Research Article

TRR
JOURNAL OF THE TRANSPORTATION RESEARCH BOARD

Transportation Research Record
1–13

DOI: 10.1177/03611981261430738
journals.sagepub.com/home/trr
Sage

Beyond Low-Stress Bicycle Lanes: Assessing the Role of Bicycle Network Density in Ridership

Nicholas N. Ferenchak[1] and Wesley E. Marshall[2]

Abstract

While the installation of lower-stress bicycle facilities has been linked with greater increases in bicycle commuting, the extent to which facilities' effectiveness is influenced by broader bicycle network characteristics remains unclear. To what degree does bicycle network density amplify the effect of bicycle facilities on bicycle commuting? Using multiple linear regression models and elasticity analyses, this study examined the interplay between bicycle facility installation and bicycle network density and their influence on bicycle commuting in 14,011 block groups across 28 U.S. cities. Findings suggest that bicycle network density exhibited stronger associations with ridership growth than the installation of individual facilities, with network effects exceeding facility installation effects by a factor of 4.6. More specifically, the installation of protected and buffered bicycle lanes was consistently and significantly associated with increased bicycle commuting, but the installation of standard bicycle lanes lost significance after the presence of a wider bicycle network was accounted for (the installation of shared-lane markings and off-road trails demonstrated non-significant relationships with bicycle commuter changes). Protected bicycle lane installations also produced meaningful ridership gains even in lower-density bicycle network contexts (elasticity of 0.48) with diminishing returns as bicycle network density increased (elasticity of 0.24). In contrast, higher-stress facilities demonstrated higher elasticities when moving from medium to high network density (elasticity of 0.57), indicating that their effectiveness is more dependent on a well-connected bicycle network. Taken together, these findings highlight the importance of prioritizing not only high-quality, low-stress bicycle facilities but also the development of continuous and connected low-stress networks.

Keywords

bicycle infrastructure, low-stress facilities, network connectivity, bicycle commuting, urban mobility

Introduction

The installation of lower-stress bicycle facilities has been linked with greater increases in bicycle commuting than higher-stress bicycle facilities (*1*). However, the extent to which the effectiveness of these facilities is influenced by their integration into a broader bicycle network remains unclear. Does the presence of a bicycle network amplify the impact of low-stress facilities on bicycle commuting, and if so, to what degree?

To explore these research questions, we examined 6 years of longitudinal data on bicycle facility installations across 14,011 block groups in 28 U.S. cities. To account for the impact of the bicycle networks, we chose to analyze network density as it has been shown to be the network characteristic with the strongest link to bicycle ridership and is highly correlated with other network connectivity metrics (*2*).

We began by analyzing ridership changes in all study block groups using multiple linear regression models that simultaneously accounted for both bicycle facility installation and bicycle network density. Our analysis differentiated between the installation of off-road trails, protected bicycle lanes (PBL), buffered bicycle lanes

[1]Gerald May Department of Civil, Construction, and Environmental Engineering, University of New Mexico, Albuquerque, NM
[2]Department of Civil Engineering, University of Colorado Denver, Denver, CO

Corresponding Author:
Nicholas N. Ferenchak, ferenchak@unm.edu

(BBL), standard bicycle lanes (SBL), and shared-lane markings (SHR). For block groups in which specific types of bicycle facility were installed, we then examined the elasticity of ridership changes in relation to variations in network density. It is important to note that this research focused specifically on bicycle commuting per the American Community Survey (ACS) and future work is needed to validate whether the findings align with overall bicycling activity.

Literature Review

First-Generation Bicycle Facilities and Ridership

Early research on the association between bicycle facilities and ridership was performed by Nelson and Allen in their cross-sectional study of 18 U.S. cities (*3*). They discovered a positive association between miles of bicycle pathways per 100,000 residents and the percentage of commuters using bicycles, with each additional mile of bicycle pathway per 100,000 people being associated with 0.069% higher bicycle commute mode share (adjusted R^2 of 0.825) after controlling for weather, terrain, and the number of college students.

While Nelson and Allen's work was formative, Dill and Carr noted two primary areas for improvement: 1) the quality of the National Bicycling and Walking Study commuting data used by Nelson and Allen varied significantly between cities; and 2) Nelson and Allen's four cities with the highest levels of bicycle commuting were all college towns (*4*). Dill and Carr therefore performed another cross-sectional study, this time on a more representative set of 43 large U.S. cities using more consistent commuting data from the U.S. census and data on bicycle facilities of both Class I (i.e., off-street bicycle ways physically separated from motorized vehicle traffic, such as bicycle paths or shared use paths) and Class II (i.e., on-street bicycle lanes, although protected facilities were neither explicitly mentioned nor differentiated). Dill and Carr's work largely affirmed the earlier research and showed the strongest relationship with Class II facilities, suggesting that Class I facilities are not as strongly associated with commuting, likely because they are often installed in parks and greenbelts and not necessarily connected to major employment locations (*4*).

In confirmation of the two studies above, Buehler and Pucher examined 90 of the 100 largest U.S. cities (*5*). Bicycle commuter data was obtained from the 2006–2008 ACS, and bicycle facility data, including bicycle lanes and bicycle paths, was provided by the League of American Bicyclists and the Alliance for Biking and Walking. The bicycle lane category excluded shared-lane markings and, again, protected facilities were not explicitly mentioned or differentiated. After controlling for bicycling safety, socioeconomic factors, land use, gasoline prices, public transport supply, and climate, Buehler and Pucher's cross-sectional results again confirmed that cities with a greater supply of bicycle facilities had significantly higher bicycle commute rates (*5*). Interestingly, Buehler and Pucher found similar positive and statistically significant associations for both bicycle lanes and bicycle paths, while Dill and Carr had found that only the Class II facilities had a meaningful association with bicycle commuting.

While the three studies cited above established a link between bicycle facilities and ridership, they were based on cross-sectional data and therefore did not provide evidence of causality (*6*). Longitudinal research is necessary to determine whether the installation of bicycle facilities leads to increased ridership, or if bicycle facilities are simply installed in areas that already exhibit high levels of ridership.

