Bicycle Use and Cyclist Safety Following Boston's Bicycle Infrastructure Expansion, 2009–2012

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Objectives. To evaluate changes in bicycle use and cyclist safety in Boston, Massachusetts, following the rapid expansion of its bicycle infrastructure between 2007 and 2014.

Methods. We measured bicycle lane mileage, a surrogate for bicycle infrastructure expansion, and quantified total estimated number of commuters. In addition, we calculated the number of reported bicycle accidents from 2009 to 2012. Bicycle accident and injury trends over time were assessed via generalized linear models. Multivariable logistic regression was used to examine factors associated with bicycle injuries.

Results. Boston increased its total bicycle lane mileage from 0.034 miles in 2007 to 92.2 miles in 2014 ($P < .001$). The percentage of bicycle commuters increased from 0.9% in 2005 to 2.4% in 2014 ($P = .002$) and the total percentage of bicycle accidents involving injuries diminished significantly, from 82.7% in 2009 to 74.6% in 2012. The multivariable logistic regression analysis showed that for every 1-year increase in time from 2009 to 2012, there was a 14% reduction in the odds of being injured in an accident.

Conclusions. The expansion of Boston's bicycle infrastructure was associated with increases in both bicycle use and cyclist safety. (*Am J Public Health.* 2016;106:2171–2177. doi:10.2105/AJPH.2016.303454)

See also Pucher, p. 2089, and Galea and Vaughan, p. 2091.

In the United States, the reliance on personal automobiles as the main form of transportation has repercussions not only for the infrastructure of a city, owing to vehicular congestion, but also for the health of its citizens, as a result of increased air pollution and reduced physical activity.[1] Many cities are now implementing programs designed to promote commuter biking as a means of reducing automobile use and thus improving both air quality and the health of citizens.[2,3] Individual modifications of a city's bicycle infrastructure, including increasing bicycle lane mileage,[4,5] adding bicycle share programs,[6] and improving signage and street markings,[7] have been shown to enhance overall bike use. However, broad integrated approaches to improving a city's bicycle infrastructure have been shown to be the most effective approach to increasing bicycle use.[2]

A major concern with bicycle infrastructure expansion is cyclist safety. Therefore, the main goal of improving a city's bicycle infrastructure is to increase bike use while enhancing safety. A recent systematic review showed insufficient evidence of a relationship between bicycle infrastructure and cycling collisions; however, this investigation was limited by the number of available studies and study quality.[8] Therefore, more information is necessary to better inform decisions on effective bicycle infrastructure expansion.

The city of Boston, Massachusetts, has recently undergone a dramatic change in its bicycle infrastructure, providing a unique opportunity to study the effects of bicycle infrastructure expansion on both bike use and cyclist safety. From 1999 to 2006, Boston had been named 3 times by *Bicycle* magazine as one of the nation's worst cities in which to bike.[9] During that period, Boston's bicycle infrastructure was nonexistent, with only 60 yards of bicycle lanes.

In 2007 the city initiated a program, "Boston Bikes," that has transformed its bicycle infrastructure, including an increase in total bicycle lane mileage from 0.034 miles in 2007 to 92.2 miles in 2014.[10] The program's integrated approach to bicycle infrastructure expansion involved not only an increase in bicycle lane mileage but also improvements in bicycle signage, parking, and cyclist awareness, and the addition of a bike share program. Boston's broad expansion of its bicycle infrastructure in such a short period of time has resulted in a unique opportunity to evaluate the effects of its infrastructure expansion. We hypothesized that the expansion of Boston's bicycle infrastructure would lead to significant increases in overall bike use and a reduction in bicycle accidents and injuries.

METHODS

We defined a bicycle lane as part of a road that is marked off and separated for the explicit use of bicyclists. Total bicycle lane mileage was used as a surrogate for degree of bicycle infrastructure expansion. Publicly available data on aggregate total bicycle lane mileage in Boston for each

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individual year from 2007 to 2014 were obtained from the Massachusetts Department of Transportation Web site.

