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ORIGINAL PAPER

Incidence and Profile of Severe Cycling Injuries After Bikeway Infrastructure Changes

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Abstract
The objective of this study was to evaluate whether bicycling infrastructure changes in the city of Minneapolis effectively reduced the incidence or severity of traumatic bicycling related injuries sustained by patients admitted to our Level 1 Trauma Center. Data for this retrospective cohort study was obtained from the trauma database at our institution and retrospective chart review. The total number of miles of bikeway in the city on a yearly basis was used to demonstrate the change in cycling infrastructure. Adjusted regression analysis demonstrated a significant reduction in ISS when total bike lane miles increased (Coef. −0.04, P < 0.001). Increasing bike lane miles was also associated with a significant reduction in severe head injury (OR 0.99, P < 0.001) and ICU LOS (Coef. −0.17, P = 0.013). The miles of bike lanes were not associated with any significant changes in mortality or mechanical ventilation days when adjusted for other factors. We were able to demonstrate a reduction in the severity of injuries incurred by cyclists in the setting of a significant increase in the total number of bicycle lane miles. Our data lends credence to the existing evidence that the addition of bicycle lane miles increases cyclist safety.

Keywords Bicycle · Bike · Trauma · Infrastructure

Background

Bicycling has continued to gain popularity as a form of recreation and commuter transportation [1]. There are significant health benefits to an active lifestyle, particularly when regularly commuting by bike or foot [2]. However, as with any form of outdoor active recreation and mobility, there is an associated risk of traumatic events to the participants. Beck et al. found a relative risk of 2.3 for a fatal injury while bicycling compared to fatal injury of a vehicle occupant in a motor vehicle collision [3]. The perception and reality of this increased risk may be a barrier for many who would otherwise enjoy the freedom and exhilaration of bicycling.

Despite a sometimes harsh and severe winter climate, Minneapolis has one of the highest rates of bicycle commuters in the country (3.9%) [4]. Between the years 2007 and 2016, Minneapolis saw a 49% increase in the number of bicyclists on city streets and trails [5]. Much of this increase was likely due to the overall cultural trend of cycling as an appealing and popular form of exercise and recreation. In addition to this, the city of Minneapolis was a participant in the "Nonmotorized Transportation Pilot Program" which was a federally-funded bill through the US Department of Transportation. This provided $25 million to each of four communities in the US from 2007 through 2009 to demonstrate the ability of infrastructure changes to increase rates of cycling and walking [6].

The data clearly shows an increased number of cyclists in Minneapolis, but there are drawbacks to this increase in shared road space. Cycling alongside larger motorized vehicles results in increased injury severity when a crash does occur [7]. Previous studies suggest that making bicycle safety infrastructure changes can reduce injury risk [8, 9]. In 2011, the city developed a bicycle master plan with a goal of reducing bicycle-motorist crashes by 10% [10]. As a result, the city has continued to invest heavily in yearly increases in cycling boulevard designations, off-street bike paths, and physically-separated bicycling lanes on existing city streets. These factors combine to place the Minneapolis metropolitan area in a unique position to evaluate the effects of infrastructure changes on bicycle crashes. The objective

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of this study was to evaluate whether bicycling infrastructure changes in the city of Minneapolis effectively reduced the incidence or severity of traumatic bicycling-related injuries sustained by patients admitted to our Level 1 Trauma Center. We hypothesize that the increase of bikeway miles will demonstrate significant reductions in injury severity associated with cycling accidents.

Methods

Data for this retrospective review was obtained from the trauma database at our institution. Our center is one of three Level 1 Trauma Centers in Minneapolis. There is one adult, one pediatric, and we are an adult and pediatric Level 1 Trauma Center. Trauma admissions with a cause code equal to "bike" or "bicycle" over the time period of January 2005 to December 2016 were included in analysis. Patients who were evaluated for cycling-related injuries in the emergency department but not admitted, are not included in the database. Patient demographics, mode of arrival, Abbreviated Injury Severity Scale (AIS), Injury Severity Score (ISS), Intensive Care Unit (ICU) status, mechanical ventilator days, helmet use, alcohol or drug use, mechanism of injury, and discharge disposition were all coded into the database. Retrospective chart review was carried out to address missing data from the registry. The city of Minneapolis provided specific infrastructure changes implemented each year.