Second-Generation Bicycle Facilities and Ridership

Two new types of bicycle facility began to gain popularity at about the same time that much of the above research was being conducted. First, on-street protected bicycle lanes that provide a physical barrier between bicyclists and motor vehicle traffic started becoming popular in the early 2010s (*7*). Protected bicycle lanes may also be referred to as "separated bicycle lanes" or "cycle tracks," although we use the term "protected bicycle lanes" throughout this paper for consistency. Second, shared-lane markings were added to the FHWA's Manual on Uniform Traffic Control Devices in 2009. Before we delve into the literature exploring the association between protected bicycle lanes and shared-lane markings and ridership, we first explore how riders perceive those types of facilities.

McNeil et al. found that 71% of all residents and 88% of "interested but concerned" bicyclists—defined as people who are interested in bicycling or bicycling more, but are concerned about traffic safety—living near recently built protected bicycle lanes in five U.S. cities indicated that they would be more likely to ride a bicycle if motor vehicles and bicycles were physically separated by a barrier (*8*).

Clark et al. surveyed residents of 10 neighborhoods in the southeast U.S. (six rural/small urban neighborhoods and four urban Atlanta neighborhoods; $n = 2{,}157$) asking about comfort, perceived safety, and willingness to try different types of bicycle facility (*9*). Relative to a baseline of shared-lane markings, the researchers derived linear regression coefficients for perceived comfort of 0.53, 0.92, and 1.59 for standard bicycle lanes, buffered bicycle lanes, and protected bicycle lanes, respectively; coefficients for perceived safety of 0.58, 1.10, and 1.96, respectively; and coefficients for willingness to try of

0.36, 0.65, and 1.22, respectively (*9*). The positive coefficients indicated that all the bicycle lane types were preferred relative to shared-lane markings, with protected bicycle lanes being most strongly preferred for all the perception categories.

As suggested by the research above exploring perceptions, Monsere et al.'s examination of before/after count and video ridership observations of protected bicycle lanes installed in five cities (Austin, TX; Chicago, IL; Portland, OR; San Francisco, CA; and Washington, DC) identified ridership increases of between 21% and 171% after the installation of protected bicycling facilities (*10*). Furthermore, survey data from bicyclists on protected facilities showed that 10% of the riders had switched from other modes of transportation and 24% had shifted from other bicycle routes. A total of 49% of riders surveyed on the protected facilities indicated that they were riding more frequently on the protected routes than before the installation, while 24% indicated that they were riding more in general because of the protected bicycle lanes.

Karpinski examined a protected bicycle lane that was installed on Commonwealth Avenue in Boston, MA, and found that not only did the ridership of "BlueBikes" (a local bicycle sharing system) almost triple on the corridor in the year following installation, but ridership on routes near the new protected bicycle lane also saw dramatic increases in ridership (*11*). Bicycle-share ridership increases on routes affected by the protected bicycle lanes were estimated at 80% (*11*).

Garber et al. examined changes in distance cycled using Strava data (calibrated with data from 15 on-the-ground counters) for two protected bicycle lane installations in Atlanta's urban core (*12*). Findings suggested that there were no significant changes in ridership after the protected bicycle lane installations, although they did note that the study was performed exclusively in a highly car-dominated setting and that the individual bicycle facility elements studied may not have been supported by a wider bicycle network. Furthermore, the Strava data was likely overrepresented with recreational riding, whereas protected bicycle lanes might serve more utilitarian bicycling activity (*12*).

Exploring shared-lane markings and ridership, our prior work found that block groups in Chicago that had shared-lane markings installed (and no other type of bicycle facility installed) saw a statistically significant increase of 5.19 bicycle commuters after installation (*13*). However, since ridership changes were not studied for different types of bicycle lane, it is difficult to gauge whether that was a smaller or larger increase relative to bicycle lanes.

Another piece of our prior research represented the most comprehensive study of bicycle facilities and ridership to date by longitudinally exploring changes in bicycle commuting over 6 years relative to the installation of shared-lane markings, standard bicycle lanes, buffered bicycle lanes, and protected bicycle lanes in 28 U.S. cities (*1*). After controlling for built environment and socioeconomic factors, our prior findings suggested that protected bicycle lanes were linked with significantly larger increases in bicycle commuting on the block group level than standard bicycle lanes or shared-lane markings, producing 1.6 and 1.8 times greater increases in ridership, respectively.

While prior studies offer a solid foundation for understanding the relationship between bicycle facilities and ridership, they largely overlook the role of these facilities' placement within their broader bicycle networks. Furthermore, no past research has examined the installation of protected or buffered bicycle facilities and network connectivity simultaneously.

Bicycle Networks and Ridership

Schoner and Levinson examined the relationship between bicycle facilities and ridership while accounting for bicycle network connectivity for 74 mid- and large-sized U.S. cities (*2*). After operationalizing the bicycle network structure of each city (i.e., bicycle network size, connectivity, density, fragmentation, and directness), the researchers compared the network characteristics to bicyclist commuter numbers from the 2005–2009 ACS. The researchers included separated bicycle facilities (e.g., bicycle lanes, side paths, and paved trails) in their analysis but did not include mixed-traffic facilities (e.g., shared-lane markings, signed bicycle routes, and bicycle boulevards). Linear regression models revealed that, while bicycle network density had the strongest association with increased bicycle commuting (i.e., the presence of more bicycle facilities was associated with more bicycle commuting), bicycle network connectivity and directness also had statistically significant and positive associations with bicycle commuting (*2*). In other words, not only did the presence of bicycle facilities positively affect ridership, but the manner in which those facilities were tied together in a network also affected ridership.

Schoner and Levinson's work made an important contribution by demonstrating that characteristics of bicycle networks, particularly network density, are significantly associated with ridership. However, their analysis does not differentiate facilities by stress level (e.g., protected lanes versus shared-lane markings), nor does it account for the overall stress level of the surrounding bicycle network. As a result, the influence of low- versus high-stress bicycle facilities and networks on ridership outcomes remains unclear and understudied.

Methods

City Selection

Because a key goal of this research was to obtain meaningfully representative results, we sought to examine cities with varying bicycle cultures across wide ranges of geography and population. We would have liked to immediately explore the prevalence of bicycle facilities during our city selection process to ensure that we had large sample sizes for each bicycle facility type, but most cities did not have updated bicycle facility data readily available. Instead, we first obtained city-level 2019 ACS 5-year estimates on bicycle commute mode share, and selected cities with more than double the national average of bicycle commuting, designating those cities as possible high-bicycling cities.

