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Bicycling facility inequalities and the causality dilemma with socioeconomic/sociodemographic change

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A R T I C L E I N F O

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A B S T R A C T

How well has the recent expansion of bicycling networks advanced transportation justice through appropriate distribution across the socioeconomic/demographic (SED) spectrum? Furthermore, does the installation of bicycling facilities lead to SED changes in a neighborhood or vice versa? We longitudinally assess 11,010 miles of bicycling facilities over ten years (2010–2019) in 11,293 block groups across 29 U.S. cities by facility type. Findings suggest inequalities in bicycling facility installation with People of Color (POC) experiencing the lowest rates of overall facility installation. However, bike lane installation was concentrated in lower-income areas (both POC and White). The causality relationships between bicycling facilities and SED changes were weak and largely non-significant. Income increases were followed by bicycling facility installations more so than increases in White populations were followed by bicycling facility installations. SED changes were more correlated with later bicycling facility installation than the inverse, suggesting that bicycling facilities were not linked to displacement.

1. Introduction

Participation in modern society requires access to a transportation system. However, the historical placement of transportation infrastructure has not been equitably distributed across space or demographic groups (Karner et al., 2018). In their 1957 manual about arterial highways in urban areas, for example, the American Association of State Highway Officials stated:

“Most cities have blighted areas slated for redevelopment. Where they are near general desire lines of travel, arterial routes might be located through them in coordination with slum clearance and redevelopment programs” (AASHO, 1957).

Mobility justice is dependent upon three dimensions: “equitable access to participation in the planning process; equitable exposure to localized environmental burdens; and equitable distribution of the benefits of transportation investments and systems” (Karner et al., 2018). Infrastructure such as the urban highways referenced by AASHO impeded mobility justice by marginalizing many lower-income and minority populations from the planning process, leading to displacement of many of those populations as neighborhoods were cleared to make way for highway construction. People that remained were exposed to environmental burdens as the arterial highways became the high-injury networks of most cities. Such practices and decisions tend to disadvantage local populations, many of whom choose not to drive, or cannot afford to, and therefore get little direct benefit from the highways (Golub et al., 2013). Such infrastructure also served – and continues to serve – as barriers to active transportation, sources of air/noise pollution, and

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impediments to health and safety (Ferenchak and Marshall, 2020). In a recent study looking at 24 years of nationwide data, lower-income neighborhoods experienced road fatality rates more than 3.6 times higher than wealthier neighborhoods (Marshall and Ferenchak, 2017). The research also suggests that Black and Hispanic populations tend to be at higher risk on the road – particularly as pedestrians and bicyclists – than White populations (Mayrose and Jehle, 2002, Braver, 2003, Campos-Outcalt et al., 2003, McAndrews et al., 2013, Marshall and Ferenchak, 2017).

Title VI of the 1964 Civil Rights Act legislated nondiscrimination in all federally-assisted programs, including transportation. In 1994, then President Clinton signed Executive Order 12898, titled "Federal Actions to Address Environmental Justice in Minority Populations and Low-Income Populations" (Chakraborty, 2006, Deakin, 2007). This mandate added some specifics, requiring federal transportation agencies to identify and address any new, federally-funded transportation infrastructure that would disproportionately impact minority and/or low-income populations in terms of human health or environmental effects. This eventually led to changes in federal transportation funding with TEA-21 (Transportation Equity Act for the 21st Century) in 1998. Although problems continue to persist, and it is debatable whether the mandates advance equity or are merely perfunctory, equity considerations are at least a part of the standard process with our federal transportation infrastructure decisions (Chakraborty, 2006).

Cities – rather than the federal government – now seem to be leading the charge on the urban transportation revolution. Reductions in building urban arterial highways have coincided with exponential growth of bicycling facilities over the last decade. For the sake of this paper, we consider all types of bicycling facilities including protected bike lanes, buffered bike lanes, standard bike lanes, sharrows (i.e. shared-lane markings), and off-street trails. However, we recognize that sharrows do not represent bicycling infrastructure and their effectiveness remains under debate (Ferenchak and Marshall, 2019; Harris et al., 2013). Illustrating the recent increase in bicycling facilities, according to a PeopleForBikes database, there were only 78 total protected bike lanes nationwide as of 2011; now, there are more than 550 such facilities spread across at least 125 U.S. cities (PeopleForBikes, 2018). This number does not include all the new standard or buffered bike lanes and off-street trails that continue to emerge. However, cities do not necessarily have to follow the equity mandates for the installation of bicycling facilities if federal funding is not being used. As a result, there is less information regarding how these bicycling facilities are being distributed across different populations.

Accordingly, the first question this paper considers is: how well has the expansion of bicycling facilities been distributed across the socioeconomic and demographic (SED) spectrum? At present, there are about a dozen papers that have asked similar questions (see the Literature Review section), but almost all of these papers are cross-sectional or focused on a relatively small sample size. Many of these papers also aggregated the broad range of different types and levels of bicycling facilities into a single measure, which makes it hard to distinguish between, for example, where protected bike lanes are being built versus sharrows. To answer this first research question, and resolve some of the limitations of the existing research, we systematically track and measure various types of bicycling facilities for

Table 1
Literature Review Summary (* = statistically significant at 95% confidence).

Author(s)	Year	Location	Unit of Analysis	Facility Type	Relevant Variable(s)	Direction of Relationship	Inequitable
Cradock et al.	2009	USA	County	Bike Facility	Poverty	− *	Y
					Education	+ *	Y
Dill and Haggerty	2009	Portland, OR	Block group	Bikeway	Income	− *	N
					Non-White	+	N
Deka and Connelly	2011	New Jersey	Block group	Bike Facility	Income	− *	N
					Non-White	+ *	N
Pistoll & Goodman	2014	Melbourne, Australia	Neighborhood	Bike Lane	Income	−	N
				Trail	Income	+ *	Y
Teunissen et al.	2015	Bogotá, Colombia	Block	Bike lane	Income	+	Y
Flanagan et al.	2016	Chicago, IL	Census tract	Bike-related Infrastructure	White	+ *	Y
		Portland, OR			Income	− *	N
Fuller & Winters	2017	8 Canadian cities	Census tract	Bike facility	Income	+ *	Y
Wang & Lindsey	2017	Minnesota, MN	Block group	Bike facility	Poverty	−	Y
					Black	−	Y
Houde et al.	2018	Montreal metropolitan area	Census tract	Bike facility	Income	− *	N
Parra et al.	2018	Bogotá, Colombia	Block	Bike lane	Income	+	Y
Tucker & Manaugh	2018	Rio de Janeiro & Curitiba, Brazil	Neighborhood	Bike lane	Income	+	Y
Winters et al.	2018	Victoria, Canada	Dissemination Areas	Bike facilities	Income	− *	N
		Kelowna, Canada			Income	− *	N
		Halifax, Canada			Income	−	N
Braun et al.	2019	22 populous U.S. cities	Block group	Bike lane	Income	+ *	Y
					Minority	− *	Y

11,293 block groups across 29 U.S. cities from 2010 through 2019 and longitudinally consider where these facilities were built with respect to the SED composition of the associated neighborhoods. This facilitates the ability to look at how different types of bicycling facilities have been distributed across the SED spectrum.

This initial analysis provides useful information regarding how well facilities are being distributed, but things are not quite so simple. The truth is that many people are skeptical of new bicycling facilities, especially since they have seen road safety issues go unaddressed for decades. People then tend to ask questions like: Will the installation of bicycling facilities lead to socioeconomic and/or sociodemographic changes in my neighborhood? This is a very difficult question to answer, as there are myriad factors associated with what most people define as gentrification in terms of neighborhoods becoming more affluent and/or an increase in the relative percentage of White residents. Accordingly, while we do not attempt to explore gentrification itself, the second part of this paper explores the causality dilemma question. In other words, does investment in bicycling facilities lead to changing SED conditions more or less so than changing SED conditions lead to investment in bicycling facilities? While we identify the strength and direction of these relationships, it is important to note that we do not claim to solve this dilemma nor definitively state that one factor causes the other.

2. Literature review

The earliest study to consider disparities in bike facilities that we found dates back to only 2009 with Dill and Haggerty's examination of Portland, OR (Dill and Haggerty, 2009) (Table 1). Dill and Haggerty analyzed the SED characteristics of Portland neighborhoods where bike facilities were located at that time. The results suggested that the density of bike facilities was actually higher for low-income populations, but this seemed to be a function of these neighborhoods also being located near downtown where such bicycling facilities were more common. The differences on race were non-significant. Another early study by Deka and Connelly focused on understanding obesity and physical activity in New Jersey but found that block groups with lower-income and minority populations tended to live closer to existing bicycling facilities (Deka and Connelly, 2011). At the time of the data collection in 2005, however, they only identified 48 bicycling facilities (including bike lanes, bike routes, and shared use paths) in the entire state of New Jersey. They also considered 46 planned bicycling facility projects but unfortunately had to study those at the municipal level of geography where the results were non-significant. At an even larger level of geography, the county level, Cradock et al. looked at more than a decade of bicycling facility projects from across the U.S. and found that wealthier counties were more likely to be the ones implementing them (Cradock et al., 2009). Cradock et al. did not consider race/ethnicity in their paper.

