit by a
43 motor vehicle, may be assigned a greater urgency score. CTAS has been frequently tested for
44 reliability, with kappas for agreement beyond chance spanning a broad range from 0.25 to 0.89.²⁸
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49 We found no comparison of CTAS to Injury Severity Scores. We found no validity or reliability data
50 for continuing to cycle.
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CONCLUSIONS

In two of Canada's largest cities, approximately one-third of the bicycle crashes were collisions with a motor vehicle and the resulting injuries were more severe than in other crash circumstances.

Certain route types (in particular multi-use paths and sidewalks), downhill grades, and higher motor vehicle speeds were also associated with increased injury severity. These results suggest an urgent need to provide bike facilities that separate cyclists from motor vehicle traffic, that do not mix cyclists with pedestrians, and that minimize slopes. These bicycle infrastructure modifications would reduce both crashes and injury severity after a crash.

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2
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4
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50
51 consent before taking part in the study.
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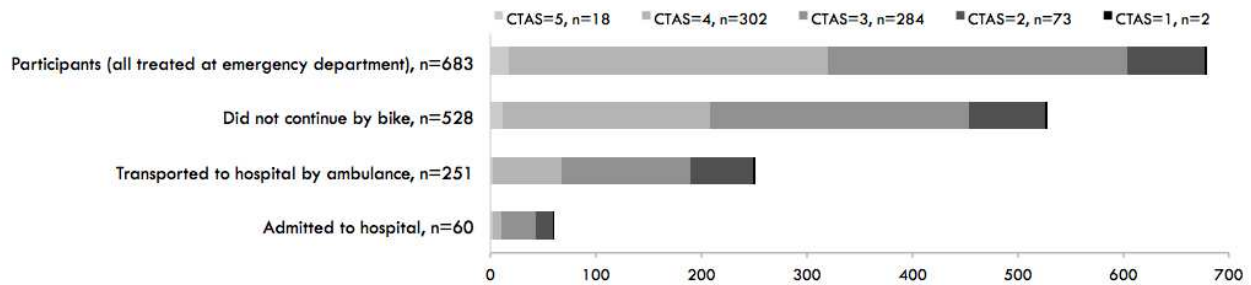


Figure 1. Metrics of severity of cycling injuries to 683 study participants, stratified by CTAS. CTAS = Canadian Triage and Acuity Scale, where 5 is the least medically urgent and 1 is the most.

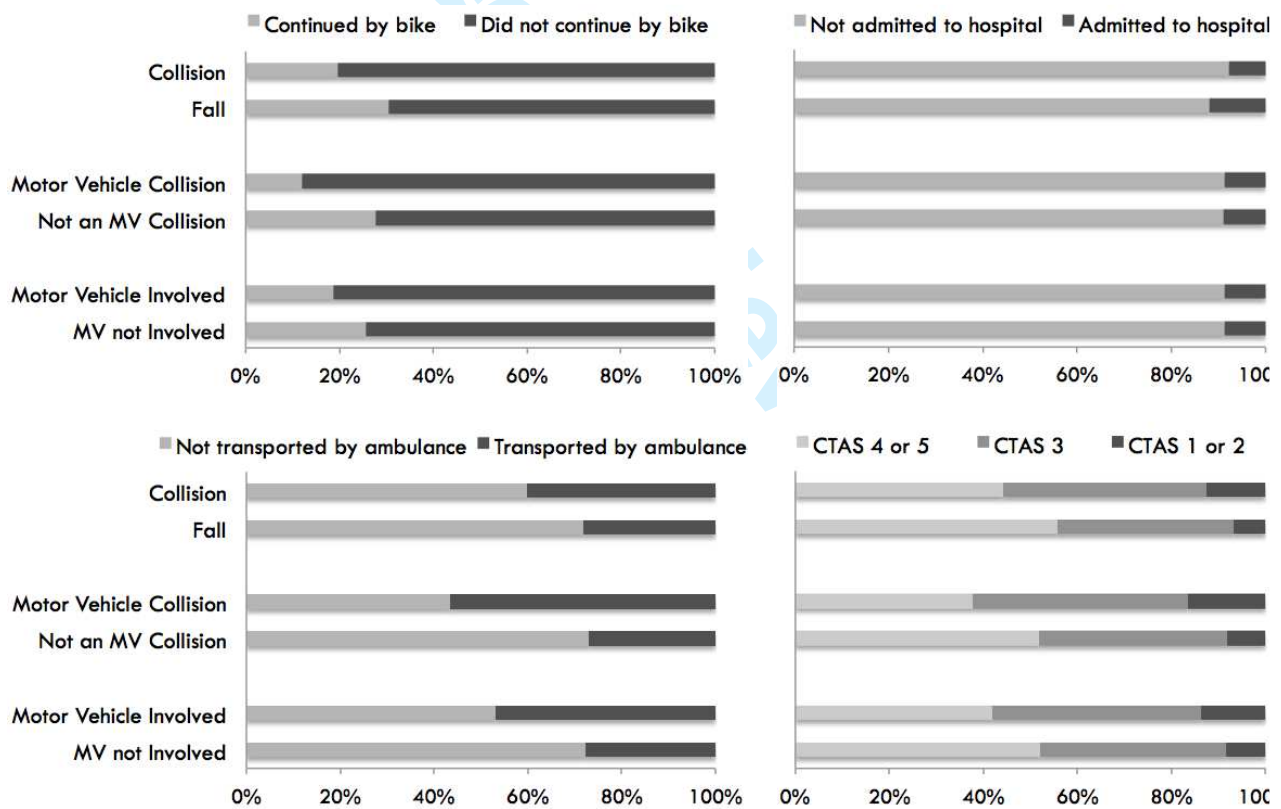


Figure 2. Crash circumstances vs. metrics of severity. Collisions could be with a motor vehicle, obstacle, surface feature, cyclist, pedestrian, or animal. Motor vehicle “involved” includes both direct collisions with vehicles and crashes resulting from manoeuvres to avoid a motor vehicle.

BMJ Open

Severity of urban cycling injuries in two Canadian cities and their relationship with personal, trip, route and crash characteristics: Case-control analyses using four severity metrics

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4 **Severity of urban cycling injuries in two Canadian cities and their relationship with personal,**
5 **trip, route and crash characteristics: Case-control analyses using four severity metrics**
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ABSTRACT

Objective: To examine the relationship between cycling injury severity and personal, trip, route and crash characteristics.

Methods: Data from the Bicyclists' Injuries and the Cycling Environment Study conducted in Toronto and Vancouver, Canada, were used to classify injury severity using four metrics: 1) did not continue trip by bike; 2) transported to hospital by ambulance; 3) admitted to hospital; and 4) Canadian Triage and Acuity Scale (CTAS). Multiple logistic regression was used to examine associations with personal, trip, route and crash characteristics.

Results: Of 683 adults injured while cycling, 528 did not continue their trip by bike, 251 were transported by ambulance, and 60 were admitted to hospital for further treatment. Treatment urgencies included 75 as CTAS=1 or 2 (most medically urgent), 284 as CTAS=3, and 320 as CTAS=4 or 5 (least medically urgent). Older age and collision with a motor vehicle were each significantly associated with increased severity in three metrics (both variables with ambulance transport and CTAS; age with hospital admission; and motor vehicle collision with did not continue by bike). Factors significantly associated with more severe injuries in one metric included more frequent cycling (medically urgent); female sex and crashes at non-intersection locations (did not continue by bike), on multi-use paths or local streets (admitted to hospital) and on sidewalks, downhill grades, and sites with higher motor vehicle speeds (ambulance transport).

Conclusions: In two of Canada's largest cities, about one-third of the bicycle crashes were collisions with motor vehicles and the resulting injuries were more severe than in other crash circumstances, underscoring the importance of separating cyclists from motor vehicle traffic. Our results also

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3 suggest that facilities that are not designed with pedestrians in mind and that minimize slopes would
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5 reduce both bicycling injury severity and crash risk.
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10 11 **Strengths and Limitations of this Study** 12

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16 • This study is one of few to examine the relationship between route characteristics and
17 severity of bicycling injuries. Its major strength was use of data from a study of bicycling
18 injury crash risk. This made it possible to consider whether route characteristics that
19 increased crash risk were similar to or different from those that increased bicycling injury
20 severity.
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22
- 23 • The results show that bike facilities that separate cyclists from motor vehicle traffic, that are
24 not designed for pedestrians, and that minimize slopes would reduce both injury severity
25 after a crash and reduce crash risk.
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- 28 • The analyses examined four metrics covering different aspects of injury severity (not able to
29 continue the trip by bike, transport to hospital by ambulance, admission to hospital, and
30 treatment urgency) and identified factors that were consistently associated with increased
31 risk: increased age and collision with a motor vehicle.
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- 34 • The study included a range of injury severities resulting in emergency treatment at a hospital
35 but did not include those so severely injured they could not remember their trip, nor those
36 with such minor injuries that emergency treatment was not required.
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- 39 • The influence of route characteristics on severity was adjusted for potential confounding by
40 personal and trip characteristics in the regression models, but the potential for uncontrolled
41 confounding by unmeasured characteristics remains.
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INTRODUCTION

Cycling is used for transportation and is a popular recreational activity. Its health benefits are clear, [1,2] in contrast to motor vehicle travel. Transportation cycling has risks in the same order of magnitude as driving and walking in the US and Canada.[3,4] However it is not nearly as safe as in some European countries where cycling participation is much higher.[5-8]

In 2010, there were 618 cyclist traffic deaths in the United States and 60 in Canada.[9,10] Broader data (including bicycling sports such as mountain biking) indicate that about 27,800 Americans and 4,300 Canadians were hospitalized for cycling injuries in 2009.[11,12] Although bicycling injuries are a small proportion of all traffic injuries and deaths in North America (~2 to 4%),[9,10] reducing their incidence is important because of the direct harm that they do and because they deter potential cyclists.[13-15]

The reason postulated for the inversion of cycling activity and injury risk between North America and Europe is the well-designed bicycle-specific infrastructure in Europe *vs.* its relative paucity in North America. We reviewed published studies and found that bicycle-specific infrastructure was associated with decreased injury risk, but a small range of infrastructure had been studied, often with uncertain control of exposure to risk.[16] We subsequently conducted a case-crossover study of the association between route infrastructure and crash risk: the Bicyclists' Injuries and the Cycling Environment Study.[17,18] It found that infrastructure that was bicycle-specific (e.g., cycle tracks separated from traffic, bike lanes) or "bicycle-friendly" (e.g., local streets with traffic diversion) had considerably lower injury risk. Other features were found to increase risk: streetcar or train tracks, downhill grades, construction, major street intersections, and traffic circles at local street intersections. This work was designed to estimate associations with injury risk, with a no-injury control.

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3 An alternative line of inquiry is what factors are associated with injury severity, among those who
4 have been injured. Many studies have found that collisions with motor vehicles increase cyclist injury
5 severity.[11,19-22] However few authors have examined severity with respect to route
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8 infrastructure.[23-25] Higher severity has been found with grades, higher speed roads, and crashes in
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10 traffic or on shared paths.[23-25] Although these results suggest that predictors of cycling injury risk
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12 may be similar to predictors of injury severity, this is not established, and our study offers the
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14 opportunity to examine both sets of outcomes, adding a level of context for policy makers,
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16 infrastructure designers and other stakeholders. In our opinion, injury severity, not just the fact of
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18 an injury, is a second and equally important criterion used by the lay public to evaluate the apparent
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20 safety of cycling.
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27 Therefore we conducted additional analyses of data from the Bicyclists' Injuries and the Cycling
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29 Environment Study to examine the relationship between injury severity and personal, trip, route and
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31 crash characteristics.
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37 **METHODS**

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40 Methods of study conduct and reliability testing have been described in detail elsewhere.[17,26] The
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42 study population consisted of adult (≥ 19 years) residents of Toronto and Vancouver who were
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44 injured while riding a bicycle in the city and treated within 24 hours in the emergency departments
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46 of the following hospitals between May 18, 2008 and November 30, 2009: St. Paul's or Vancouver
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48 General in Vancouver; St. Michael's, Toronto General or Toronto Western in Toronto. Those who
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50 were fatally injured or so severely injured that they were unable to remember their trip were not
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52 included.
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3 Data on characteristics related to severity were abstracted from emergency department records. In
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5 addition, eligible participants were interviewed in person by trained interviewers about personal
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7 characteristics, trip characteristics, and crash circumstances, using a structured questionnaire
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10 (<http://cyclingingcities.spph.ubc.ca/files/2011/10/InterviewFormFinal.pdf>).
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13 The study was not designed to focus on severity, so the data did not include classical severity scoring
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15 using the Abbreviated Injury Scale. However we did have access to four other indicators of severity:
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18 1. Whether the subject continued their trip by bicycle (self-reported in the interview), no vs. yes
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20 2. Whether the subject was transported by ambulance (hospital data), yes vs. no
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22 3. Whether the subject was admitted to hospital (hospital data), yes vs. no
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24 4. Canadian Triage and Acuity Scale (CTAS) (hospital data), levels 1 to 5, defined as
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26 follows:[27,28]

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29 • 1 – Resuscitation; need to be seen immediately
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31 • 2 – Emergent; need to be seen within 15 minutes
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33 • 3 – Urgent; need to be seen within 30 minutes
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35 • 4 – Less urgent; need to be seen within 60 minutes
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37 • 5 – Non urgent, need to be seen within 120 minutes
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43 The relationship between these severity metrics was examined descriptively using cross-tabulations
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45 and Pearson correlation coefficients.

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47 Site observations were made to document characteristics of crash and control sites, and allow route
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49 infrastructure classification.[17,18] The observations were made blind to whether an injury took
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51 place at the site or not. In the current analyses, only the crash site data was used.
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55 Unconditional logistic regression was used to examine associations of each of the following
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57 independent variables with each severity outcome metric:
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- personal characteristics: sex; age; how frequently he/she cycled; whether the cyclist considered himself/herself experienced, had taken a cycling training course, had a driver's license
- trip characteristics: time of day; weather; helmet use; use of visible clothing on the trunk; whether bike lights were turned on; alcohol and drug use in the 6 hours prior
- route characteristics at the injury crash site: type of route; intersection location; presence of bike signage; junctions; construction; streetcar tracks; grade; average vehicle speed; distance visible along route.
- crash circumstances: collision (with a motor vehicle, obstacle, surface feature, cyclist, pedestrian, or animal) vs. fall; collision with a motor vehicle vs. not; motor vehicle "involvement" (i.e., both direct collisions with vehicles and crashes resulting from motor vehicle avoidance manoeuvres) vs. not. No data on fault in the crash was collected.

All independent variables significant at $p < 0.05$ in simple logistic regression (unadjusted analysis) of any severity metric were included in multiple regression models for all four severity metrics. The rationale for this broad inclusion of variables in the final models was to maximize control of potential confounding by personal and trip characteristics, to allow comparison of results across severity metrics, and to ensure that characteristics previously shown to be consistently related to injury severity were included in all the models (i.e., age, crash circumstance).

For dichotomous severity metrics (did not continue by bike, ambulance transport, hospital admission), traditional logistic regression was used, with the more severe injury category treated as the outcome ("case") group and the less severe as the comparison ("control") group. For CTAS, ordinal logistic regression modeled the odds of a more urgent CTAS group, after verifying that the proportional odds assumption was valid. CTAS categories were grouped as follows: most urgent, levels 1 or 2; moderate urgency, 3; least urgency, 4 or 5.

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3 Additional analyses were conducted to evaluate the models. Analyses were run without the motor
4 vehicle collision variable and, separately, without the route type variable to determine whether either
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6 vehicle collision variable and, separately, without the route type variable to determine whether either
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8 changed the relationship of the other to severity in the full models. Separate analyses were conducted
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10 for motor vehicle collisions and other collisions to determine whether there was interaction between
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12 the motor vehicle collision and route type variables.
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14 15 16 17 18 **RESULTS** 19

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21 The study included 690 injured cyclists (414 in Vancouver, 276 in Toronto). Seven were unable to
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23 recall their crash circumstances, so were removed from analyses; none of these continued by bike,
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25 six were transported by ambulance, their CTAS scores were either 1 or 2, and one was admitted to
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27 hospital. After these subjects were excluded, 683 subjects remained for most analyses, though four
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29 additional subjects did not have information on CTAS or ambulance transport.
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33 Descriptive data about the study participants, the trips when their injuries occurred, the
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35 characteristics of the route at the crash site, and the crash circumstances are presented in Table 1.
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37 Most participants were men, young, and regular cyclists. Most wore a helmet, but few wore bright
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39 clothing or used bike lights. Most of the injury sites were on major or local streets with little or no
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41 cycling infrastructure and most were at non-intersection locations. A minority of injuries occurred at
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43 sites with bike-specific infrastructure.
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47 Most of the crashes were collisions (74%, n=506) rather than falls. Direct collisions with motor
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49 vehicles (34%, n=231) were the most frequent collision type. Crashes “involving” motor vehicles
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51 (48%, n=330) included direct collisions, as well as crashes to avoid motor vehicle collisions (14%,
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53 n=99). Few collisions involved other cyclists (3%, n=22), pedestrians (2%, n=12) or animals (1%,
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55 n=6).
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Table 1. Personal characteristics of the cyclists, characteristics of the trip when the injury occurred, characteristics of the route at the site where the crash occurred, and crash circumstances (N=683)

	N (%)
Personal characteristics	
Male	404 (59%)
Age	
19 to 29	262 (39%)
30 to 39	167 (25%)
40 to 49	115 (17%)
50 to 59	81 (12%)
≥ 60	55 (8.1%)
Regular cyclist (cycled ≥ 52 times per year)	602 (88%)
Had a driver's license	613 (90%)
Considered themselves experienced	637 (93%)
Had taken a cycling training course	42 (6.1%)
Trip characteristics	
Time of day	
Day	530 (78%)
Dawn or dusk	50 (7.3%)
Night	103 (15%)
Clear weather	473 (69%)
Helmet worn	472 (69%)
Bright clothing worn	228 (33%)
Bike lights turned on	133 (19%)
Alcohol consumed in previous 6 h	70 (10%)
Drugs consumed in previous 6 h	78 (11%)
Route characteristics at the injury sites	
Route types	
Major streets (arterials and collectors, most with no bicycle infrastructure, a few with shared lanes, n=22)	289 (42%)
Local streets (mainly residential, many designated as bikeways, n=99)	187 (27%)
Sidewalks	52 (7.6%)
Multi-use paths (designated for pedestrian and bicyclists)	73 (11%)
Bicycle-specific infrastructure (bike lanes on major streets, n=59; cycle tracks alongside major streets, n=2; and off-street bike paths, n=21)	82 (12%)
At an intersection	
Junctions in last 100 m	211 (31%)
Bike signage present	593 (87%)
Bike signage present	76 (11%)
Construction present	85 (12%)
Streetcar or train tracks present	149 (22%)
Downhill grade	329 (48%)
Average vehicle speed > 30 km/h	363 (53%)
Forward distance visible < 20 m	12 (1.8%)
Crash circumstances	
Collision with motor vehicle	231 (34%)
Collision with streetcar or train tracks	97 (14%)
Collision with other surface features (e.g., pothole, rock, roots, leaves, ice)	69 (10%)
Collision with obstacle (e.g., post, curb, planter, lane divider)	69 (10%)
Collision with cyclist, pedestrian, animal	40 (5.9%)
Falls	177 (26%)

Figure 1 shows the distribution of subjects by the severity metrics, stratified by CTAS. The most urgent CTAS scores (1 or 2, n=75) were assigned to 11% of all subjects, 14% of those who did not continue by bike, 25% of those transported by ambulance and 28% of those who were admitted to

hospital. Table 2 provides additional detail on the relationship between the metrics. Of the 251 subjects transported to hospital by ambulance, 99% did not continue by bike. Of the 60 subjects admitted to hospital, 100% did not continue by bike, and 75% were transported by ambulance. Pearson correlations show associations in the expected directions, but the correlations were not strong. Thus the four metrics had logical relationships to each other, but did not measure identical constructs.