This was a convenience sample of patients identified with our institutional trauma registry that collects data on all patients admitted from the emergency department or die in the emergency department following traumatic injury. We conducted retrospective chart view to collect any missing data from the registry. We examined the descriptive data by dividing the cohort into two groups: a pre-implementation group, which included admissions from January 1, 2005 to December 31, 2010, and a post-implementation group, which included admissions from January 1, 2011 to December 31, 2016. This coincided with Minneapolis' strategic plan to improve motorist/cyclist collisions in 2011. We were also able to utilize data from the city regarding estimated daily bicyclist traffic at a representative selection of intersections that were tracked on an annual basis [11]. The total number of miles of bikeway in the city on a yearly basis was used to demonstrate the change in cycling infrastructure.

Differences in demographic, injury, and infrastructure changes were assessed with unpaired Student's *T* test and Chi square test. We performed linear regression analysis to assess factors associated with ISS. Our secondary outcome measures were severe head injury (defined as AIS head ≥ 3), ICU LOS, mechanical ventilation days, and mortality. We utilized logistic and linear regression analysis to identify factors associated with the secondary outcome measures. The Institutional Review Board for Human Subjects Research approved this study. We followed the STrenthening the Reporting of Observational studies in Epidemiology (STROBE) guidelines for reporting cohort studies [12]. Statistical analysis was carried out using Stata 15.2, StataCorp (College Station, TX).

Results

There were 1127 cycling-related trauma admissions between 2005 and 2016 with 415 pre-implementation and 712 post-implementation (Table 1). The mean age was 36.1 years (range 2–86), 77% were male, and 73.7% were non-Hispanic White (Table 1). Alcohol use or other intoxicating substance was noted to be involved in 15.1% and 1.7% of cases, respectively. A greater percentage of cyclists had documentation of wearing helmets at the time of their injury in the post group 36.1% versus 26.3%. ISS was higher in the pre-implementation group and 28.4% of patients had ISS in the severe or extreme category (16–75) compared to 18.2% in the post-implementation group (Table 1). Patients were more likely to have a severe head injury (AIS > 3) in the pre-implementation group (39.3% vs. 23.7%, $P < 0.001$). The percentage of patients admitted to the ICU was lower after the implementation of the bicycle master plan (43.4% vs. 25.7%, $P < 0.001$) and mean length of stay decreased in the post-implementation group as well (6.0 vs. 3.9 days, $P < 0.001$). Mortality was higher prior to the implementation of the plan (3.4% vs. 1.5%, $P = 0.044$).

The total number of miles of protected bikeways over the study period are included in Fig. 1. In 2006, there were 125 miles of designated bikeway primarily consisting of separate bike paths and painted bike lanes (Fig. 1). This increased to 235 miles in 2016 which also included newly designated bike boulevards and shared lanes (Fig. 1). In the early study period, the mean number of bike miles totaled 129 and increased to 208 for the later period (Table 1). Estimated daily ridership (EDT), measured by the city of Minneapolis on specific days throughout the year at 30 benchmark bicycling intersections increased by 49%; from 22,490 in 2007 to 34,510 in 2015 (Fig. 2). Figure 2 demonstrates the upward trend in estimated daily ridership, bikeway miles, and an associated increase in yearly cycling related trauma admission which all trend up in the study period. Figure 3 illustrates the ratio of median ISS to miles of protected bikeway for every year of the study period demonstrating a downward trend of median ISS per bikeway mile.

Age and bicycle accidents involving motor vehicles were associated with increased ISS (Table 2). Bike lane miles was associated with a decrease in ISS in unadjusted analysis (Table 2). There was a small, but statistically significant, reduction in ISS with increasing bike lane miles (coef.