To determine bicycle ridership in Boston, we used the publicly available database from the US Census Bureau's American Community Survey and calculated the percentage of bicycle commuters during 2005 to 2014, a period representing 2 years prior to the infrastructure expansion and 7 years following the start of the expansion. The American Community Survey is conducted yearly nationwide and in Boston via a random address sampling strategy incorporating all housing units and group quarters. Individuals are initially notified via mail to complete the online survey; if there is no response, they are notified via mail to complete a paper survey. If there continues to be no response, they are contacted to complete an automated telephone survey and, finally, contacted via a personal visit.

The American Community Survey database includes an estimate of the proportion of workers older than 16 years who commute to work regularly and their mode of transportation. Using data for Boston on the total number of individuals surveyed and the proportion who commuted by bicycle, we were able to calculate the estimated number of bicycle commuters during each year of our study. We also obtained total counts by gender to assess whether changes in numbers of commuters have differed between men and women.

Bicycle-Related Accidents

We used a publicly available database supported by the city of Boston to assess total numbers of reported bicycle accidents. The database was created through a collaborative effort between the Boston Police Department, the Boston Emergency Medical Services, and the Boston Area Research Initiative in Cambridge, Massachusetts. The database includes all police records of reported bicycle accidents in Boston during the years 2009 to 2012 as well as information on predetermined variables for each accident such as victims' demographic characteristics; year, day of week, time of day, and location (main road, residential road, intersection) of the accident; weather and lighting conditions at the time of the accident; helmet use; and the cause of the accident. The database included information on 1808 individuals, 11 of whom (0.6%) were removed from our analysis as a result of missing data.

Costs of Bicycle Injuries

We used the Centers for Disease Control and Prevention's Web-based Injury Statistics Query and Reporting System calculator to estimate costs (medical and work loss) associated with bicycle injuries during each of the years examined.[11]

Statistical Analysis

We tabulated patient and accident demographics for each study year. We used the χ^2 test to compare categorical variables and analyses of variance to compare continuous covariates. Generalized linear models with robust standard errors were used to evaluate both the increase in bicycle lane mileage in Boston across time and trends from 2005 to 2014 in the total numbers of estimated workers older than 16 years who commuted by bicycle.

We also used generalized linear models to evaluate aggregate and gender-specific trends over time (2009–2012) in numbers of bicycle accidents. Bicycle accident data were evaluated in separate models as total number of accidents, total number of individuals injured in bicycle accidents (injury-related accidents), total proportion of accidents resulting in cyclist injuries, accident rate (total number of accidents divided by total number of commuters), and injury rate (total number of injury-related accidents divided by total number of commuters). We calculated accident and injury rates by dividing total numbers of accidents and injury-related accidents, respectively, by the total number of estimated bicycle commuters during each year.

Finally, we fit a multivariable logistic regression model to evaluate factors associated with being injured in a bicycle accident in Boston. Initially, all variables considered as relevant potential risk factors for bicycle-related injuries were evaluated via univariate logistic regression and calculated as crude odds ratios (ORs). A multivariable logistic regression model including all variables shown to be relevant or significant in the univariate analysis was fit to allow an evaluation of the effects of the bicycle infrastructure expansion on the probability of an injury-related accident.

Several sensitivity analyses were performed. Given the possibility of poor reporting of helmet documentation at the scene or selection bias with respect to reporting of helmet use among those injured more frequently, documented helmet use was excluded in an additional multivariable model. In another sensitivity analysis, year was considered a categorical variable instead of a continuous variable given the possibility of nonuniformity between study years in infrastructure changes.

Stata version 14.1 (StataCorp LP, College Station, TX) was used in conducting all of our statistical analyses. The significance level was set at a P value of less than .05.