The next set of studies also focused on income but in non-U.S. cities. These studies include Pistoll and Goodman (2014) in Melbourne, Australia; Teunissen et al. (2015) in Bogotá, Colombia; Fuller and Winters (2017) in eight Canadian cities; Tucker and Manaugh (2018) in Rio de Janeiro and Curitiba, Brazil; and Parra et al. (2018) in Bogotá, Colombia. All the studies found socioeconomic disparities in access, with most of the research suggesting that higher-income areas had more access to bicycle facilities. Conversely, Winters et al. (2018) looked at three Canadian cities and did not find evidence of significant socioeconomic inequities (Winters et al., 2018).

In one of the more comprehensive cross-sectional studies, Braun et al. (2019) analyzed 22 of the 25 most populous U.S. cities at the block group level and found that lower-income block groups, as well as those with higher proportions of minority residents, had significantly lower access to on-street bike lanes (Braun et al., 2019). One point that Braun and her co-authors make is that the longitudinal work on this topic is limited and an important area for future research.

Flanagan et al. (2016) appears to be the first longitudinal study on this topic, looking at two cities (Chicago, IL, and Portland, OR) at the Census tract level between 1990 and 2010 (Flanagan et al., 2016). Focusing more on gentrification, they found inequities that were only getting worse over time, tending to benefit White populations in gentrified neighborhoods. They also found that "marginalized communities are unlikely to attract as much cycling infrastructure investment without the presence of privileged populations, even when considering density and distance to downtown" (Flanagan et al., 2016). However, this study combined all bicycle-related infrastructure – including bike parking and bike share stations – into a single z-score measure and did not distinguish among the various types of bicycling infrastructure.

Wang and Lindsey (2017) collected bicycling facility data for 378 block groups in Minnesota at three points in time (2008, 2010, and 2014) and also found inequities (such as lower access by block groups with a higher percentage of households below the poverty line or a higher percentage of Black residents) but further found that the situation was improving over time (Wang and Lindsey, 2017). Similar to most of the existing research, their bicycling facility measures did not distinguish the different types of on-street bicycling facilities, summing them into a single bikeway length measure. Houde et al. (2018) longitudinally analyzed bicycling facilities for the Montreal metropolitan area at five-year intervals over a twenty-five year period (1991–2016) (Houde et al., 2018). The authors found that the overall bicycling network increased by 162% over the study period, but interestingly, bicycling network connectivity did not significantly increase. In terms of results, they found that "low-income individuals have generally enjoyed good accessibility over the entire period" but less so for recent immigrants and children. This paper also distinguished between separated bike facilities and regular on-street bike lanes.

At this point in time, there is less research on whether bicycling facilities precede SED changes or vice versa. Flanagan et al.'s paper, discussed above, found that factors associated with gentrification, in part, drive investment in bicycling facilities in both Chicago and Portland (Flanagan et al., 2016). Hoffmann and Lugo (2014) and Stehlin (2015) discuss the use of bike facilities to attract 'talent' or the 'creative class', although they do not quantitatively assess their success in doing so (Hoffmann and Lugo, 2014, Stehlin, 2015). Stein points out that bike facilities in New York City tended to be located in what he considered to be the city's most gentrified neighborhoods because these same neighborhoods also had two of the city's largest employment centers (Stein, 2011). Stein argues that these neighborhoods were already logical places for bicycling facilities because they tended to have a higher concentration of creative-class workers that are also “able-bodied people with liberal attitudes toward the environment” (Stein, 2011). While Stein does not rely on data to make his case, he argues that this combination leads to high bicycling rates and can mistakenly give the impression that gentrification follows bike facilities. At the same time, Stein says that the NYC DOT has not done enough to build bicycling facilities for working-class and immigrant riders.

Our paper looks to better understand these issues using longitudinal data for 29 U.S. cities and in such a way that distinguishes among the different types of bicycling facilities. Because different facility types have been shown to be associated with varying safety outcomes (both perceived and real), such an approach is important for both measuring the distribution of various bicycling facilities across the SED spectrum as well as for connecting the right facilities with the right neighborhood need (Harris et al., 2013; Tilahun et al., 2007). In addition, our paper combines income and race/ethnicity variables to illuminate new trends and is some of the first quantitative work to explore the causality dilemma.

3. Data & methods

3.1. City selection

To answer the research questions, we sought a broad spectrum of cities that varied in terms of bicycling facilities, socioeconomics/sociodemographics, population, and geographic diversity. Since we did not want to solely focus on cities with robust bike networks, we first sought to match bike-friendly cities with cities less friendly to bicycling. As an initial proxy for bicycling facilities, we acquired city-level American Community Survey (ACS) data and longitudinally assessed bicycling commute mode share for all U.S. cities. We sought to identify fifteen bike-friendly cities that were in the top 10% of all U.S. cities in terms of bicycle commute mode share (1.7% mode share and above) and fifteen paired comparison cities that had bicycle commute mode shares below that level. Given that bicycling facilities have been associated in the literature with lower road fatality rates (Marshall and Ferenchak, 2019), we supplemented the mode share data with bicyclist fatality data from the Fatality Analysis Reporting System (FARS) to aid in our bike-friendly and paired comparison selections.

We then gathered population, race/ethnicity, and income data for every U.S. city from the U.S. Census to ensure that both our bike-friendly cities and paired comparisons were spread across the SED spectrums. We tailored our bike-friendly/paired comparison selections to have both large cities (defined as 400,000 residents and more) and medium cities (defined as 50,000–200,000 residents). We had eight large bike-friendly cities, seven large paired comparison cities, seven medium bike-friendly cities, and seven medium paired comparison cities. For race/ethnicity, we looked at the proportion of the population that identified as White non-Hispanic and sought cities that were both majority People of Color (POC) and majority White non-Hispanic. We had seven bike-friendly cities majority POC, nine paired comparison cities majority POC, eight bike-friendly cities majority White non-Hispanic, and five paired comparison cities majority White non-Hispanic. For income, we sought cities that had median household incomes that were both above

Table 2
Selected Cities (with 2019 ACS characteristics).

	Population	White non-Hispanic (%)	Med. Household income ($)	Bike commute mode share (%)	Non-downtown block groups
Chicago, IL	2,718,555	32.8	55,198	1.7	2088
Houston, TX	2,295,982	24.6	51,140	0.4	1195
Philadelphia, PA	1,575,522	34.6	43,744	2.1	1319
Dallas, TX	1,318,806	29.0	50,100	0.2	841
Austin, TX	935,755	48.3	67,462	1.3	431
San Francisco, CA	870,044	40.6	104,552	4.0	568
Seattle, WA	708,823	64.5	85,562	3.6	462
Denver, CO	693,417	53.7	63,793	2.3	473
Washington, DC	684,498	36.2	82,604	4.5	414
Memphis, TN	653,248	25.7	39,108	0.2	464
Portland, OR	639,387	70.5	65,740	6.3	391
Oklahoma City, OK	637,284	53.9	54,034	0.1	448
Baltimore, MD	614,700	27.5	48,840	0.9	617
Kansas City, MO	481,417	55.1	52,405	0.2	382
Minneapolis, MN	416,021	59.8	58,993	4.1	331
Alexandria, VA	156,505	51.8	96,733	1.2	100
Pasadena, CA	141,246	35.4	78,941	1.9	99
Fullerton, CA	139,866	32.3	73,360	0.7	87
Columbia, SC	133,352	48.8	45,663	0.6	32
New Haven, CT	130,529	30.5	41,142	2.9	88
Norman, OK	121,090	71.7	56,229	1.6	81
Cambridge, MA	115,665	60.8	95,404	7.3	72
Boulder, CO	107,360	79.8	66,117	10.3	40
Iowa City, IA	74,566	75.0	47,275	3.4	27
Passaic, NJ	70,131	16.2	36,226	0.5	42
Eau Claire, WI	68,086	88.9	50,940	0.9	28
Portland, ME	66,735	82.0	56,977	2.5	46
Youngstown, OH	64,734	42.2	26,951	0.1	71
East Orange, NJ	64,400	2.1	44,809	0.1	56

and below $55,000 – approximately the median household income for all U.S. urban households (Bishaw and Posey, 2016). We had ten bike-friendly cities above the median U.S. household income, four paired comparison cities above median, five bike-friendly cities below median, and ten paired comparison cities below median.

To illustrate this selection process, while Minneapolis, MN, and Kansas City, MO, have relatively similar populations, POC proportions, household incomes, and geographic locations, Minneapolis has a bike commute mode share that is nearly twenty times higher than Kansas City and more than three times the amount of bike facility lane miles. Chicago, IL, has approximately the same median household income but a significantly larger population and POC proportion. Alexandria, VA, has approximately the same population and POC proportion but significantly higher median household income. In this way, we included cities spread across SED spectrums to obtain an analysis that was more illustrative of the U.S. as a whole.

Based on our assessment of the above characteristics, we originally selected thirty study cities. After preliminary analysis, we concentrated our study on non-downtown areas because they were more representative of the relationship between bicycling facilities and SED characteristics. While much biking occurs in downtown areas and many bike facilities are concentrated there, some study cities almost ubiquitously concentrate bike facilities in downtown areas regardless of income and race/ethnicity, so we instead focused on areas outside of downtowns. We defined downtown block groups (or some cities used terms such as central business district or center city) using either a city's GIS layer or an official city map translated into GIS. We considered any block group that was at all contained in the downtown boundary as belonging to downtown. Downtown block groups made up only 3.3% of all block groups in the study cities and had high variability in income and race/ethnicity. We removed New York City from our original list of study cities because much of it could be considered "downtown" relative to peer U.S. cities. The remaining twenty-nine cities are shown in Table 2.