Table 2. Relationship between the four metrics of severity: Pearson correlation coefficients above the diagonal; numbers of subjects below the diagonal.

	Did not continue by bike	Transported to hospital by ambulance	Admitted to hospital	CTAS*
Did not continue by bike (n=528)	–	0.40	0.17	-0.29
Transported to hospital by ambulance (n=251)	249	–	0.24	-0.39
Admitted to hospital (n=60)	60	45	–	-0.20
CTAS = 1 or 2 (n=75)	74	62	17	–

* Correlations with CTAS were negative because the scale was in the opposite direction, with 1 = most urgent and 5 = least urgent. All other metrics were assigned 1 = more vs. 0 = less severe.

Figure 2 shows the severity metrics against crash circumstances, classified three ways. Collisions tended to be more severe than falls, and crashes “involving” motor vehicles tended to be more severe than those not. Direct collisions with motor vehicles had the highest proportion in the more severe category of every metric except admitted to hospital. In unadjusted analyses, collision (of any type) and motor vehicle “involvement” both had elevated odds ratios for the same severity metrics as motor vehicle collision (data not shown), but the odds ratios were lower, indicating that it was direct collision with a motor vehicle that led to increased severity. Only the motor vehicle collision variable was included in multiple regression models.

Table 3 shows the results of the multiple logistic regression models for each severity metric, including all independent variables statistically significant in at least one unadjusted analysis. Four personal characteristic variables were included: age, sex, cycling experience, and cycling frequency.

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3 Age showed consistent associations across all severity metrics; older age groups had more severe
4 injuries, significantly so for ambulance transport, admission to hospital and CTAS. Women were
5 significantly more likely to stop their trip by bike than men. There was a tendency for more
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7 experienced and more regular cyclists to have higher injury severity, though only one association was
8 statistically significant in multiple regression.
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15 Cyclists whose crash was a direct collision with a motor vehicle had elevated odds ratios for all
16 severity metrics, statistically significant for not continuing by bike, being transported by ambulance
17 and more urgent triage score (CTAS). Those whose crash sites were on multi-use paths, sidewalks
18 and local streets tended to have more severe injuries than those who crashed on major streets;
19 significant associations were observed for certain associations with ambulance transport and hospital
20 admission. Crashes at intersections had inconsistent results; the only significant odds ratio indicated
21 that those injured at an intersection were less likely to stop their trip by bike. Downhill grades were
22 consistently related to greater injury severity, significantly so for transportation by ambulance. The
23 same pattern was observed for higher average motor vehicle speeds at the crash location. Time of
24 day and presence of streetcar tracks were both significant in some unadjusted analyses, but did not
25 remain so in multiple regression.
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41 The following independent variables were not associated with any of the injury severity metrics in
42 unadjusted analyses and were not included in multiple regression: whether the participant had taken
43 a cycling training course or had a driver's license; weather; use of a helmet, visible clothing on the
44 trunk, or bike lights; alcohol or drug use in the 6 hours prior to the trip; presence of bike signage,
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46 junctions, or construction; and distance visible along the route.
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Table 3. Odds ratios (OR) and 95% confidence intervals (CI) for associations between metrics of injury severity and personal, trip, crash circumstance, and route characteristics (N=683). Multiple logistic regression models; all independent variables significant in at least one unadjusted analysis included.

	Did not continue by bike N=528 (77%) OR (95% CI)	Transported to hospital by ambulance N=251 (37%) OR (95% CI)	Admitted to hospital N=60 (8.8%) OR (95% CI)	CTAS † 1 or 2, N=75 (11%) 3, N=284 (42%) 4 or 5, N=320 (47%) OR (95% CI)
Sex				
Male	1 (reference)	1 (reference)	1 (reference)	1 (reference)
Female	1.91 (1.26 – 2.92)	1.34 (0.93 – 1.93)	1.07 (0.59 – 1.94)	0.98 (0.71 – 1.35)
Age				
19 to 29	1 (reference)	1 (reference)	1 (reference)	1 (reference)
30 to 39	1.15 (0.70 – 1.88)	1.18 (0.75 – 1.85)	1.18 (0.54 – 2.61)	1.29 (0.87 – 1.91)
40 to 49	1.22 (0.70 – 2.14)	1.40 (0.83 – 2.34)	1.96 (0.89 – 4.33)	2.07 (1.33 – 3.23)
50 to 59	1.50 (0.77 – 2.95)	1.04 (0.57 – 1.91)	1.02 (0.35 – 2.97)	1.57 (0.95 – 2.62)
≥ 60	1.33 (0.63 – 2.82)	2.57 (1.31 – 5.05)	3.52 (1.37 – 9.04)	1.42 (0.78 – 2.60)
Considered themselves an experienced cyclist				
No	1 (reference)	1 (reference)	1 (reference)	1 (reference)
Yes	1.36 (0.63 – 2.95)	2.16 (0.97 – 4.83)	1.03 (0.28 – 3.84)	1.52 (0.78 – 2.95)
Cycling frequency °				
	1.00 (0.78 – 1.76)	0.92 (0.72 – 1.08)	1.18 (0.85 – 1.50)	1.18 (1.00 – 1.38)
Time of day				
Day	1 (reference)	1 (reference)	1 (reference)	1 (reference)
Dusk or dawn	0.65 (0.33 – 1.29)	0.53 (0.24 – 1.13)	0.75 (0.21 – 2.62)	0.72 (0.39 – 1.30)
Night	0.90 (0.53 – 1.54)	1.16 (0.71 – 1.90)	1.87 (0.90 – 3.86)	0.90 (0.58 – 1.40)
Motor vehicle collision				
No	1 (reference)	1 (reference)	1 (reference)	1 (reference)
Yes	3.46 (2.07 – 5.76)	3.66 (2.44 – 5.48)	1.27 (0.63 – 2.54)	2.03 (1.41 – 2.90)
Route type				
Major street	1 (reference)	1 (reference)	1 (reference)	1 (reference)
Local street	1.08 (0.61 – 1.92)	1.44 (0.86 – 2.39)	2.76 (1.15 – 6.62)	1.18 (0.75 – 1.84)
Sidewalk	1.15 (0.42 – 3.19)	3.72 (1.37 – 10.1)	3.26 (0.51 – 20.7)	1.31 (0.56 – 3.06)
Multi-use path	1.33 (0.52 – 3.44)	2.18 (0.83 – 5.77)	7.56 (1.43 – 40.0)	1.22 (0.55 – 2.68)
Bicycle-specific infrastructure	0.98 (0.50 – 1.94)	1.02 (0.55 – 1.89)	0.89 (0.27 – 2.99)	1.27 (0.74 – 2.18)
Intersection				
No	1 (reference)	1 (reference)	1 (reference)	1 (reference)
Yes	0.57 (0.36 – 0.88)	1.44 (0.98 – 2.13)	1.04 (0.53 – 2.04)	0.89 (0.63 – 1.26)
Streetcar or train tracks				
No	1 (reference)	1 (reference)	1 (reference)	1 (reference)
Yes	1.11 (0.65 – 1.91)	1.03 (0.63 – 1.70)	0.98 (0.39 – 2.47)	1.36 (0.88 – 2.10)
Grade				

Flat or uphill	1 (reference)	1 (reference)	1 (reference)	1 (reference)
Downhill	1.32 (0.89 – 1.96)	1.62 (1.14 – 2.32)	1.23 (0.68 – 2.22)	1.31 (0.96 – 1.79)
Motor vehicle speed β	1.05 (0.89 – 1.24)	1.21 (1.01 – 1.43)	1.24 (0.91 – 1.69)	1.08 (0.94 – 1.24)

† CTAS = Canadian Triage and Acuity Scale, grouped into 3 categories for analysis using ordinal logistic regression; the odds ratio represents the comparison of categories 1 & 2 vs. 3, 4 & 5 and categories 1, 2 & 3 vs. 4 & 5 under the proportional odds assumption. The proportional odds assumption was met, meaning that the odds ratios for these two comparisons are equivalent.

° Mean cycling frequency = 152 trips/y, SD = 81 trips/y; Odds ratios and confidence intervals calculated for a one standard deviation increase

β Mean motor vehicle speed = 36 km/h, SD = 9.5 km/h; odds ratios and confidence intervals calculated for a one standard deviation increase. This is a mean of means: 683 sites, each with 5 speed measurements taken during the site observation period (~30 minutes), then averaged. Speeds were measured using a Bushnell Velocity Speed Gun (Overland Park, KS).

DISCUSSION

In this study, using four severity metrics that spanned rider self-evaluation (unable to continue by bike) to clinical-practitioner evaluation (CTAS), we found that the following characteristics were associated with more severe injuries: older age; female sex; more experience and frequency of cycling; collision with a motor vehicle; crash on a multi-use path, sidewalk or local street, at non-intersection location, on a downhill grade, and at locations with higher motor vehicle speeds.

Personal Characteristics

Older age has frequently been associated with more severe injuries in bicycling crashes.[19-22, 29-33]

We observed the same for all metrics, though the odds ratio was not always statistically significant.

This pattern is attributed to increasing frailty with age and has been observed for all vulnerable road users.[32]

Although sex has frequently been associated with bicycling injury severity, the evidence does not show a clear pattern. We found that women were less likely to continue their trip by bicycle and had a non-significant increased chance of ambulance transport. Moore *et al.* found women to have more severe injuries,[31] but others have found higher severities in men.[19,22,32] Theories for each of these results are available. The smaller average size of women may make them more vulnerable and

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3 men may be more comfortable handling minor injuries without help. A greater propensity for risk-
4 taking and speed may provide opportunities for men to have higher impact crashes.[34-36]
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8 We found that experienced cyclists and those who cycled more frequently had greater injury severity
9 (more likely to need ambulance transport, or to have a more urgent triage score, respectively).
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11 Similarly Heesh *et al.* found that frequent and experienced cyclists had more severe injuries.[21]
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13 These cyclists may travel at higher speeds and incur higher impact forces in a crash.
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16 17 18 **Crash Circumstances** 19

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21 About a third of the injuries were collisions with motor vehicles. These were strongly associated
22 with three of our four injury severity metrics. In other research, collisions with motor vehicles have
23 consistently been associated with increased severity.[11,19-22] Collisions with larger vehicles have
24 resulted in more severe injuries and fatalities.[29,31,33,37]
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29 Previous analyses of our Bicyclists' Injuries and the Cycling Environment study data showed that
30 collisions with motor vehicles were associated with route type.[38] They never occurred on off-street
31 bike paths or on cycle tracks (separated bike lanes), and were over-represented on major streets with
32 parked cars and no bike infrastructure. Therefore, for the severity analyses presented here, we
33 considered whether route type confounded the association between collision with a motor vehicle
34 and severity (and vice versa), but this was not the case, nor was there interaction between the two
35 variables (data not shown).
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47 The severity of direct collisions with motor vehicles provides clear rationale for transportation
48 planners to minimize interactions between cyclists and vehicles. This planning approach is
49 supported by the results of our earlier analyses of injury crash risk: cycle tracks (bike lanes that
50 physically separate cyclists and motor vehicle traffic) were associated with 1/9th the risk compared to
51 streets with no bicycle infrastructure.[17] Separating modes of traffic with large differences in speed
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3 and mass is a principle used by countries such as Sweden, Germany, Denmark and the Netherlands
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5 where bicycling injury risk is much lower than in North America.[6,8] A rationale for this approach
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7 is that human error is inevitable, so it is important to minimize the consequences of such errors.
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9 Bicycling facilities separated from motor vehicles minimize the likelihood of a collision and the
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11 potential for severe injury when either a driver or a cyclist makes an error.
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14 15 **Route Characteristics** 16

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18 Our main interest in this analysis was to determine whether route characteristics were associated
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20 with increased or reduced injury severity. Route type, presence of an intersection, grade, and average
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22 motor vehicle speed at the crash location were all associated with injury severity.
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26 In comparison to crashes on major streets without cycling infrastructure, crashes on sidewalks and
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28 multi-use paths had considerably higher odds of ambulance transport (odds ratio for multi-use paths
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30 not significant). Crashes on sidewalks and multi-use paths also had considerably higher odds of
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32 hospital admission (odds ratio for sidewalks not significant). In our earlier analyses of crash risk,
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34 multi-use paths and sidewalks had among the highest risks, despite being off-street.[17,18] The
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36 increased severity after a crash adds to concern about these route types. Local streets (mainly
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38 residential streets) were found to be a safe route type in our earlier analyses, with only about half the
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40 risk of a crash.[17] The current analysis indicates that if a crash did occur, there was an increased
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42 odds of one severity measure – hospitalization.
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47 Few studies have examined route type and injury severity. De Rome *et al.* found that more severe
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49 injuries were associated with crashes in traffic and on multi-use paths, and less severe with crashes in
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51 bike lanes and on sidewalks.[25] Slaughter *et al.* found lower severity in bike lane crashes.[39] In
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53 earlier analyses of our study, bicycle-specific infrastructure was found to have lower crash risk than
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55 major streets without such infrastructure,[17] but the current analysis indicates that if a crash did
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3 occur, injury severity was similar. This may in part be because most of the injury sites with bicycle-
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5 specific infrastructure in our study were bike lanes without physical separation from motor vehicles.
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8 Intersection vs. non-intersection crash locations did not present a clear pattern of association with
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10 severity in this study. Moore *et al.* found differing patterns of injury severity at intersections and non-
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12 intersections.[31]
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15 Downhill grade was significantly associated with increased severity for all metrics in unadjusted
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17 analyses, and remained significant in the final model for ambulance transport. Three previous studies
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19 have shown that injury severity is greater with grades.[23,24,31] Downhill grade is likely to be
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21 associated with increased cyclist (and motor vehicle) speed, and therefore increased force of impact.
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24 Our earlier analyses found that downhill slopes were associated with higher injury crash risk, and
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26 that uphill grades deter cycling.[15,17,18] This suggests that, wherever possible, routing bicycle
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28 facilities where slopes are gentle is a good strategy for both reducing injuries and motivating cycling.
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32 Higher average motor vehicle speed was associated with increased severity for all metrics, and
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34 remained significant in the final model for ambulance transport. Other studies found higher speed
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36 roads to be associated with greater injury severity to cyclists.[23,24,37] Our earlier analyses found
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38 that injury crash risk was lower at intersections where motor vehicle speeds were 30 km/h or lower
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40 and that routes with high vehicle speeds deter cycling.[15,18] This supports recent changes in some
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42 European and North American cities to lower urban speed limits.
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46 47 **Trip Characteristics**

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49 Only one trip characteristic was associated with injury severity. Time of day (night riding) was
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51 associated with a higher odds of hospital admission in unadjusted analyses and was elevated but not
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53 significant in multiple regression. Night-time riding has been associated with increased injury
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55 severity in other studies, especially where roadways were not lit.[24,29,32,33]
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3 Although much of the bicycle safety literature focuses on helmets and head injury mitigation,
4 [22,37,40,41,42] helmet use was not associated with any of the severity metrics in this study. Both
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6 biomechanical studies[42] and epidemiological studies[22,37,40,41] have demonstrated that helmets
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8 can prevent serious skull and brain injuries. This study was not limited to head injuries, likely
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10 contributing to our result that helmet use was not associated with injury severity. In one of the
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12 largest studies to examine helmets, their use was found to significantly reduce head injuries, but was
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14 not associated with serious injury mitigation across all body regions.[22,41] In this context, it is
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16 important to recognize that cyclists may sustain injuries, including serious trauma, to any body part,
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18 including their thorax, abdomen, neck and extremities.[22] A helmet can do nothing to prevent non-
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20 head injuries. Our earlier analyses of crash risk show the potential for all injuries to be significantly
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22 decreased for cyclists separated from motor vehicle traffic in a cycle track or a local street with
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24 traffic diversion[17,18] and the present results show that injury severity significantly increases in a
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26 collision with a motor vehicle. Together these results point to bicycle infrastructure that physically
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28 separates cyclists from motor vehicle traffic to prevent trauma to any area of the body.
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35 36 **Strengths and limitations**

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38 Strengths of the study include two study cities with differing climates, terrain, cycling mode shares
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40 and cycling infrastructure, an urban-only cycling sample, the prospective accrual of subjects,
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42 observation of route characteristics blinded to whether the site was an injury site, and the number of
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44 clinical and cyclist self-report severity metrics.
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48 Study limitations include a relatively small sample of injured cyclists, restriction to Canadian cities
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50 and lack of data on the anatomical location of the injury. As in all injury studies, only a portion of
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52 injured cyclists were included; here, those whose injuries were serious enough to be treated at a
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54 hospital emergency department, but not to cause death or a head injury so severe that the trip could
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3 not be recalled. This reduced the pool of the most severely injured cases: 2 potential participants
4 were fatally injured, 26 of those contacted could not remember their route, and 7 could not recall
5 their crash circumstances. An unknown number of cyclists had injuries so minor that no emergency
6 department visit was made.
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12 Our overall Bicyclists' Injuries and the Cycling Environment study had a case-crossover design that
13 compared injury sites to control sites within a person-trip, fully controlling for differences between
14 individuals and trips that might confound the relationship between injury crash risk and
15 infrastructure (the primary focus of the study). To examine severity of injuries in the current analysis,
16 the analysis compared participants with more severe injuries ("cases") to those with less severe
17 injuries ("controls"), introducing the potential for confounding by personal and trip characteristics.
18 We addressed this via adjustment in our regression models, but the potential for uncontrolled
19 confounding by unmeasured characteristics remains.
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32 Given that we did not have data on more traditional measures of severity, the Abbreviated Injury
33 Scale and Injury Severity Score, it is important to consider our outcome metrics, their relationship to
34 each other and their potential reliability and validity as measures of severity. The four metrics
35 measured different aspects of severity, as described above (Figure 1, Table 2).
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42 Hospital admission is based on an in depth medical assessment and should reflect the most severe
43 injuries. There are no standardized decision criteria, and physicians' decisions to admit emergency
44 department patients to hospital have been found to differ substantially.[43] Data from Rivara *et al.*
45 were available to compare hospitalization to Injury Severity Scores above *vs.* below 9.[22]
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50 Hospitalization had high specificity (0.94) but lower sensitivity (0.72), suggesting that few patients
51 with minor injuries are admitted to hospital, but some who are severely injured are not admitted.
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55 This could be because some patients with severe injuries (e.g., some extremity fractures, intra-
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3 abdominal trauma) may be treated and stabilized in an emergency department then discharged home,
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5 but scheduled for later surgical repair. This may have contributed to our somewhat different results
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7 for hospital admission and its lower correlations with the other metrics.
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10 Ambulance transport is based, in part, on whether or not someone at the scene called an ambulance.
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12 It had the strongest correlations with all other outcome metrics. Data from Lang *et al.* were available
13
14 to compare ambulance transport to Injury Severity Scores above *vs.* below 12.[44] Ambulance
15
16 transfer had low specificity (0.26) but high sensitivity (0.95), opposite to the pattern for
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18 hospitalization. This suggests that most severely injured patients are transported by ambulance, but
19
20 so are many who are not severely injured.
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25 The CTAS scale is based on assessment by a triage nurse of a standardized list of presenting
26
27 complaints, vital sign modifiers, and pain severity.[27] Certain injury mechanisms, e.g., being hit by a
28
29 motor vehicle, may be assigned a greater urgency score. CTAS has been frequently tested for
30
31 reliability, with kappas for agreement beyond chance spanning a broad range from 0.25 to 0.89.[28]
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33 We found no comparison of CTAS to Injury Severity Scores. We found no validity or reliability data
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35 for continuing to cycle.
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42 CONCLUSIONS

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45 In two of Canada's largest cities, approximately one-third of the bicycle crashes were collisions with
46
47 a motor vehicle and the resulting injuries were more severe than in other crash circumstances.