RESULTS

The mean age for all individuals involved in an accident was 29.7 years (SD = 13.0; range = 4–79). No significant age differences were observed according to study year. Also, overall, there were no relevant differences by study year in terms of gender or ethnicity (Table 1). The mean age for individuals injured in a bicycle accident was 29.5 years (SD = 13.09), and the mean for those not injured was 29.9 years (SD = 12.7). A major component of Boston's bicycle infrastructure expansion was an increase in total bicycle lane mileage, which increased significantly from 0.034 miles in 2007 to 92.2 miles in 2014 ($P < .01$; Figure A, available as a supplement to the online version of this article at http://www.ajph.org).

There was almost a 3-fold increase over the study period in the estimated percentage of workers older than 16 years in Boston who commuted by bicycle to work, from 0.9% (SD = 0.4) in 2005 to 2.4% (SD = 0.4) in 2014 ($P < .01$). Stratification by gender showed that a greater proportion of male than female workers commuted by bicycle

TABLE 1—Patient and Accident Characteristics: Bicycle Commuters in Boston, MA, 2009–2012

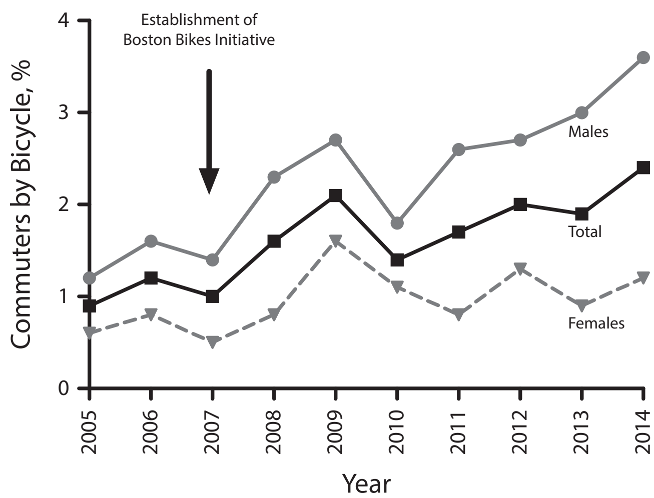
Characteristic	2009, No. (%) or Mean ±SD	2010, No. (%) or Mean ±SD	2011, No. (%) or Mean ±SD	2012, No. (%) or Mean ±SD	P^a
No. of accidents	358	476	475	488	.18
Age, y	29.6 ±13.6	29.3 ±12.8	28.8 ±12.5	31.0 ±13.3	.09
Gender					.56
Male	269 (75.1)	337 (70.8)	354 (74.5)	358 (73.4)	
Female	78 (21.8)	118 (24.8)	105 (22.1)	104 (21.3)	
Unknown	11 (3.1)	21 (4.4)	16 (3.4)	26 (5.3)	
Race/ethnicity					.61
White	200 (55.9)	263 (55.3)	256 (53.9)	259 (53.1)	
Non-White	119 (33.2)	145 (30.5)	160 (33.7)	156 (32.0)	
Unknown	39 (10.9)	68 (14.3)	59 (12.4)	73 (15.0)	
Injured					.33
Yes	296 (82.7)	378 (79.4)	367 (77.3)	364 (74.6)	
No	56 (15.6)	56 (11.8)	70 (14.7)	90 (18.4)	
Unknown	6 (1.7)	42 (8.8)	38 (8.0)	34 (7.0)	
Type of accident					.005
Cyclist only	8 (2.2)	26 (5.5)	27 (5.7)	15 (3.1)	
Bike/auto	342 (95.5)	425 (89.3)	432 (91.0)	441 (91.9)	
Bike/pedestrian	5 (1.4)	15 (3.2)	12 (2.5)	22 (4.6)	
Bike/bike	1 (0.3)	2 (0.4)	0 (0.0)	2 (0.4)	
Bike related	2 (0.6)	8 (1.7)	4 (0.8)	0 (0.0)	
Auto-related accident					.012
Yes	342 (95.5)	425 (89.3)	432 (90.9)	441 (91.9)	
No	16 (4.5)	51 (10.7)	43 (9.1)	39 (8.1)	
Accident caused by opened car door					.012
Yes	49 (13.7)	35 (7.4)	62 (13.1)	55 (11.3)	
No	309 (86.3)	441 (92.6)	413 (86.9)	431 (88.3)	
Unknown	0 (0.0)	0 (0.0)	0 (0.0)	2 (0.4)	
Accident occurred on a main road					.13
Yes	113 (31.6)	158 (33.2)	146 (30.7)	187 (38.3)	
No	233 (65.1)	303 (63.7)	299 (62.9)	290 (59.4)	
Unknown	12 (3.4)	15 (3.2)	30 (6.3)	11 (2.3)	
Documented helmet use					.19
Yes	32 (8.9)	29 (6.1)	40 (8.4)	48 (9.8)	
No	326 (91.1)	447 (93.9)	435 (91.6)	439 (90.0)	
Unknown	0 (0.0)	0 (0.0)	0 (0.0)	1 (0.2)	