3.2. Data acquisition

Although most of our cities had bike facility GIS layers available, only Portland, OR, included the year each facility was built as an attribute. Collecting longitudinal bike facility data proved to be a relatively difficult and time-consuming manual process. We needed to categorize and time stamp (to the closest year) each bike facility in each city by type. This required a combination of emails/phone calls with city planners, an in-depth review of old bike maps, as well as reviewing historic satellite imagery in Google Earth. The goal was to be as accurate as possible with facility type and year. Given the data limitations, this was generally a manual effort completed by a single coder. When we compared our ability to discern bike facilities via Google Earth imagery against old bike maps, our results matched up well. During the Google Earth work, however, we noticed that some protected/separated cycle tracks, for instance, were converted from standard bike lanes or sharrows, especially in the later years of the study. This led us to manually conduct the same review for Portland, OR, as well.

After categorizing and time stamping each bike facility based on Federal Highway Administration (FHWA) definitions (Table 3), we calculated the cumulative length of each facility type for each year in each block group (FHWA, 2015). Bike facilities that were present on both sides of the road were counted twice, while bike facilities on one side were counted once. We used block group geographies from the 2010 decennial census to perform these counts. A 30-foot buffer allowed facilities that formed the boundary of two block groups to be counted for both, thereby avoiding edge issues. While a buffer sensitivity analysis showed that much of the effect of buffer size occurred in buffers of less than ten feet, we chose a 30-foot buffer because some cities' bike facility GIS layers had low spatial accuracy and utilizing such a buffer to account for those cities did not skew overall results (Fig. 1). We derived bike facility counts for each year of the study. We then calculated the length of bike facilities installed between 2010 and 2019 for each block group.

3.3. Longitudinal analysis

For our first longitudinal analysis, we normalized the bike facility metric by dividing the length of bike facilities by the total length of roadway for each block group. The outcome variable is therefore the proportion of centerline miles that had a bike facility installed. Roadway data was provided by the United States Geological Survey (USGS) National Transportation Dataset (NTD) in GIS polyline format. The California and Texas datasets provided by USGS were last updated in April 2019 and the dataset containing all the other

Table 3
FHWA Bike Facility Definitions.

FHWA Bike Facility Name (Name used in this paper)	FHWA Definition
Shared Lane Markings (Sharrows)	A shared roadway with pavement markings providing wayfinding guidance to bicyclists and alerting drivers that bicyclists are likely to be operating in mixed traffic.
On-Street Bike Lanes (Standard Bike Lanes)	An on-road bicycle facility designated by striping, signing, and pavement markings.
On-Street Buffered Bike Lanes (Buffered Bike Lanes)	Bike lanes with a painted buffer increase lateral separation between bicyclists and motor vehicles.
Separated Bike Lanes (Protected Bike Lanes)	A separated bike lane is an exclusive facility for bicyclists that is located within or directly adjacent to the roadway and that is physically separated from motor vehicle traffic with a vertical element.
Off Street Trails/Sidepaths (Trails)	Bicycle facilities physically separated from traffic, but intended for shared use by a variety of groups, including pedestrians, bicyclists, and joggers.

Source: FHWA, 2015

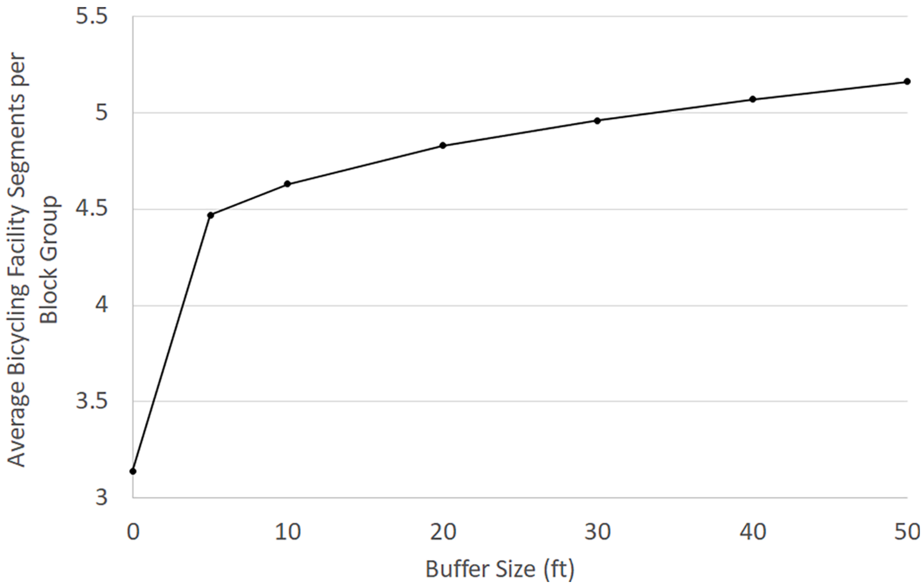

Fig. 1. Buffer Sensitivity Analysis.

cities was last updated in May 2020. We chose to normalize for roadway length as opposed to population because while block groups are intended to be somewhat consistent in population, population density can vary greatly. High-density block groups would be smaller, have fewer roads, and therefore less chance of having bike facilities. In that way, road length is a proxy for population density that allows us to keep a consistent and more intuitive unit of analysis (miles of bike facilities per miles of roadways). Quantifying this concept, the mean population in our study block groups was 1343 people with a standard deviation of 733 people (relatively low variation). The mean road length was 6.68 miles with a standard deviation of 6.03 miles (relatively high variation). For this reason, we normalized for total road length instead of population. We intend to look more closely at population in future research.

We obtained ACS five-year estimates of SED data on the block group level for each year between 2010 and 2019 from the National Historical Geographic Information System (NHGIS) (Manson et al., 2017). The income variable for each year was the median household income over the past twelve months. The race/ethnicity variable was the proportion of the total population that identified as non-Hispanic White.

To first understand how bike facilities are distributed in the study cities, we calculated the average median household income and the average proportion of non-Hispanic White residents over the entire study period for each block group. Individually for each city, we divided the block groups into four income and race/ethnicity categories. Block groups below the 50th percentile of income were considered 'lower-income' while those above the 50th percentile were considered 'higher-income'. This approach is similar to those utilized by other studies that defined low-income populations as any population below the 50th percentile of household income (Boarnet et al., 2017, Guzman et al., 2017, Beiler and Mohammed, 2016). Block groups below the 50th percentile proportion of non-Hispanic White residents were considered 'non-White or Hispanic' (referred to as 'People of Color' (POC) for the rest of the study)

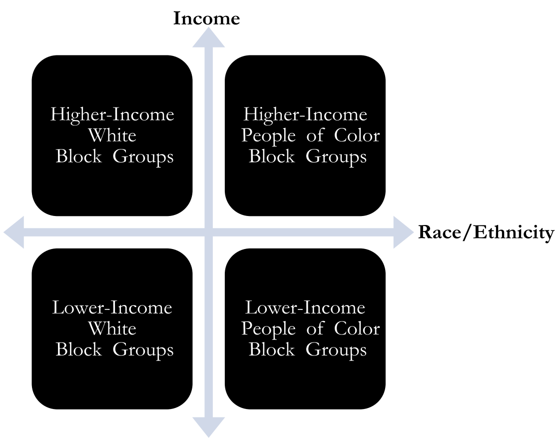

Fig. 2. Income and Race/Ethnicity Rubric.

while those above the 50th percentile were considered 'non-Hispanic White' (referred to as 'White' for the rest of the study). Because we completed this categorization for each individual city, the divisions better represented whether a city's bicycling facility installations were made in lower- vs. higher-income and POC vs. White neighborhoods in that particular city. For example, although a block group with a median household income of $75,000 may be considered higher-income in Youngstown and lower-income in San Francisco, our analysis could differentiate this distinction. We completed a dichotomous split because there were no unique trends illuminated after splitting the data into quartiles in a preliminary analysis and the quartile presentation became overly confusing.

Each block group was designated as either 'lower-income White', 'lower-income POC', 'higher-income White', or 'higher-income POC,' as shown in Fig. 2. There were important differences illuminated by combining the two socioeconomic/sociodemographic variables.

For each of the four income and race/ethnicity categories, we calculated the mean proportion of centerline miles that had bike facilities installed between 2010 and 2019. We tested the statistical significance of the differences between these means with Kruskal-Wallis tests. The Kruskal-Wallis test is a one-way ANOVA test used to determine whether two or more independent samples are derived from the same distribution of a continuous dependent variable. The test adjusts for multiple comparisons, a primary reason to apply Kruskal-Wallis as opposed to a standard *t*-test.

3.4. Causality dilemma

3.4.1. Multi-level random effects logistic regression models

For the causality dilemma (i.e. chicken or egg) analysis, we compared two multi-level random effects logistic regression models for each type of bike facility:

(1) Facilities installed between 2010 and 2014 vs. changes in income and race/ethnicity from 2014 to 2019;
(2) Changes in income and race/ethnicity from 2010 to 2015 vs. facilities installed between 2015 and 2019;

By comparing results from these regression models, we could see whether bike facility installation led to higher incomes/more White residents or whether higher incomes/more White residents led to more bike lane installation (or both, or neither). Such models have been proven effective at exploring whether bike facility installation is statistically correlated with outcomes in earlier or later periods (Rebentisch et al., 2019).