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49 Certain route types (in particular multi-use paths and sidewalks), downhill grades, and higher motor
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51 vehicle speeds were also associated with increased injury severity. These results suggest an urgent
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53 need to provide bike facilities that separate cyclists from motor vehicle traffic, that are not designed
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3 for pedestrians, and that minimize slopes. These bicycle infrastructure modifications would reduce
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5 both crashes and injury severity after a crash.
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14 Columbia's Bridge Program Grant Development course (2005-2006) and benefitted from input
15 from the participants of that class.
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23
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25 of the study. KT, MAH, CCOR, PC, MW, SB, MC, MDC, JB, SMF, Garth Hunte and Kishore
26 Mulpuri were responsible for the funding proposal. CCOR, MAH, MW, MDC, KT, Melody Monroe
27 and Lee Vernich designed and tested data collection instruments. MW, HS and KT developed
28 algorithms for defining route infrastructure. HS was responsible for data analyses. All authors had
29 full access to the results of all analyses. PC, HS and KT drafted the article. All authors contributed to
30 study design and implementation, analysis decisions, interpretation of results, and critical revision of
31 the article. Evan Beaupré, Niki Blakely, Jill Dalton, Martin Kang, Kevin McCurley, and Andrew
32 Thomas were responsible for interviews or site observations. Vartouji Jazmaji, Melody Monroe and
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26 **PATIENT CONSENT:** Obtained
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29
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44 participants and site observations by study personnel. It cannot be shared by the authors with
45 anyone without approval from the University and Hospital human subjects review boards.
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Figure Legend

Figure 1. Metrics of severity of cycling injuries to 683 study participants, stratified by CTAS.
CTAS = Canadian Triage and Acuity Scale, where 5 is the least medically urgent and 1 is the most.

Figure 2. Crash circumstances vs. metrics of severity.
Collisions could be with a motor vehicle, obstacle, surface feature, cyclist, pedestrian, or animal. Motor vehicle “involved” includes both direct collisions with vehicles and crashes resulting from manoeuvres to avoid a motor vehicle.

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4 **Severity of urban cycling injuries in two Canadian cities and their relationship with personal,**
5 **trip, route and crash characteristics: Case-control analyses using four severity metrics**
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ABSTRACT

Objective: To examine the relationship between cycling injury severity and personal, trip, route and crash characteristics.

Methods: Data from the **Bicyclists' Injuries and the Cycling Environment Study** conducted in Toronto and Vancouver, Canada, were used to classify injury severity using four metrics: 1) did not continue trip by bike; 2) transported to hospital by ambulance; 3) admitted to hospital; and 4) Canadian Triage and Acuity Scale (CTAS). Multiple logistic regression was used to examine associations with personal, trip, route and crash characteristics.

Results: Of 683 **adults injured while cycling**, 528 did not continue their trip by bike, 251 were transported by ambulance, and 60 were admitted to hospital for further treatment. Treatment urgencies included 75 as CTAS=1 or 2 (most medically urgent), 284 as CTAS=3, and 320 as CTAS=4 or 5 (least medically urgent). Older age and collision with a motor vehicle were each significantly associated with increased severity in three metrics (**both variables with ambulance transport and CTAS; age with hospital admission; and motor vehicle collision with did not continue by bike**). Factors significantly associated with more severe injuries in one metric included **more frequent cycling (medically urgent); female sex and crashes at non-intersection locations (did not continue by bike), on multi-use paths or local streets (admitted to hospital) and on sidewalks, downhill grades, and sites with higher motor vehicle speeds (ambulance transport)**.

Conclusions: In two of Canada's largest cities, about one-third of the bicycle crashes were collisions with motor vehicles and the resulting injuries were more severe than in other crash circumstances, underscoring the importance of separating cyclists from motor vehicle traffic. Our results also

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3 suggest that facilities **that are not designed with pedestrians in mind** and that minimize slopes would
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5 reduce both bicycling injury severity and crash risk.
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10 11 **Strengths and Limitations of this Study** 12

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16 • This study is one of few to examine the relationship between route characteristics and
17 severity of bicycling injuries. Its major strength was use of data from a study of bicycling
18 injury crash risk. This made it possible to consider whether route characteristics that
19 increased crash risk were similar to or different from those that increased bicycling injury
20 severity.
21
22
- 23 • The results show that bike facilities that separate cyclists from motor vehicle traffic, **that are**
24 **not designed for pedestrians**, and that minimize slopes would reduce both injury severity
25 after a crash and reduce crash risk.
26
27
- 28 • The analyses examined four metrics covering different aspects of injury severity (not able to
29 continue the trip by bike, transport to hospital by ambulance, admission to hospital, and
30 treatment urgency) and identified factors that were consistently associated with increased
31 risk: increased age and collision with a motor vehicle.
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- 34 • The study included a range of injury severities resulting in emergency treatment at a hospital
35 but did not include those so severely injured they could not remember their trip, nor those
36 with such minor injuries that emergency treatment was not required.
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- 39 • The influence of route characteristics on severity was adjusted for potential confounding by
40 personal and trip characteristics in the regression models, but the potential for uncontrolled
41 confounding by unmeasured characteristics remains.
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INTRODUCTION

Cycling is used for transportation and is a popular recreational activity. Its health benefits are clear, [1,2] in contrast to motor vehicle travel. Transportation cycling has risks in the same order of magnitude as driving and walking in the US and Canada.[3,4] However it is not nearly as safe as in some European countries where cycling participation is much higher.[5-8]

In 2010, there were 618 cyclist traffic deaths in the United States and 60 in Canada.[9,10] Broader data (including bicycling sports such as mountain biking) indicate that about 27,800 Americans and 4,300 Canadians were hospitalized for cycling injuries in 2009.[11,12] Although bicycling injuries are a small proportion of all traffic injuries and deaths in North America (~2 to 4%),[9,10] reducing their incidence is important because of the direct harm that they do and because they deter potential cyclists.[13-15]

The reason postulated for the inversion of cycling activity and injury risk between North America and Europe is the well-designed bicycle-specific infrastructure in Europe *vs.* its relative paucity in North America. We reviewed published studies and found that bicycle-specific infrastructure was associated with decreased injury risk, but a small range of infrastructure had been studied, often with uncertain control of exposure to risk.[16] We subsequently conducted a case-crossover study of the association between route infrastructure and crash risk: **the Bicyclists' Injuries and the Cycling Environment Study**. [17,18] **It found that** infrastructure that was bicycle-specific (e.g., cycle tracks separated from traffic, bike lanes) or “bicycle-friendly” (e.g., local streets with traffic diversion) had considerably lower injury risk. Other features were found to increase risk: streetcar or train tracks, downhill grades, construction, major street intersections, and traffic circles at local street intersections. This work was designed to estimate associations with injury risk, with a no-injury control.

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3 An alternative line of inquiry is what factors are associated with injury severity, among those who
4 have been injured. Many studies have found that collisions with motor vehicles increase cyclist injury
5 severity.[11,19-22] However few authors have examined severity with respect to route
6 infrastructure.[23-25] Higher severity has been found with grades, higher speed roads, and crashes in
7 traffic or on shared paths.[23-25] Although these results suggest that predictors of cycling injury risk
8 may be similar to predictors of injury severity, this is not established, and our study offers the
9 opportunity to examine both sets of outcomes, adding a level of context for policy makers,
10 infrastructure designers and other stakeholders. In our opinion, injury severity, not just the fact of
11 an injury, is a second and equally important criterion used by the lay public to evaluate the apparent
12 safety of cycling.
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27 Therefore we **conducted additional analyses of data from the Bicyclists' Injuries and the Cycling**
28 **Environment Study to examine** the relationship between injury severity and personal, trip, route and
29 crash characteristics.
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37 **METHODS**

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40 Methods of study conduct and reliability testing have been described in detail elsewhere.[17,26] The
41 study population consisted of adult (≥ 19 years) residents of Toronto and Vancouver who were
42 injured while riding a bicycle in the city and treated within 24 hours in the emergency departments
43 of the following hospitals between May 18, 2008 and November 30, 2009: St. Paul's or Vancouver
44 General in Vancouver; St. Michael's, Toronto General or Toronto Western in Toronto. Those who
45 were fatally injured or so severely injured that they were unable to remember their trip were not
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3 Data on characteristics related to severity were abstracted from emergency department records. In
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5 addition, eligible participants were interviewed in person by trained interviewers about personal
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7 characteristics, trip characteristics, and crash circumstances, using a structured questionnaire
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10 (<http://cyclingingcities.spph.ubc.ca/files/2011/10/InterviewFormFinal.pdf>).
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13 The study was not designed to focus on severity, so the data did not include classical severity scoring
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15 using the Abbreviated Injury Scale. However we did have access to four other indicators of severity:
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18 1. Whether the subject continued their trip by bicycle (self-reported in the interview), no vs. yes
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20 2. Whether the subject was transported by ambulance (hospital data), yes vs. no
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22 3. Whether the subject was admitted to hospital (hospital data), yes vs. no
- 23
24 4. Canadian Triage and Acuity Scale (CTAS) (hospital data), levels 1 to 5, defined as
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26 follows:[27,28]

- 27
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29 • 1 – Resuscitation; need to be seen immediately
- 30
31 • 2 – Emergent; need to be seen within 15 minutes
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33 • 3 – Urgent; need to be seen within 30 minutes
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35 • 4 – Less urgent; need to be seen within 60 minutes
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37 • 5 – Non urgent, need to be seen within 120 minutes
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43 The relationship between these severity metrics was examined descriptively using cross-tabulations
44
45 and Pearson correlation coefficients.
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48 Site observations were made to document characteristics of crash and control sites, and allow route
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50 infrastructure classification.[17,18] The observations were made blind to whether an injury took
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52 place at the site or not. In the current analyses, only the crash site data was used.
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56 Unconditional logistic regression was used to examine associations of each of the following
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58 independent variables with each severity outcome metric:
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- personal characteristics: sex; age; how frequently he/she cycled; whether the cyclist considered himself/herself experienced, had taken a cycling training course, had a driver's license
- trip characteristics: time of day; weather; helmet use; use of visible clothing on the trunk; whether bike lights were turned on; alcohol and drug use in the 6 hours prior
- route characteristics at the injury crash site: type of route; intersection location; presence of bike signage; junctions; construction; streetcar tracks; grade; average vehicle speed; distance visible along route.
- crash circumstances: collision (with a motor vehicle, obstacle, surface feature, cyclist, pedestrian, or animal) vs. fall; collision with a motor vehicle vs. not; motor vehicle "involvement" (i.e., both direct collisions with vehicles and crashes resulting from motor vehicle avoidance manoeuvres) vs. not. No data on fault in the crash was collected.

All independent variables significant at $p < 0.05$ in simple logistic regression (unadjusted analysis) of any severity metric were included in multiple regression models for all four severity metrics. The rationale for this broad inclusion of variables in the final models was to maximize control of potential confounding by personal and trip characteristics, to allow comparison of results across severity metrics, and to ensure that characteristics previously shown to be consistently related to injury severity were included in all the models (i.e., age, crash circumstance).

For dichotomous severity metrics (did not continue by bike, ambulance transport, hospital admission), traditional logistic regression was used, with the more severe injury category treated as the outcome ("case") group and the less severe as the comparison ("control") group. For CTAS, ordinal logistic regression modeled the odds of a more urgent CTAS group, after verifying that the proportional odds assumption was valid. CTAS categories were grouped as follows: most urgent, levels 1 or 2; moderate urgency, 3; least urgency, 4 or 5.

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3 Additional analyses were conducted to evaluate the models. Analyses were run without the motor
4 vehicle collision variable and, separately, without the route type variable to determine whether either
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6 changed the relationship of the other to severity in the full models. Separate analyses were conducted
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8 for motor vehicle collisions and other collisions to determine whether there was interaction between
9
10 the motor vehicle collision and route type variables.
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18 RESULTS

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20 The study included 690 injured cyclists (414 in Vancouver, 276 in Toronto). Seven were unable to
21 recall their crash circumstances, so were removed from analyses; none of these continued by bike,
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23 six were transported by ambulance, their CTAS scores were either 1 or 2, and one was admitted to
24
25 hospital. After these subjects were excluded, 683 subjects remained for most analyses, though four
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27 additional subjects did not have information on CTAS or ambulance transport.
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33 Descriptive data about the study participants, the trips when their injuries occurred, the
34 characteristics of the route at the crash site, and the crash circumstances are presented in Table 1.
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36 Most participants were men, young, and regular cyclists. Most wore a helmet, but few wore bright
37
38 clothing or used bike lights. Most of the injury sites were on major or local streets with little or no
39
40 cycling infrastructure and most were at non-intersection locations. A minority of injuries occurred at
41
42 sites with bike-specific infrastructure.
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47 Most of the crashes were collisions (74%, n=506) rather than falls. Direct collisions with motor
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49 vehicles (34%, n=231) were the most frequent collision type. Crashes “involving” motor vehicles
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51 (48%, n=330) included direct collisions, as well as crashes to avoid motor vehicle collisions (14%,
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53 n=99). Few collisions involved other cyclists (3%, n=22), pedestrians (2%, n=12) or animals (1%,
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55 n=6).
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Table 1. Personal characteristics of the cyclists, characteristics of the trip when the injury occurred, characteristics of the route at the site where the crash occurred, and crash circumstances (N=683)

	N (%)
Personal characteristics	
Male	404 (59%)
Age	
19 to 29	262 (39%)
30 to 39	167 (25%)
40 to 49	115 (17%)
50 to 59	81 (12%)
≥ 60	55 (8.1%)
Regular cyclist (cycled ≥ 52 times per year)	602 (88%)
Had a driver's license	613 (90%)
Considered themselves experienced	637 (93%)
Had taken a cycling training course	42 (6.1%)
Trip characteristics	
Time of day	
Day	530 (78%)
Dawn or dusk	50 (7.3%)
Night	103 (15%)
Clear weather	473 (69%)
Helmet worn	472 (69%)
Bright clothing worn	228 (33%)
Bike lights turned on	133 (19%)
Alcohol consumed in previous 6 h	70 (10%)
Drugs consumed in previous 6 h	78 (11%)
Route characteristics at the injury sites	
Route types	
Major streets (arterials and collectors, most with no bicycle infrastructure, a few with shared lanes, n=22)	289 (42%)
Local streets (mainly residential, many designated as bikeways, n=99)	187 (27%)
Sidewalks	52 (7.6%)
Multi-use paths (designated for pedestrian and bicyclists)	73 (11%)
Bicycle-specific infrastructure (bike lanes on major streets, n=59; cycle tracks alongside major streets, n=2; and off-street bike paths, n=21)	82 (12%)
At an intersection	
Junctions in last 100 m	211 (31%)
Bike signage present	593 (87%)
Construction present	76 (11%)
Streetcar or train tracks present	85 (12%)
Downhill grade	149 (22%)
Average vehicle speed > 30 km/h	329 (48%)
Forward distance visible < 20 m	363 (53%)
Forward distance visible < 20 m	12 (1.8%)
Crash circumstances	
Collision with motor vehicle	231 (34%)
Collision with streetcar or train tracks	97 (14%)
Collision with other surface features (e.g., pothole, rock, roots, leaves, ice)	69 (10%)
Collision with obstacle (e.g., post, curb, planter, lane divider)	69 (10%)
Collision with cyclist, pedestrian, animal	40 (5.9%)
Falls	177 (26%)

Figure 1 shows the distribution of subjects by the severity metrics, stratified by CTAS. The most urgent CTAS scores (1 or 2, n=75) were assigned to 11% of all subjects, 14% of those who did not continue by bike, 25% of those transported by ambulance and 28% of those who were admitted to

hospital. Table 2 provides additional detail on the relationship between the metrics. Of the 251 subjects transported to hospital by ambulance, 99% did not continue by bike. Of the 60 subjects admitted to hospital, 100% did not continue by bike, and 75% were transported by ambulance. Pearson correlations show associations in the expected directions, but the correlations were not strong. Thus the four metrics had logical relationships to each other, but did not measure identical constructs.

Table 2. Relationship between the four metrics of severity: Pearson correlation coefficients above the diagonal; numbers of subjects below the diagonal.

	Did not continue by bike	Transported to hospital by ambulance	Admitted to hospital	CTAS*
Did not continue by bike (n=528)	–	0.40	0.17	-0.29
Transported to hospital by ambulance (n=251)	249	–	0.24	-0.39
Admitted to hospital (n=60)	60	45	–	-0.20
CTAS = 1 or 2 (n=75)	74	62	17	–

* Correlations with CTAS were negative because the scale was in the opposite direction, with 1 = most urgent and 5 = least urgent. All other metrics were assigned 1 = more vs. 0 = less severe.

Figure 2 shows the severity metrics against crash circumstances, classified three ways. Collisions tended to be more severe than falls, and crashes “involving” motor vehicles tended to be more severe than those not. Direct collisions with motor vehicles had the highest proportion in the more severe category of every metric except admitted to hospital. In unadjusted analyses, collision (of any type) and motor vehicle “involvement” both had elevated odds ratios for the same severity metrics as motor vehicle collision (data not shown), but the odds ratios were lower, indicating that it was direct collision with a motor vehicle that led to increased severity. Only the motor vehicle collision variable was included in multiple regression models.

Table 3 shows the results of the multiple logistic regression models for each severity metric, including all independent variables statistically significant in at least one unadjusted analysis. Four personal characteristic variables were included: age, sex, cycling experience, and cycling frequency.

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3 Age showed consistent associations across all severity metrics; older age groups had more severe
4 injuries, significantly so for ambulance transport, admission to hospital and CTAS. Women were
5 significantly more likely to stop their trip by bike than men. There was a tendency for more
6 experienced and more regular cyclists to have higher injury severity, though only one association was
7 statistically significant in multiple regression.
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11 Cyclists whose crash was a direct collision with a motor vehicle had elevated odds ratios for all
12 severity metrics, statistically significant for not continuing by bike, being transported by ambulance
13 and more urgent triage score (CTAS). Those whose crash sites were on multi-use paths, sidewalks
14 and local streets tended to have more severe injuries than those who crashed on major streets;
15 significant associations were observed for certain associations with ambulance transport and hospital
16 admission. Crashes at intersections had inconsistent results; the only significant odds ratio indicated
17 that those injured at an intersection were less likely to stop their trip by bike. Downhill grades were
18 consistently related to greater injury severity, significantly so for transportation by ambulance. The
19 same pattern was observed for higher average motor vehicle speeds at the crash location. Time of
20 day and presence of streetcar tracks were both significant in some unadjusted analyses, but did not
21 remain so in multiple regression.
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41 The following independent variables were not associated with any of the injury severity metrics in
42 unadjusted analyses and were not included in multiple regression: whether the participant had taken
43 a cycling training course or had a driver's license; weather; use of a helmet, visible clothing on the
44 trunk, or bike lights; alcohol or drug use in the 6 hours prior to the trip; presence of bike signage,
45 junctions, or construction; and distance visible along the route.
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Table 3. Odds ratios (OR) and 95% confidence intervals (CI) for associations between metrics of injury severity and personal, trip, crash circumstance, and route characteristics (N=683). Multiple logistic regression models; all independent variables significant in at least one unadjusted analysis included.