Next, we sought to identify cities with lower levels of bicycle commute mode share (i.e., generally less than half than that of the high-bicycling cities) but with similar population distribution, geographic location, terrain, climate, and function (e.g., cities housing a major university or being just outside a major city). Wanting to select enough cities for a large enough sample size to ensure statistical significance but balancing that with the need to manually identify the installation month of each bicycle facility, our final city selection resulted in 28 cities (Table 1).

Data

To match the smallest ACS commute mode share geography, we conducted this study at the block group level and included all block groups that were in the study cities' place boundaries as provided by the U.S. Census Bureau.

We obtained bicycle commuting data from 5-year ACS estimates. Because of relatively high variability in bicycle commuter numbers, we averaged the number of bicycle commuters in 2013 and 2014 for our "before" period and averaged the number of bicycle commuters in 2018 and 2019 for our "after" period. These study periods allowed us to use consistent geographies, as the 2010 block group boundaries were unchanged throughout the decade beginning 2010 and allowed us to avoid any COVID-related travel behavior changes that began in 2020. The 2013/2014 "before" period was also convenient because it was approximately when the installation of protected bicycle lanes and shared-lane markings began increasing substantially (*14*). While we relied on

Table 1. Study Cities and Selection Criteria Data

City	Population (2019)	Block groups	Census region	Bicycle commute mode share (2013/2014) (%)	Bicycle commute mode share (2018/2019) (%)	Bicycle commute mode share change (%)
Alexandria, VA	159,428	137	South	1.1	1.4	0.3
Austin, TX	979,263	555	South	1.2	1.4	0.1
Baltimore, MD	593,490	711	South	0.6	0.7	0.0
Boulder, CO	105,670	77	West	7.6	8.9	1.3
Cambridge, MA	118,925	110	Northeast	5.4	7.4	1.9
Chicago, IL	2,693,959	2,294	Midwest	0.9	1.3	0.3
Columbia, SC	131,323	178	South	0.4	0.4	0.0
Dallas, TX	1,343,565	1,056	South	0.2	0.2	0.0
Denver, CO	727,211	572	West	1.7	1.9	0.2
East Orange, NJ	64,357	92	Northeast	0.1	0.0	0.0
Eau Claire, WI	68,936	56	Midwest	1.0	0.9	−0.1
Fullerton, CA	138,638	138	West	0.6	0.8	0.2
Houston, TX	2,316,797	1,705	South	0.3	0.4	0.0
Iowa City, IA	75,149	43	Midwest	3.1	3.6	0.5
Kansas City, MO	495,278	546	Midwest	0.3	0.2	−0.1
Memphis, TN	651,088	556	South	0.2	0.2	0.0
Minneapolis, MN	429,605	693	Midwest	2.3	2.6	0.3
Norman, OK	124,867	104	South	1.5	1.8	0.2
Oklahoma City, OK	655,158	617	South	0.3	0.2	−0.1
Pasadena, CA	141,040	156	West	1.1	1.4	0.3
Passaic, NJ	69,694	67	Northeast	0.5	0.5	0.0
Philadelphia, PA	1,584,064	1,392	Northeast	1.5	1.7	0.2
Portland, ME	66,218	64	Northeast	1.8	2.5	0.7
Portland, OR	653,467	459	West	5.3	5.8	0.5
San Francisco, CA	881,549	562	West	2.8	3.6	0.8
Seattle, WA	753,655	477	West	3.0	3.5	0.5
Washington, DC	705,749	482	South	2.5	3.6	1.1
Youngstown, OH	65,479	112	Midwest	0.0	0.1	0.1

bicycle commuting data because it was available consistently across all our study cities, future research that examines more comprehensive bicycle activity data in smaller geographic areas would be warranted.

For bicycle facilities, we obtained geographic information system (GIS) shapefiles of the bicycle network from the corresponding city or regional agencies when available. In cases where shapefiles were not available, we developed our own GIS shapefiles using official bicycle maps as a baseline. All bicycle facility data were then verified through cross-referencing city or regional shapefiles, bicycle maps, interviews with city employees, Google Maps, and satellite imagery to support the completeness and accuracy of the dataset.

We manually derived the installation month of each bicycle facility in our study cities using historic bicycle maps, interviews with city employees, historic satellite images from Google Earth, and historic Google Street Views. We differentiated between off-road trails, protected bicycle lanes, buffered bicycle lanes, standard bicycle lanes, and shared-lane markings. We utilized the intersect tool in a GIS to calculate the length of each facility type present in each block group for 2014 and 2019. Not only did this time period align well with our bicycle commuting before/after periods, but it allowed us to avoid some of the early "first-generation" protected bicycle lanes that were installed before 2014. We used a 50 ft buffer to account for facilities that were on the boundary of multiple block groups, therefore counting such boundary facilities in both block groups.

To account for socioeconomic status (SES) covariates, we used 2016 5-year estimates from the ACS, as this timeframe represented the midpoint of our study period and was, therefore, most reflective of conditions during the study period. For each block group, we collected data on the proportion of the population holding a bachelor's degree, the proportion of households living below the poverty line, and the proportion of residents identifying as non-Hispanic White, variables commonly employed as SES indicators in previous bicycle ridership research (*4*).

For built environment covariates, we utilized data from the U.S. EPA's Smart Location Database, which reflected conditions in 2017 and 2018. These variables, measured at the block group level, included population density, residential density, employment density, road network density, and intersection density, which were consistent with prior studies on the built environment and transportation behavior (*15*).

Analytical Approach

Multiple Linear Regression Methods. Multiple linear regression analysis was conducted at the block group level. The dependent variable was the change in the number of bicycle commuters between the periods 2013/2014 and 2018/2019. The first primary independent variable was the mileage of each bicycle facility type installed between 2014 and 2019. The second primary independent variable was bicycle network density, calculated by averaging the length of each facility type over the 2014–2019 period and dividing this value by the land area of each block group.

The overall bicycle network density variable, which incorporated all facility types, exhibited moderate-to-strong correlations with the network densities of each individual bicycle facility type (Table 2) (*16*). To assess whether networks of different bicycle facility types were differently associated with changes in ridership, we estimated separate models for each facility type's network independently. Notably, bicycle network density was only weakly correlated with facility installation during the study period. In other words, some block groups with low bicycle network density had new bicycle facilities installed between 2014 and 2019, while others with high network density did not. Since multicollinearity was not detected, both bicycle network density and facility installation were included in the final statistical models.