[a]Means were compared with analyses of variance and proportions with the χ^2 test.

to work. Although data for both men and women showed a sharp rise in bicycle commuting from 2004 to 2014, the increase was significant only among men. Specifically, whereas the percentage of male bicycle commuters increased 3-fold from 1.2% (SD = 0.5) in 2005 to 3.6% (SD = 0.7) in 2014 ($P < .01$), there was a (nonsignificant) doubling in the percentage of female commuters, from 0.6% (SD = 0.5) in 2005 to 1.2% (SD = 0.4) in 2014 ($P = .12$; Figure 1 and Table A, available as a supplement to the online version of this article at http://www.ajph.org).

Accident Data

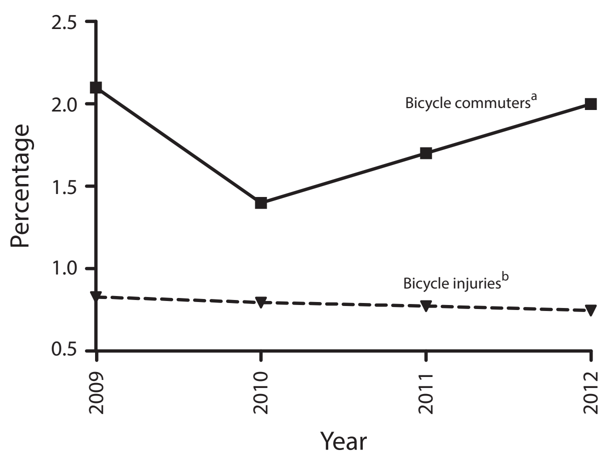
Total numbers of accidents increased significantly from 2009 to 2012 ($P = .016$). Analysis of the total number of accidents by gender showed a significant increase over time among men ($P = .002$) and a nonsignificant increase among women ($P = .29$). Total numbers of injury-related accidents remained unchanged over the study period both overall and for men and women separately. However, the proportion of accidents that resulted in injuries, a surrogate for accident severity, diminished over time in the study sample overall ($P < .001$; Figure 2 and Table B, available as a supplement to the online version of this article at http://www.ajph.org) and among men ($P < .001$) while remaining largely unchanged among women (Table B). Accident and injury rates did not change over time (Table B).



Source. US Census Bureau, American Community Survey data.

