Exploring the health and spatial equity implications of the New York City Bike share system

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ABSTRACT

Introduction: This paper examines spatial equity and estimates the health impact of Citi Bike, New York City's (NYC) bike share system. We discuss how further system expansion and utilization by residents in high-poverty communities of color could affect the potential benefit of the largest bicycle share system in the United States.

Methods: First, we compared the Citi Bike station distribution by census tract poverty during the system's 2013 launch and after the 2015 geographic expansion. Second, we applied the World Health Organization's Health Economic Assessment Tool (HEAT) to estimate the benefit of cycling associated with annual Citi Bike members for two 12-month time periods and analyzed change of the benefit over time.

Results: The results showed that the greatest proportion of Citi Bike stations were located in low-poverty (wealthier) NYC census tracts (41% per period), and there were no significant changes in station distribution during expansion. HEAT estimated an increase from two to three premature deaths prevented and an increased annual economic benefit from $18,800,000 to $28,300,000 associated with Citi Bike use.

Conclusion: In conclusion, although Citi Bike stations are not equitably located, the estimated annual health benefits are substantial and have increased over time. Our findings underscore the potential for even greater benefits with increased spatial access in higher-poverty neighborhoods and communities of color. Our findings highlight the importance of the built environment in shaping health and the need for a health equity lens to consider the social and political processes that perpetuate inequities.

1. Introduction

In the United States and internationally, bike share systems are becoming increasingly popular. They offer an opportunity for active transportation and have been shown to increase cycling (Buck et al., 2013; Fuller et al., 2013; Midgley, 2011; Shaheen et al., 2010). Bike share may increase population levels of physical activity and improve health outcomes (Kelly et al., 2014; Rodriguez, 2009). Although the benefits of physical activity are widespread, including reductions in chronic diseases and all-cause mortality (Wen et al., 2011), sedentary behavior and obesity remain at epidemic levels in the United States (Dwyer-Lindgren et al., 2013) and

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disproportionately burden higher-poverty neighborhoods and communities of color (Gordon-Larsen et al., 2006).

Health is rooted in the circumstances and environments of our daily lives. It is well established that built environment elements such as sidewalks, bike lanes and parks can influence physical activity levels (Sallis et al., 2012). Research has shown that bike share utilization is influenced by spatial access, namely living or working within the geography of the bike share system (Bachand-Marleau et al., 2012). Thus, where the bike share system is located and, consequently, who it serves is an important factor in assessing the system's impact on health.

Both nationally and in New York City (NYC), there is a long history of higher-poverty neighborhoods and communities of color being deprived of new resources and infrastructure. Discriminatory housing practices and subsequent systematic racialized disinvestment have limited the opportunities available to residents (Sanchez et al., 2003). In NYC neighborhoods with very high (≥ 30% of the population living below the Federal Poverty Level (FPL)) and high poverty (20–29% below FPL), the majority of residents are Black or Latino (77% and 63% respectively). Meanwhile, in neighborhoods with medium (10–19% below FPL) or low poverty (< 10% below FPL), Black or Latino residents are the minority (42% and 28%) (U.S. Census Bureau, 2009-2013a). NYC residents aged 20–64 in very high-poverty neighborhoods die at a rate 2.07 times higher than residents living in low-poverty neighborhoods (Bureau of Vital Statistics, 2013). The difference in mortality rates is not the result of residents in higher-poverty neighborhoods dying from unusual causes; they are dying of the same diseases – mostly heart disease and cancer – at younger ages and at higher rates (King et al., 2015).

1.1. Study objective

Within this context of vast neighborhood racialized economic and health inequities, to better understand spatial equity in bike share access, we examine station distribution of Citi Bike, the NYC bike share system, in relation to neighborhood poverty at two time periods: at launch and after the system's first expansion. We then calculate the health economic benefit associated with Citi Bike, a public-private partnership receiving no city money, and examine how the system benefits are influenced by spatial access, therein using the health economic benefit analysis to further explore spatial equity of the Citi Bike system. Finally, we discuss how further system expansion and utilization by residents in high-poverty communities of color could affect the potential benefit of the largest bike share system in the United States.