To select SES and built environment covariates for our statistical analysis, we derived Pearson's correlations to identify any multicollinearity and help, if needed, narrow down our variables of interest. There was moderate-to-strong correlation between all the SES variables (Table 2). We therefore included the proportion of residents with a bachelor's degree in the statistical model, as this variable demonstrated the strongest correlation with the dependent variable. We also included educational attainment, as this variable has been shown to be strongly associated with overall bicycling ridership, making it a theoretically justified control variable, even though our present study focused specifically on bicycle trips to work (*17*). Population density and employment density were found to be strongly correlated, as were road density and intersection density. To address potential multicollinearity, employment density and intersection density were excluded from the analysis, as their correlations with the dependent variable were weaker than those of their collinear counterparts. Additionally, the total number of commuters within each block group was included in the statistical model because areas with more commuters have a greater potential to exhibit larger absolute changes in the number of bicycle commuters.

Because the dependent variable was normally distributed, we employed a multiple linear regression model for the analysis. Independent variables identified as sources of multicollinearity, as described above, were excluded to ensure the validity of the model estimates. All

Table 2. Pearson's Correlation Coefficients between Variables (Moderate [0.40–0.59], Strong [0.60–0.79], and Very Strong [0.80–0.99] Correlations)

work	Population density	Employment density	Road density	Intersection density	Bicycle network density (all)	Bicycle network density (ORT, PBL, BBL)	Bicycle network density (SBL)	Bicycle network density (SHR)	ORT (2014–2019)	PBL (2014–2019)	BBL (2014–2019)	SBL (2014–2019)	SHR (2014–2019)	White non-Hispanic	Bachelors	Poverty
Population density	1.00															
Employment density	**0.68**	1.00														
Road density	0.31	0.07	1.00													
Intersection density	0.23	0.08	**0.75**	1.00												
Bicycle network density (all)	0.28	0.08	0.36	0.30	1.00											
Bicycle network density (ORT, PBL, BBL)	0.12	0.07	0.21	0.16	**0.50**	1.00										
Bicycle network density (SBL)	0.21	0.05	0.26	0.21	**0.78**	0.09	1.00									
Bicycle network density (SHR)	0.18	0.04	0.19	0.18	**0.51**	0.04	0.06	1.00								
ORT (2014–2019)	−0.01	0.01	0.01	0.01	0.02	0.04	0.00	0.01	1.00							
PBL (2014–2019)	0.00	0.04	0.06	0.06	0.10	0.15	0.04	0.02	0.06	1.00						
BBL (2014–2019)	0.01	0.01	0.08	0.05	0.16	0.23	0.09	0.01	0.03	0.02	1.00					
SBL (2014–2019)	0.00	0.01	−0.01	−0.01	0.00	−0.09	0.06	−0.01	0.01	0.03	**−0.41**	1.00				
SHR (2014–2019)	0.02	0.02	0.07	0.07	0.16	0.05	0.03	0.25	0.04	0.09	0.02	−0.01	1.00			
White non-Hispanic	−0.05	0.03	−0.06	0.03	0.08	0.08	0.01	0.09	0.01	0.04	−0.02	0.03	0.09	1.00		
Bachelors	0.07	0.05	0.08	0.13	0.19	0.13	0.08	0.18	0.02	0.04	0.01	0.03	0.09	**0.68**	1.00	
Poverty	0.11	0.04	0.13	0.07	0.05	0.02	0.09	−0.05	−0.01	0.03	0.04	−0.02	−0.02	**−0.53**	**−0.50**	1.00
Change in bicycle commuters	0.10	0.02	0.09	0.08	0.16	0.07	0.13	0.08	0.02	0.04	0.04	0.01	0.03	0.09	0.13	−0.03

Note: bold type = moderate (0.40–0.59), strong (0.60–0.79), or very strong (0.80–0.99) correlation; BBL = buffered bicycle lane; ORT = off-road trail; PBL = protected bicycle lane; SBL = standard bicycle lane; SHR = shared-lane markings.

Table 3. City-Level Descriptive Statistics

City	Population density (1,000 people/mi^2)	Road density (mi/mi^2)	% Bachelor's degree	Protected bicycle lanes in 2014 (mi)	Protected bicycle lanes in 2019 (mi)	Protected bicycle lanes change (mi)
Alexandria, VA	10.7	25.9	30.0	0.0	0.0	0.0
Austin, TX	3.1	18.3	30.8	3.6	11.1	7.6
Baltimore, MD	7.3	28.6	14.7	0.9	8.3	7.5
Boulder, CO	4.0	19.4	33.4	0.7	0.7	0.0
Cambridge, MA	18.6	34.6	29.7	2.3	3.1	0.8
Chicago, IL	11.8	29.9	19.7	15.0	19.4	4.4
Columbia, SC	1.0	16.4	22.0	0.0	0.0	0.0
Dallas, TX	4.0	22.8	20.0	1.7	2.6	0.9
Denver, CO	4.8	25.2	26.6	0.8	5.1	4.2
East Orange, NJ	16.4	26.3	13.3	0.0	0.0	0.0
Eau Claire, WI	2.1	18.0	20.7	0.0	0.0	0.0
Fullerton, CA	6.2	24.1	24.3	0.0	0.0	0.0
Houston, TX	3.6	23.2	18.6	0.0	1.3	1.3
Iowa City, IA	2.9	15.5	26.8	0.0	0.0	0.0
Kansas City, MO	1.6	19.0	18.8	0.0	0.0	0.0
Memphis, TN	2.2	17.2	13.6	0.3	6.9	6.6
Minneapolis, MN	8.0	25.5	26.3	0.9	10.0	9.2
Norman, OK	0.7	15.4	22.6	0.0	0.0	0.0
Oklahoma City, OK	1.1	18.0	17.8	0.0	0.0	0.0
Pasadena, CA	6.1	22.2	27.2	0.0	0.4	0.4
Passaic, NJ	22.3	26.7	13.6	0.0	0.0	0.0
Philadelphia, PA	11.8	31.9	14.8	0.0	2.2	2.2
Portland, ME	3.1	20.5	29.1	0.0	0.0	0.0
Portland, OR	4.9	26.8	28.8	2.5	14.5	12.0
San Francisco, CA	18.8	32.0	32.8	6.8	7.7	0.9
Seattle, WA	9.0	28.8	34.6	2.1	16.6	14.5
Washington, DC	11.5	26.6	22.0	4.5	5.9	1.4
Youngstown, OH	1.9	16.7	8.8	0.0	0.0	0.0

independent variables were standardized using z-scores to allow for direct comparison of effect sizes.