FIGURE 1—Percentages of Workers Older Than 16 Years Who Commute Via Bicycle, by Gender: Boston, MA, 2005–2014

The univariate analyses revealed several independent predictors of being involved in an injury-related accident (Table 2). These predictors included auto-related mechanism of injury (OR = 1.86; 95% confidence interval [CI] = 1.23, 2.81), being hit by an opened door (OR = 3.49; 95% CI = 1.87, 6.50), and being involved in an accident occurring on a main (i.e., nonresidential) thoroughfare (OR = 0.62; 95% CI = 0.48, 0.81) or intersection (OR = 0.75; 95% CI = 0.57, 0.98). Interestingly, individuals with documented helmet use were found to have 1.85 (95% CI = 1.05, 3.26) times the odds of non–helmet users of being involved in an injury-related accident. There was also a 1.02-fold (95% CI = 1.01, 1.03) rise in the odds of an injury-related accident with every 1°C increase in temperature on the day and time of the accident. There was a significant 11% reduction in the odds of the occurrence of an injury-related accident for each successive increase in study year (OR = 0.89; 95% CI = 0.79, 1.00).



[a]Percentage of commuters (workers older than 16 years) by bicycle. Data from US Census Bureau, American Community Survey data.

[b]Bicycle accidents resulting in an injury (reported as percentage/100 accidents).

FIGURE 2—Trends in Bicycle Use and Cyclist Injuries: Boston, MA, 2009–2012

We created a multivariable logistic regression model that included the following binary variables: auto-related accident, hit by an open door, documented helmet use at the scene, accident on a main road, and accident at an intersection. In addition, temperature and year were included as continuous variables. For every 1-year increase in time from 2009 to 2012, there was a 14% (OR = 0.86; 95% CI = 0.76, 0.97) reduction in the odds of being involved in an accident resulting in an injury with all other factors held constant. Riders who were hit by an opened door or involved in an auto-related accident had significantly increased odds of incurring an injury.

Not surprisingly, given that there are more bikers in warmer temperatures, there was a 2% (OR = 1.02; 95% CI = 1.01, 1.03) increase in the odds of an accident resulting in an injury for every 1°C increase in temperature. The odds of being involved in an accident resulting in an injury were 118% (OR = 2.18; 95% CI = 1.22, 3.89) higher among helmet users than among nonusers. Also, being involved in an accident on a main road led to a 37% reduction in the odds of incurring a bicycle accident injury. Finally, involvement in an accident at an intersection was not found to result in any significant differences in injury odds.

Sensitivity Analyses

As noted, we conducted several sensitivity analyses that excluded documented helmet use at the scene of an accident. The results showed that exclusion of helmet use did not lead to any substantial changes in the odds ratios for the other variables or in the significance of the model (Table C, available as a supplement to the online version of this article at http://www.ajph.org). Including year as a categorical variable also did not lead to substantial changes in the odds ratios or significance of the other variables (Table D, available as a supplement to the online version of this article at http://www.ajph.org).

TABLE 2—Crude and Adjusted Odds Ratios for Injury-Related Accidents Among Bicycle Commuters: Boston, MA, 2009–2012

Variable	Crude OR (95% CI)	Adjusted OR (95% CI)
Year (2009–2012)	0.89 (0.79, 1.00)	0.86 (0.76, 0.97)
Age, y	1.00 (0.99, 1.01)	
Male gender	0.83 (0.59, 1.15)	
Non-White race/ethnicity	1.17 (0.86, 1.58)	
Auto-related accident	1.86 (1.23, 2.81)	1.76 (1.15, 2.71)
Accident caused by opened car door	3.49 (1.87, 6.50)	3.25 (1.72, 6.15)
Documented helmet use	1.85 (1.05, 3.26)	2.18 (1.22, 3.89)
Temperature	1.02 (1.01, 1.03)	1.02 (1.01, 1.03)
Accident occurred at night[a]	0.94 (0.68, 1.29)	
Accident occurred at dusk[a]	0.83 (0.58, 1.17)	
Accident occurred on a main road	0.62 (0.48, 0.81)	0.63 (0.48, 0.83)
Accident occurred at an intersection	0.75 (0.57, 0.98)	0.85 (0.64, 1.13)

Note. CI = confidence interval; OR = odds ratio.
[a]Reference category: daytime.