2. Methods

2.1. Citi Bike station distribution

2.1.1. Neighborhood poverty
Neighborhood poverty based on census tract (CT) was defined as the percent of residents with incomes below 100% of the FPL, using the American Community Survey 5-Year Estimate for 2009–2013 (U.S. Census Bureau, 2009-2013b). Each NYC CT was categorized by neighborhood poverty: very high poverty (≥ 30% of residents below FPL); high poverty (20 to < 30% below FPL); medium poverty (10 to < 20% below FPL); and low poverty (< 10% below FPL) (Toprani and Hadler, 2013).

2.1.2. Mortality rate
For each poverty level, crude mortality rates were calculated by aggregating 2013 NYC death records for all adults aged 20–64 years by CT (Bureau of Vital Statistics, 2013).

2.1.3. Citi Bike station locations
At the May 2013 launch of Citi Bike in NYC, all 335 bike share stations and approximately 5,400 bicycles were concentrated around the central business districts of Lower Manhattan and adjacent parts of Brooklyn. From August 2015 to December 2015, the Citi Bike system network underwent its first phase of expansion. Contiguous neighborhoods were added to the system, with an additional 141 stations installed in NYC, and 35 stations installed in Jersey City, New Jersey. In August 2015, there were approximately 7,300 bicycles available (NYC Bike Share, 2017).

A master list of all Citi Bike stations from the network's 2013 launch and those installed during the 2015 expansion was provided by Citi Bike (Khazan, 2016). The list included station location and date of station installation. Citi Bike stations were geocoded and projected in ArcMap version 10.2.1 (ESRI, Redlands CA), and NYC stations were spatially joined to a 2010 CT map.

2.2. Annual impacts for mortality and economic value

The World Health Organization's (WHO) Health Economic Assessment Tool (HEAT) is an online instrument developed to estimate the value of reduced mortality that results from habitual walking or cycling at a population level (Kahlmeier et al., 2017). Users of HEAT 4.1 have the option to consider the impacts on physical activity, air pollution, road crashes and carbon emissions. HEAT uses established dose-response functions to estimate the impacts, and users can adapt certain parameters to tailor the assessment to their particular geographic setting and population of interest. To the best of our knowledge, the NYC bike share system has not previously been assessed using HEAT.

We used HEAT 4.1 to compare two 12-month time periods identified based on the launch and expansion of the bike share system. The first period, T1, started in August 2013, shortly after the bike share system launched in NYC. The second period, T2, started in

August 2015, during a geographic expansion of the system. We conducted two separate "single case" assessments at the city level to separately evaluate the potential health benefit for each time period given the changing system geography and underlying characteristics. Our assessments accounted for both the benefit of physical activity and the exposure risks of air pollution and cycling crashes associated with Citi Bike for each time period.

2.2.1. HEAT user inputs

Although one-day and multi-day passes are available, our analysis included only membership and trip data for annual Citi Bike members as HEAT was designed for habitual cycling behavior (Kahlmeier et al., 2017). All Citi Bike user inputs to the model were calculated averages of real-world data for annual members for each of our 12-month time periods. Citi Bike membership data was extracted from Citi Bike's public monthly operating reports (NYC Bike Share, 2017). The total annual Citi Bike membership for each time period was calculated by averaging the actual number of registered annual members at the end of each month for each 12-month time period.

The duration of NYC bike share trips completed by annual Citi Bike members was calculated using public use Citi Bike data of actual travel records (Citi Bike, 2017). Data pertaining to casual pass customers were excluded. The duration of all trips completed by annual Citi Bike members for T1 and T2 was averaged across all annual members during each time period to estimate the daily minutes cycled per registered member, respectively. While attributing the NYC trips equally to all members underestimates the duration ridden by some, and therein underestimates their reduction in risk, it overestimates the duration ridden and the benefit for others. Analyses of public use Citi Bike data were done in R version 3.3.3 (The R Foundation for Statistical Computing, Boston MA).

We assume 25% physical activity substitution. That is to say, our estimate treats three-quarters of the activity associated with the Citi Bike system as newly added physical activity.

We calculated concentrations of fine particulate matter that are 2.5 μm in diameter and smaller ($PM_{2.5}$) for each of the two time periods to estimate the health effects of cyclists' exposure to air pollution. We found the mean of the average $PM_{2.5}$ concentration values in NYC CTs with Citi Bike stations present during the 2013 launch, and after the 2015 system expansion, respectively (New York City Department of Health and Mental Hygiene). Accounting for changes in ventilation rate and location, this increase in inhaled dose, compared to exposure to baseline concentrations, is used by HEAT to adjust the relative risk for cycling (Kahlmeier et al., 2017).