The sample was all non-downtown block groups from the study cities. To better account for bike facility access, we used a half-mile buffer for the causality analysis. The models' dichotomous dependent variables represented whether or not each block group (with a half-mile buffer) had a particular facility installed between the beginning of the period and the end. In general, block groups were evenly split between having and not having facilities installed. For instance, 46.6% of block groups had a facility installed between 2015 and 2019, showing that logistic regression was an appropriate test given the data distribution.

The models' continuous independent variables were changes in income and race/ethnicity between the beginning of the period and the end, again originally in the form of median household income and proportion of population that identified as non-Hispanic White, respectively. Because this ACS data came in five-year estimates and we needed to ensure that there was no overlap in our models, we chose offset time frames for these SED variables. Specifically, the SED before period was 2010 to 2015 (with a 2015 five-year estimate of 2011–2015) and the SED after period was 2014 to 2019 (with a 2019 five-year estimate of 2015–2019). There was therefore no overlap of ACS estimates within the individual models.

We also controlled for the distance from each block group to its city's downtown area as past research has found this to be a significant variable in terms of mode choice, vehicle miles traveled, and bike facility availability (Dill and Haggerty, 2009, Flanagan et al., 2016, Marshall and Garrick, 2010, Marshall and Garrick, 2012). Block groups closer to downtown areas are more likely to have bike facilities regardless of other factors; hence it is an important variable to control for in our models. We entered this variable as an independent variable into each regression model.

For the multi-level aspect of the models, we included a variable connoting each block group's city. Doing so accounted for random spatial effects on the city level.

Because of the Great Recession, household incomes were generally lower between 2010 and 2014 and then had stronger increases between 2015 and 2019, precluding a homogenous comparison between the periods. Thus, we standardized each variable by deriving z-scores, subtracting the mean of the sample from each observed value and dividing the difference by the standard deviation of the sample.

We performed the same z-score standardization for the race/ethnicity variable and the distance to downtown variable. This allowed us to compare changes during the first period to changes during the second period as well as to compare changes between variables. The z-scores for the causality dilemma were not city-specific. This was because we were interested in answering the general question: do bike facility installations correlate with increases in income or White populations (or vice versa)? For instance, in cities where there was little increase in income, a small income increase might correlate with a large city-specific z-score. A city-specific z-score therefore would not help us answer the generalized question we sought to answer.

We used the *glmer* command in the *lme4* package of R with a binomial family for the multi-level random effects logistic regression models.

3.4.2. Difference-in-difference analyses

We confirmed our multi-level random effects logistic regression results with difference-in-difference (DID) analyses. A DID analysis compares changes in outcomes over time between a sample that experienced a treatment and a sample that did not using linear regression models. For the DID analyses, we only explored the category that combined all bike facilities, not individual facility types. We ran four DID analyses:

1. Facility installation was the treatment and changes in income was the outcome
2. Facility installation was the treatment and changes in race/ethnicity was the outcome
3. Changes in income was the treatment and facility installation was the outcome
4. Changes in race/ethnicity was the treatment and facility installation was the outcome

We translated each treatment variable to a dummy variable. When facilities was the treatment, block groups (with a half-mile buffer) that had a facility installed between 2010 and 2014 were designated as 1 and those that did not have a facility installed were designated as 0. Again, this split was approximately 50/50. When income was the treatment, block groups with an income increase between 2010 and 2015 were designated as 1 (58.5% of block groups) and those that had an income decrease were designated as 0. When race/ethnicity was the treatment, block groups with an increase in the White proportion between 2010 and 2015 were designated as 1 (48.5% of block groups) and those with a decrease were designated as 0. The White proportion was designated as 1 so that the direction of inequitable relationships was consistent across analyses.

We also created a dummy variable for time where before was designated as 0 and after was designated as 1. We derived a DID interaction variable by multiplying the treatment and time dummy variables.

Outcome variables were continuous. When facility installation was the outcome variable, we used the miles of all bike facilities installed as our metric. When income was the outcome variable, we used median household income as our metric. When race/ethnicity was the outcome variable, we used White proportion as our metric. For each outcome variable, we took the average for each period so we had one before data point and one after data point for each block group in each model.

We used the *lm* command in R with the two dummy variables, the DID interaction variable, and the outcome variable. By examining the statistical significance of the DID interaction variable, we could determine whether the treatment had a significant impact on the outcome variable in the test sample relative to the control sample.

4. Results

Over the course of ten years, the prevalence of bicycling facilities nearly doubled in our study cities. Table 4 highlights the changes, breaking out the bike facilities by type. We combined results into an "All Bike Facilities" category that included all facility types and an "All Bike Lanes" category that included protected, buffered, and standard bike lanes. Sharrows had the largest absolute increase in mileage. Protected bike lanes and buffered bike lanes were relatively rare in 2010 and saw the largest percentage increases. Standard bike lanes had large absolute increases but were relatively common in 2010, leading to small percentage increases. Trails had smallest absolute and percentage increases.

The right-most section of Table 4 displays block group-level descriptive statistics for the miles of facilities installed. The block group with the most bike facilities installed saw 15.0 total miles established (or 7.5 miles of roadway centerline if there was a facility on both sides of the street). Negative numbers for certain bike facility types can primarily be explained by block groups that had sharrows, standard bike lanes, or buffered bike lanes replaced by more protected facilities such as buffered or protected bike lanes or, in some instances, by facilities that were simply removed and not replaced.

Table 5 overviews the block group statistics with respect to the 2 × 2 income and race/ethnicity rubric described in Fig. 2. There were 11,293 block groups analyzed in the 29 cities. While there is variation in category sample sizes (there are more POC block groups that are lower-income and more White block groups that are higher-income), we would expect such differences based on prevailing SED distributions.

Table 4
Average Miles of Bike Facilities per City and Overall Block Group Descriptive Statistics.

	Avg. Miles of Facilities Per City				Block Group Changes			
	2010	2019	Change	% Change	Min	Max	Avg	SD
All Bike Facilities	127.0	234.4	107.4	84.6	-0.1	15.0	0.28	0.63
All Bike Lanes	79.9	140.6	60.7	75.9	-0.1	11.1	0.16	0.46
Protected Bike Lanes	0.1	6.6	6.5	7841.7	0.0	6.1	0.02	0.15
Buffered Bike Lanes	1.0	19.6	18.6	1945.0	-1.0	4.8	0.05	0.22
Standard Bike Lanes	78.9	114.4	35.5	45.0	-2.5	7.5	0.09	0.40
Sharrows	8.1	45.2	37.1	460.1	-0.7	5.9	0.10	0.31
Trails	39.0	48.7	9.7	24.9	0.0	11.4	0.02	0.23

Table 5
Block Group Counts and Average Characteristics of Categories.

	POC			White		
	n	% White	Income ($)	n	% White	Income ($)
Lower-Income	4379	15.3	33,510	1268	48.5	38,715
Higher-Income	1270	22.0	60,947	4376	67.1	84,094

4.1. Longitudinal analysis

Lower-income White block groups saw the highest percentage increase in bike facility installation between 2010 and 2019 (Fig. 3). To clarify the units in the figure below, 2.6% of roadway miles in lower-income White block groups had sharrows installed over the study period. Lower-income White block groups had the highest percentage of protected bike lanes, standard bike lanes, and sharrows installed. The POC block groups saw the least facilities installed, indicating that the inequality in overall facility distribution is primarily a race/ethnicity issue. As detailed elsewhere in the paper, more work is needed to understand how well this supply matches demand, but there are clear equality issues where a focus on lower-income White communities may be leaving other communities behind, especially those of color.

However, while POC block groups had fewer overall bike facilities installed, much of that difference was driven by high rates of sharrow installation in White block groups. POC block groups had the most buffered bike lanes installed and had more overall bike lanes than higher-income White block groups, although only slightly so.

Kruskal-Wallis results support the main findings from above (Table 6). The p-values express the statistical significance of the Kruskal-Wallis test, which compares the means of the four income and race/ethnicity categories for each facility type. Lower-income White block groups had “All Bike Facilities” and “All Bike Lanes” installation rates that were higher than every other SED category, and all these relationships were strong and statistically significant at 95% confidence. Both POC categories had “All Bike Facilities” installation rates that were lower than both White categories, and all these relationships were statistically significant.

For protected bike lanes, lower-income areas saw more installation than higher-income areas, regardless of race. For buffered bike lanes, there were no significant differences between SED categories. For standard bike lanes, the only significant relationships were lower-income White having more standard bike lanes than all other SED categories. For sharrows, White block groups saw more installation than POC. For trails, the only significant difference was higher-income White having more trails than lower-income POC.

In conclusion, while overall facilities appear to have inequalities in terms of race/ethnicity, these differences are driven by high rates of sharrow installation. Protected bike lanes – while having much lower rates of installation – actually favor lower-income areas, largely regardless of race. Bike lanes overall also appear to favor lower-income areas, although they are found primarily in lower-income White areas.