DISCUSSION

Commuting by bicycle has been shown to result in considerable health benefits, including significant reductions in obesity and cardiovascular disease.[12] Given the health benefits associated with biking as well as improvements in automobile congestion and pollution, cities are making alternative modes of transportation a priority. Our findings show that an integrated approach to improving the bicycle infrastructure of a single city was associated with a significant increase in commuting by bicycle and an improvement in overall cyclist safety, as evidenced by a reduction over time in the proportion of accidents resulting in injuries.

Several studies have shown that improvements in cyclist infrastructure, specifically changes related to bicycle lane mileage, improve overall ridership.[4,5] An early study evaluating this issue revealed that, after adjustment for several variables associated with ridership, there was a 0.075% increase in the number of bicycle commuters for every mile of bikeway per 100 000 residents.[5] In a later study, Dill and Carr found that the strongest predictor of increased commuter use was an increase in the total number of bicycle lane miles per square mile.[4] Specifically, they found that for every 1-mile increase in bicycle lanes per square mile, there was a 1% rise in the total number of bicycle commuters.

Our data show that, from 2007 to 2014, the city of Boston increased its total bicycle lane mileage from 0.034 miles to more than 92 miles, resulting in a 140% increase in the overall proportion of bicycle commuters. However, this significant increase in bicycle commuters occurred among men only, indicating that bicycle infrastructure preferences may vary between men and women or that other factors not assessed in our study prevented an increase in female ridership. Therefore, more research will be necessary to better understand infrastructure changes and their influence on bike use among women.

Another component of Boston's bicycle infrastructure expansion was the addition of a bike share program in 2011 called Hubway, with impressive results. In just 10 weeks following its launch, the program logged more than 100 000 rides. Several studies have also shown increases in ridership after the introduction of similar city bike share programs.[2] However, these programs may lead to increased use among mainly inexperienced riders, which may result in overall increases in bicycle accidents and injuries. One recent study assessed this issue and evaluated numbers of total injuries before and after the introduction of a bike share program in a major city; the results of that study showed a significant reduction in the overall number of injuries after the program's introduction.[6] In another study, Graves et al. found that the percentage of head injuries among bicycle-related injuries as a whole increased from 42.3% to 50.1% after implementation of bike share programs, which the authors attributed to the programs' lack of helmet availability.[13]

We were able to perform a similar analysis in our cohort and found a significant reduction in the proportion of bicycle injuries when we compared data from 1 year prior to and 1 year after introduction of the bike share program. However, the degree to which the introduction of the program influenced Boston's increase in number of commuters and improvements in safety cannot clearly be defined given the city's multifactorial approach to bicycle infrastructure expansion.

A past belief has been that increases in numbers of cyclists will lead to proportionate increases in numbers of accidents. One study that evaluated this assumption in several population data sets (from California, Denmark, Europe, the United Kingdom, and the Netherlands) showed that there was "safety in numbers"; that is, there was an inverse relationship between an increasing number of cyclists and the likelihood of being struck by a motorist.[14]

Our results showed, as noted, that there was a 140% rise in the percentage of bicycle commuters between 2007 and 2014, from 1.0% (SD = 0.3) to 2.4% (SD = 0.4), along with an increase in the total number of accidents over time. However, no significant changes in the total number of accidents or injury-related accidents were observed when our data were standardized to the number of commuters over time (Table B). Furthermore, although the injury rate did not increase over time, there was a nonsignificant rise in the total number of injuries from 2009 to 2012. This greater number of injuries may have been associated with Boston's rise in estimated combined costs (medical and work loss) from emergency room visits attributable to bicycle accidents not resulting in hospitalization (from an estimated $2.09 million to $2.57 million), increasing the societal burden associated with the city's bicycle infrastructure expansion.