Table 1 Demographics, injury characteristics, outcomes, and infrastructure changes

	Cohort N = 1127	Pre-implementation[a] N = 415	Post-implementation[a] N = 712	P value[b]
Total bike lanes, mean (SD)	179.1 (42.0)	129.4 (7.3)	208.1 (21.9)	< 0.001
Shared lane	9.2 (5.2)	3.0 (1.6)	12.8 (2.2)	< 0.001
Bike boulevard	10.7 (9.2)	0 (0)	16.9 (5.3)	< 0.001
Bike lane	64.9 (21.1)	39.3 (3.5)	79.8 (9.6)	< 0.001
Protected bikeway	94.3 (6.0)	87.1 (2.8)	98.5 (6.0)	< 0.001
Age, mean (SD)	36.1 (19.6)	33.4 (19.7)	37.7 (19.3)	< 0.001
Sex male, N (%)	868 (77.0)	319 (76.9)	549 (77.1)	0.917
Race White non-Hispanic, N (%)	830 (73.7)	301 (72.5)	529 (74.3)	0.516
Alcohol involved, N (%)	170 (15.1)	58 (14.0)	112 (15.7)	0.427
Drug involved, N (%)	19 (1.7)	13 (3.1)	6 (0.8)	0.004
Protection device, N (%)				< 0.001
No	619 (54.9)	232 (55.9)	387 (54.4)	
Yes	366 (32.5)	109 (26.3)	257 (36.1)	
Unknown/not documented	142 (12.6)	74 (17.8)	68 (9.6)	
Car vs. bike, N (%)	398 (35.4)	148 (35.8)	250 (35.1)	0.829
Referred from OSH, N (%)	268 (23.8)	155 (37.4)	113 (15.9)	< 0.001
Transportation mode, N (%)				<0.001
Private auto	109 (9.7)	35 (8.5)	74 (10.4)	
Ambulance	960 (85.4)	344 (83.3)	616 (86.6)	
Air	55 (4.9)	34 (8.2)	21 (3.0)	
ISS, N (%)				< 0.001
Mild: 1 - 8	477 (42.3)	147 (35.4)	330 (46.4)	
Moderate: 9 - 15	402 (35.7)	150 (36.1)	150 (36.1)	
Severe: 16 - 24	163 (14.5)	71 (17.1)	92 (12.9)	
Extreme: 25 - 75	85 (7.5)	47 (11.3)	38 (5.3)	
AIS head ≥ 3, N (%)	332 (29.5)	163 (39.3)	169 (23.7)	<0.001
AIS face ≥ 3, N (%)	3 (0.3)	2 (0.5)	1 (0.1)	0.283
AIS chest ≥ 3, N (%)	135 (12.0)	61 (14.7)	74 (10.4)	0.032
AIS abdomen ≥ 3, N (%)	43 (3.8)	14 (3.4)	29 (4.1)	0.557
AIS upper extremity ≥ 3, N (%)	22 (2.0)	10 (2.4)	12 (1.7)	0.397
AIS lower extremity ≥ 3, N (%)	124 (11.0)	41 (9.9)	83 (11.7)	0.358
LOS days, mean (SD)	4.7 (7.2)	6.0 (9.0)	3.9 (5.7)	< 0.001
ICU, N (%)	362 (32.1)	180 (43.4)	182 (25.7)	< 0.001
ICU LOS hours, mean (SD)	107.7 (170.5)	122.7 (195.5)	92.9 (140.5)	0.097
Mechanical ventilation, N (%)	144 (12.8)	79 (19.0)	65 (9.1)	< 0.001
Mechanical ventilation days, mean (SD)	7.1 (9.3)	7.6 (9.4)	6.6 (9.3)	0.534
Discharge, N (%)				0.059
Home	946 (83.9)	345 (83.1)	601 (84.4)	
Morgue	25 (2.2)	14 (2.4)	11 (1.5)	
Skilled nursing	55 (4.9)	17 (4.1)	38 (5.3)	
Rehabilitation	92 (8.2)	34 (8.2)	58 (8.2)	
Long-term care	2 (0.2)	0 (0)	2 (0.3)	
Acute care/transfer	6 (0.5)	5 (1.2)	1 (0.1)	
Unknown	1 (0.1)	0 (0)	1 (0.1)	
Mortality	25 (2.2)	14 (3.4)	11 (1.5)	0.044

AIS Abbreviated Injury Severity Scale, *ICU* Intensive Care Unit, *ISS* Injury Severity Score, *LOS* length of hospital stay, *OSH* outside hospital

[a]Pre group: admissions from January 1, 2005 to December 31, 2010. Post group: admissions from January 1, 2011 to December 31, 2016. This coincided with Minneapolis' strategic plan to improve motorist/cyclist collisions in 2011