	Did not continue by bike N=528 (77%) OR (95% CI)	Transported to hospital by ambulance N=251 (37%) OR (95% CI)	Admitted to hospital N=60 (8.8%) OR (95% CI)	CTAS † 1 or 2, N=75 (11%) 3, N=284 (42%) 4 or 5, N=320 (47%) OR (95% CI)
Sex				
Male	1 (reference)	1 (reference)	1 (reference)	1 (reference)
Female	1.91 (1.26 – 2.92)	1.34 (0.93 – 1.93)	1.07 (0.59 – 1.94)	0.98 (0.71 – 1.35)
Age				
19 to 29	1 (reference)	1 (reference)	1 (reference)	1 (reference)
30 to 39	1.15 (0.70 – 1.88)	1.18 (0.75 – 1.85)	1.18 (0.54 – 2.61)	1.29 (0.87 – 1.91)
40 to 49	1.22 (0.70 – 2.14)	1.40 (0.83 – 2.34)	1.96 (0.89 – 4.33)	2.07 (1.33 – 3.23)
50 to 59	1.50 (0.77 – 2.95)	1.04 (0.57 – 1.91)	1.02 (0.35 – 2.97)	1.57 (0.95 – 2.62)
≥ 60	1.33 (0.63 – 2.82)	2.57 (1.31 – 5.05)	3.52 (1.37 – 9.04)	1.42 (0.78 – 2.60)
Considered themselves an experienced cyclist				
No	1 (reference)	1 (reference)	1 (reference)	1 (reference)
Yes	1.36 (0.63 – 2.95)	2.16 (0.97 – 4.83)	1.03 (0.28 – 3.84)	1.52 (0.78 – 2.95)
Cycling frequency °				
	1.00 (0.78 – 1.76)	0.92 (0.72 – 1.08)	1.18 (0.85 – 1.50)	1.18 (1.00 – 1.38)
Time of day				
Day	1 (reference)	1 (reference)	1 (reference)	1 (reference)
Dusk or dawn	0.65 (0.33 – 1.29)	0.53 (0.24 – 1.13)	0.75 (0.21 – 2.62)	0.72 (0.39 – 1.30)
Night	0.90 (0.53 – 1.54)	1.16 (0.71 – 1.90)	1.87 (0.90 – 3.86)	0.90 (0.58 – 1.40)
Motor vehicle collision				
No	1 (reference)	1 (reference)	1 (reference)	1 (reference)
Yes	3.46 (2.07 – 5.76)	3.66 (2.44 – 5.48)	1.27 (0.63 – 2.54)	2.03 (1.41 – 2.90)
Route type				
Major street	1 (reference)	1 (reference)	1 (reference)	1 (reference)
Local street	1.08 (0.61 – 1.92)	1.44 (0.86 – 2.39)	2.76 (1.15 – 6.62)	1.18 (0.75 – 1.84)
Sidewalk	1.15 (0.42 – 3.19)	3.72 (1.37 – 10.1)	3.26 (0.51 – 20.7)	1.31 (0.56 – 3.06)
Multi-use path	1.33 (0.52 – 3.44)	2.18 (0.83 – 5.77)	7.56 (1.43 – 40.0)	1.22 (0.55 – 2.68)
Bicycle-specific infrastructure	0.98 (0.50 – 1.94)	1.02 (0.55 – 1.89)	0.89 (0.27 – 2.99)	1.27 (0.74 – 2.18)
Intersection				
No	1 (reference)	1 (reference)	1 (reference)	1 (reference)
Yes	0.57 (0.36 – 0.88)	1.44 (0.98 – 2.13)	1.04 (0.53 – 2.04)	0.89 (0.63 – 1.26)
Streetcar or train tracks				
No	1 (reference)	1 (reference)	1 (reference)	1 (reference)
Yes	1.11 (0.65 – 1.91)	1.03 (0.63 – 1.70)	0.98 (0.39 – 2.47)	1.36 (0.88 – 2.10)
Grade				

Flat or uphill	1 (reference)	1 (reference)	1 (reference)	1 (reference)
Downhill	1.32 (0.89 – 1.96)	1.62 (1.14 – 2.32)	1.23 (0.68 – 2.22)	1.31 (0.96 – 1.79)
Motor vehicle speed β	1.05 (0.89 – 1.24)	1.21 (1.01 – 1.43)	1.24 (0.91 – 1.69)	1.08 (0.94 – 1.24)

† CTAS = Canadian Triage and Acuity Scale, grouped into 3 categories for analysis using ordinal logistic regression; the odds ratio represents the comparison of categories 1 & 2 vs. 3, 4 & 5 and categories 1, 2 & 3 vs. 4 & 5 under the proportional odds assumption. **The proportional odds assumption was met, meaning that the odds ratios for these two comparisons are equivalent.**

◦ **Mean cycling frequency = 152 trips/y, SD = 81 trips/y; Odds ratios and confidence intervals calculated for a one standard deviation increase**

β **Mean motor vehicle speed = 36 km/h, SD = 9.5 km/h; odds ratios and confidence intervals calculated for a one standard deviation increase. This is a mean of means: 683 sites, each with 5 speed measurements taken during the site observation period (~30 minutes), then averaged. Speeds were measured using a Bushnell Velocity Speed Gun (Overland Park, KS).**

DISCUSSION

In this study, using four severity metrics that spanned rider self-evaluation (unable to continue by bike) to clinical-practitioner evaluation (CTAS), we found that the following characteristics were associated with more severe injuries: older age; female sex; more experience and frequency of cycling; collision with a motor vehicle; crash on a multi-use path, sidewalk or local street, at non-intersection location, on a downhill grade, and at locations with higher motor vehicle speeds.

Personal Characteristics

Older age has frequently been associated with more severe injuries in bicycling crashes.[19-22, 29-33]

We observed the same for all metrics, though the odds ratio was not always statistically significant.

This pattern is attributed to increasing frailty with age and has been observed for all vulnerable road users.[32]

Although sex has frequently been associated with bicycling injury severity, the evidence does not show a clear pattern. We found that women were less likely to continue their trip by bicycle and had a non-significant increased chance of ambulance transport. Moore *et al.* found women to have more severe injuries,[31] but others have found higher severities in men.[19,22,32] Theories for each of these results are available. The smaller average size of women may make them more vulnerable and

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3 men may be more comfortable handling minor injuries without help. A greater propensity for risk-
4 taking and speed may provide opportunities for men to have higher impact crashes.[34-36]
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8 We found that experienced cyclists and those who cycled more frequently had greater injury severity
9 (more likely to need ambulance transport, or to have a more urgent triage score, respectively).
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11 Similarly Heesh *et al.* found that frequent and experienced cyclists had more severe injuries.[21]
12

13 These cyclists may travel at higher speeds and incur higher impact forces in a crash.
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16 17 18 **Crash Circumstances** 19

20 About a third of the injuries were collisions with motor vehicles. These were strongly associated
21 with three of our four injury severity metrics. In other research, collisions with motor vehicles have
22 consistently been associated with increased severity.[11,19-22] Collisions with larger vehicles have
23 resulted in more severe injuries and fatalities.[29,31,33,37]
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30 Previous analyses of our **Bicyclists' Injuries and the Cycling Environment study data** showed that
31 collisions with motor vehicles were associated with route type.[38] They never occurred on off-street
32 bike paths or on cycle tracks (separated bike lanes), and were over-represented on major streets with
33 parked cars and no bike infrastructure. **Therefore, for the severity analyses presented here,** we
34 considered whether route type confounded the association between collision with a motor vehicle
35 and severity (and vice versa), but this was not the case, nor was there interaction between the two
36 variables (data not shown).
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47 The severity of direct collisions with motor vehicles provides clear rationale for transportation
48 planners to minimize interactions between cyclists and vehicles. This planning approach is
49 supported by the results of our earlier analyses of injury crash risk: cycle tracks (bike lanes that
50 physically separate cyclists and motor vehicle traffic) were associated with 1/9th the risk compared to
51 streets with no bicycle infrastructure.[17] Separating modes of traffic with large differences in speed
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3 and mass is a principle used by countries such as Sweden, Germany, Denmark and the Netherlands
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5 where bicycling injury risk is much lower than in North America.[6,8] A rationale for this approach
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7 is that human error is inevitable, so it is important to minimize the consequences of such errors.
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10 Bicycling facilities separated from motor vehicles minimize the likelihood of a collision and the
11
12 potential for severe injury when either a driver or a cyclist makes an error.
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15 16 **Route Characteristics**

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18 Our main interest in this analysis was to determine whether route characteristics were associated
19
20 with increased or reduced injury severity. Route type, presence of an intersection, grade, and average
21
22 motor vehicle speed at the crash location were all associated with injury severity.
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26 In comparison to crashes on major streets without cycling infrastructure, crashes on sidewalks and
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28 multi-use paths had considerably higher odds of ambulance transport (odds ratio for multi-use paths
29
30 not significant). Crashes on sidewalks and multi-use paths also had considerably higher odds of
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32 hospital admission (odds ratio for sidewalks not significant). In our earlier analyses of crash risk,
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34 multi-use paths and sidewalks had among the highest risks, despite being off-street.[17,18] The
35
36 increased severity after a crash adds to concern about these route types. Local streets (mainly
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38 residential streets) were found to be a safe route type in our earlier analyses, with only about half the
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40 risk of a crash.[17] The current analysis indicates that if a crash did occur, there was an increased
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42 odds of one severity measure – hospitalization.
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47 Few studies have examined route type and injury severity. De Rome *et al.* found that more severe
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49 injuries were associated with crashes in traffic and on multi-use paths, and less severe with crashes in
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51 bike lanes and on sidewalks.[25] Slaughter *et al.* found lower severity in bike lane crashes.[39] In
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53 earlier analyses of our study, bicycle-specific infrastructure was found to have lower crash risk than
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55 major streets without such infrastructure,[17] but the current analysis indicates that if a crash did
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3 occur, injury severity was similar. This may in part be because most of the injury sites with bicycle-
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5 specific infrastructure in our study were bike lanes without physical separation from motor vehicles.
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8 Intersection vs. non-intersection crash locations did not present a clear pattern of association with
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10 severity in this study. Moore *et al.* found differing patterns of injury severity at intersections and non-
11
12 intersections.[31]
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15 Downhill grade was significantly associated with increased severity for all metrics in unadjusted
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17 analyses, and remained significant in the final model for ambulance transport. Three previous studies
18
19 have shown that injury severity is greater with grades.[23,24,31] Downhill grade is likely to be
20
21 associated with increased cyclist (and motor vehicle) speed, and therefore increased force of impact.
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23 Our earlier analyses found that downhill slopes were associated with higher injury crash risk, and
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25 that uphill grades deter cycling.[15,17,18] This suggests that, wherever possible, routing bicycle
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27 facilities where slopes are gentle is a good strategy for both reducing injuries and motivating cycling.
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31 Higher average motor vehicle speed was associated with increased severity for all metrics, and
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33 remained significant in the final model for ambulance transport. Other studies found higher speed
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35 roads to be associated with greater injury severity to cyclists.[23,24,37] Our earlier analyses found
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37 that injury crash risk was lower at intersections where motor vehicle speeds were 30 km/h or lower
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39 and that routes with high vehicle speeds deter cycling.[15,18] This supports recent changes in some
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41 European and North American cities to lower urban speed limits.
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46 47 **Trip Characteristics**

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49 Only one trip characteristic was associated with injury severity. Time of day (night riding) was
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51 associated with a higher odds of hospital admission in unadjusted analyses and was elevated but not
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53 significant in multiple regression. Night-time riding has been associated with increased injury
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55 severity in other studies, especially where roadways were not lit.[24,29,32,33]
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3 Although much of the bicycle safety literature focuses on helmets and head injury mitigation,
4 [22,37,40,41,42] helmet use was not associated with any of the severity metrics in this study. Both
5
6 biomechanical studies[42] and epidemiological studies[22,37,40,41] have demonstrated that helmets
7
8 can prevent serious skull and brain injuries. This study was not limited to head injuries, likely
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10 contributing to our result that helmet use was not associated with injury severity. In one of the
11
12 largest studies to examine helmets, their use was found to significantly reduce head injuries, but was
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14 not associated with serious injury mitigation across all body regions.[22,41] In this context, it is
15
16 important to recognize that cyclists may sustain injuries, including serious trauma, to any body part,
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18 including their thorax, abdomen, neck and extremities.[22] A helmet can do nothing to prevent non-
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20 head injuries. Our earlier analyses of crash risk show the potential for all injuries to be significantly
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22 decreased for cyclists separated from motor vehicle traffic in a cycle track or a local street with
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24 traffic diversion[17,18] and the present results show that injury severity significantly increases in a
25
26 collision with a motor vehicle. Together these results point to bicycle infrastructure that physically
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28 separates cyclists from motor vehicle traffic to prevent trauma to any area of the body.
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35 36 **Strengths and limitations**

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38 Strengths of the study include two study cities with differing climates, terrain, cycling mode shares
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40 and cycling infrastructure, an urban-only cycling sample, the prospective accrual of subjects,
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42 observation of route characteristics blinded to whether the site was an injury site, and the number of
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44 clinical and cyclist self-report severity metrics.
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48 Study limitations include a relatively small sample of injured cyclists, restriction to Canadian cities
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50 and lack of data on the anatomical location of the injury. As in all injury studies, only a portion of
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52 injured cyclists were included; here, those whose injuries were serious enough to be treated at a
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54 hospital emergency department, but not to cause death or a head injury so severe that the trip could
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3 not be recalled. This reduced the pool of the most severely injured cases: 2 potential participants
4 were fatally injured, 26 of those contacted could not remember their route, and 7 could not recall
5 their crash circumstances. An unknown number of cyclists had injuries so minor that no emergency
6 department visit was made.
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13 Our overall **Bicyclists' Injuries and the Cycling Environment study** had a case-crossover design that
14 **compared injury sites to control sites within a person-trip**, fully controlling for differences between
15 individuals and trips that might confound the relationship between injury crash risk and
16 infrastructure (the primary focus of the study). To examine severity of injuries in the current analysis,
17 **the analysis compared participants with more severe injuries ("cases") to those with less severe**
18 **injuries ("controls")**, introducing the potential for confounding by personal and trip characteristics.
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27 We addressed this via adjustment in our regression models, but the potential for uncontrolled
28 confounding by unmeasured characteristics remains.
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32 Given that we did not have data on more traditional measures of severity, the Abbreviated Injury
33 Scale and Injury Severity Score, it is important to consider our outcome metrics, their relationship to
34 each other and their potential reliability and validity as measures of severity. The four metrics
35 measured different aspects of severity, as described above (Figure 1, Table 2).
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42 Hospital admission is based on an in depth medical assessment and should reflect the most severe
43 injuries. There are no standardized decision criteria, and physicians' decisions to admit emergency
44 department patients to hospital have been found to differ substantially.[43] Data from Rivara *et al.*
45 were available to compare hospitalization to Injury Severity Scores above *vs.* below 9.[22]
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51 Hospitalization had high specificity (0.94) but lower sensitivity (0.72), suggesting that few patients
52 with minor injuries are admitted to hospital, but some who are severely injured are not admitted.
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55 This could be because some patients with severe injuries (e.g., some extremity fractures, intra-
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3 abdominal trauma) may be treated and stabilized in an emergency department then discharged home,
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5 but scheduled for later surgical repair. This may have contributed to our somewhat different results
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7 for hospital admission and its lower correlations with the other metrics.
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10 Ambulance transport is based, in part, on whether or not someone at the scene called an ambulance.
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12 It had the strongest correlations with all other outcome metrics. Data from Lang *et al.* were available
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14 to compare ambulance transport to Injury Severity Scores above *vs.* below 12.[44] Ambulance
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16 transfer had low specificity (0.26) but high sensitivity (0.95), opposite to the pattern for
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18 hospitalization. This suggests that most severely injured patients are transported by ambulance, but
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20 so are many who are not severely injured.
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25 The CTAS scale is based on assessment by a triage nurse of a standardized list of presenting
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27 complaints, vital sign modifiers, and pain severity.[27] Certain injury mechanisms, e.g., being hit by a
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29 motor vehicle, may be assigned a greater urgency score. CTAS has been frequently tested for
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31 reliability, with kappas for agreement beyond chance spanning a broad range from 0.25 to 0.89.[28]
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33 We found no comparison of CTAS to Injury Severity Scores. We found no validity or reliability data
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35 for continuing to cycle.
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42 CONCLUSIONS

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45 In two of Canada's largest cities, approximately one-third of the bicycle crashes were collisions with
46
47 a motor vehicle and the resulting injuries were more severe than in other crash circumstances.
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49 Certain route types (in particular multi-use paths and sidewalks), downhill grades, and higher motor
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51 vehicle speeds were also associated with increased injury severity. These results suggest an urgent
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53 need to provide bike facilities that separate cyclists from motor vehicle traffic, **that are not designed**
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3 for pedestrians, and that minimize slopes. These bicycle infrastructure modifications would reduce
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5 both crashes and injury severity after a crash.
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15 from the participants of that class.
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25 of the study. KT, MAH, CCOR, PC, MW, SB, MC, MDC, JB, SMF, Garth Hunte and Kishore
26 Mulpuri were responsible for the funding proposal. CCOR, MAH, MW, MDC, KT, Melody Monroe
27 and Lee Vernich designed and tested data collection instruments. MW, HS and KT developed
28 algorithms for defining route infrastructure. HS was responsible for data analyses. All authors had
29 full access to the results of all analyses. PC, HS and KT drafted the article. All authors contributed to
30 study design and implementation, analysis decisions, interpretation of results, and critical revision of
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25

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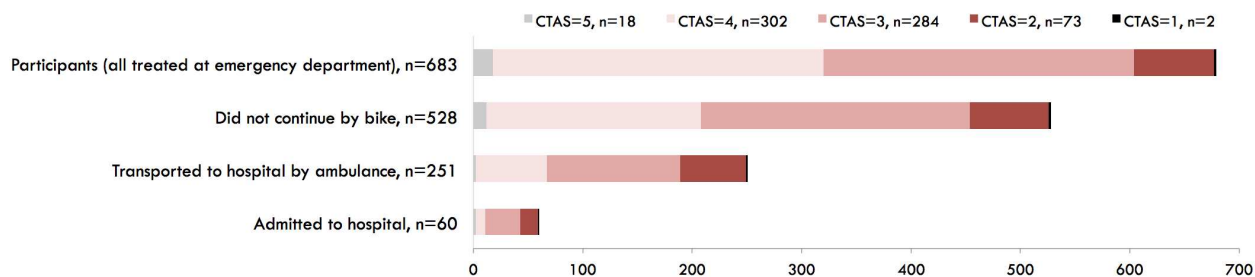


Figure 1. Metrics of severity of cycling injuries to 683 study participants, stratified by CTAS. CTAS = Canadian Triage and Acuity Scale, where 5 is the least medically urgent and 1 is the most.