As changes in a city's bicycle infrastructure are implemented, it is important to understand modifiable factors associated with cyclist injuries. Our multivariable model showed that there was a 14% reduction in the odds of being injured in a bicycle accident over each succeeding year (from 2009 to 2012) during Boston's bicycle infrastructure expansion. Hence, we can surmise an association between bicycle infrastructure improvements during 2009 to 2012 and overall cycling safety improvements in Boston. This notion is supported by a study showing that bicycle lane expansion in a section of roadway in New York City did not result in a significant increase in overall number of accidents.[15]

Furthermore, our findings suggest that there was an estimated 37% significant reduction in the odds of being injured during a bicycle accident when the accident occurred on a main road as compared with a residential road. Given that a majority of bicycle infrastructure improvements were made on main roads, specifically with the addition of bicycle lanes, these improvements may have provided increased cyclist protection. This premise is backed by research showing that cyclists are at 3 to 4 times higher risk of being involved in an accident on roads without bicycle lanes than on roads with lanes, which are primarily seen on main roads.[16]

One interesting result in our study was the 118% increase in the odds of being injured in a bicycle accident among individuals who were wearing a helmet at the time of the accident. Although the reasons for this finding are unknown, helmet use is probably confounded by the riding behavior of helmet users, who may be more aggressive, faster riders. Furthermore, as noted, there may be selection bias in reporting of helmet use at the scene among those who are injured.

Limitations

Our study involves several limitations. First, our analysis was limited to available data collected for accidents in Boston during 2009 to 2012. Data on the number of accidents occurring prior to 2008, before improvements in Boston's bicycle infrastructure, may have helped us gain a better understanding of the effect of the expansion on total number of accidents during the study period.

Second, we used data from the US Census Bureau's American Community Survey, which limited our analysis to Boston commuters who were older than 16 years and who agreed to complete the survey. This may have resulted in an underestimation of the total number of bicyclists in Boston during the study period given that the data may have not captured all bicycle riders in Boston (e.g., cyclists not categorized in the survey as commuters). However, regardless of this limitation, our results still showed a significant reduction in the proportion of accidents resulting in injuries. Therefore, given the possible inherent underestimation of total numbers of cyclists, we can assume that the improvements in cyclist safety subsequent to Boston's bicycle infrastructure expansion may be of an even greater magnitude than that reported here.

Third, the demographic data available for commuters were restricted to stratification by gender, limiting any further analysis of other possible confounders (e.g., race/ethnicity, income, socioeconomic status). Fourth, we captured only the number of reported accidents during the study period; we were unable to assess the number of accidents overall. However, unreported accidents were likely unreported owing to their decreased severity, with riders able to mobilize themselves afterward.

Fifth, we used bicycle lane mileage alone as a surrogate for infrastructure expansion, although several other programs and interventions were also implemented during the study period. Finally, given the large number of changes made in Boston's bicycle infrastructure, teasing out the component parts that were most effective remains a difficult task and will require future studies. However, with the assistance of previous research, we can conclude that the increase in total bicycle lane mileage was a large contributor to improvements in ridership and safety in Boston.

Public Health Implications

We have shown that a broad expansion of a city's bicycle infrastructure, with a focus on increasing total bicycle lane mileage, can result in significant increases in overall ridership while simultaneously improving cyclist safety. Furthermore, we have described specific factors associated with increased risk of incurring an injury in a bicycle accident, providing areas for improvement. Our findings may have broad implications for bicycle infrastructure expansion with respect to several areas of public health, including public policy, environmental health, and personal health. Cities wishing to improve overall bicycle commuting, reduce automobile congestion and pollution, and improve the health of their citizens might consider policies similar to those of Boston for their bicycle infrastructure expansion plans. AJPH

CONTRIBUTORS

F. E. Pedroso originated and supervised the study, completed the analysis, and led the writing and revisions of the article. F. Angriman originated and supervised the study, completed the analysis, and assisted in the writing and revisions of the article. A. L. Bellows assisted with the analysis and contributed to the writing and revisions of the article. K. Taylor supervised the study, assisted with the analysis, and contributed to revisions of the article.

HUMAN PARTICIPANT PROTECTION

No protocol approval was needed for this study because secondary data were used and no human participants were involved.

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