[b]Student's T-test for continuous variables and Chi2 test for categorical variables

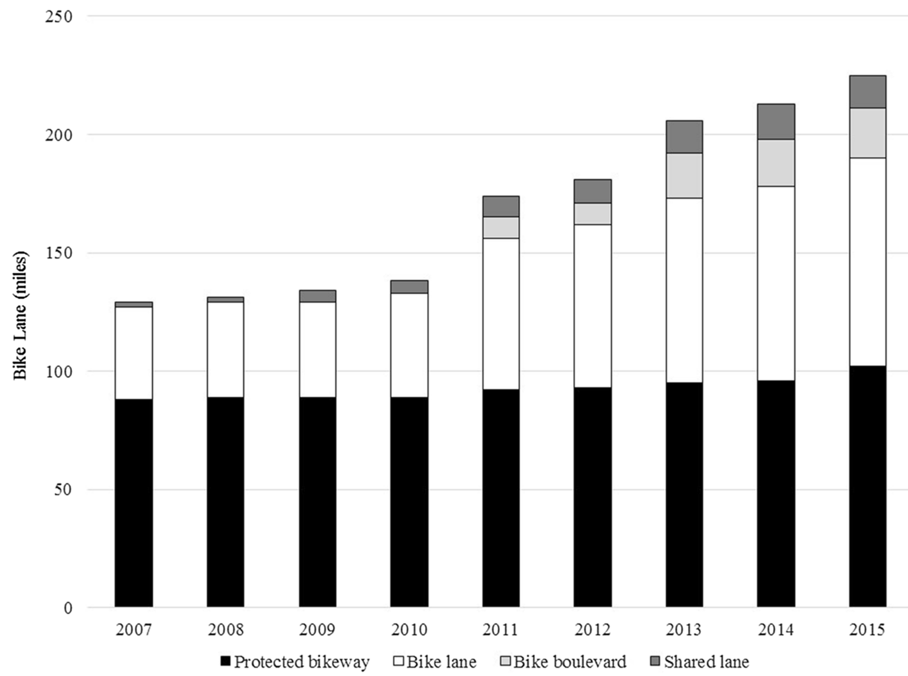

Fig. 1 Data provided by the city of Minneapolis documents the total number of miles of protected bikeways over the study period

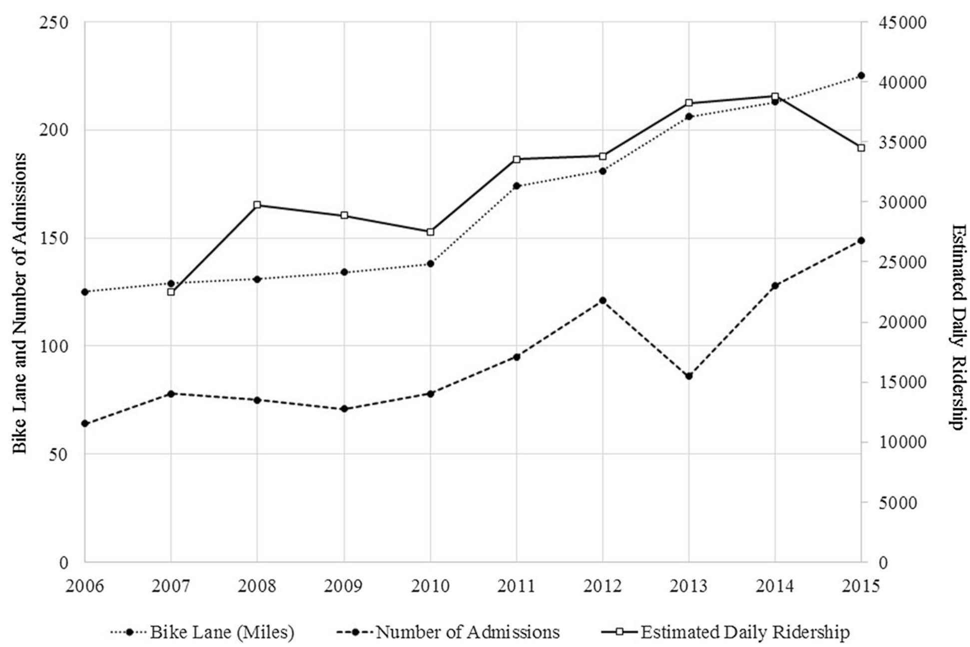

Fig. 2 Bike lane miles and number of bicycle trauma admissions (1st Y-axis). Estimated daily ridership (2nd Y-axis)

− 0.04, P < 0.001) when adjusting with age, helmet use, and accidents involving motor vehicles (Table 2).