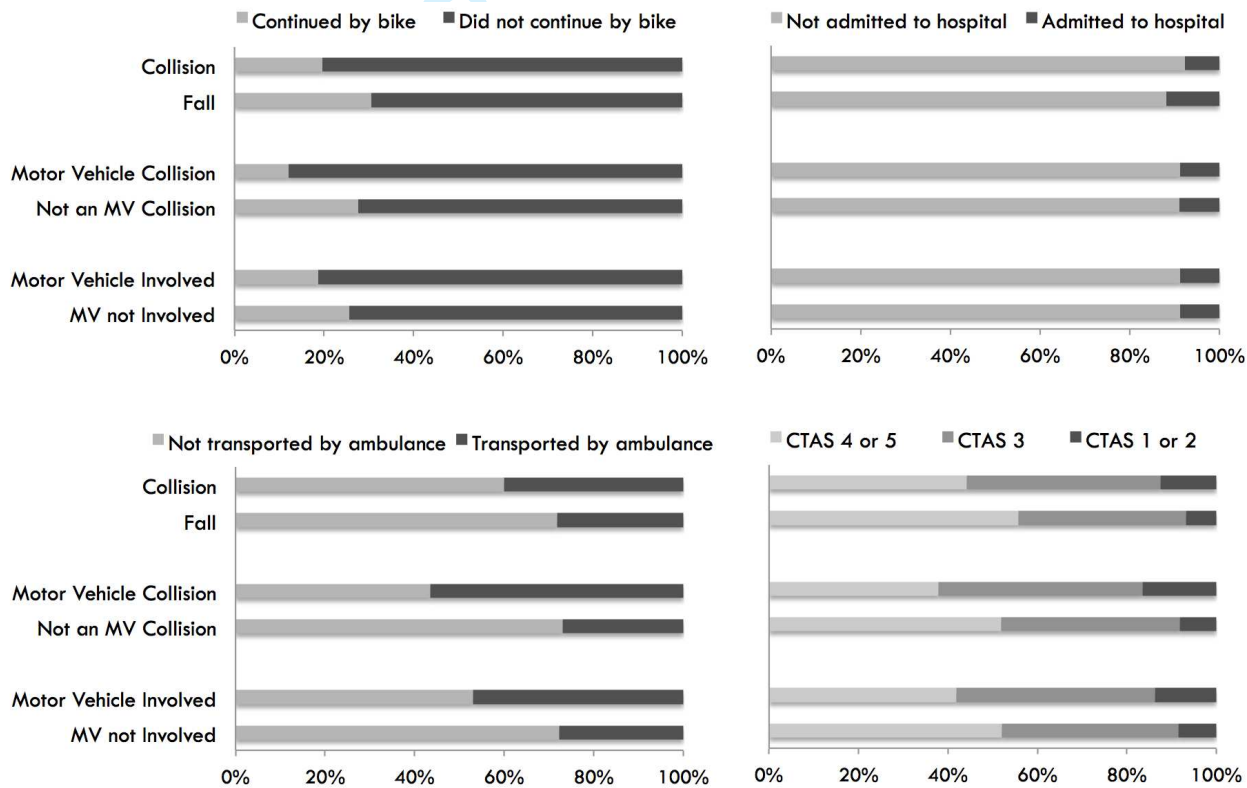


Figure 2. Crash circumstances vs. metrics of severity.

Collisions could be with a motor vehicle, obstacle, surface feature, cyclist, pedestrian, or animal. Motor vehicle “involved” includes both direct collisions with vehicles and crashes resulting from manoeuvres to avoid a motor vehicle.

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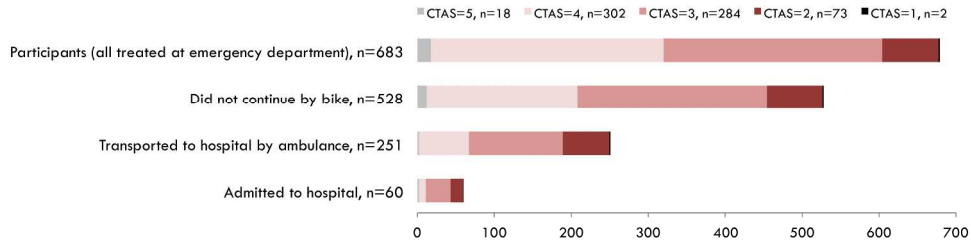


Figure 1. Metrics of severity of cycling injuries to 683 study participants, stratified by CTAS. CTAS = Canadian Triage and Acuity Scale, where 5 is the least medically urgent and 1 is the most.

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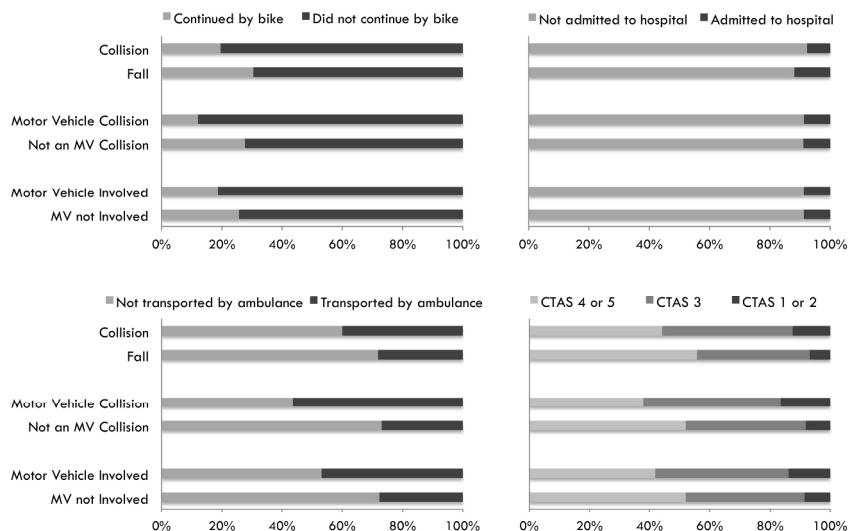


Figure 2. Crash circumstances vs. metrics of severity. Collisions could be with a motor vehicle, obstacle, surface feature, cyclist, pedestrian, or animal. Motor vehicle "involved" includes both direct collisions with vehicles and crashes resulting from manoeuvres to avoid a motor vehicle.

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Severity of urban cycling injuries and the relationship with personal, trip, route and crash characteristics: Analyses using four severity metrics

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Manuscripts

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4 **Severity of urban cycling injuries and the relationship with personal, trip, route and crash**
5 **characteristics: Analyses using four severity metrics**
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ABSTRACT

Objective: To examine the relationship between cycling injury severity and personal, trip, route and crash characteristics.

Methods: Data from a previous study of injury risk, conducted in Toronto and Vancouver, Canada, were used to classify injury severity using four metrics: 1) did not continue trip by bike; 2) transported to hospital by ambulance; 3) admitted to hospital; and 4) Canadian Triage and Acuity Scale (CTAS). Multiple logistic regression was used to examine associations with personal, trip, route and crash characteristics.

Results: Of 683 adults injured while cycling, 528 did not continue their trip by bike, 251 were transported by ambulance, and 60 were admitted to hospital for further treatment. Treatment urgencies included 75 as CTAS=1 or 2 (most medically urgent), 284 as CTAS=3, and 320 as CTAS=4 or 5 (least medically urgent). Older age and collision with a motor vehicle were consistently associated with increased severity in all four metrics and statistically significant in three each (both variables with ambulance transport and CTAS; age with hospital admission; and motor vehicle collision with did not continue by bike). Other factors were consistently associated with more severe injuries, but statistically significant in one metric each: downhill grades; higher motor vehicle speeds; multi-use paths (these significant for ambulance transport); sidewalks; and local streets (both significant for hospital admission).

Conclusions: In two of Canada's largest cities, about one-third of the bicycle crashes were collisions with motor vehicles and the resulting injuries were more severe than in other crash circumstances, underscoring the importance of separating cyclists from motor vehicle traffic. Our results also suggest that both bicycling injury severity and injury risk would be reduced on facilities that

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3 minimize slopes, have lower vehicle speeds, and that are designed for bicycling rather than shared
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5 with pedestrians.
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8 9 **Strengths and Limitations of this Study**

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- 13 • This study is one of few to examine the relationship between route characteristics and
14 severity of bicycling injuries. Its major strength was use of data from a study of bicycling
15 injury risk. This made it possible to consider whether route characteristics that increased
16 injury risk were similar to or different from those that increased bicycling injury severity.
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 - 19 • The results show that facilities that separate cyclists from motor vehicle traffic and
20 pedestrians, minimize slopes, and lower motor vehicle speeds would reduce both injury
21 severity after a crash and reduce injury risk.
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 - 24 • The analyses examined four metrics covering different aspects of injury severity (not able to
25 continue the trip by bike, transport to hospital by ambulance, admission to hospital, and
26 treatment urgency) and identified factors that were consistently associated with increased
27 severity: increased age and collision with a motor vehicle.
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 - 30 • The study included a range of injury severities resulting in emergency treatment at a hospital
31 but did not include those so severely injured they could not remember their trip, nor those
32 with such minor injuries that emergency treatment was not required.
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 - 35 • The influence of route characteristics on severity was adjusted for potential confounding by
36 personal and trip characteristics in the regression models, but the potential for uncontrolled
37 confounding by unmeasured characteristics remains.
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INTRODUCTION

Cycling is used for transportation and is a popular recreational activity. Its health benefits are clear, [1,2] in contrast to motor vehicle travel. Transportation cycling has risks in the same order of magnitude as driving and walking in the US and Canada.[3,4] However injury and fatality risks are higher than in some European countries where cycling participation is much higher.[5-8]

In 2010, there were 618 cyclist traffic deaths in the United States and 60 in Canada.[9,10] Broader data (including bicycling sports such as mountain biking) indicate that about 27,800 Americans and 4,300 Canadians were hospitalized for cycling injuries in 2009.[11,12] Although bicycling injuries are a small proportion of all traffic injuries and deaths in North America (~2 to 4%),[9,10] reducing their incidence is important because of the direct harm that they do and because they deter potential cyclists.[13-15]

The reason postulated for the inversion of cycling activity and injury risk between North America and Europe is the well-designed bicycle-specific infrastructure in Europe vs. its relative paucity in North America. We reviewed published studies and found that bicycle-specific infrastructure was associated with decreased injury risk, but a small range of infrastructure had been studied, often with uncertain control of exposure.[16] We subsequently conducted a case-crossover study of the association between route infrastructure and injury risk.[17,18] It found that infrastructure that was bicycle-specific (e.g., cycle tracks separated from traffic, bike lanes) or “bicycle-friendly” (e.g., local streets with traffic diversion) had considerably lower injury risk. Other features were found to increase injury risk: streetcar or train tracks, downhill grades, construction, major street intersections, and traffic circles at local street intersections. This work was designed to estimate associations with injury risk, with a no-injury control.

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3 An alternative line of inquiry is what factors are associated with injury severity, among those who
4 have been injured. Many studies have found that collisions with motor vehicles increase cyclist injury
5 severity.[11,19-22] However few authors have examined severity with respect to route
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8 infrastructure.[23-25] Higher severity has been found with grades, higher speed roads, and crashes in
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10 traffic or on shared paths.[23-25] Although these results suggest that predictors of cycling injury risk
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12 may be similar to predictors of injury severity, this is not established, and our study offers the
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14 opportunity to examine both sets of outcomes, adding a level of context requested by policy makers,
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16 infrastructure designers and other stakeholders. In our opinion, injury severity, not just the fact of
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18 an injury, is a second and equally important criterion used by the lay public to evaluate the apparent
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20 safety of cycling.
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27 Therefore we conducted additional analyses of data from our previous case-crossover study [17,18]
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29 to examine the relationship between injury severity and personal, trip, route and crash characteristics.
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35 **METHODS**

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37 Details about overall study conduct and reliability testing are described elsewhere [17,26]; methods
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39 related to the analyses presented here are described below. The study population consisted of adult
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41 (≥ 19 years) residents of Toronto and Vancouver who were injured while riding a bicycle in the city
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43 and treated within 24 hours in the emergency departments of the following hospitals between May
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45 18, 2008 and November 30, 2009: St. Paul's or Vancouver General in Vancouver; St. Michael's,
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47 Toronto General or Toronto Western in Toronto. Injured cyclists were identified by research staff
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49 at each hospital who relayed contact information to the study co-ordinators. Introductory letters
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51 were sent to all potential participants, followed by a phone call from the study co-ordinator to invite
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53 participation and screen for eligibility. Those who were fatally injured or so severely injured that they
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3 were unable to remember their trip were not included, nor were those injured during mountain
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5 biking, trick riding, or racing.
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8 Data on characteristics related to severity were abstracted from emergency department records. In
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10 addition, eligible participants were interviewed in person by trained interviewers about personal
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12 characteristics, trip characteristics, and crash circumstances, using a structured questionnaire
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14 (<http://cyclingincities.spph.ubc.ca/files/2011/10/InterviewFormFinal.pdf>).
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17 The study was not designed to focus on severity, so the data did not include classical severity scoring
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19 using the Abbreviated Injury Scale. However we did have access to four indicators of severity:
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- 22 1. Whether the subject continued their trip by bicycle (self-reported in the interview), no vs. yes
- 23 2. Whether the subject was transported by ambulance (hospital data), yes vs. no
- 24 3. Whether the subject was admitted to hospital (hospital data), yes vs. no
- 25 4. Canadian Triage and Acuity Scale (CTAS) (hospital data), levels 1 to 5, defined as

26 follows:[27,28]

- 27 • 1 – Resuscitation; need to be seen immediately
- 28 • 2 – Emergent; need to be seen within 15 minutes
- 29 • 3 – Urgent; need to be seen within 30 minutes
- 30 • 4 – Less urgent; need to be seen within 60 minutes
- 31 • 5 – Non urgent, need to be seen within 120 minutes

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47 The relationship between these severity metrics was examined descriptively using cross-tabulations
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49 and Pearson correlation coefficients.
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52 Site observations were made to document characteristics of injury and control sites, and allow route
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54 infrastructure classification.[17,18] The observations were made blind to whether an injury took
55
56 place at the site or not. In the current analyses, only the injury site data was used.
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3 Unconditional logistic regression was used to examine associations of each of the following
4
5 independent variables with each severity outcome metric:
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- 8 • personal characteristics: sex; age; how frequently he/she cycled; whether the cyclist
9 considered himself/herself experienced, had taken a cycling training course, had a driver's
10 license
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- 13 • trip characteristics: time of day; weather; helmet use; use of visible clothing on the trunk;
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15 whether bike lights were turned on; alcohol and drug use in the 6 hours prior
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- 18 • route characteristics at the injury site: type of route; intersection location; presence of bike
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20 signage; junctions; construction; streetcar tracks; grade; average vehicle speed; distance
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22 visible along route.
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- 25 • crash circumstances: collision (with a motor vehicle, obstacle, surface feature, cyclist,
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27 pedestrian, or animal) vs. fall; collision with a motor vehicle vs. not; motor vehicle
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29 "involvement" (i.e., both direct collisions with vehicles and crashes resulting from motor
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31 vehicle avoidance manoeuvres) vs. not. No data on fault in the crash was collected.
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36 All independent variables significant at $p < 0.05$ in simple logistic regression (unadjusted analysis) of
37
38 any severity metric were included in multiple regression models for all four severity metrics. The
39
40 rationale for this broad inclusion of variables in the final models was to maximize control of
41
42 potential confounding by personal and trip characteristics, to allow comparison of results across
43
44 severity metrics, and to ensure that characteristics previously shown to be consistently related to
45
46 injury severity were included in all the models (i.e., age, crash circumstance).
47
48

49 For dichotomous severity metrics (did not continue by bike *vs.* did, ambulance transport *vs.* not,
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51 admitted to hospital *vs.* not), traditional logistic regression was used. For CTAS, ordinal logistic
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53 regression modeled the odds of a more urgent CTAS group, after verifying that the proportional
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3 odds assumption was valid. CTAS categories were grouped as follows: most urgent, levels 1 or 2;
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5 moderate urgency, 3; least urgency, 4 or 5.
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8 Additional analyses were conducted to evaluate the models. Analyses were run without the motor
9 vehicle collision variable and, separately, without the route type variable to determine whether either
10 vehicle collision variable and, separately, without the route type variable to determine whether either
11 changed the relationship of the other to severity in the full models. Separate analyses were
12 conducted for motor vehicle collisions and other collisions to determine whether there was
13 interaction between the motor vehicle collision and route type variables.
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23 RESULTS

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26 The study included 690 injured cyclists (414 in Vancouver, 276 in Toronto). Seven were unable to
27 recall their crash circumstances, so were removed from analyses; none of these continued by bike,
28 six were transported by ambulance, their CTAS scores were either 1 or 2, and one was admitted to
29 hospital. After these subjects were excluded, 683 subjects remained for most analyses, though four
30 additional subjects did not have information on CTAS or ambulance transport.
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38 Descriptive data about the study participants, the trips when their injuries occurred, the
39 characteristics of the route at the injury site, and the crash circumstances are presented in Table 1.
40 Most participants were men, young, and regular cyclists. Most wore a helmet, but few wore bright
41 clothing or used bike lights. Most of the injury sites were on major or local streets with little or no
42 cycling infrastructure and most were at non-intersection locations. A minority of injuries occurred at
43 sites with bike-specific infrastructure.
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52 Most of the crashes were collisions (74%, n=506) rather than falls. Direct collisions with motor
53 vehicles (34%, n=231) were the most frequent collision type. Crashes “involving” motor vehicles
54 (48%, n=330) included direct collisions, as well as crashes to avoid motor vehicle collisions (14%,
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n=99). Few collisions involved other cyclists (3%, n=22), pedestrians (2%, n=12) or animals (1%, n=6).

Table 1. Personal characteristics of the cyclists, characteristics of the trip when the injury occurred, characteristics of the route at the site where the injury occurred, and crash circumstances (N=683)

	N (%)
Personal characteristics	
Male	404 (59%)
Age	
19 to 29	262 (39%)
30 to 39	167 (25%)
40 to 49	115 (17%)
50 to 59	81 (12%)
≥ 60	55 (8.1%)
Regular cyclist (cycled ≥ 52 times per year)	602 (88%)
Had a driver's license	613 (90%)
Considered themselves experienced	637 (93%)
Had taken a cycling training course	42 (6.1%)
Trip characteristics	
Time of day	
Day	530 (78%)
Dawn or dusk	50 (7.3%)
Night	103 (15%)
Clear weather	473 (69%)
Helmet worn	472 (69%)
Bright clothing worn	228 (33%)
Bike lights turned on	133 (19%)
Alcohol consumed in previous 6 h	70 (10%)
Drugs consumed in previous 6 h	78 (11%)
Route characteristics at the injury sites	
Route types	
Major streets (arterials and collectors, most with no bicycle infrastructure, a few with shared lanes, n=22)	289 (42%)
Local streets (mainly residential, many designated as bikeways, n=99)	187 (27%)
Sidewalks	52 (7.6%)
Multi-use paths (designated for pedestrian and bicyclists)	73 (11%)
Bicycle-specific infrastructure (bike lanes on major streets, n=59; cycle tracks alongside major streets, n=2; and off-street bike paths, n=21)	82 (12%)
At an intersection	211 (31%)
Junctions in last 100 m	593 (87%)
Bike signage present	76 (11%)
Construction present	85 (12%)
Streetcar or train tracks present	149 (22%)
Downhill grade	329 (48%)
Average vehicle speed > 30 km/h	363 (53%)
Forward distance visible < 20 m	12 (1.8%)
Crash circumstances	
Collision with motor vehicle	231 (34%)
Collision with streetcar or train tracks	97 (14%)
Collision with other surface features (e.g., pothole, rock, roots, leaves, ice)	69 (10%)
Collision with obstacle (e.g., post, curb, planter, lane divider)	69 (10%)
Collision with cyclist, pedestrian, animal	40 (5.9%)
Falls	177 (26%)

Figure 1 shows the distribution of subjects by the severity metrics, stratified by CTAS. The most urgent CTAS scores (1 or 2, n=75) were assigned to 11% of all subjects, 14% of those who did not continue by bike, 25% of those transported by ambulance and 28% of those who were admitted to hospital. Table 2 provides additional detail on the relationship between the metrics. Of the 251 subjects transported to hospital by ambulance, 99% did not continue by bike. Of the 60 subjects admitted to hospital, 100% did not continue by bike, and 75% were transported by ambulance. Pearson correlations show associations in the expected directions, but the correlations were not strong. Thus the four metrics had logical relationships to each other, but did not measure identical constructs.

Table 2. Relationship between the four metrics of severity: Pearson correlation coefficients above the diagonal; numbers of subjects below the diagonal.

	Did not continue by bike	Transported to hospital by ambulance	Admitted to hospital	CTAS*
Did not continue by bike (n=528)	–	0.40	0.17	-0.29
Transported to hospital by ambulance (n=251)	249	–	0.24	-0.39
Admitted to hospital (n=60)	60	45	–	-0.20
CTAS = 1 or 2 (n=75)	74	62	17	–

* Correlations with CTAS were negative because the scale was in the opposite direction, with 1 = most urgent and 5 = least urgent. All other metrics were assigned 1 = more vs. 0 = less severe.