There were important differences between individual cities that can be further explored in future research. For instance, specifically examining all bike lanes, Oklahoma City and Boulder both had all their bike lanes installed in lower-income POC areas over the study period (Fig. 4). However, note that the meaningfulness of some of these proportion results is tempered by low absolute numbers (only 0.04% of roadway miles in Oklahoma City had bike lanes installed and Columbia, East Orange, Iowa City, and Youngstown did not see any new bike lanes between 2010 and 2019). On the other hand, Dallas’ bike lane installation rates were significantly higher in higher-income White neighborhoods with nearly 50% of their bike lanes installed in such neighborhoods. Fullerton installed more than 90% of its bike lanes in POC block groups, but most were in higher-income POC block groups. The categorical averages for all cities that had

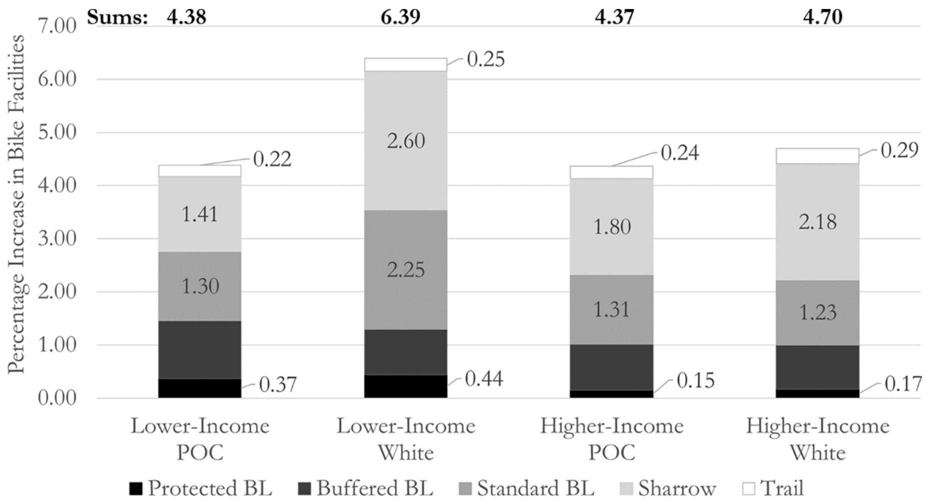

Fig. 3. Average Increases in Bike Facilities between 2010 and 2019.

Table 6
Percent Differences and Kruskal-Wallis Significance between Income and Race/Ethnicity Categories (LPOC = lower-income POC; LW = lower-income White; HPOC = higher-income POC; HW = higher-income White) (*<0.10; **<0.05; ***<0.01).

	LPOC to LW	LPOC to HPOC	LPOC to HW	LW to HPOC	LW to HW	HPOC to HW
All Bike Facilities	45.9% ***	-0.2%	7.3% ***	-31.6% ***	-26.4% ***	7.6% **
All Bike Lanes	28.3% ***	-15.9%	-19.2%	-34.5% ***	-37.0% ***	-3.9%
Protected Bike Lanes	18.9%	-59.5% ***	-54.1% ***	-65.9% ***	-61.4% ***	13.3%
Buffered Bike Lanes	-22.0%	-21.1%	-23.9%	1.2%	-2.4%	-3.5%
Standard Bike Lanes	73.1% ***	0.8%	-5.4%	-41.8% ***	-45.3% ***	-6.1%
Sharrows	84.4% ***	27.7% **	54.6% ***	-30.8% ***	-16.2% *	21.1% **
Trails	13.6%	9.1%	31.8% **	-4.0%	16.0%	20.8%

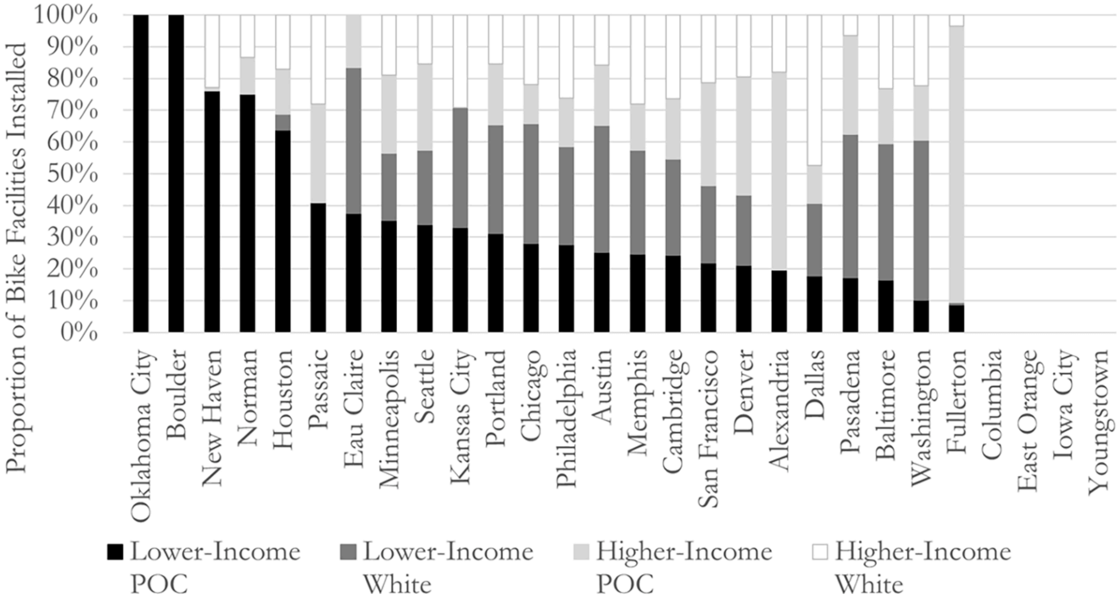

Fig. 4. Average Increases in all Bike Lanes between 2010 and 2019.

bike lanes installed were 37.1% in lower-income POC, 22.8% in lower-income White, 21.7% in higher-income POC, and 18.4% in higher-income White. These findings largely mirror the overall results, namely that bike lane installations have concentrated in lower-income areas. As with the main longitudinal analysis, the SED categories in Fig. 4 are relative to each individual city.

4.2. *Causality dilemma*

4.2.1. *Multi-level random effects logistic regression models*

How did household income and race/ethnicity change within the study period relative to bike facility installation, and vice versa? Were increases in income/White residents followed by increases in bike facilities, or were increases in bike facilities followed by increases in income/White residents?

Table 7 highlights the causality dilemma results. The left side of the table shows results for the bike facility to SED regressions while the right side shows results for the SED to bike facility regressions. Focusing first on the strongest and most statistically significant variable, a block group's distance to downtown is the strongest predictor of having bike facilities installed. Since we standardized all the variables in all the models, we can compare results between variables and across models. The negative distance to downtown coefficients signify that block groups farther from downtown saw less bike facilities installed.

The income and race/ethnicity coefficients are weak compared to distance to downtown. The coefficients are largely positive, which can be interpreted as increases in bike facilities being followed by increases in income/White proportion and increases income/White proportion being followed by increases in bike facilities. The strength of the coefficients from the causality models indicate that there is not a significant difference in strength between income and race/ethnicity. However, five of the income results were

Table 7
Multi-Level Random Effects Logistic Regressions Comparing Changes in Bike Facilities to Changes in Socioeconomic/Demographic (SED) Variables and Distance to Downtown.

		Changes in Bike (2010 → 2014) to SED (2014 → 2019)			Changes in SED (2010 → 2015) to Bike (2015 → 2019)		
		Coef.	SE	p-value	Coef.	SE	p-value
All Bike Facilities	Income	0.02	0.02	0.346	0.09	0.02	**<0.001**
	% White	0.03	0.02	0.172	0.08	0.02	**<0.001**
	Dist. to downtown	−0.54	0.03	**<0.001**	−0.51	0.03	**<0.001**
All Bike Lanes	Income	0.01	0.02	0.541	0.02	0.02	0.455
	% White	0.04	0.02	0.131	0.01	0.02	0.791
	Dist. to downtown	−0.61	0.03	**<0.001**	−0.58	0.03	**<0.001**
Protected Bike Lanes	Income	−0.12	0.04	**0.002**	−0.02	0.04	0.532
	% White	−0.00	0.05	0.975	0.05	0.04	0.162
	Dist. to downtown	−1.81	0.09	**<0.001**	−2.25	0.09	**<0.001**
Buffered Bike Lanes	Income	0.00	0.03	0.962	−0.01	0.03	0.623
	% White	0.02	0.03	0.456	0.01	0.03	0.691
	Dist. to downtown	−0.92	0.05	**<0.001**	−0.28	0.03	**<0.001**
Standard Bike Lanes	Income	0.00	0.02	0.848	0.03	0.03	0.247
	% White	0.03	0.02	0.254	0.02	0.03	0.469
	Dist. to downtown	−0.28	0.03	**<0.001**	−0.49	0.04	**<0.001**
Sharrows	Income	0.07	0.03	**0.010**	0.06	0.03	**0.048**
	% White	0.03	0.03	0.288	0.05	0.03	0.082
	Dist. to downtown	−0.37	0.04	**<0.001**	−0.57	0.04	**<0.001**
Trails	Income	0.04	0.04	0.389	0.16	0.05	**<0.001**
	% White	0.02	0.04	0.675	0.09	0.05	0.061
	Dist. to downtown	−0.59	0.05	**<0.001**	−0.14	0.06	**0.016**

statistically significant while only one race/ethnicity coefficient was significant, indicating that the relationship between income and bike facilities may be more meaningful, as suggested in the longitudinal analysis above.