Network Density Elasticity Methods. After examining whether bicycle facility installations and bicycle network density were significantly associated with changes in ridership, we next sought to assess the elasticity of these relationships. Drawing on both previous research and our own findings indicating that potential riders are more likely to use lower-stress bicycle facilities, we classified each block group according to the lowest-stress facility type installed between 2014 and 2019. In other words, if a block group had both shared-lane markings and protected bicycle lanes installed during the study period, the block group was classified as a protected bicycle lane block group. This classification was applied regardless of the presence or type of bicycle facility existing on the roadway before the study period.

Each set of block groups was subsequently divided into quartiles based on overall bicycle network density, with thresholds selected to maintain approximately balanced sample sizes across groups. The highest quartile included block groups with a bicycle network density ranging from 2.0 to 14.5 mi/mi^2, followed by quartiles with densities of 0.8–2.0 and 0–0.8 mi/mi^2. The lowest quartile consisted of block groups with no bicycle facilities. For each set of block groups (based on bicycle facility type installed), we then calculated and compared changes in ridership across the different network density quartiles. We compared these ridership changes using 90% confidence intervals and then derived elasticity coefficients by dividing the percentage change in the dependent variable (i.e., ridership change) by the percentage change in the independent variable (i.e., bicycle network density).

Results

The study cities varied widely in key SES and built environment characteristics. Population density ranged from 700 to 22,300 residents/mi^2, roadway density ranged from 15.5 to 34.6 mi/mi^2, and educational attainment ranged from 8.8% to 34.6% of the population with a bachelor's degree (Table 3). Concerning bicycle facilities, Seattle, WA, installed the greatest length of protected bicycle lanes during the study period (14.5 mi), whereas Chicago, IL, had the highest total mileage of protected bicycle lanes by the end of the study period with 19.4 mi.

Table 4. Descriptive Statistics for Bicycle Facility Block Group Types

Category	Block groups (*n*)	Change in bicycle commuter count (2013/14→2018/19)	Population density (1,000 people/mi^2)	Road density (mi/mi^2)	% Bachelor's degree
PBL	317	10.9	10.7	31.7	29.2
BBL	534	5.8	10.9	30.7	20.8
SBL	725	6.1	11.5	28.3	23.1
SHR	631	6.9	11.2	29.7	28.7
None	11,804	2.5	7.1	24.6	20.6

Note: BBL = buffered bicycle lane; PBL = protected bicycle lane; SBL = standard bicycle lane; SHR = shared-lane markings.

Using the categorization described in the Network Density Elasticity Methods Section, we obtained relatively large block group sample sizes for all bicycle facility types (Table 4). Block groups in which bicycle facilities were installed during the study period experienced greater increases in the number of bicycle commuters, although these results do not yet control for covariates in Table 3. Additionally, block groups that had bicycle facilities installed tended to be located in higher-density areas than those without any bicycle infrastructure installation.

Multiple Linear Regression Results

Across all study block groups, the installation of protected and buffered bicycle lanes was strongly and significantly associated with increases in bicycle commuting in all statistical models (Table 5). In contrast, the installation of standard bicycle lanes was positively associated with changes in ridership only in models that did not fully account for the broader bicycle network; this association became non-significant once network-level effects were included. Shared-lane markings exhibited weak and statistically non-significant associations in all models. Similarly, the installation of off-road trails was not significantly associated with increases in commuter bicycling, which may reflect their stronger alignment with recreational rather than utilitarian travel patterns (*4*). Protected bicycle lanes were associated with increases in bicycle commuting that were 1.8 times greater than those associated with standard bicycle lanes and 3.1 times greater than those linked to off-road trails. In contrast, shared-lane markings were associated with a decrease in ridership and are, therefore, not directly comparable.

All types of bicycle network density were significantly associated with growth in ridership, with the comprehensive network, which included all facility types and is featured in Model 1, showing the strongest relationship (Table 5). The effect size of comprehensive bicycle network density was 4.6 times greater than that of the most effective facility type installation, protected bicycle lanes. These findings suggest that, while individual facility improvements support ridership growth, their effectiveness is substantially enhanced when integrated into a cohesive network.

Following the comprehensive bicycle network metric that incorporated all facility types, the network composed exclusively of standard bicycle lanes exhibited the next strongest association with increases in bicycle commuting. In contrast, the separated facility network, which included off-road trails, protected bicycle lanes, and buffered bicycle lanes, demonstrated a comparatively weaker association. This may be attributable to the limited extent and connectivity of the separated facility network. For example, in Philadelphia, PA (Figure 1), standard bicycle lanes form a relatively cohesive and continuous network, whereas protected and buffered facilities remain fragmented and discontinuous. Therefore, these findings should not be interpreted as a rejection of the effectiveness of separated facility networks, but rather as a reflection of data limitations, particularly the sparse and fragmented nature of such facilities within the study area.

All built environment and socioeconomic variables (i.e., population density, road network density, total number of commuters, and educational attainment) were significantly and positively associated with increases in bicycle commuting (Table 5). Although the strength of these associations exceeded that of individual facility installations, they remained weaker than the effect observed for comprehensive bicycle network density.

Network Density Elasticity Results

Consistent with the findings presented in the Multiple Linear Regression Results Section, block groups in which protected bicycle lanes were installed experienced the largest increases in bicycle commuting over the study period (see the "PBL" column in Table 6). Across all block group categories, denser bicycle networks were associated with greater increases in bicycle commuting. Although statistical significance was somewhat limited because of reduced sample sizes resulting from