Figure 2 shows the severity metrics against crash circumstances, classified three ways. Collisions tended to be more severe than falls, and crashes “involving” motor vehicles tended to be more severe than those not. Direct collisions with motor vehicles had the highest proportion in the more severe category of every metric except admitted to hospital. In unadjusted analyses, collision (of any type) and motor vehicle “involvement” both had elevated odds ratios for the same severity metrics as motor vehicle collision (data not shown), but the odds ratios were lower, indicating that it was direct collision with a motor vehicle that led to increased severity. Only the motor vehicle collision variable was included in multiple regression models.

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3 Table 3 shows the results of the multiple logistic regression models for each severity metric,
4 including all independent variables statistically significant in at least one unadjusted analysis. Four
5 personal characteristic variables were included: age, sex, cycling experience, and cycling frequency.
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7 Age showed consistent associations across all severity metrics; older age groups had more severe
8 injuries, significantly so for ambulance transport, admission to hospital and CTAS. Women were
9 significantly more likely to stop their trip by bike than men. There was a tendency for more
10 experienced and more regular cyclists to have higher injury severity, though only one association was
11 statistically significant in multiple regression.
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22 Cyclists whose crash was a direct collision with a motor vehicle had elevated odds ratios for all
23 severity metrics, statistically significant for not continuing by bike, being transported by ambulance
24 and more urgent triage score (CTAS). Those whose crashes were on multi-use paths, sidewalks and
25 local streets tended to have more severe injuries than those who crashed on major streets; significant
26 associations were observed for certain associations with ambulance transport and hospital admission.
27
28 Crashes at intersections had inconsistent results; the only significant odds ratio indicated that those
29 injured at an intersection were less likely to stop their trip by bike. Downhill grades were consistently
30 related to greater injury severity, significantly so for transportation by ambulance. The same pattern
31 was observed for higher average motor vehicle speeds at the crash location. Time of day and
32 presence of streetcar tracks were both significant in some unadjusted analyses, but did not remain so
33 in multiple regression.
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48 The following independent variables were not associated with any of the injury severity metrics in
49 unadjusted analyses and were not included in multiple regression: whether the participant had taken
50 a cycling training course or had a driver's license; weather; use of a helmet, visible clothing on the
51 trunk, or bike lights; alcohol or drug use in the 6 hours prior to the trip; presence of bike signage,
52 junctions, or construction; and distance visible along the route.
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Table 3. Odds ratios (OR) and 95% confidence intervals (CI) for associations between metrics of injury severity and personal, trip, crash circumstance, and route characteristics (N=683). Multiple logistic regression models; all independent variables significant in at least one unadjusted analysis included.

	Did not continue by bike N=528 (77%) OR (95% CI)	Transported to hospital by ambulance N=251 (37%) OR (95% CI)	Admitted to hospital N=60 (8.8%) OR (95% CI)	CTAS † 1 or 2, N=75 (11%) 3, N=284 (42%) 4 or 5, N=320 (47%) OR (95% CI)
Sex				
Male	1 (reference)	1 (reference)	1 (reference)	1 (reference)
Female	1.91 (1.26 – 2.92)	1.34 (0.93 – 1.93)	1.07 (0.59 – 1.94)	0.98 (0.71 – 1.35)
Age				
19 to 29	1 (reference)	1 (reference)	1 (reference)	1 (reference)
30 to 39	1.15 (0.70 – 1.88)	1.18 (0.75 – 1.85)	1.18 (0.54 – 2.61)	1.29 (0.87 – 1.91)
40 to 49	1.22 (0.70 – 2.14)	1.40 (0.83 – 2.34)	1.96 (0.89 – 4.33)	2.07 (1.33 – 3.23)
50 to 59	1.50 (0.77 – 2.95)	1.04 (0.57 – 1.91)	1.02 (0.35 – 2.97)	1.57 (0.95 – 2.62)
≥ 60	1.33 (0.63 – 2.82)	2.57 (1.31 – 5.05)	3.52 (1.37 – 9.04)	1.42 (0.78 – 2.60)
Considered themselves an experienced cyclist				
No	1 (reference)	1 (reference)	1 (reference)	1 (reference)
Yes	1.36 (0.63 – 2.95)	2.16 (0.97 – 4.83)	1.03 (0.28 – 3.84)	1.52 (0.78 – 2.95)
Cycling frequency °				
	1.00 (0.78 – 1.76)	0.92 (0.72 – 1.08)	1.18 (0.85 – 1.50)	1.18 (1.00 – 1.38)
Time of day				
Day	1 (reference)	1 (reference)	1 (reference)	1 (reference)
Dusk or dawn	0.65 (0.33 – 1.29)	0.53 (0.24 – 1.13)	0.75 (0.21 – 2.62)	0.72 (0.39 – 1.30)
Night	0.90 (0.53 – 1.54)	1.16 (0.71 – 1.90)	1.87 (0.90 – 3.86)	0.90 (0.58 – 1.40)
Motor vehicle collision				
No	1 (reference)	1 (reference)	1 (reference)	1 (reference)
Yes	3.46 (2.07 – 5.76)	3.66 (2.44 – 5.48)	1.27 (0.63 – 2.54)	2.03 (1.41 – 2.90)
Route type				
Major street	1 (reference)	1 (reference)	1 (reference)	1 (reference)
Local street	1.08 (0.61 – 1.92)	1.44 (0.86 – 2.39)	2.76 (1.15 – 6.62)	1.18 (0.75 – 1.84)
Sidewalk	1.15 (0.42 – 3.19)	3.72 (1.37 – 10.1)	3.26 (0.51 – 20.7)	1.31 (0.56 – 3.06)
Multi-use path	1.33 (0.52 – 3.44)	2.18 (0.83 – 5.77)	7.56 (1.43 – 40.0)	1.22 (0.55 – 2.68)
Bicycle-specific infrastructure	0.98 (0.50 – 1.94)	1.02 (0.55 – 1.89)	0.89 (0.27 – 2.99)	1.27 (0.74 – 2.18)
Intersection				
No	1 (reference)	1 (reference)	1 (reference)	1 (reference)
Yes	0.57 (0.36 – 0.88)	1.44 (0.98 – 2.13)	1.04 (0.53 – 2.04)	0.89 (0.63 – 1.26)
Streetcar or train tracks				
No	1 (reference)	1 (reference)	1 (reference)	1 (reference)
Yes	1.11 (0.65 – 1.91)	1.03 (0.63 – 1.70)	0.98 (0.39 – 2.47)	1.36 (0.88 – 2.10)
Grade				

Flat or uphill	1 (reference)	1 (reference)	1 (reference)	1 (reference)
Downhill	1.32 (0.89 – 1.96)	1.62 (1.14 – 2.32)	1.23 (0.68 – 2.22)	1.31 (0.96 – 1.79)
Motor vehicle speed β	1.05 (0.89 – 1.24)	1.21 (1.01 – 1.43)	1.24 (0.91 – 1.69)	1.08 (0.94 – 1.24)

† CTAS = Canadian Triage and Acuity Scale, grouped into 3 categories for analysis using ordinal logistic regression; the odds ratio represents the comparison of categories 1 & 2 vs. 3, 4 & 5 and categories 1, 2 & 3 vs. 4 & 5 under the proportional odds assumption. The proportional odds assumption was met, meaning that the odds ratios for these two comparisons are equivalent.

° Mean cycling frequency = 152 trips/y, SD = 81 trips/y; Odds ratios and confidence intervals calculated for a one standard deviation increase

β Mean motor vehicle speed = 36 km/h, SD = 9.5 km/h; odds ratios and confidence intervals calculated for a one standard deviation increase. This is a mean of means: 683 sites, each with 5 speed measurements taken during the site observation period (~30 minutes), then averaged. Speeds were measured using a Bushnell Velocity Speed Gun (Overland Park, KS).

DISCUSSION

In this study, using four severity metrics that spanned rider self-evaluation (unable to continue by bike) to clinical-practitioner evaluation (CTAS), we found that the following characteristics were associated with more severe injuries: older age; female sex; more experience and frequency of cycling; collision with a motor vehicle; crash on a multi-use path, sidewalk or local street, at non-intersection location, on a downhill grade, and at locations with higher motor vehicle speeds.

Personal Characteristics

Older age has frequently been associated with more severe injuries in bicycling crashes.[19-22, 29-33]

We observed the same for all metrics, though the odds ratio was not always statistically significant.

This pattern is attributed to increasing frailty with age and has been observed for all vulnerable road users.[32]

Although sex has frequently been associated with bicycling injury severity, the evidence does not show a clear pattern. We found that women were less likely to continue their trip by bicycle and had a non-significant increased chance of ambulance transport. Moore *et al.* found women to have more severe injuries,[31] but others have found higher severities in men.[19,22,32] Theories for each of these results are available. The smaller average size of women may make them more vulnerable and

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3 men may be more comfortable handling minor injuries without help. A greater propensity for risk-
4 taking and speed may provide opportunities for men to have higher impact crashes.[34-36]
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8 We found that experienced cyclists and those who cycled more frequently had greater injury severity
9 (more likely to need ambulance transport, or to have a more urgent triage score, respectively).
10

11 Similarly Heesh *et al.* found that frequent and experienced cyclists had more severe injuries.[21]
12

13 These cyclists may travel at higher speeds and incur higher impact forces in a crash.
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16 17 18 **Crash Circumstances** 19

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21 About a third of the injuries were collisions with motor vehicles. These were strongly associated
22 with three of our four injury severity metrics. In other research, collisions with motor vehicles have
23 consistently been associated with increased severity.[11,19-22] Collisions with larger vehicles have
24 resulted in more severe injuries and fatalities.[29,31,33,37]
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29 Previous analyses of our study data showed that collisions with motor vehicles were associated with
30 route type.[38] They never occurred on off-street bike paths or on cycle tracks (separated bike lanes),
31 and were over-represented on major streets with parked cars and no bike infrastructure. Therefore,
32 for the severity analyses presented here, we considered whether route type confounded the
33 association between collision with a motor vehicle and severity (and vice versa), but this was not the
34 case, nor was there interaction between the two variables (data not shown).
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39 The severity of direct collisions with motor vehicles provides clear rationale for transportation
40 planners to minimize interactions between cyclists and vehicles. This planning approach is
41 supported by the results of our earlier analyses of injury risk: cycle tracks (bike lanes that physically
42 separate cyclists and motor vehicle traffic) were associated with 1/9th the risk compared to streets
43 with no bicycle infrastructure.[17] Separating modes of traffic with large differences in speed and
44 mass is a principle used by countries such as Sweden, Germany, Denmark and the Netherlands
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3 where bicycling injury risk is much lower than in North America.[6,8] A rationale for this approach
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5 is that human error is inevitable, so it is important to minimize the consequences of such errors.
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7 Bicycling facilities separated from motor vehicles minimize the likelihood of a collision and the
8
9 potential for severe injury when either a driver or a cyclist makes an error.
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12 13 **Route Characteristics**

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15 Our main interest in this analysis was to determine whether route characteristics were associated
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17 with increased or reduced injury severity. Route type, presence of an intersection, grade, and average
18
19 motor vehicle speed at the crash location were all associated with injury severity.
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23 In comparison to crashes on major streets without cycling infrastructure, crashes on sidewalks and
24
25 multi-use paths had considerably higher odds of ambulance transport (odds ratio for multi-use paths
26
27 not significant). Crashes on sidewalks and multi-use paths also had considerably higher odds of
28
29 hospital admission (odds ratio for sidewalks not significant). In our earlier analyses of injury risk,
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31 multi-use paths and sidewalks had among the highest risks, despite being off-street.[17,18] The
32
33 increased severity after a crash adds to concern about these route types. Local streets (mainly
34
35 residential streets) were found to be a safe route type in our earlier analyses, with only about half the
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37 injury risk.[17] The current analysis indicates that if a crash did occur, there was an increased odds of
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39 one severity measure – hospitalization.
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45 Few studies have examined route type and injury severity. De Rome *et al.* found that more severe
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47 injuries were associated with crashes in traffic and on multi-use paths, and less severe with crashes in
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49 bike lanes and on sidewalks.[25] Slaughter *et al.* found lower severity in bike lane crashes.[39] In
50
51 earlier analyses of our study, bicycle-specific infrastructure was found to have lower injury crash risk
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53 than major streets without such infrastructure,[17] but the current analysis indicates that if a crash
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55 did occur, injury severity was similar. This may in part be because most of the injury sites with
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3 bicycle-specific infrastructure in our study were bike lanes without physical separation from motor
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5 vehicles.
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8 Intersection vs. non-intersection crash locations did not present a clear pattern of association with
9
10 severity in this study. Moore *et al.* found differing patterns of injury severity at intersections and non-
11
12 intersections.[31]
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15 Downhill grade was significantly associated with increased severity for all metrics in unadjusted
16
17 analyses, and remained significant in the final model for ambulance transport. Three previous studies
18
19 have shown that injury severity is greater with grades.[23,24,31] Downhill grade is likely to be
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21 associated with increased cyclist (and motor vehicle) speed, and therefore increased force of impact.
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23 Our earlier analyses found that downhill slopes were associated with higher injury risk, and that
24
25 uphill grades deter cycling.[15,17,18] This suggests that, wherever possible, routing bicycle facilities
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27 where slopes are gentle is a good strategy for both reducing injuries and motivating cycling.
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32 Higher average motor vehicle speed was associated with increased severity for all metrics, and
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34 remained significant in the final model for ambulance transport. Other studies found higher speed
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36 roads to be associated with greater injury severity to cyclists.[23,24,37] Our earlier analyses found
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38 that injury risk was higher at intersections where motor vehicle speeds were greater than 30 km/h
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40 and that routes with high vehicle speeds deter cycling.[15,18] This supports recent changes in some
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42 European and North American cities to lower urban speed limits.
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46 47 **Trip Characteristics**

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49 Only one trip characteristic was associated with injury severity. Time of day (night riding) was
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51 associated with a higher odds of hospital admission in unadjusted analyses and was elevated but not
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53 significant in multiple regression. Night-time riding has been associated with increased injury
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55 severity in other studies, especially where roadways were not lit.[24,29,32,33]
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3 Although much of the bicycle safety literature focuses on helmets and head injury mitigation,
4 [22,37,40,41,42] helmet use was not associated with any of the severity metrics in this study. Both
5
6 biomechanical studies[42] and epidemiological studies[22,37,40,41] have demonstrated that helmets
7
8 can prevent serious skull and brain injuries. This study was not limited to head injuries, likely
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10 contributing to our result that helmet use was not associated with injury severity. In one of the
11
12 largest studies to examine helmets, their use was found to significantly reduce head injuries, but was
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14 not associated with serious injury mitigation across all body regions.[22,41] In this context, it is
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16 important to recognize that cyclists may sustain injuries, including serious trauma, to any body part,
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18 including their thorax, abdomen, neck and extremities.[22] A helmet can do nothing to prevent non-
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20 head injuries. Our earlier analyses of injury risk show the potential for all injuries to be significantly
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22 decreased for cyclists separated from motor vehicle traffic in a cycle track or a local street with
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24 traffic diversion[17,18] and the present results show that injury severity significantly increases in a
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26 collision with a motor vehicle. Together these results point to bicycle infrastructure that physically
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28 separates cyclists from motor vehicle traffic to prevent trauma to any area of the body.
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35 36 **Strengths and limitations**

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38 Strengths of the study include two study cities with differing climates, terrain, cycling mode shares
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40 and cycling infrastructure, an urban-only cycling sample, the prospective accrual of subjects,
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42 observation of route characteristics blinded to whether the site was an injury site, and the number of
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44 clinical and cyclist self-report severity metrics.
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48 Study limitations include a relatively small sample of injured cyclists, restriction to Canadian cities
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50 and lack of data on the anatomical location of the injury. As in all injury studies, only a portion of
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52 injured cyclists were included; here, those whose injuries were serious enough to be treated at a
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54 hospital emergency department, but not to cause death or a head injury so severe that the trip could
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3 not be recalled. This reduced the pool of the most severely injured cases: 2 potential participants
4 were fatally injured, 26 of those contacted could not remember their route, and 7 could not recall
5 their crash circumstances. An unknown number of cyclists had injuries so minor that no emergency
6 department visit was made.
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12 Our overall study had a case-crossover design that compared injury sites to control sites within a
13 person-trip, fully controlling for differences between individuals and trips that might confound the
14 relationship between injury risk and infrastructure (the primary focus of the study). To examine
15 severity of injuries in the current analysis, the analysis was restricted to cases only, comparing
16 participants with more severe injuries to those with less severe injuries, introducing the potential for
17 confounding by personal and trip characteristics. We addressed this via adjustment in our regression
18 models, but the potential for uncontrolled confounding by unmeasured characteristics remains.
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30 Given that we did not have data on more traditional measures of severity, the Abbreviated Injury
31 Scale and Injury Severity Score, it is important to consider our outcome metrics, their relationship to
32 each other and their potential reliability and validity as measures of severity. The four metrics
33 measured different aspects of severity, as described above (Figure 1, Table 2).
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40 Hospital admission is based on an in depth medical assessment and should reflect the most severe
41 injuries. There are no standardized decision criteria, and physicians' decisions to admit emergency
42 department patients to hospital have been found to differ substantially.[43] Data from Rivara *et al.*
43 were available to compare hospitalization to Injury Severity Scores above *vs.* below 9.[22] They
44 found that those with higher scores were 43 times more likely to be admitted to hospital.
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50 Hospitalization had high specificity (0.94) but lower sensitivity (0.72), suggesting that few patients
51 with minor injuries are admitted to hospital, but some who are severely injured are not admitted.
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56 This could be because some patients with severe injuries (e.g., some extremity fractures, intra-
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3 abdominal trauma) may be treated and stabilized in an emergency department then discharged home,
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5 but scheduled for later surgical repair. This may have contributed to our somewhat different results
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7 for hospital admission and its lower correlations with the other metrics.
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10 Ambulance transport is based, in part, on whether or not someone at the scene called an ambulance.
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12 It had the strongest correlations with all other outcome metrics. Data from Lang *et al.* were available
13
14 to compare ambulance transport to Injury Severity Scores above *vs.* below 12.[44] Ambulance
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16 transfer had low specificity (0.26) but high sensitivity (0.95), opposite to the pattern for
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18 hospitalization. This suggests that most severely injured patients are transported by ambulance, but
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20 so are many who are not severely injured.
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25 The CTAS scale is based on assessment by a triage nurse of a standardized list of presenting
26
27 complaints, vital sign modifiers, and pain severity.[27] Certain injury mechanisms, e.g., being hit by a
28
29 motor vehicle, may be assigned a greater urgency score. CTAS has been frequently tested for
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31 reliability, with kappas for agreement beyond chance spanning a broad range from 0.25 to 0.89.[28]
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33 We found no comparison of CTAS to Injury Severity Scores. We found no validity or reliability data
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35 for continuing to cycle.
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42 CONCLUSIONS

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45 In two of Canada's largest cities, approximately one-third of the bicycle crashes were collisions with
46
47 a motor vehicle and the resulting injuries were more severe than in other crash circumstances.

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49 Certain route types (in particular multi-use paths and sidewalks), downhill grades, and higher motor
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51 vehicle speeds were also associated with increased injury severity. These results suggest an urgent
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53 need to provide bike facilities that separate cyclists from motor vehicle traffic, that minimize slopes
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55 and have lower motor vehicle speeds, and that are designed specifically for bicycling rather than for
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3 sharing with pedestrians. These bicycle infrastructure modifications would reduce both crashes and
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5 injury severity after a crash.
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14 Columbia's Bridge Program Grant Development course (2005-2006) and benefitted from input
15 from the participants of that class.
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25 of the study. KT, MAH, CCOR, PC, MW, SB, MC, MDC, JB, SMF, Garth Hunte and Kishore
26 Mulpuri were responsible for the funding proposal. CCOR, MAH, MW, MDC, KT, Melody Monroe
27 and Lee Vernich designed and tested data collection instruments. MW, HS and KT developed
28 algorithms for defining route infrastructure. HS was responsible for data analyses. All authors had
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30 study design and implementation, analysis decisions, interpretation of results, and critical revision of
31 the article. Evan Beaupré, Niki Blakely, Jill Dalton, Martin Kang, Kevin McCurley, and Andrew
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25

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29
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35 consent before taking part in the study.
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44 participants and site observations by study personnel. It cannot be shared by the authors with
45 anyone without approval from the University and Hospital human subjects review boards.
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Figure Legend

Figure 1. Metrics of severity of cycling injuries to 683 study participants, stratified by CTAS.
CTAS = Canadian Triage and Acuity Scale, where 5 is the least medically urgent and 1 is the most.