This also begs the question: do SED changes tend to lead to bike facilities or vice versa? Examining "All Bike Facilities", the income and race/ethnicity coefficients for the SED to bike facility model were more than twice as strong as the same coefficients for the bike facility to SED model. The coefficients for the SED to bike facility regression were also statistically significant while the coefficients for the bike facility to SED were not. This can be interpreted as increases in income and White proportion being followed by increases in bike facilities more so than increases in bike facilities being followed by increases income or White proportion.

This relationship seems to be strongest for sharrows and trails: increases in income and proportion White were followed by relatively strong increases in sharrows and trails. On the other hand, decreases in income were followed by more protected and buffered bike lanes (although these relationships were weak and not statistically significant). Overall, there does not appear to be a strong causal relationship between bike facilities and SED variables, and there is an especially weak link in terms of bike facility installation leading to future SED changes.

4.2.2. Difference-in-difference analyses

DID results confirm the logistic regression findings in that the causal relationship between bike facility installation and SED changes is weak. There was only one model where the treatment resulted in a statistically significant change in the outcome: when bike facility installation (2010–2014) was the treatment and change in income (2014–2019) was the outcome (top left of Fig. 5). We derived the expected trends in the graphs by computing the treatment/control difference in the before period and applying that factor to the control trend in the after period. Based on prevailing trends, we would have expected block groups that had a bike facility installed between 2010 and 2014 to have an average income of $79,344. They actually had an income of $74,035. While this DID result is the inverse of the logistic regression result, where bike facilities were followed by an increase in income (although non-significantly), we did not account for distance to downtown or city-level random effects in the DID analysis, which may explain the discrepancy. The other relationships were weak and not statistically significant, which largely mirrors the logistic regression results. To further illustrate the DID analysis, the bottom right graph shows that block groups that had an increase in proportion White between 2010 and 2015 (the treatment) had slightly more bike facilities than we would expect relative to block groups that had a decrease in proportion White between 2010 and 2015 (control) (Fig. 5). However, the difference was weak and not statistically significant.

Overall, the DID results again suggest that income has a stronger causal relationship with bike facilities than race/ethnicity, although both relationships are still relatively weak. Without accounting for distance to downtown or city-level random effects, the DID analysis suggests that bike facilities lead to lower levels of income than would otherwise be expected.

The above variables in the logistic regression analyses were standardized with z-scores and the treatment variables in the DID analyses was dichotomized, meaning that the outcomes are not easily interpreted in real terms. For the sake of comparison, we went back and completed linear regressions on the raw numbers for all bike facilities installed. We accounted for distance to downtown in these models and controlled for its effect when deriving our numbers below by consistently assuming the median value of 6294 feet. All regressions and variables were statistically significant except for the regression comparing changes in race during the before period to changes in bike facilities during the after period.

For every additional $10,000 in income increase during the before period, there were 1277.3 fewer feet of bike facilities installed in

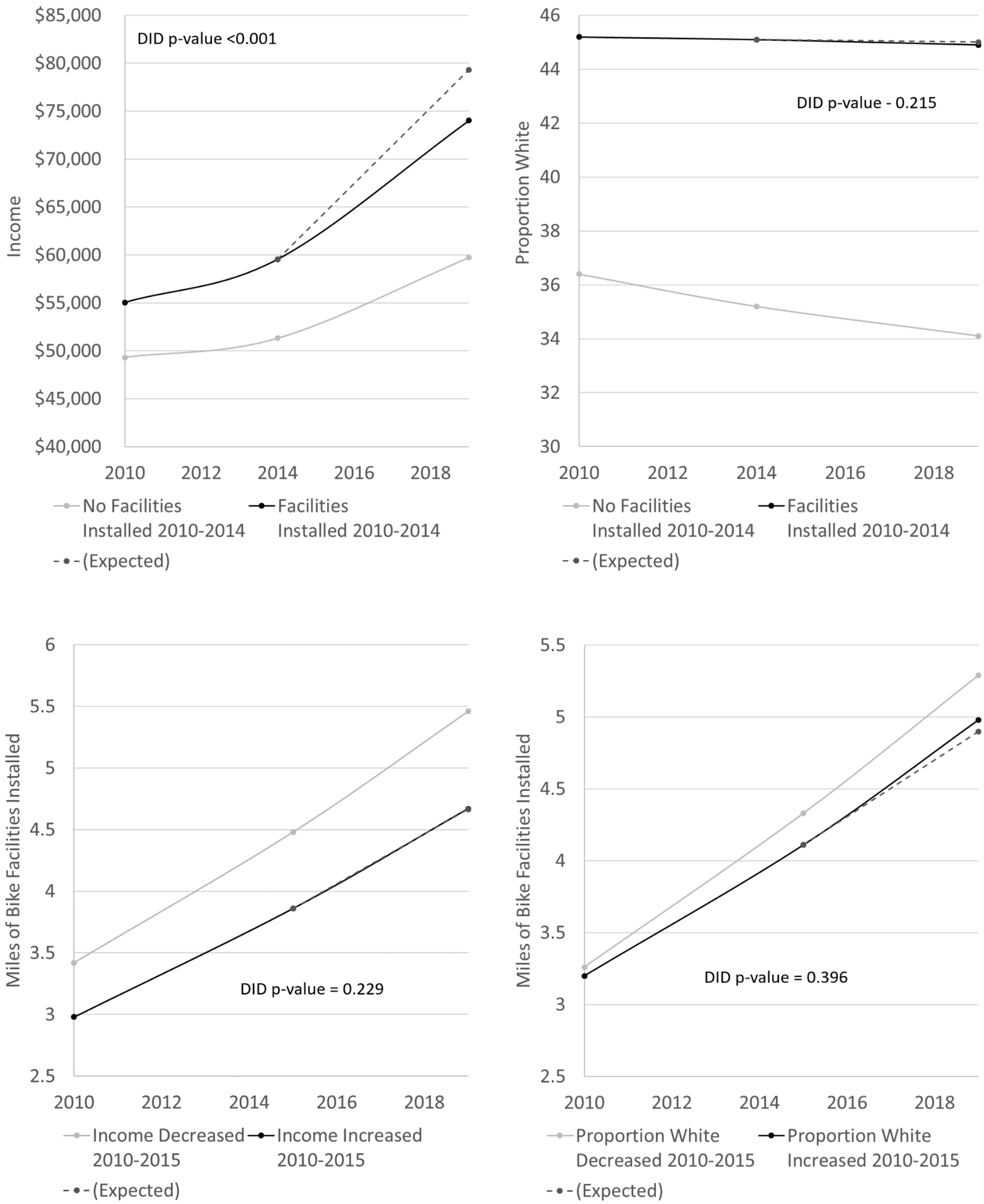

Fig. 5. Difference-in-Difference Results.

the after period. At the same time, our results suggest that for every additional 1277.3 feet of bike facilities installed during the before period, block groups had an income increase during the after period that was $1879 weaker.

In terms of race, for every additional 10% increase in White population in the before period, there were 1427.2 fewer feet of bike facilities installed in the after period (although this model was non-significant). For every 1427.2 feet of additional bike facilities installed during the before period, there was a 0.8% weaker increase in White population during the after period.

Although the numbers cited were in the negative direction, this does not necessarily mean that the relationships favor POC or lower-income block groups. In fact, all the SED coefficients were positive and the quantities cited above were in the negative direction largely because of the strength of the distance to downtown variable (which was in the negative direction).

5. Conclusions

Our results suggest inequalities in bike facility distribution outside of downtown areas. While lower-income White neighborhoods – where we might expect lower vehicle ownership and higher want or need of access to safe and comfortable active transportation facilities – had high levels of bike facilities installed, POC areas had the lowest rates of overall installation. Lower-income White block groups had 45.9% more bike facilities installed than lower-income POC block groups and 46.2% more facilities installed than higher-income POC block groups.

However, those overall differences were largely driven by sharrow installation. Bike lanes were most concentrated in lower-income areas, although lower-income White block groups again had significantly more bike lanes than any other category.

The causality dilemma results suggest that while there were relatively consistent causal relationships in the inequitable direction, the causal relationships between bike facility installation and SED changes were weak and largely statistically non-significant. The distance from a block group to its city's downtown area had a much stronger relationship with bike facility installation than SED characteristics. That being said, income appears to have had a stronger relationship than race/ethnicity. SED changes had a stronger relationship with bike facility installation than vice versa, suggesting that bike facilities were not linked to displacement.

Given these findings, and the questions surrounding heterogeneous demand for bike facilities, future research should examine how well the bike facility distribution meets demand. Bike lanes have been described as "a tell-tale sign of gentrification" (Cahen, 2016), and it is not uncommon to see popular press articles such as "why are bike lanes such heated symbols of gentrification" in *The Washington Post* or "blame it on the bike: does cycling contribute to a city's gentrification" in *The Guardian* (Stein, 2015, Geoghegan, 2016). Thus, the bicycling facility inequalities we found in the first part of this paper may be due to lack of community support in some neighborhoods. Trying to more evenly distribute such facilities by imposing them onto unwilling communities may be problematic. This point is why we use the term "inequality" throughout this paper as opposed to "inequity," as it is still possible that the inequalities observed do indeed meet demand.