Table 5. Multiple Linear Regression Models for Changes in Bicycle Commuters

	Model 1 $p < 0.001$			Model 2 $p < 0.001$			Model 3 $p < 0.001$			Model 4 $p < 0.001$			Model 5 $p < 0.001$			Model 5 $p < 0.001$		
Variable	Est.	SE	*p*-value	Est.	S.E	*p*-value	Est.	SE	*p*-value	Est.	SE	*p*-value	Est.	SE	*p*-value	Est.	SE	*p*-value
Bicycle facilities installed 2014–2019																		
ORT	0.15	0.16	0.345	0.15	0.16	0.362	0.17	0.16	0.294	0.16	0.16	0.327	0.15	0.16	0.354	0.17	0.16	0.286
PBL	**0.46**	**0.16**	**0.005**	**0.54**	**0.16**	**<0.001**	**0.55**	**0.16**	**<0.001**	**0.61**	**0.16**	**<0.001**	**0.55**	**0.16**	**<0.001**	**0.56**	**0.16**	**<0.001**
BBL	**0.45**	**0.18**	**0.013**	**0.71**	**0.18**	**<0.001**	**0.58**	**0.18**	**0.001**	**0.81**	**0.18**	**<0.001**	**0.72**	**0.18**	**<0.001**	**0.59**	**0.18**	**<0.001**
SBL	0.26	0.18	0.143	**0.40**	**0.18**	**0.024**	0.20	0.18	0.249	**0.41**	**0.18**	**0.021**	**0.42**	**0.18**	**0.020**	0.22	0.18	0.221
SHR	−0.08	0.16	0.638	0.16	0.16	0.343	0.14	0.16	0.379	−0.03	0.17	0.869	−0.04	0.17	0.835	−0.05	0.17	0.769
Bicycle network density																		
All	**2.12**	**0.18**	**<0.001**	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na
ORT, PBL, BBL	na	na	na	**0.41**	**0.17**	**0.018**	na	na	na	na	na	na	**0.43**	**0.17**	**0.012**	na	na	na
SBL	na	na	na	na	na	na	**1.82**	**0.17**	**<0.001**	na	na	na	na	na	na	**1.83**	**0.17**	**<0.001**
SHR	na	na	na	na	na	na	na	na	na	**0.84**	**0.17**	**<0.001**	**0.85**	**0.17**	**<0.001**	**0.86**	**0.17**	**<0.001**
Other built environment																		
Population density	**0.95**	**0.17**	**<0.001**	**1.33**	**0.17**	**<0.001**	**1.08**	**0.17**	**<0.001**	**1.25**	**0.17**	**<0.001**	**1.22**	**0.17**	**<0.001**	**0.97**	**0.17**	**<0.001**
Road density	**0.68**	**0.18**	**<0.001**	**1.17**	**0.18**	**<0.001**	**0.88**	**0.18**	**<0.001**	**1.13**	**0.18**	**<0.001**	**1.06**	**0.18**	**<0.001**	**0.77**	**0.18**	**<0.001**
Socioeconomics																		
Commuters (#)	**1.63**	**0.17**	**<0.001**	**1.56**	**0.17**	**<0.001**	**1.61**	**0.17**	**<0.001**	**1.57**	**0.17**	**<0.001**	**1.57**	**0.17**	**<0.001**	**1.63**	**0.17**	**<0.001**
Bachelor's degree (%)	**1.58**	**0.17**	**<0.001**	**1.86**	**0.17**	**<0.001**	**1.80**	**0.17**	**<0.001**	**1.77**	**0.17**	**<0.001**	**1.73**	**0.17**	**<0.001**	**1.67**	**0.17**	**<0.001**

Note: BBL = buffered bicycle lane; Est. = estimate; na = not applicable; ORT = off-road trail; PBL = protected bicycle lane; SBL = standard bicycle lane; SE = standard error; SHR = shared-lane markings; na = not applicable.

Estimates in bold are statistically significant at the 95% confidence level.

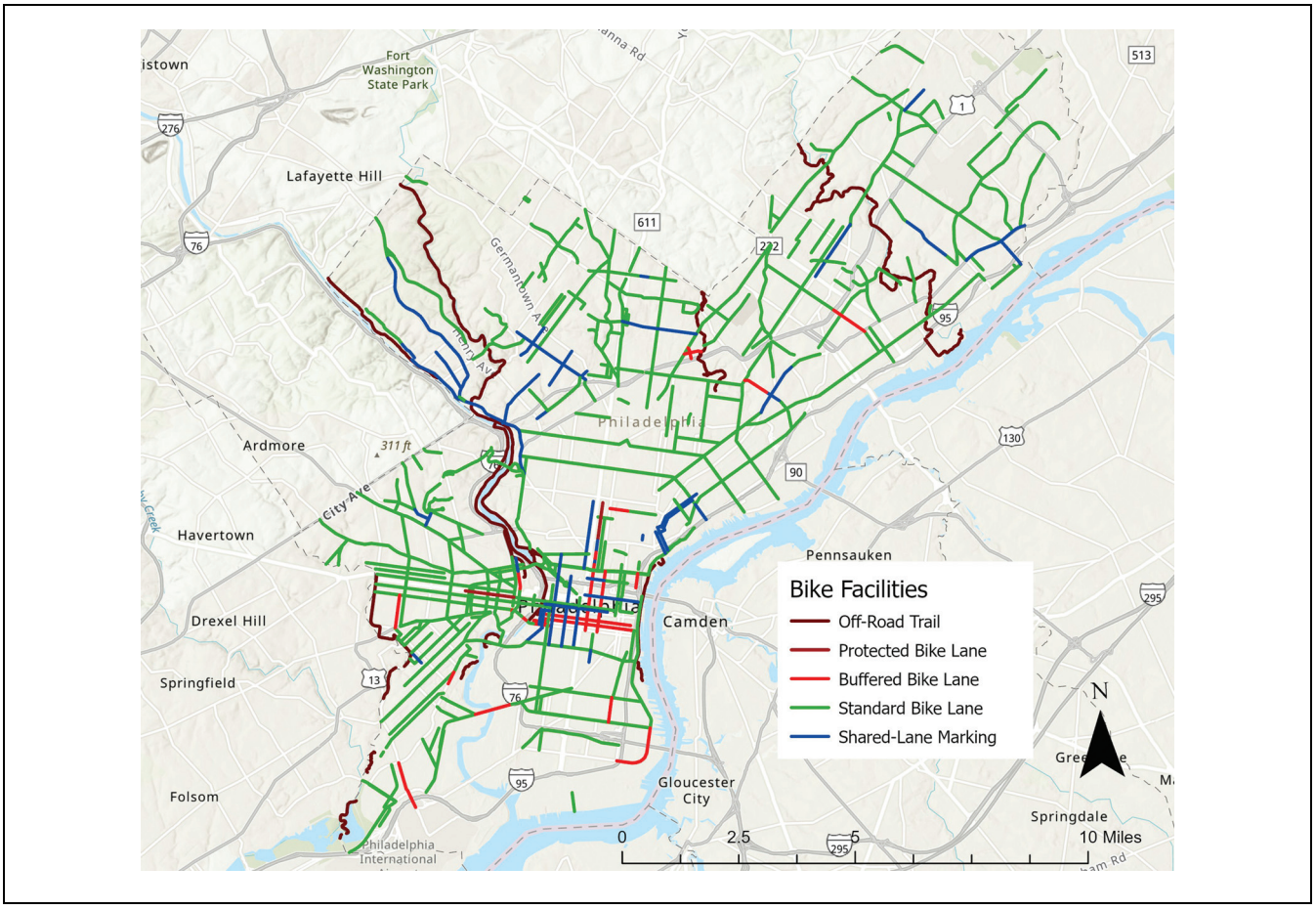

Figure 1. Bicycle network in Philadelphia, PA.