Crash risk was calculated using citywide data on all cyclist fatalities in all NYC crashes for 2013 and 2015 (New York City Department of Transportation). To estimate the distance traveled by bicycle per year, we multiplied the HEAT default trip length of 4.1 km (Kahlmeier et al., 2017) to an estimate of daily cycling trips in NYC for 2013 and 2015 (New York City Department of Transportation, 2018). We divided NYC cyclist fatalities by the calculated exposure to estimate the number of cyclist fatalities per 100 million kilometers cycled for each time period.

The number of deaths expected in the study population in a given year is estimated by the HEAT model based on user-input population-level all-cause mortality data and the size of the study population. Methodological guidance for the HEAT model recommends use of all-cause crude mortality for adults ages 20–64 years old (Kahlmeier et al., 2017). A review of publicly available Citi Bike trip data for each of our time periods confirmed that the majority of rides were taken by annual Citi Bike members in this age range. We assumed the mortality rate of annual Citi Bike members could be estimated by the mortality rate of residents in NYC CTs with a Citi Bike station, based on research showing that the proximity of residence to a bike share station was the most significant factor influencing bike share use (Bachand-Marleau et al., 2012). We calculated a crude rate of all-cause mortality for each time period by aggregating 2013 death records for adults aged 20–64 years in NYC CTs with Citi Bike stations present during the 2013 launch and the 2015 expansion of the bike share system network, respectively (Bureau of Vital Statistics, 2013).

The value of a statistical life (VSL), a measure commonly used in transport appraisals, forms the basis of the monetary savings calculated by HEAT. We input a VSL of $9,200,000, recommended for use by the United States Department of Transportation when valuing reduction of fatalities using a base year of 2013 (Rogoff and Thomson, 2014).

2.2.2. HEAT model calculations

HEAT applies the user-input mortality rate to calculate the number of deaths expected per year among the study population in the absence of cycling attributed to the bike share system. The health benefits calculated by HEAT are based on a reduced probability of death among people who cycle, assuming a linear relationship between cycling and mortality, adjusted for increased exposure to air pollution. HEAT applies the estimated protective benefit to the number of deaths expected among the study population to estimate the number of premature deaths prevented per year as a result of the input volume of cycling (Kahlmeier et al., 2017). The reduction in mortality is calculated assuming a steady state of cycling and thus reflects the benefits expected from long-term habitual use of the bike share system. Additionally, the model accounts for any deaths caused by air pollution exposure or cycling crashes. The economic impact is approximated by monetizing the net number of averted mortalities using the input value of a statistical life. The HEAT 4.1 model is summarized in Fig. 1.

2.2.3. Sensitivity analyses

To better understand the certainty in the output of the HEAT model, we did sensitivity analyses that tested the impact of: #1 the cyclist population input; #2 the proportion cycling estimated to be a substitution of physical activity; #3 the mortality rate input; and #4 adjusting all estimated or extrapolated inputs for potential uncertainty simultaneously.

#1: We tested the sensitivity of the HEAT model to the cyclist population size by halving the number of annual bike share members in T2, as not all registered bike share members ride habitually.
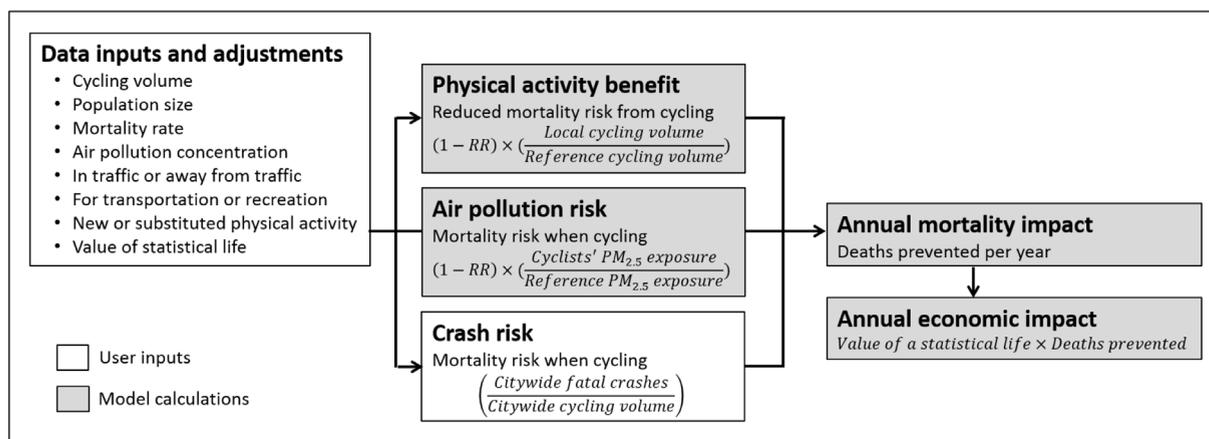
Fig. 1. Summary of HEAT model.