Based on survey results, Lusk et al. (2017) suggest that residents in lower-income and primarily minority neighborhoods may have bicycle facility preferences that vary from those of residents of other neighborhoods. For instance, the authors conclude by stating that protected bike facilities "in lower income neighborhoods should be built wide enough for side-by-side riding because Blacks and Hispanics want to ride with family and friends" more so than Whites (Lusk et al., 2017). Furthermore, past research has identified structural neighborhood conditions like crime and violence as significant reasons for differing preferences among lower-income neighborhoods (Lusk et al., 2019). This highlights the need to further explore to what extent the bike facility supply (specific to type) meets the demand.

It is important to note that there are other arguments supporting the stance that these differences are inequities because Black and Brown people have historically cycled without infrastructure and only when cycling became associated with economic revitalization did cities start to build them in disinvested neighborhoods (Lubitow and Miller, 2013). Higher rates of crashes and fatalities also suggest there are inequities present rather than simply inequalities. More research is needed to more fully tie together bicycling infrastructure, activity, and safety outcomes through the lens of SED variables to develop this inequality versus inequity argument.

At the same time, transportation planners – who tend to be both middle income and White (Sandt et al., 2016) – often point out that good bicycling facilities are important for improving safety and health (Pucher, 2001, Reynolds et al., 2009, Mulvaney et al., 2016, Marshall and Ferenchak, 2019, de Hartog et al., 2010). This should be considered critical in lower-income neighborhoods as, nationally, 39% of bicycling is done by the lowest income quartile, a population that also experiences overrepresented road safety risks (Anderson and Hall, 2014, Marshall and Ferenchak, 2017). For instance, Steinbach et al., interviewed 78 London residents and found that bicycling was less appealing to non-professional, non-White men and women (Steinbach et al., 2011). Even if bicycling is less appealing, lower-income populations are significantly less likely to own a car and more likely to bicycle (Anderson and Hall, 2014, FHWA, 2014). Unfortunately, they also have a much higher chance of dying on the roads (McAndrews et al., 2013, Marshall and Ferenchak, 2017). This could be linked to a lack of appropriate bicycling facilities; for example, immigrants and those for whom English is their second language are more likely to be forced to bicycle along roads without appropriate bicycle facilities (Chen, 2008). There also exists the idea that "bike lanes are white lanes," (Hoffmann, 2016, Piatkowski et al., 2018), but a majority of minorities agreed that they would be more likely to try bicycling for transportation if given more supportive facilities (League of American Bicyclists and Sierra Club, 2013). Thus, policymakers should continue their work to protect existing residents from displacement in conjunction with bike facility installation.

Related to this displacement point, the fact that sharrows and trails appear to have the strongest relationship with increases in income leads us to wonder whether bike facilities are causing the SED changes, or whether planners are simply cognizant of changing SED characteristics in a neighborhood and prioritize those areas for installation. Both options present equality issues, but it is an important distinction whether facilities inherently lead to SED changes or whether planners simply place facilities near existing SED changes. More research is needed to better understand this distinction.

While the size of the study is a strength, it can also be interpreted as a limitation of the work. Understanding overall statistical trends is important, but some cities are doing better than others in terms of equally distributing safe bike facilities. These cities deserve to be recognized and studied further.

Related to this idea of study scale, future work might further explore the role that bike facility access plays in these relationships. While our longitudinal analysis looked directly at which block groups are getting which bike facilities and our causal analysis used half-mile buffers to expand our definition of access, future work might run in-depth sensitivity analyses to better understand how the identified relationships shift as the definition of bike facility access is broadened or narrowed.

Another limitation is that while we examined facility length, we did not account for the quality of those facilities. While some, for example, bike lanes were wide, clean, and clearly marked, other bike lanes were narrow, barely visible with faded paint, or experienced frequent conflicts with motor vehicle turning movements. By no means are all bike facilities of the same categorization created equal, and although we accounted for bike facility type and proximity to downtown, there exists a spectrum of design characteristics and quality within each type. Similarly, while some facilities provided critical links to important destinations, other facilities lacked in terms of usefulness to the overall bicycling network. Future research could also explore a broader longitudinal time frame as the equality of installation may have shifted over longer periods.

A further limitation is that while our binary POC/White structure was analytically convenient, there are structural dynamics that affect individual racial/ethnic groups differently. Future work might further illuminate differences within our broad POC category. Ours is an initial and broad look at this issue and we imagine an individualized racial/ethnic group analysis would be better suited for a more detailed analysis of one or a few cities. With more years of data, more detailed neighborhood characteristics, and more bike facilities, we should be able to disaggregate the race/ethnicity variable further in future research.

Another limitation is our lack of understanding regarding the mechanism behind shifts in income. While changes in income had stronger relationships with bike facility installation than race/ethnicity, we are still unsure whether existing residents are displaced by populations with higher or lower incomes, or whether existing residents have simply seen changes in their own incomes. More work is needed to better define this distinction.

Furthermore, other structural factors like economic conditions, neighborhood investment, and housing availability likely have an influence on changes in SED composition. Future research would benefit from accounting for these and similar factors. Such research would likely need to take place on a smaller scale of one or a few cities for the sake of consistent data collection.

This paper provides a longitudinal assessment regarding how well cities have been meeting bicycle facility equality goals over the last decade. It also provides cities with a better understanding of the bi-directional relationship between bicycle facilities and SED changes in neighborhoods. Bicycling is a transportation mode with the potential to promote health, access to opportunities, as well as equity; however, that can only happen when facilities are distributed in a fashion that grants access to safe bicycling facilities to those in need of them.

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CRediT authorship contribution statement

Nicholas N. Ferenchak: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing - original draft, Writing - review & editing, Visualization. **Wesley E. Marshall:** Conceptualization, Methodology, Software, Validation, Resources, Writing - original draft, Writing - review & editing, Visualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

AASHO, 1957. A Policy on Arterial Highways in Urban Areas. Washington, D.C.: American Association of State Highway Officials.

Anderson, Michael, and Hall, Mary Lauran, 2014. Building Equity: Race, Ethnicity, Class, and Protected Bike Lanes: Building Equity: Race, Ethnicity, Class, and Protected Bike Lanes.

Beiler, M.O., Mohammed, M., 2016. Exploring transportation equity: development and application of a transportation justice framework. Transport. Res. Part D-Transp. Environ. 47, 285–298. https://doi.org/10.1016/j.trd.2016.06.007.

Bishaw, A., Posey, K.G., 2016. A Comparison of Rural and Urban America: Household Income and Poverty. U.S. Census Bureau, Economic and Housing Statistics Division.

Boarnet, M.G., Giuliano, G., Hou, Y.T., Shin, E.J., 2017. First/last mile transit access as an equity planning issue. Transport. Res. Part a-Policy Practice 103, 296–310. https://doi.org/10.1016/j.tra.2017.06.011.

Braun, L.M., Rodriguez, D.A., Gordon-Larsen, P., 2019. Social (in)equity in access to cycling infrastructure: cross-sectional associations between bike lanes and area-level sociodemographic characteristics in 22 large US cities. J. Transp. Geogr. 80. UNSP 10254410.1016/j.jtrangeo.2019.102544.

Braver, Elisa, 2003. Race, Hispanic origin, and socioeconomic status in relation to motor vehicle occupant death rates and risk factors among adults. Accid. Anal. Prev. 35 (3), 15p. https://doi.org/10.1016/s0001-4575(01)00106-3.

Cahen, Claire, 2016. "More Than Paint on Concrete": the winding path toward bike equity. Glob. J. Commun. Psychol. Practice 7 (3), 1–9.

Campos-Outcalt, D., Bay, C., Dellapena, A., Cota, M.K., 2003. Motor vehicle crash fatalities by race/ethnicity in Arizona, 1990–96. Injury Prevention 9 (3), 251–256. https://doi.org/10.1136/Ip.9.3.251.

Chakraborty, J., 2006. Evaluating the environmental justice impacts of transportation improvement projects in the US. Transport. Res. Part D-Transp. Environ. 11 (5), 315–323. https://doi.org/10.1016/j.trd.2006.06.003.

Chen, Cynthia, 2008. The Temporal and Social Dimension of Accessiblity for New York City Residents. University Transportatation Research Center – Region 2, New York City.

Cradock, A.L., Troped, P.J., Fields, B., Melly, S.J., Simms, S.V., Gimmler, F., Fowler, M., 2009. Factors associated with federal transportation funding for local pedestrian and bicycle programming and facilities. J. Publ. Health Policy 30 (Suppl 1), S38–S72. https://doi.org/10.1057/jphp.2008.60.