Secondary outcome measures included severe head injury (AIS ≥ 3) and mortality (Table 3) and ICU LOS and mechanical ventilation days (Table 4). Bike lanes significantly reduced ISS (adjusted OR − 0.04, P < 0.001) when adjusting for age, helmet use, and accidents involving vehicles. Documented helmet use significantly reduced severe head injury, while ISS and intoxication were associated with increased head injury (Table 3). When controlling for age, ISS, helmet use, and intoxication, bike lane miles was associated with a significant reduction in head injury (adjusted OR: 0.99, P = 0.005). Mortality was not significantly reduced by increasing bike lanes (adjusted OR = 0.99, P = 0.353). The increase in bike lane miles was associated with a reduction of ICU LOS but not mechanical ventilation days (Table 4).

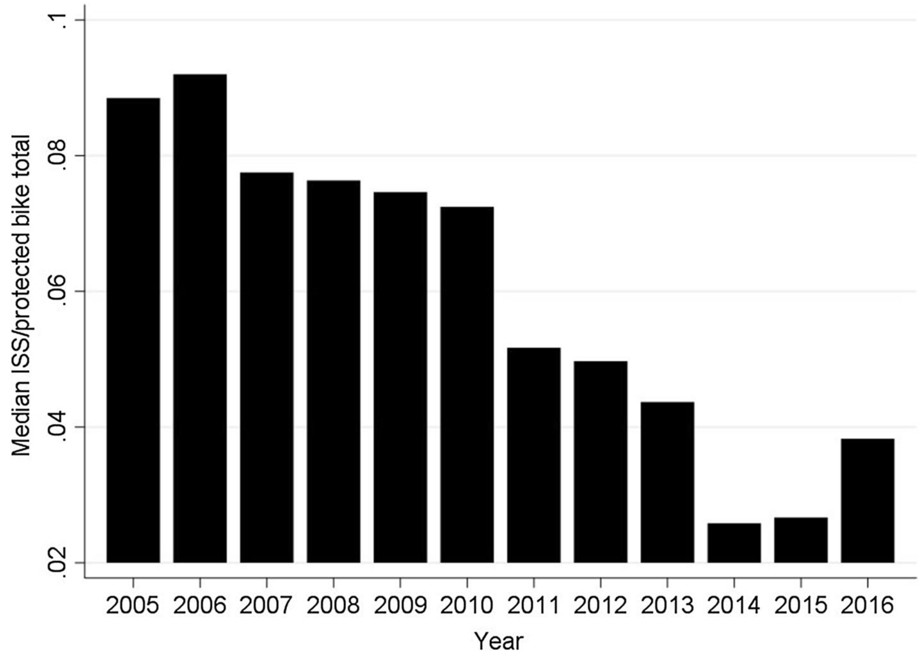

Fig. 3 Median ISS by bike lane miles for each year

Table 2 Linear regression analysis of factors associated with ISS

Primary Outcome: ISS	Unadjusted Coef. (CI)	P value[a]	Adjusted Coef. (CI)	P value[b]
Age	0.04 (0.01, 0.07)	0.004	0.07 (0.04, 0.09)	< 0.001
Gender male	0.52 (− 0.74, 1.77)	0.421		
Race non-White	− 0.57 (− 1.77, 0.63)	0.349		
Total bike lanes	− 0.03 (− 0.04, − 0.02)	< 0.001	− 0.04 (− 0.05, − 0.02)	< 0.001
Intoxicated	0.46 (− 0.97, 1.90)	0.525		
Helmet				
Yes	− 0.82 (− 1.99, 0.35)	0.169	− 1.11 (− 2.26, 0.05)	0.061
Unknown	− 1.2 (− 2.9, 0.4	0.141	− 1.64 (− 3.25, − 0.02)	0.047
Bike vs. car	3.43 (2.34, 4.52)	<0.001	3.71 (2.64, 4.79)	<0.001