Table 6. Block Group Changes in Bicycle Commuters by Network Density Quartiles (90% Confidence Interval in Parentheses)

Bicycle network density (d) (all facility types)	Block group category for bicycle facilities installed				
	PBL	BBL	SBL	SHR	None
High ($2.0 < d \leq 14.5$)	14.1 (9.1–19.1) $n = 161$	9.6 (7.0–12.2) $n = 238$	10.5 (7.5–13.5) $n = 261$	9.6 (6.4–12.7) $n = 265$	8.4 (7.1–9.7) $n = 1,457$
Medium ($0.8 < d \leq 2.0$)	9.8 (5.1–14.5) $n = 88$	4.8 (2.7–7.0) $n = 177$	4.8 (2.1–7.6) $n = 197$	5.3 (2.7–8.0) $n = 204$	4.2 (3.3–5.0) $n = 1,716$
Low ($0 < d \leq 0.8$)	5.0 (0.8–9.1) $n = 68$	-0.5 (-2.9–1.9) $n = 119$	2.8 (0.7–4.9) $n = 267$	4.7 (2.0–7.5) $n = 162$	2.3 (1.7–3.0) $n = 1,768$
No network ($d = 0$)	na	na	na	na	0.9 (0.7–1.2) $n = 6,863$

Note: BBL = buffered bicycle lane; na = not applicable; ORT = off-road trail; PBL = protected bicycle lane; SBL = standard bicycle lane; SHR = shared-lane markings.

stratification into network density quartiles, ridership increases were statistically larger in high-density block groups than in their low-density counterparts for all bicycle facility types except shared-lane markings.

In protected bicycle lane block groups, the elasticity of ridership with respect to network density was 0.48 when moving from low to medium density and 0.24 from medium to high density, indicating a substantial installation effect even in areas with relatively sparse network coverage. In contrast, block groups that had other bicycle facility types installed exhibited elasticities that were approximately twice as high when moving from medium to high bicycle network density, suggesting that higher levels of network density were more critical to driving ridership gains in those contexts.

Conclusions

Our results suggest that both the type and connectivity of bicycle infrastructure play critical roles in influencing bicycle commuting patterns at the block group level. Across all models, the installation of protected and buffered bicycle lanes was significantly and consistently associated with increases in bicycle commuting, with protected bicycle lanes yielding the strongest standalone facility effects. In contrast, standard bicycle lanes were only associated with ridership gains in models that did not account for broader network context, and shared-lane markings showed no significant association, with some evidence of negative impacts. These findings align with existing literature emphasizing the importance of low-stress bicycling infrastructure for encouraging mode shift.

The presence of a bicycle network emerged as a much stronger predictor of bicyclist commuter increases than any individual facility type's installation. The comprehensive bicycle network, which encompassed all facility types, demonstrated an effect size 4.6 times greater than that of protected bicycle lane installation alone. This underscores the critical role of network cohesion in enabling meaningful increases in bicycle commuting. While protected and buffered bicycle facilities have strong standalone effects, their full potential appears to be realized when integrated into a broader bicycle network.

The analysis also revealed that standard bicycle lane networks, despite being a higher-stress facility type, were more strongly associated with ridership gains than the separated facility network (composed of off-road trails, protected lanes, and buffered lanes). This result likely reflects differences in network connectivity and spatial coverage, particularly in the study area where standard bicycle lanes formed a more cohesive system than their separated counterparts. As demonstrated by the example of Philadelphia, the fragmented nature of protected and buffered facilities may have limited their network's impact, suggesting that network completeness and continuity are essential considerations regardless of facility type.

Built environment and socioeconomic characteristics such as population density, road network density, and educational attainment were also significantly associated with increased bicycle commuting. While these contextual factors had stronger associations than most individual facility installations, their influence remained secondary to the presence of a comprehensive bicycle network.

Elasticity analysis further supported these findings. Protected bicycle lane block groups exhibited meaningful increases in ridership even in lower-density bicycle network contexts, with diminishing returns as bicycle network density increased. In contrast, other facility types demonstrated higher elasticities when moving from medium to high network density, indicating that their effectiveness is more dependent on a well-connected network. These findings suggest that cities in early stages of developing their bicycle networks—particularly those relying on higher-stress infrastructure—may not experience the same ridership increases as cities with more extensive, lower-stress networks.

Future research could build on the present study by further examining how the stress levels of overall bicycle networks are associated with ridership. Because of data limitations, the current work was unable to differentiate the effects of low-stress and high-stress bicycle networks, primarily because of the sparse and fragmented nature of protected and buffered bicycle facilities. Additionally, future work could incorporate sensitivity analyses using GIS to assess the spatial extent of network influence on ridership. For instance, such analyses could examine whether the association between bicycle infrastructure and ridership remains consistent when applying buffer distances of 0.5, 1, and 5 mi. Furthermore, variations in network density and spacing could be evaluated, such as comparing the effects of 0.5 versus 1 mi grid configurations.

While network density is commonly used as a proxy for network connectivity, and was shown by Schoner and Levinson to be highly correlated with connectivity as well as being the network characteristic most strongly associated with bicycle commuting, it is technically possible for a network to exhibit high density and low connectivity (*2*). Future research could investigate additional network characteristics (i.e., fragmentation, directness, or more direct measures of connectivity such as link-to-node ratios) to provide a more comprehensive understanding of the association between networks and ridership.