Figure 2. Crash circumstances vs. metrics of severity.
Collisions could be with a motor vehicle, obstacle, surface feature, cyclist, pedestrian, or animal. Motor vehicle “involved” includes both direct collisions with vehicles and crashes resulting from manoeuvres to avoid a motor vehicle.

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4 **Severity of urban cycling injuries and the relationship with personal, trip, route and crash**
5 **characteristics: Analyses using four severity metrics**
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ABSTRACT

Objective: To examine the relationship between cycling injury severity and personal, trip, route and crash characteristics.

Methods: Data from a previous study of injury risk, conducted in Toronto and Vancouver, Canada, were used to classify injury severity using four metrics: 1) did not continue trip by bike; 2) transported to hospital by ambulance; 3) admitted to hospital; and 4) Canadian Triage and Acuity Scale (CTAS). Multiple logistic regression was used to examine associations with personal, trip, route and crash characteristics.

Results: Of 683 adults injured while cycling, 528 did not continue their trip by bike, 251 were transported by ambulance, and 60 were admitted to hospital for further treatment. Treatment urgencies included 75 as CTAS=1 or 2 (most medically urgent), 284 as CTAS=3, and 320 as CTAS=4 or 5 (least medically urgent). Older age and collision with a motor vehicle were consistently associated with increased severity in all four metrics and statistically significant in three each (both variables with ambulance transport and CTAS; age with hospital admission; and motor vehicle collision with did not continue by bike). Other factors were consistently associated with more severe injuries, but statistically significant in one metric each: downhill grades; higher motor vehicle speeds; multi-use paths (these significant for ambulance transport); sidewalks; and local streets (both significant for hospital admission).

Conclusions: In two of Canada's largest cities, about one-third of the bicycle crashes were collisions with motor vehicles and the resulting injuries were more severe than in other crash circumstances, underscoring the importance of separating cyclists from motor vehicle traffic. Our results also suggest that both bicycling injury severity and injury risk would be reduced on facilities that

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3 minimize slopes, have lower vehicle speeds, and that are designed for bicycling rather than shared
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5 with pedestrians.
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8 9 **Strengths and Limitations of this Study**

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- 13 • This study is one of few to examine the relationship between route characteristics and
14 severity of bicycling injuries. Its major strength was use of data from a study of bicycling
15 injury risk. This made it possible to consider whether route characteristics that increased
16 injury risk were similar to or different from those that increased bicycling injury severity.
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 - 19 • The results show that facilities that separate cyclists from motor vehicle traffic and
20 pedestrians, minimize slopes, and lower motor vehicle speeds would reduce both injury
21 severity after a crash and reduce injury risk.
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 - 24 • The analyses examined four metrics covering different aspects of injury severity (not able to
25 continue the trip by bike, transport to hospital by ambulance, admission to hospital, and
26 treatment urgency) and identified factors that were consistently associated with increased
27 severity: increased age and collision with a motor vehicle.
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 - 30 • The study included a range of injury severities resulting in emergency treatment at a hospital
31 but did not include those so severely injured they could not remember their trip, nor those
32 with such minor injuries that emergency treatment was not required.
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 - 35 • The influence of route characteristics on severity was adjusted for potential confounding by
36 personal and trip characteristics in the regression models, but the potential for uncontrolled
37 confounding by unmeasured characteristics remains.
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INTRODUCTION

Cycling is used for transportation and is a popular recreational activity. Its health benefits are clear, [1,2] in contrast to motor vehicle travel. Transportation cycling has risks in the same order of magnitude as driving and walking in the US and Canada.[3,4] However **injury and fatality risks are higher than** in some European countries where cycling participation is much higher.[5-8]

In 2010, there were 618 cyclist traffic deaths in the United States and 60 in Canada.[9,10] Broader data (including bicycling sports such as mountain biking) indicate that about 27,800 Americans and 4,300 Canadians were hospitalized for cycling injuries in 2009.[11,12] Although bicycling injuries are a small proportion of all traffic injuries and deaths in North America (~2 to 4%),[9,10] reducing their incidence is important because of the direct harm that they do and because they deter potential cyclists.[13-15]

The reason postulated for the inversion of cycling activity and injury risk between North America and Europe is the well-designed bicycle-specific infrastructure in Europe *vs.* its relative paucity in North America. We reviewed published studies and found that bicycle-specific infrastructure was associated with decreased injury risk, but a small range of infrastructure had been studied, often with uncertain control of exposure.[16] We subsequently conducted a case-crossover study of the association between route infrastructure and **injury** risk.[17,18] It found that infrastructure that was bicycle-specific (e.g., cycle tracks separated from traffic, bike lanes) or “bicycle-friendly” (e.g., local streets with traffic diversion) had considerably lower injury risk. Other features were found to increase **injury** risk: streetcar or train tracks, downhill grades, construction, major street intersections, and traffic circles at local street intersections. This work was designed to estimate associations with injury risk, with a no-injury control.

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3 An alternative line of inquiry is what factors are associated with injury severity, among those who
4 have been injured. Many studies have found that collisions with motor vehicles increase cyclist injury
5 severity.[11,19-22] However few authors have examined severity with respect to route
6 infrastructure.[23-25] Higher severity has been found with grades, higher speed roads, and crashes in
7 traffic or on shared paths.[23-25] Although these results suggest that predictors of cycling injury risk
8 may be similar to predictors of injury severity, this is not established, and our study offers the
9 opportunity to examine both sets of outcomes, adding a level of context requested by policy makers,
10 infrastructure designers and other stakeholders. In our opinion, injury severity, not just the fact of
11 an injury, is a second and equally important criterion used by the lay public to evaluate the apparent
12 safety of cycling.
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17 Therefore we conducted additional analyses of data from our previous case-crossover study [17,18]
18 to examine the relationship between injury severity and personal, trip, route and crash characteristics.
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27 28 29 30 31 32 33 34 35 **METHODS**

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38 Details about overall study conduct and reliability testing are described elsewhere [17,26]; methods
39 related to the analyses presented here are described below. The study population consisted of adult
40 (≥ 19 years) residents of Toronto and Vancouver who were injured while riding a bicycle in the city
41 and treated within 24 hours in the emergency departments of the following hospitals between May
42 18, 2008 and November 30, 2009: St. Paul's or Vancouver General in Vancouver; St. Michael's,
43 Toronto General or Toronto Western in Toronto. Injured cyclists were identified by research staff
44 at each hospital who relayed contact information to the study co-ordinators. Introductory letters
45 were sent to all potential participants, followed by a phone call from the study co-ordinator to invite
46 participation and screen for eligibility. Those who were fatally injured or so severely injured that they
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3 were unable to remember their trip were not included, nor were those injured during mountain
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5 biking, trick riding, or racing.
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9 Data on characteristics related to severity were abstracted from emergency department records. In
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11 addition, eligible participants were interviewed in person by trained interviewers about personal
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13 characteristics, trip characteristics, and crash circumstances, using a structured questionnaire
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15 (<http://cyclingincities.spph.ubc.ca/files/2011/10/InterviewFormFinal.pdf>).
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19 The study was not designed to focus on severity, so the data did not include classical severity scoring
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21 using the Abbreviated Injury Scale. However we did have access to four indicators of severity:
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- 24 1. Whether the subject continued their trip by bicycle (self-reported in the interview), no vs. yes
- 25 2. Whether the subject was transported by ambulance (hospital data), yes vs. no
- 26 3. Whether the subject was admitted to hospital (hospital data), yes vs. no
- 27 4. Canadian Triage and Acuity Scale (CTAS) (hospital data), levels 1 to 5, defined as
28
29 follows:[27,28]

- 30 • 1 – Resuscitation; need to be seen immediately
- 31 • 2 – Emergent; need to be seen within 15 minutes
- 32 • 3 – Urgent; need to be seen within 30 minutes
- 33 • 4 – Less urgent; need to be seen within 60 minutes
- 34 • 5 – Non urgent, need to be seen within 120 minutes

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47 The relationship between these severity metrics was examined descriptively using cross-tabulations
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49 and Pearson correlation coefficients.
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53 Site observations were made to document characteristics of injury and control sites, and allow route
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55 infrastructure classification.[17,18] The observations were made blind to whether an injury took
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57 place at the site or not. In the current analyses, only the injury site data was used.
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3 Unconditional logistic regression was used to examine associations of each of the following
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5 independent variables with each severity outcome metric:
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- 8 • personal characteristics: sex; age; how frequently he/she cycled; whether the cyclist
9 considered himself/herself experienced, had taken a cycling training course, had a driver's
10 license
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- 13 • trip characteristics: time of day; weather; helmet use; use of visible clothing on the trunk;
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15 whether bike lights were turned on; alcohol and drug use in the 6 hours prior
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- 18 • route characteristics at the injury site: type of route; intersection location; presence of bike
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20 signage; junctions; construction; streetcar tracks; grade; average vehicle speed; distance
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22 visible along route.
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- 25 • crash circumstances: collision (with a motor vehicle, obstacle, surface feature, cyclist,
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27 pedestrian, or animal) vs. fall; collision with a motor vehicle vs. not; motor vehicle
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29 "involvement" (i.e., both direct collisions with vehicles and crashes resulting from motor
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31 vehicle avoidance manoeuvres) vs. not. No data on fault in the crash was collected.
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36 All independent variables significant at $p < 0.05$ in simple logistic regression (unadjusted analysis) of
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38 any severity metric were included in multiple regression models for all four severity metrics. The
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40 rationale for this broad inclusion of variables in the final models was to maximize control of
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42 potential confounding by personal and trip characteristics, to allow comparison of results across
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44 severity metrics, and to ensure that characteristics previously shown to be consistently related to
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46 injury severity were included in all the models (i.e., age, crash circumstance).
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50 For dichotomous severity metrics (did not continue by bike vs. did, ambulance transport vs. not,
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52 admitted to hospital vs. not), traditional logistic regression was used. For CTAS, ordinal logistic
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54 regression modeled the odds of a more urgent CTAS group, after verifying that the proportional
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3 odds assumption was valid. CTAS categories were grouped as follows: most urgent, levels 1 or 2;
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5 moderate urgency, 3; least urgency, 4 or 5.
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8 Additional analyses were conducted to evaluate the models. Analyses were run without the motor
9 vehicle collision variable and, separately, without the route type variable to determine whether either
10 vehicle collision variable and, separately, without the route type variable to determine whether either
11 changed the relationship of the other to severity in the full models. Separate analyses were
12 conducted for motor vehicle collisions and other collisions to determine whether there was
13 interaction between the motor vehicle collision and route type variables.
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23 RESULTS

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26 The study included 690 injured cyclists (414 in Vancouver, 276 in Toronto). Seven were unable to
27 recall their crash circumstances, so were removed from analyses; none of these continued by bike,
28 six were transported by ambulance, their CTAS scores were either 1 or 2, and one was admitted to
29 hospital. After these subjects were excluded, 683 subjects remained for most analyses, though four
30 additional subjects did not have information on CTAS or ambulance transport.
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38 Descriptive data about the study participants, the trips when their injuries occurred, the
39 characteristics of the route at the injury site, and the crash circumstances are presented in Table 1.
40 Most participants were men, young, and regular cyclists. Most wore a helmet, but few wore bright
41 clothing or used bike lights. Most of the injury sites were on major or local streets with little or no
42 cycling infrastructure and most were at non-intersection locations. A minority of injuries occurred at
43 sites with bike-specific infrastructure.
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52 Most of the crashes were collisions (74%, n=506) rather than falls. Direct collisions with motor
53 vehicles (34%, n=231) were the most frequent collision type. Crashes “involving” motor vehicles
54 (48%, n=330) included direct collisions, as well as crashes to avoid motor vehicle collisions (14%,
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n=99). Few collisions involved other cyclists (3%, n=22), pedestrians (2%, n=12) or animals (1%, n=6).

Table 1. Personal characteristics of the cyclists, characteristics of the trip when the injury occurred, characteristics of the route at the site where the injury occurred, and crash circumstances (N=683)

	N (%)
Personal characteristics	
Male	404 (59%)
Age	
19 to 29	262 (39%)
30 to 39	167 (25%)
40 to 49	115 (17%)
50 to 59	81 (12%)
≥ 60	55 (8.1%)
Regular cyclist (cycled ≥ 52 times per year)	602 (88%)
Had a driver's license	613 (90%)
Considered themselves experienced	637 (93%)
Had taken a cycling training course	42 (6.1%)
Trip characteristics	
Time of day	
Day	530 (78%)
Dawn or dusk	50 (7.3%)
Night	103 (15%)
Clear weather	473 (69%)
Helmet worn	472 (69%)
Bright clothing worn	228 (33%)
Bike lights turned on	133 (19%)
Alcohol consumed in previous 6 h	70 (10%)
Drugs consumed in previous 6 h	78 (11%)
Route characteristics at the injury sites	
Route types	
Major streets (arterials and collectors, most with no bicycle infrastructure, a few with shared lanes, n=22)	289 (42%)
Local streets (mainly residential, many designated as bikeways, n=99)	187 (27%)
Sidewalks	52 (7.6%)
Multi-use paths (designated for pedestrian and bicyclists)	73 (11%)
Bicycle-specific infrastructure (bike lanes on major streets, n=59; cycle tracks alongside major streets, n=2; and off-street bike paths, n=21)	82 (12%)
At an intersection	211 (31%)
Junctions in last 100 m	593 (87%)
Bike signage present	76 (11%)
Construction present	85 (12%)
Streetcar or train tracks present	149 (22%)
Downhill grade	329 (48%)
Average vehicle speed > 30 km/h	363 (53%)
Forward distance visible < 20 m	12 (1.8%)
Crash circumstances	
Collision with motor vehicle	231 (34%)
Collision with streetcar or train tracks	97 (14%)
Collision with other surface features (e.g., pothole, rock, roots, leaves, ice)	69 (10%)
Collision with obstacle (e.g., post, curb, planter, lane divider)	69 (10%)
Collision with cyclist, pedestrian, animal	40 (5.9%)
Falls	177 (26%)

Figure 1 shows the distribution of subjects by the severity metrics, stratified by CTAS. The most urgent CTAS scores (1 or 2, n=75) were assigned to 11% of all subjects, 14% of those who did not continue by bike, 25% of those transported by ambulance and 28% of those who were admitted to hospital. Table 2 provides additional detail on the relationship between the metrics. Of the 251 subjects transported to hospital by ambulance, 99% did not continue by bike. Of the 60 subjects admitted to hospital, 100% did not continue by bike, and 75% were transported by ambulance. Pearson correlations show associations in the expected directions, but the correlations were not strong. Thus the four metrics had logical relationships to each other, but did not measure identical constructs.

Table 2. Relationship between the four metrics of severity: Pearson correlation coefficients above the diagonal; numbers of subjects below the diagonal.

	Did not continue by bike	Transported to hospital by ambulance	Admitted to hospital	CTAS*
Did not continue by bike (n=528)	–	0.40	0.17	-0.29
Transported to hospital by ambulance (n=251)	249	–	0.24	-0.39
Admitted to hospital (n=60)	60	45	–	-0.20
CTAS = 1 or 2 (n=75)	74	62	17	–

* Correlations with CTAS were negative because the scale was in the opposite direction, with 1 = most urgent and 5 = least urgent. All other metrics were assigned 1 = more vs. 0 = less severe.

Figure 2 shows the severity metrics against crash circumstances, classified three ways. Collisions tended to be more severe than falls, and crashes “involving” motor vehicles tended to be more severe than those not. Direct collisions with motor vehicles had the highest proportion in the more severe category of every metric except admitted to hospital. In unadjusted analyses, collision (of any type) and motor vehicle “involvement” both had elevated odds ratios for the same severity metrics as motor vehicle collision (data not shown), but the odds ratios were lower, indicating that it was direct collision with a motor vehicle that led to increased severity. Only the motor vehicle collision variable was included in multiple regression models.

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2
3 Table 3 shows the results of the multiple logistic regression models for each severity metric,
4 including all independent variables statistically significant in at least one unadjusted analysis. Four
5 personal characteristic variables were included: age, sex, cycling experience, and cycling frequency.
6
7 Age showed consistent associations across all severity metrics; older age groups had more severe
8 injuries, significantly so for ambulance transport, admission to hospital and CTAS. Women were
9 significantly more likely to stop their trip by bike than men. There was a tendency for more
10 experienced and more regular cyclists to have higher injury severity, though only one association was
11 statistically significant in multiple regression.
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22 Cyclists whose crash was a direct collision with a motor vehicle had elevated odds ratios for all
23 severity metrics, statistically significant for not continuing by bike, being transported by ambulance
24 and more urgent triage score (CTAS). Those whose crashes were on multi-use paths, sidewalks and
25 local streets tended to have more severe injuries than those who crashed on major streets; significant
26 associations were observed for certain associations with ambulance transport and hospital admission.
27
28 Crashes at intersections had inconsistent results; the only significant odds ratio indicated that those
29 injured at an intersection were less likely to stop their trip by bike. Downhill grades were consistently
30 related to greater injury severity, significantly so for transportation by ambulance. The same pattern
31 was observed for higher average motor vehicle speeds at the crash location. Time of day and
32 presence of streetcar tracks were both significant in some unadjusted analyses, but did not remain so
33 in multiple regression.
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48 The following independent variables were not associated with any of the injury severity metrics in
49 unadjusted analyses and were not included in multiple regression: whether the participant had taken
50 a cycling training course or had a driver's license; weather; use of a helmet, visible clothing on the
51 trunk, or bike lights; alcohol or drug use in the 6 hours prior to the trip; presence of bike signage,
52 junctions, or construction; and distance visible along the route.
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Table 3. Odds ratios (OR) and 95% confidence intervals (CI) for associations between metrics of injury severity and personal, trip, crash circumstance, and route characteristics (N=683). Multiple logistic regression models; all independent variables significant in at least one unadjusted analysis included.