de Hartog, Jeroen, Johan, Hanna Boogaard, Nijland, Hans, Hoek, Gerard, 2010. Do the health benefits of cycling outweigh the risks? Environ. Health Perspect. 118 (8) https://doi.org/10.1289/ehp.0901747.
Deakin, Elizabeth, 2007. Equity and Environmental Justice in Sustainable Transportation: Toward A Research Agenda. University of California Transportation Center, Berkeley, CA.
Deka, D., Connelly, M., 2011. Does proximity to activity-inducing facilities explain lower rates of physical activity by low-income and minority populations? Transp. Res. Rec. 2264, 83–91. https://doi.org/10.3141/2264-10.
Dill, Jennifer, Haggerty, Brendon, 2009. Equity analysis of Portland's draft bicycle master plan – findings. Urban Studies and Planning Faculty Publications and Presentations. Portland State University, Portland, OR.
Ferenchak, N.N., Marshall, W.E., 2019. Advancing healthy cities through safer cycling: an examination of shared lane markings. Int. J. Transp. Sci. Technol. 8 (2), 136–145.
Ferenchak, N.N., Marshall, W.E., 2020. Quantifying suppressed child pedestrian and bicycle trips. Travel Behav. Soc. 20, 91–103.
FHWA, 2014. NHTS Brief: Mobility Challenges for Household in Poverty. Federal Highway Administration, Washington, D.C.
FHWA, 2015. Separated Bike Lane Planning and Design Guide. Federal Highway Administration, Washington, D.C.
Flanagan, E., Lachapelle, U., El-Geneidy, A., 2016. Riding tandem: does cycling infrastructure investment mirror gentrification and privilege in Portland, OR and Chicago, IL? Res. Transport. Econ. 60, 14–24. https://doi.org/10.1016/j.retrec.2016.07.027.
Fuller, D., Winters, M., 2017. Income inequalities in Bike Score and bicycling to work in Canada. J. Transp. Health 7, 264–268. https://doi.org/10.1016/j.jth.2017.09.005.
Geoghegan, Peter, 2016. Blame it on the bike: does cycling contribute to a city's gentrification? The Guardian, October 6. www.theguardian.com/cities/2016/oct/05/blame-bike-cycling-contribute-city-gentrification.
Golub, A., Marcantonio, R.A., Sanchez, T.W., 2013. Race, space, and struggles for mobility: transportation impacts on African Americans in Oakland and the East Bay. Urban Geography 34 (5), 699–728.
Guzman, L.A., Oviedo, D., Rivera, C., 2017. Assessing equity in transport accessibility to work and study: the Bogota region. J. Transp. Geogr. 58, 236–246. https://doi.org/10.1016/j.jtrangeo.2016.12.016.
Harris, M.A., Reynolds, C.C., Winters, M., Cripton, P.A., Shen, H., Chipman, M.L., Cusimano, M.D., Babul, S., Brubacher, J.R., Friedman, S.M., Hunte, G., 2013. Comparing the effects of infrastructure on bicycling injury at intersections and non-intersections using a case-crossover design. Injury Prevent. 19 (5), 303–310.
Hoffmann, Melody L., 2016. Bike Lanes Are White Lanes: Bicycle Advocacy and Urban Planning. University of Nebraska Press, Lincoln, NE.
Hoffmann, Melody Lynn, Lugo, Adonia, 2014. Who is 'world class'? Transportation justice and bicycle policy. Urbanities 4 (1), 45–61.
Houde, M., Apparicio, P., Seguin, A.M., 2018. A ride for whom: has cycling network expansion reduced inequities in accessibility in Montreal, Canada? J. Transp. Geogr. 68, 9–21. https://doi.org/10.1016/j.jtrangeo.2018.02.005.
Karner, A., Golub, A., Martens, K., Robinson, G., 2018. Transportation and environmental justice: history and emerging practice. Routledge Handbook Environ. Justice 400–411.
League of American Bicyclists, and Sierra Club, 2013. The New Majority: Pedaling towards Equity.
Lubitow, A., Miller, T.R., 2013. Contesting sustainability: bikes, race, and politics in Portlandia. Environ. Justice 6 (4), 121–126.
Lusk, A.C., Anastasio, A., Shaffer, N., Wu, J., Li, Y., 2017. Biking practices and preferences in a lower income, primarily minority neighborhood: learning what residents want. Prevent. Med. Rep. 7, 232–238. https://doi.org/10.1016/j.pmedr.2017.01.006.
Lusk, A.C., Willett, W.C., Morris, V., Byner, C., Li, Y., 2019. Bicycle facilities safest from crime and crashes: perceptions of residents familiar with higher crime/lower income neighborhoods in Boston. Int. J. Environ. Res. Publ. Health 16 (3), 484.
Manson, S., Schroeder, J., Van Riper, D., Ruggles, S., 2017. IPUMS National Historical Geographic Information System: Version 12.0. University of Minnesota, Minneapolis.
Marshall, W., Ferenchak, N., 2017. Assessing equity and urban/rural road safety disparities in the U.S. J. Urban. https://doi.org/10.1080/17549175.2017.1310748.
Marshall, Wesley E., Ferenchak, Nick, 2019. Why cities with high bicycling rates are safer for all road users. J. Transp. Health 13, 285–301. https://doi.org/10.1016/j.jth.2019.03.004.
Marshall, W.E., Garrick, N.W., 2010. Effect of street network design on walking and biking. Transp. Res. Rec. 2198 (1), 103–115.
Marshall, W.E., Garrick, N.W., 2012. Community design and how much we drive. J. Transp. Land Use 5 (2), 5–20.
Mayrose, J., Jehle, D.V.K., 2002. An analysis of race and demographic factors among motor vehicle fatalities. J. Trauma-Injury Infect. Critical Care 52 (4), 752–755. https://doi.org/10.1097/00005373-200204000-00024.
McAndrews, Carolyn, Beyer, Kirsten, Guse, Clare E., Layde, Peter, 2013. Revisiting exposure: Fatal and non-fatal traffic injury risk across different populations of travelers in Wisconsin, 2001–2009. Accid. Anal. Prev. 60, 103–112.
Mulvaney, C.A., Smith, S., Watson, M.C., Parkin, J., Coupland, C., Miller, P., Kendrick, D., McClintock, H., 2016. Cycling infrastructure for reducing cycling injuries in cyclists: a cochrane review. Injury Prevent. 22. A108-A108.
Parra, D.C., Gomez, L.F., Pinzon, J.D., Brownson, R.C., Milett, C., 2018. Equity in cycle lane networks: examination of the distribution of the cycle lane network by socioeconomic index in Bogotá, Colombia. Cities Health 2 (1), 60–68.
PeopleForBikes, 2018. Inventory of Protected Bike Lanes. Boulder, CO. https://docs.google.com/spreadsheets/d/11H0gArHxo6kMop1I18yMcq7ArbNrwaGBLmIXgqI1Gjk/edit#gid=3.
Piatkowski, Daniel P., Marshall, Wesley E., Hoffmann, Melody L., 2018. If we build it, will they come? environmental approaches to bicycle promotion. In: Bopp, M., Sims, D., Piatkowski, D. (Eds.), Bicycling for Transportation. Elsevier, Cambridge, MA.
Pistoll, C., Goodman, A., 2014. The link between socioeconomic position, access to cycling infrastructure and cycling participation rates: an ecological study in Melbourne, Australia. J. Transp. Health 1 (4), 251–259. https://doi.org/10.1016/j.jth.2014.09.011.
Pucher, J., 2001. Cycling safety on bikeways vs. roads. Transport. Quarterly 55 (4), 9–11.
Rebentisch, H., Wasfi, R., Piatkowski, D.P., Manaugh, K., 2019. Safe streets for all? Analyzing infrastructural response to pedestrian and cyclist crashes in New York City, 2009–2018. Transp. Res. Rec. 2673 (2), 672–685.
Reynolds, C.C.O., Harris, M.A., Teschke, K., Cripton, P.A., Winters, M., 2009. The impact of transportation infrastructure on bicycling injuries and crashes: a review of the literature. Artn 47 Environ. Health 8. https://doi.org/10.1186/1476-069x-8-47.
Sandt, Laura, Combs, Tabitha, Cohn, Jesse, 2016. Pursuing Equity in Pedestrian and Bicycle Planning. Federal Highway Administration.
Stehlin, J., 2015. Cycles of investment: bicycle infrastructure, gentrification, and the restructuring of the San Francisco Bay Area. Environ. Plann. a-Econ. Space 47 (1), 121–137. https://doi.org/10.1068/a130098p.
Stein, Perry, 2015. Why are bike lanes such heated symbols of gentrification? The Washington Post, November 12. https://www.washingtonpost.com/news/local/wp/2015/11/12/why-are-bike-lanes-such-heated-symbols-of-gentrification.
Stein, Samuel, 2011. Bike Lanes and Gentrification, vol. 188, pp. 34–37.
Steinbach, Rebecca, Green, Judith, Datta, Jessica, Edwards, Phil, 2011. Cycling and the city: a case study of how gendered, ethnic and class identities can shape healthy transport choices. Soc. Sci. Med. 72 (7), 1123–1130.
Teunissen, Thijs, Sarmiento, Olga, Zuidgeest, Mark, Brussel, Mark, 2015. Mapping equality in access: the case of Bogotá's sustainable transportation initiatives. Int. J. Sustain. Transport. 9 (7), 457–467.
Tilahun, N.Y., Levinson, D.M., Krizek, K.J., 2007. Trails, lanes, or traffic: valuing bicycle facilities with an adaptive stated preference survey. Transport. Res. Part A: Policy Practice 41 (4), 287–301.

Tucker, B., Manaugh, K., 2018. Bicycle equity in Brazil: Access to safe cycling routes across neighborhoods in Rio de Janeiro and Curitiba. Int. J. Sustain. Transport. 12 (1), 29–38. https://doi.org/10.1080/15568318.2017.1324585.
Wang, J.Y., Lindsey, G., 2017. Equity of bikeway distribution in Minneapolis, Minnesota. Transp. Res. Rec. 2605, 18–31. https://doi.org/10.3141/2605-02.
Winters, M., Fischer, J., Nelson, T., Fuller, D., Whitehurst, D.G.T., 2018. Equity in spatial access to bicycling infrastructure in mid-sized Canadian cities. Transp. Res. Rec. 2672 (36), 24–32. https://doi.org/10.1177/0361198118791630.