ISS Injury Severity Score

[a]Unadjusted linear regression

[b]Adjusted linear regression

Discussion

Like many other major metropolitan areas around the country, Minneapolis has made a concerted effort to increase the safety of its citizens who choose to engage in non-motorized forms of transportation [8]. There was a 49% increase in the estimated daily traffic of cyclists in Minneapolis over the time frame from 2007 to 2016. This corresponded with an increase in the number of miles of protected bike lanes established by the city over a similar time period, from 113 miles in 2005 to 245 miles in 2017. The City also committed to decrease bicyclist motorist crashes by 10% in the 2011 Bicycle Master Plan [10]. We identified significant reductions in injury severity and severe head injury associated with increased in bike lane miles.

The overall health benefits associated with cycling are clear, although there is also some degree of risk associated with cycling [2, 3]. Previous studies have demonstrated a reduction in injuries and fatalities after cycling infrastructure improvements were implemented [13, 14]. We found a reduction in mortality even with dramatic increases in ridership, however this difference was not significant when adjusting for other factors. This is supported by similar results obtained in Boston from 2009 to 2012, where "…the proportion of accidents that resulted in injuries…. diminished over time." [8]. Similarly, their metro area had undergone a period of rapid growth in the total number of bike lane miles over the study period. Most importantly, our data

Table 3 Secondary outcomes logistic regression analysis

Severe head injury: AIS ≥ 3	Unadjusted OR (CI)	P value[a]	Adjusted OR (CI)	P value[b]
Age	1.01 (1.00, 1.01)	0.095	1.01 (1.00, 1.02)	0.107
Gender male	1.06 (0.78, 1.44)	0.721		
Race non-White	0.87 (0.65, 1.16)	0.336		
Total bike lanes	0.99 (0.98, 0.99)	< 0.001	0.99 (0.99, 1.00)	0.005
ISS	1.34 (1.29, 1.39)	< 0.001	1.34 (1.29, 1.39)	< 0.001
Intoxicated	1.76 (1.27, 2.44)	0.001	1.69 (1.06, 2.69)	0.027
Helmet				
Yes	0.41 (0.30, 0.55)	< 0.001	0.30 (0.19, 0.47)	< 0.001
Unknown	0.72 (0.48, 1.07)	0.107	0.68 (0.37, 1.24)	0.212
Bike vs. car	0.99 (0.76, 1.30)	0.962		
Mortality	**Unadjusted OR (CI)**	**P value[a]**	**Adjusted OR (CI)**	**P value[b]**
Age	1.02 (1.00, 1.04)	0.041	1.04 (1.01, 1.07)	0.006
Gender male	1.20 (0.45, 3.22)	0.720		
Race non-white	1.32 (0.57, 3.10)	0.518		
Total bike lanes	0.99 (0.98, 1.00)	0.142	0.99 (0.98, 1.01)	0.353
ISS	1.19 (1.14, 1.24)	< 0.001	1.21 (1.15, 1.30)	< 0.001
Intoxicated	0.98 (0.33, 2.90)	0.974		
Helmet				
Yes	0.97 (0.40, 2.32)	0.938		
Unknown	0.93 (0.26, 3.29)	0.914		
Bike vs. car	2.81 (1.25, 6.32)	0.012	0.97 (0.31, 3.02)	0.963

AIS Abbreviated Injury Severity Scale, *ISS* Injury Severity Score

[a]Unadjusted logistic regression

[b]Adjusted logistic regression

demonstrated significant reduction in the severity of injuries, measured by severe head injury, ISS, and ICU LOS, suffered by cyclists when bike lane mile increased.

There is a very large body of data that has been published establishing the clear benefit in reducing injury severity by wearing a helmet while cycling [15]. Fortunately, our data suggests that more cyclists are heeding this information. Our data shows that helmet use and cycling infrastructure changes reduced severe head injuries in cycling accidents. There was a reduction in ISS when patients were noted to be wearing helmets, although this did not reach significance when adjusting for other factors.

Previous studies have stated that increasing bicycle infrastructure results in increasing ridership. We also showed this correlation but it is likely confounded by increasing social acceptance and overall popularity of cycling as a form of transportation over the same time period. There would likely have been increases in bicycle ridership regardless of infrastructure changes, and we were not able to determine how great that relative effect may have been. We did not establish a decrease in the actual rate of cyclist crashes vs numbers of riders as has been previously been reported [16]. We did show in our study, however, that riders were less seriously injured when there are more cyclists and miles of protected bike space. This further supports our position that cyclists are protected when physically separated from motor vehicles.