	Did not continue by bike N=528 (77%) OR (95% CI)	Transported to hospital by ambulance N=251 (37%) OR (95% CI)	Admitted to hospital N=60 (8.8%) OR (95% CI)	CTAS † 1 or 2, N=75 (11%) 3, N=284 (42%) 4 or 5, N=320 (47%) OR (95% CI)
Sex				
Male	1 (reference)	1 (reference)	1 (reference)	1 (reference)
Female	1.91 (1.26 – 2.92)	1.34 (0.93 – 1.93)	1.07 (0.59 – 1.94)	0.98 (0.71 – 1.35)
Age				
19 to 29	1 (reference)	1 (reference)	1 (reference)	1 (reference)
30 to 39	1.15 (0.70 – 1.88)	1.18 (0.75 – 1.85)	1.18 (0.54 – 2.61)	1.29 (0.87 – 1.91)
40 to 49	1.22 (0.70 – 2.14)	1.40 (0.83 – 2.34)	1.96 (0.89 – 4.33)	2.07 (1.33 – 3.23)
50 to 59	1.50 (0.77 – 2.95)	1.04 (0.57 – 1.91)	1.02 (0.35 – 2.97)	1.57 (0.95 – 2.62)
≥ 60	1.33 (0.63 – 2.82)	2.57 (1.31 – 5.05)	3.52 (1.37 – 9.04)	1.42 (0.78 – 2.60)
Considered themselves an experienced cyclist				
No	1 (reference)	1 (reference)	1 (reference)	1 (reference)
Yes	1.36 (0.63 – 2.95)	2.16 (0.97 – 4.83)	1.03 (0.28 – 3.84)	1.52 (0.78 – 2.95)
Cycling frequency °				
	1.00 (0.78 – 1.76)	0.92 (0.72 – 1.08)	1.18 (0.85 – 1.50)	1.18 (1.00 – 1.38)
Time of day				
Day	1 (reference)	1 (reference)	1 (reference)	1 (reference)
Dusk or dawn	0.65 (0.33 – 1.29)	0.53 (0.24 – 1.13)	0.75 (0.21 – 2.62)	0.72 (0.39 – 1.30)
Night	0.90 (0.53 – 1.54)	1.16 (0.71 – 1.90)	1.87 (0.90 – 3.86)	0.90 (0.58 – 1.40)
Motor vehicle collision				
No	1 (reference)	1 (reference)	1 (reference)	1 (reference)
Yes	3.46 (2.07 – 5.76)	3.66 (2.44 – 5.48)	1.27 (0.63 – 2.54)	2.03 (1.41 – 2.90)
Route type				
Major street	1 (reference)	1 (reference)	1 (reference)	1 (reference)
Local street	1.08 (0.61 – 1.92)	1.44 (0.86 – 2.39)	2.76 (1.15 – 6.62)	1.18 (0.75 – 1.84)
Sidewalk	1.15 (0.42 – 3.19)	3.72 (1.37 – 10.1)	3.26 (0.51 – 20.7)	1.31 (0.56 – 3.06)
Multi-use path	1.33 (0.52 – 3.44)	2.18 (0.83 – 5.77)	7.56 (1.43 – 40.0)	1.22 (0.55 – 2.68)
Bicycle-specific infrastructure	0.98 (0.50 – 1.94)	1.02 (0.55 – 1.89)	0.89 (0.27 – 2.99)	1.27 (0.74 – 2.18)
Intersection				
No	1 (reference)	1 (reference)	1 (reference)	1 (reference)
Yes	0.57 (0.36 – 0.88)	1.44 (0.98 – 2.13)	1.04 (0.53 – 2.04)	0.89 (0.63 – 1.26)
Streetcar or train tracks				
No	1 (reference)	1 (reference)	1 (reference)	1 (reference)
Yes	1.11 (0.65 – 1.91)	1.03 (0.63 – 1.70)	0.98 (0.39 – 2.47)	1.36 (0.88 – 2.10)
Grade				

Flat or uphill	1 (reference)	1 (reference)	1 (reference)	1 (reference)
Downhill	1.32 (0.89 – 1.96)	1.62 (1.14 – 2.32)	1.23 (0.68 – 2.22)	1.31 (0.96 – 1.79)
Motor vehicle speed β	1.05 (0.89 – 1.24)	1.21 (1.01 – 1.43)	1.24 (0.91 – 1.69)	1.08 (0.94 – 1.24)

† CTAS = Canadian Triage and Acuity Scale, grouped into 3 categories for analysis using ordinal logistic regression; the odds ratio represents the comparison of categories 1 & 2 vs. 3, 4 & 5 and categories 1, 2 & 3 vs. 4 & 5 under the proportional odds assumption. The proportional odds assumption was met, meaning that the odds ratios for these two comparisons are equivalent.

° Mean cycling frequency = 152 trips/y, SD = 81 trips/y; Odds ratios and confidence intervals calculated for a one standard deviation increase

β Mean motor vehicle speed = 36 km/h, SD = 9.5 km/h; odds ratios and confidence intervals calculated for a one standard deviation increase. This is a mean of means: 683 sites, each with 5 speed measurements taken during the site observation period (~30 minutes), then averaged. Speeds were measured using a Bushnell Velocity Speed Gun (Overland Park, KS).

DISCUSSION

In this study, using four severity metrics that spanned rider self-evaluation (unable to continue by bike) to clinical-practitioner evaluation (CTAS), we found that the following characteristics were associated with more severe injuries: older age; female sex; more experience and frequency of cycling; collision with a motor vehicle; crash on a multi-use path, sidewalk or local street, at non-intersection location, on a downhill grade, and at locations with higher motor vehicle speeds.

Personal Characteristics

Older age has frequently been associated with more severe injuries in bicycling crashes.[19-22, 29-33]

We observed the same for all metrics, though the odds ratio was not always statistically significant.

This pattern is attributed to increasing frailty with age and has been observed for all vulnerable road users.[32]

Although sex has frequently been associated with bicycling injury severity, the evidence does not show a clear pattern. We found that women were less likely to continue their trip by bicycle and had a non-significant increased chance of ambulance transport. Moore *et al.* found women to have more severe injuries,[31] but others have found higher severities in men.[19,22,32] Theories for each of these results are available. The smaller average size of women may make them more vulnerable and

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3 men may be more comfortable handling minor injuries without help. A greater propensity for risk-
4 taking and speed may provide opportunities for men to have higher impact crashes.[34-36]
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8 We found that experienced cyclists and those who cycled more frequently had greater injury severity
9 (more likely to need ambulance transport, or to have a more urgent triage score, respectively).
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11 Similarly Heesh *et al.* found that frequent and experienced cyclists had more severe injuries.[21]
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13 These cyclists may travel at higher speeds and incur higher impact forces in a crash.
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16 17 18 **Crash Circumstances** 19

20 About a third of the injuries were collisions with motor vehicles. These were strongly associated
21 with three of our four injury severity metrics. In other research, collisions with motor vehicles have
22 consistently been associated with increased severity.[11,19-22] Collisions with larger vehicles have
23 resulted in more severe injuries and fatalities.[29,31,33,37]
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28 Previous analyses of our study data showed that collisions with motor vehicles were associated with
29 route type.[38] They never occurred on off-street bike paths or on cycle tracks (separated bike lanes),
30 and were over-represented on major streets with parked cars and no bike infrastructure. Therefore,
31 for the severity analyses presented here, we considered whether route type confounded the
32 association between collision with a motor vehicle and severity (and vice versa), but this was not the
33 case, nor was there interaction between the two variables (data not shown).
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45 The severity of direct collisions with motor vehicles provides clear rationale for transportation
46 planners to minimize interactions between cyclists and vehicles. This planning approach is
47 supported by the results of our earlier analyses of injury risk: cycle tracks (bike lanes that physically
48 separate cyclists and motor vehicle traffic) were associated with 1/9th the risk compared to streets
49 with no bicycle infrastructure.[17] Separating modes of traffic with large differences in speed and
50 mass is a principle used by countries such as Sweden, Germany, Denmark and the Netherlands
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3 where bicycling injury risk is much lower than in North America.[6,8] A rationale for this approach
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5 is that human error is inevitable, so it is important to minimize the consequences of such errors.
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7 Bicycling facilities separated from motor vehicles minimize the likelihood of a collision and the
8
9 potential for severe injury when either a driver or a cyclist makes an error.
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12 13 **Route Characteristics**

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15 Our main interest in this analysis was to determine whether route characteristics were associated
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17 with increased or reduced injury severity. Route type, presence of an intersection, grade, and average
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19 motor vehicle speed at the crash location were all associated with injury severity.
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23 In comparison to crashes on major streets without cycling infrastructure, crashes on sidewalks and
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25 multi-use paths had considerably higher odds of ambulance transport (odds ratio for multi-use paths
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27 not significant). Crashes on sidewalks and multi-use paths also had considerably higher odds of
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29 hospital admission (odds ratio for sidewalks not significant). In our earlier analyses of injury risk,
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31 multi-use paths and sidewalks had among the highest risks, despite being off-street.[17,18] The
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33 increased severity after a crash adds to concern about these route types. Local streets (mainly
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35 residential streets) were found to be a safe route type in our earlier analyses, with only about half the
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37 injury risk.[17] The current analysis indicates that if a crash did occur, there was an increased odds of
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39 one severity measure – hospitalization.
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45 Few studies have examined route type and injury severity. De Rome *et al.* found that more severe
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47 injuries were associated with crashes in traffic and on multi-use paths, and less severe with crashes in
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49 bike lanes and on sidewalks.[25] Slaughter *et al.* found lower severity in bike lane crashes.[39] In
50
51 earlier analyses of our study, bicycle-specific infrastructure was found to have lower injury crash risk
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53 than major streets without such infrastructure,[17] but the current analysis indicates that if a crash
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55 did occur, injury severity was similar. This may in part be because most of the injury sites with
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3 bicycle-specific infrastructure in our study were bike lanes without physical separation from motor
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5 vehicles.
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8 Intersection vs. non-intersection crash locations did not present a clear pattern of association with
9
10 severity in this study. Moore *et al.* found differing patterns of injury severity at intersections and non-
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12 intersections.[31]
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15 Downhill grade was significantly associated with increased severity for all metrics in unadjusted
16
17 analyses, and remained significant in the final model for ambulance transport. Three previous studies
18
19 have shown that injury severity is greater with grades.[23,24,31] Downhill grade is likely to be
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21 associated with increased cyclist (and motor vehicle) speed, and therefore increased force of impact.
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23 Our earlier analyses found that downhill slopes were associated with higher injury risk, and that
24
25 uphill grades deter cycling.[15,17,18] This suggests that, wherever possible, routing bicycle facilities
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27 where slopes are gentle is a good strategy for both reducing injuries and motivating cycling.
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32 Higher average motor vehicle speed was associated with increased severity for all metrics, and
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34 remained significant in the final model for ambulance transport. Other studies found higher speed
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36 roads to be associated with greater injury severity to cyclists.[23,24,37] Our earlier analyses found
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38 that injury risk was higher at intersections where motor vehicle speeds were greater than 30 km/h
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40 and that routes with high vehicle speeds deter cycling.[15,18] This supports recent changes in some
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42 European and North American cities to lower urban speed limits.
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46 47 **Trip Characteristics**

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49 Only one trip characteristic was associated with injury severity. Time of day (night riding) was
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51 associated with a higher odds of hospital admission in unadjusted analyses and was elevated but not
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53 significant in multiple regression. Night-time riding has been associated with increased injury
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55 severity in other studies, especially where roadways were not lit.[24,29,32,33]
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3 Although much of the bicycle safety literature focuses on helmets and head injury mitigation,
4 [22,37,40,41,42] helmet use was not associated with any of the severity metrics in this study. Both
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6 biomechanical studies[42] and epidemiological studies[22,37,40,41] have demonstrated that helmets
7
8 can prevent serious skull and brain injuries. This study was not limited to head injuries, likely
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10 contributing to our result that helmet use was not associated with injury severity. In one of the
11
12 largest studies to examine helmets, their use was found to significantly reduce head injuries, but was
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14 not associated with serious injury mitigation across all body regions.[22,41] In this context, it is
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16 important to recognize that cyclists may sustain injuries, including serious trauma, to any body part,
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18 including their thorax, abdomen, neck and extremities.[22] A helmet can do nothing to prevent non-
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20 head injuries. Our earlier analyses of injury risk show the potential for all injuries to be significantly
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22 decreased for cyclists separated from motor vehicle traffic in a cycle track or a local street with
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24 traffic diversion[17,18] and the present results show that injury severity significantly increases in a
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26 collision with a motor vehicle. Together these results point to bicycle infrastructure that physically
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28 separates cyclists from motor vehicle traffic to prevent trauma to any area of the body.
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35 36 **Strengths and limitations**

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38 Strengths of the study include two study cities with differing climates, terrain, cycling mode shares
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40 and cycling infrastructure, an urban-only cycling sample, the prospective accrual of subjects,
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42 observation of route characteristics blinded to whether the site was an injury site, and the number of
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44 clinical and cyclist self-report severity metrics.
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48 Study limitations include a relatively small sample of injured cyclists, restriction to Canadian cities
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50 and lack of data on the anatomical location of the injury. As in all injury studies, only a portion of
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52 injured cyclists were included; here, those whose injuries were serious enough to be treated at a
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54 hospital emergency department, but not to cause death or a head injury so severe that the trip could
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3 not be recalled. This reduced the pool of the most severely injured cases: 2 potential participants
4 were fatally injured, 26 of those contacted could not remember their route, and 7 could not recall
5 their crash circumstances. An unknown number of cyclists had injuries so minor that no emergency
6 department visit was made.
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13 **Our overall study** had a case-crossover design that compared injury sites to control sites within a
14 person-trip, fully controlling for differences between individuals and trips that might confound the
15 relationship between injury risk and infrastructure (the primary focus of the study). To examine
16 severity of injuries in the current analysis, the analysis was restricted **to cases only, comparing**
17 **participants with more severe injuries to those with less severe injuries**, introducing the potential for
18 confounding by personal and trip characteristics. We addressed this via adjustment in our regression
19 models, but the potential for uncontrolled confounding by unmeasured characteristics remains.
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30 Given that we did not have data on more traditional measures of severity, the Abbreviated Injury
31 Scale and Injury Severity Score, it is important to consider our outcome metrics, their relationship to
32 each other and their potential reliability and validity as measures of severity. The four metrics
33 measured different aspects of severity, as described above (Figure 1, Table 2).
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40 Hospital admission is based on an in depth medical assessment and should reflect the most severe
41 injuries. There are no standardized decision criteria, and physicians' decisions to admit emergency
42 department patients to hospital have been found to differ substantially.[43] Data from Rivara *et al.*
43 were available to compare hospitalization to Injury Severity Scores above *vs.* below 9.[22] **They**
44 **found that those with higher scores were 43 times more likely to be admitted to hospital.**
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52 Hospitalization had high specificity (0.94) but lower sensitivity (0.72), suggesting that few patients
53 with minor injuries are admitted to hospital, but some who are severely injured are not admitted.
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56 This could be because some patients with severe injuries (e.g., some extremity fractures, intra-
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3 abdominal trauma) may be treated and stabilized in an emergency department then discharged home,
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5 but scheduled for later surgical repair. This may have contributed to our somewhat different results
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7 for hospital admission and its lower correlations with the other metrics.
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10 Ambulance transport is based, in part, on whether or not someone at the scene called an ambulance.
11
12 It had the strongest correlations with all other outcome metrics. Data from Lang *et al.* were available
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14 to compare ambulance transport to Injury Severity Scores above *vs.* below 12.[44] Ambulance
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16 transfer had low specificity (0.26) but high sensitivity (0.95), opposite to the pattern for
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18 hospitalization. This suggests that most severely injured patients are transported by ambulance, but
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20 so are many who are not severely injured.
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25 The CTAS scale is based on assessment by a triage nurse of a standardized list of presenting
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27 complaints, vital sign modifiers, and pain severity.[27] Certain injury mechanisms, e.g., being hit by a
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29 motor vehicle, may be assigned a greater urgency score. CTAS has been frequently tested for
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31 reliability, with kappas for agreement beyond chance spanning a broad range from 0.25 to 0.89.[28]
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33 We found no comparison of CTAS to Injury Severity Scores. We found no validity or reliability data
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35 for continuing to cycle.
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42 CONCLUSIONS

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45 In two of Canada's largest cities, approximately one-third of the bicycle crashes were collisions with
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47 a motor vehicle and the resulting injuries were more severe than in other crash circumstances.

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49 Certain route types (in particular multi-use paths and sidewalks), downhill grades, and higher motor
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51 vehicle speeds were also associated with increased injury severity. These results suggest an urgent
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53 need to provide bike facilities that separate cyclists from motor vehicle traffic, that minimize slopes
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55 and have lower motor vehicle speeds, and that are designed specifically for bicycling rather than for
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3 sharing with pedestrians. These bicycle infrastructure modifications would reduce both crashes and
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5 injury severity after a crash.
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15 from the participants of that class.
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25 of the study. KT, MAH, CCOR, PC, MW, SB, MC, MDC, JB, SMF, Garth Hunte and Kishore
26 Mulpuri were responsible for the funding proposal. CCOR, MAH, MW, MDC, KT, Melody Monroe
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3 the perspective of professionals or advocates involved in cycling transportation. Data were double
4 entered by Express Data Ltd.
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23 **COMPETING INTERESTS:** None.
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26 **PATIENT CONSENT:** Obtained
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30 **ETHICS APPROVAL:** The study methods were reviewed and approved by the human subjects
31 ethics review boards of the University of British Columbia (BREB REB H06-03833), the University
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34 General Hospital and Toronto Western Hospital; REB 07-0839-AE). All participants gave informed
35 consent before taking part in the study.
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43 **DATA SHARING STATEMENT:** The study database was compiled from interviews with study
44 participants and site observations by study personnel. It cannot be shared by the authors with
45 anyone without approval from the University and Hospital human subjects review boards.
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Figure Legend

Figure 1. Metrics of severity of cycling injuries to 683 study participants, stratified by CTAS.
CTAS = Canadian Triage and Acuity Scale, where 5 is the least medically urgent and 1 is the most.

Figure 2. Crash circumstances vs. metrics of severity.
Collisions could be with a motor vehicle, obstacle, surface feature, cyclist, pedestrian, or animal. Motor vehicle “involved” includes both direct collisions with vehicles and crashes resulting from manoeuvres to avoid a motor vehicle.

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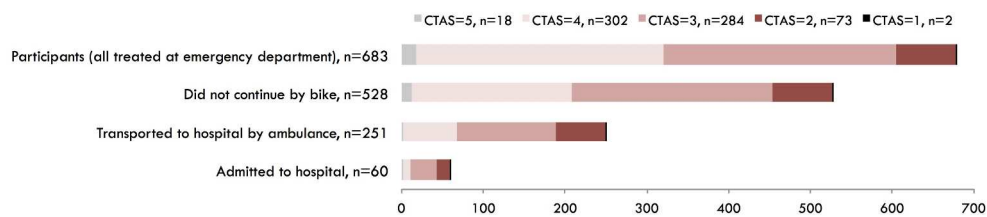
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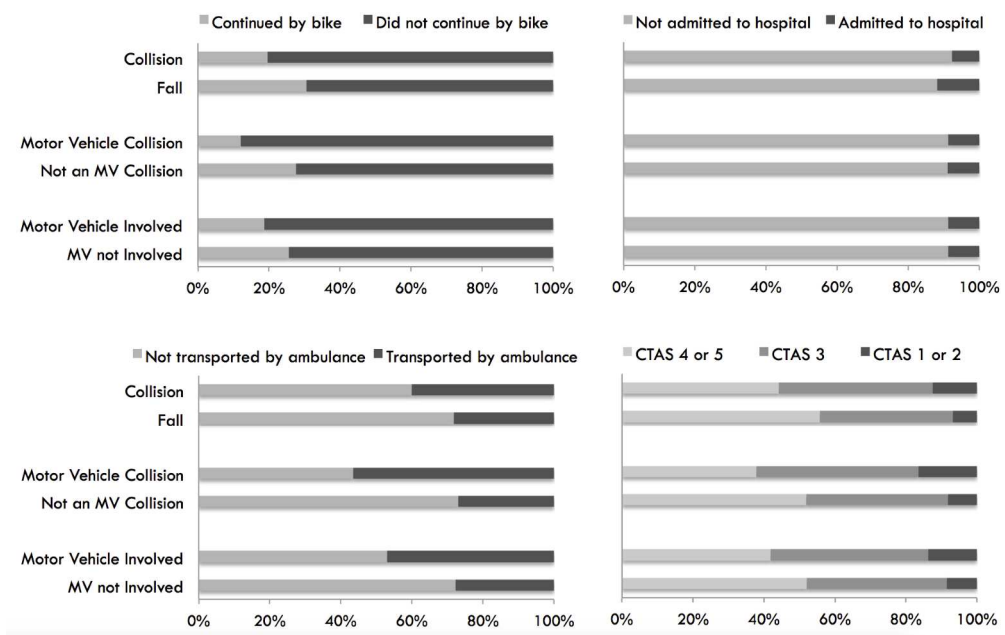
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