Our findings reflect bicycle commuting from the ACS which may capture only a portion of total bicycling activity. A national survey by NHTSA and the Bureau of Transportation Statistics found that only about 6% of U.S. bicycle trips were work-related, and research from Toronto indicates that recreational bicycling is more

common in suburban areas while utilitarian bicycling dominates in urban cores (*18*, *19*). Our results may therefore more accurately reflect urban bicycle activity patterns. However, other research has shown bicycle-to-work commuting to be a strong proxy for overall bicycling levels (Spearman's $\rho = 0.53$), particularly in large and medium metropolitan areas ($\rho = 0.58$ and 0.57, respectively) (*20*). Future research that captures both recreational and utilitarian bicycling exposure may be most feasible at the city or regional scale, though consistent longitudinal data will likely remain challenging to obtain.

Taken together, these findings highlight the importance of prioritizing not only high-quality, low-stress bicycle facilities but also the development of continuous and connected low-stress networks. Investments in isolated infrastructure may yield limited results if not part of a broader strategy to build cohesive networks that support safe, convenient, and direct bicycle travel. Future planning and policy efforts should therefore emphasize both facility quality and spatial integration to maximize the impact of bicycle infrastructure on commuting behavior.

Author Contributions

The authors confirm contribution to the paper as follows: study conception and design: N.N. Ferenchak; data collection: N.N. Ferenchak; analysis and interpretation of results: N.N. Ferenchak, W.E. Marshall; draft manuscript preparation: N.N. Ferenchak, W.E. Marshall. All authors reviewed the results and approved the final version of the manuscript.

Declaration of Conflicting Interests

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

ORCID iDs

Nicholas N. Ferenchak https://orcid.org/0000-0002-3766-9205
Wesley E. Marshall https://orcid.org/0000-0002-3106-7342

References

1. Ferenchak, N. N., and W. E. Marshall. The Link between Low-Stress Bicycle Facilities and Bicycle Commuting. *Nature Cities*, Vol. 2, no. 6, 2025, pp. 555–559.
2. Schoner, J. E., and D. M. Levinson. The Missing Link: Bicycle Infrastructure Networks and Ridership in 74 US Cities. *Transportation*, Vol. 41, 2014, pp. 1187–1204.
3. Nelson, A. C., and D. Allen. If You Build Them, Commuters Will Use Them: Association between Bicycle Facilities and Bicycle Commuting. *Transportation Research Record*, Vol. 1578, No. 1, 1997, pp. 79–83.
4. Dill, J., and T. Carr. Bicycle Commuting and Facilities in Major US Cities: If You Build Them, Commuters Will Use Them. *Transportation Research Record*, Vol. 1828, No. 1, 2003, pp. 116–123.
5. Buehler, R., and J. Pucher. Cycling to Work in 90 Large American Cities: New Evidence on the Role of Bike Paths and Lanes. *Transportation*, Vol. 39, 2012, pp. 409–432.
6. Krizek, K. J., G. Barnes, and K. Thompson. Analyzing the Effect of Bicycle Facilities on Commute Mode Share over Time. *Journal of Urban Planning and Development*, Vol. 135, No. 2, 2009, pp. 66–73.
7. Schmitt, A. *The Rise of the North American Protected Bike Lane*. Momentum Mag, Toronto, ON, Canada, 2013.
8. McNeil, N., C. M. Monsere, and J. Dill. Influence of Bike Lane Buffer Types on Perceived Comfort and Safety of Bicyclists and Potential Bicyclists. *Transportation Research Record*, Vol. 2520, No. 1, 2015, pp. 132–142.
9. Clark, C., P. L. Mokhtarian, G. Circella, and K. Watkins. The Role of Attitudes in Perceptions of Bicycle Facilities: A Latent-Class Regression Approach. *Transportation Research Part F: Traffic Psychology and Behaviour*, Vol. 77, 2021, pp. 129–148.
10. Monsere, C., J. Dill, N. McNeil, K. J. Clifton, N. Foster, T. Goddard, M. Berkow, et al. *Lessons from the Green Lanes: Evaluating Protected Bike Lanes in the US*. National Institute for Transportation and Communities, Portland, OR, 2014.
11. Karpinski, E. Estimating the Effect of Protected Bike Lanes on Bike-Share Ridership in Boston: A Case Study on Commonwealth Avenue. *Case Studies on Transport Policy*, Vol. 9, No. 3, 2021, pp. 1313–1323.
12. Garber, M. D., W. D. Flanders, K. E. Watkins, F. Lobelo, M. R. Kramer, and L. E. McCullough. Have Paved Trails and Protected Bike Lanes Led to More Bicycling in Atlanta? A Generalized Synthetic-Control Analysis. *Epidemiology*, Vol. 33, No. 4, 2022, pp. 493–504.
13. Ferenchak, N. N., and W. E. Marshall. Advancing Healthy Cities Through Safer Cycling: An Examination of Shared Lane Markings. *International Journal of Transportation Science and Technology*, Vol. 8, No. 2, 2019, pp. 136–145.
14. PeopleForBikes. *Inventory of Protected Bike Lanes*. PeopleForBikes, Boulder, CO, 2018.
15. Marshall, W. E., and N. W. Garrick. Effect of Street Network Design on Walking and Biking. *Transportation Research Record*, Vol. 2198, No. 1, 2010, pp. 103–115.
16. Campbell, M. J. *Statistics at Square One*. John Wiley & Sons, Hoboken, NJ, 2021.

17. Hudde, A. Educational Differences in Cycling: Evidence from German Cities. *Sociology*, Vol. 56, No. 5, 2022, pp. 909–929.
18. Royal, D., and D. Miller-Steiger. *National Survey of Bicyclist and Pedestrian Attitudes and Behavior: Volume I: Summary Report*, DOT HS 810 971, U.S. Department of Transportation, Washington, D.C., 2011.
19. Ledsham, T., Y. Zhang, S. Farber, and P. Hess. Beyond Downtown: Factors Influencing Utilitarian and Recreational Cycling in a Low-Income Suburb. *International Journal of Sustainable Transportation*, Vol. 17, No. 7, 2023, pp. 740–761.
20. Soto, G. W., B. J. Webber, K. Fletcher, T. J. Chen, M. D. Garber, A. Smith, G. Wilt, M. Conn, and G. P. Whitfield. Association between Passively Collected Walking and Bicycling Data and Purposefully Collected Active Commuting Survey Data—United States, 2019. *Health & Place*, Vol. 81, 2023, p. 103002.