The city of Minneapolis made several different types of cycling infrastructure changes during the study period. This ranged from simple designation of thoroughfare residential streets as "bike boulevards," to complete redesign of major city arterials to include separate bicycle lanes with markers and bollards as a means of physically obstructing vehicle crossover. Regression analysis demonstrated a positive change in reducing injury for each of these infrastructure changes. Along with the physical changes to city streets, the Master Plan included many proposals for education, bike advocacy, and changes in enforcement.

As a single institution study our dataset is somewhat limited, but likely representative of a Level 1 trauma center in one of the country's "Best Cities for Cycling" [17]. Our study has the typical limitations of a single center study and bias associated with reliance on a database to identify our study cohort. We were unable to obtain specific information on which of these additional avenues for crash reduction were funded and there may be other factors associated with

Table 4 Secondary outcomes linear regression analysis

ICU LOS	Unadjusted OR (CI)	P value[a]	Adjusted OR (CI)	P value[b]
Age	−0.17 (−0.50, 0.15)	0.304		
Gender male	12.12 (−2.99, 27.23)	0.116	5.95 (−7.57, 19.47)	0.388
Race non-White	11.27 (−3.17, 25.70)	0.126	5.66 (−7.59, 18.91)	0.402
Total bike lanes	−0.35 (−0.50, −0.20)	<0.001	−0.17 (−0.31, −0.04)	0.013
ISS	5.23 (4.60, 5.86)	<0.001	4.80 (4.16, 5.45)	<0.001
Intoxicated	2.86 (−14.41, 20.12)	0.746		
Helmet				
Yes	−27.50 (−41.51, −13.50)	<0.001	−19.95 (−32.73, −7.16)	0.002
Unknown	−3.06 (−22.81, 16.70)	0.762	1.33 (−16.68, 19.33)	0.885
Bike vs car	46.62 (33.57, 59.66)	<0.001	29.36 (17.29, 41.43)	<0.001
Mechanical ventilation days	**Unadjusted OR (CI)**	**P value[a]**	**Adjusted OR (CI)**	**P value[b]**
Age	0.002 (−0.01, 0.01)	0.728		
Gender male	0.36 (−0.21, 0.23)	0.214		
Race non-white	0.08 (−0.46, 0.62)	0.767		
Total bike lanes	−0.01 (−0.02, −0.01)	<0.001	−0.002 (−0.04, 0.04)	0.899
ISS	0.18 (0.16, 0.21)	<0.001	0.11 (0.01, 0.21)	0.041
Intoxicated	0.21 (−0.44, 0.85)	0.532		
Helmet				
Yes	−0.89 (−1.41, −0.36)	0.001	−4.43 (−8.28, −0.59)	0.024
Unknown	−0.07 (−0.81, 0.67)	0.847	−0.99 (−5.04, 3.06)	0.631
Bike vs. car	1.50 (1.00, 1.99)	<0.001	4.56 (1.53, 7.59)	0.003

AIS Abbreviated Injury Severity Scale, *ICU* Intensive Care Unit, *ISS* Injury Severity Score, *LOS* length of hospital

[a]Unadjusted logistic regression

[b]Adjusted logistic regression

the reduction that we could not account for in this study. We did not differentiate between pediatric and adult patient populations in this study which could have some bearing on the results as many fewer children are likely to be utilizing bike lanes on city streets.

Conclusion

We have demonstrated a pronounced reduction in the severity of injuries incurred by cyclists in the setting of a significant increase in the total number of bicycle lane miles. Our data lends credence to the existing evidence that the addition of bicycle lane miles may increase cyclist safety.

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Author Contributions Goerke: Literature search, study design, data interpretation, data analysis, writing. Zolfaghari: Data analysis, critical revision. Marek: Data interpretation, writing, critical revision. Endorf: Study design, data interpretation, critical revision. Nygaard: Study design, data collection, data analysis, data interpretation, critical revision.

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Compliance with Ethical Standards

Conflict of interest The authors have no conflicts of interest to report.

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