#2: Additionally, we tested model sensitivity to the proportion of bike use as a substitution of physical activity by assuming 50% of cycling through bike share was replacing other physical activity, an overestimate according to Citi Bike participant surveys that suggested as much as 38% of rides might be substituting for other physical activity (Yu et al., 2018).

#3: We examined model sensitivity to mortality rate in two ways. First (#3a), we estimated the health benefit of the T2 cycling amount, cyclist population, $PM_{2.5}$ concentration, and cyclist fatality risk while using the mortality rate from T1, thereby allowing us to better understand the contribution of increased mortality rate versus cycling amount to the greater health benefit estimated for T2. Then (#3b), to show the potential of a bike share system which reached populations living in higher poverty CTs, we assessed the estimated health benefit of the T2 cycling volume using the crude mortality rate from NYC's high-poverty CTs (20 to < 30% below FPL) and very high-poverty CTs (≥ 30% below FPL).

#4: Finally, we estimated upper and lower bounds for the annual impacts for mortality and economic value for T2 by varying inputs that we estimated or extrapolated by plus or minus 25%: proportion of cycling in traffic, proportion of cycling for transport, proportion of physical activity substitution, all-cause mortality rate, $PM_{2.5}$ concentration, and cyclist fatality rate (Table 3).

3. Results

3.1. Citi Bike station distribution

The NYC Citi Bike station locations for each phase are mapped in Fig. 2, alongside neighborhood poverty. At the 2013 launch, the Citi Bike system network consisted of 335 stations located in 165 of the 2,166 NYC CTs. After the 2015 expansion, the Citi Bike system network comprised 511 stations across 273 CTs in NYC and Jersey City. As shown in Fig. 3, the greatest proportion of NYC CTs with the presence of any Citi Bike stations at T1 and T2 were low-poverty (41% in each phase). The 2015 expansion of the Citi Bike system added 108 CTs to the system network, 80 of which were NYC CTs. The increase in the proportion of very high-poverty NYC CTs in the Citi Bike system network from 12% in T1 to 16% in T2 was not statistically significant.

3.2. Annual impacts for mortality and economic value

Table 1 shows Citi Bike utilization characteristics for our two time periods. Annual Citi Bike members took an average of 20,997 trips per day during T1, and 30,024 trips per day during T2, a 43% increase. The average trip duration increased 1.24 min between the two time periods, with trips in T2 averaging 14.07 min. Table 2 shows all HEAT 4.1 user inputs and model calculations. As a result of the increase in the number of trips and trip duration, the average number of minutes of Citi Bike use per day per member increased from 2.735 during T1 to 3.843 during T2, a 41% increase. The number of annual Citi Bike members increased 1% from T1 to T2 (95,228 vs. 96,142).

With the 2015 expansion into 80 additional NYC CTs, the crude mortality rate for adults age 20–64 increased by nearly 8 deaths per 100,000 population from about 161 per 100,000 during T1 to about 169 per 100,000 during T2 (Table 2). The average $PM_{2.5}$ concentration was 11.64 μg per cubic meter of air in T1 and decreased nearly 20% to 9.56 in T2. In 2013, there were 13 cyclist fatalities citywide, an estimated 2.286 fatalities per 100 million kilometers cycled, and in 2015 there were 16 cyclist fatalities citywide, an estimated 2.376 fatalities per 100 million kilometers cycled. For context, HEAT's default value for London's $PM_{2.5}$ concentration is 12 μg per cubic meter of air, and the default cyclist fatality rate for the United Kingdom is 2.1377 fatalities per 100 million kilometers cycled (Kahlmeier et al., 2017).

Calculating the estimated protective effect of cycling in T1 resulted in an estimated annual reduction of two premature deaths. In T2, the protective effect of cycling was increased to preventing three premature deaths annually (Table 2). Per the VSL of $9,200,000, the economic value of the level of cycling during T1 amounts to approximately $18,800,000 per year, and the level of cycling during
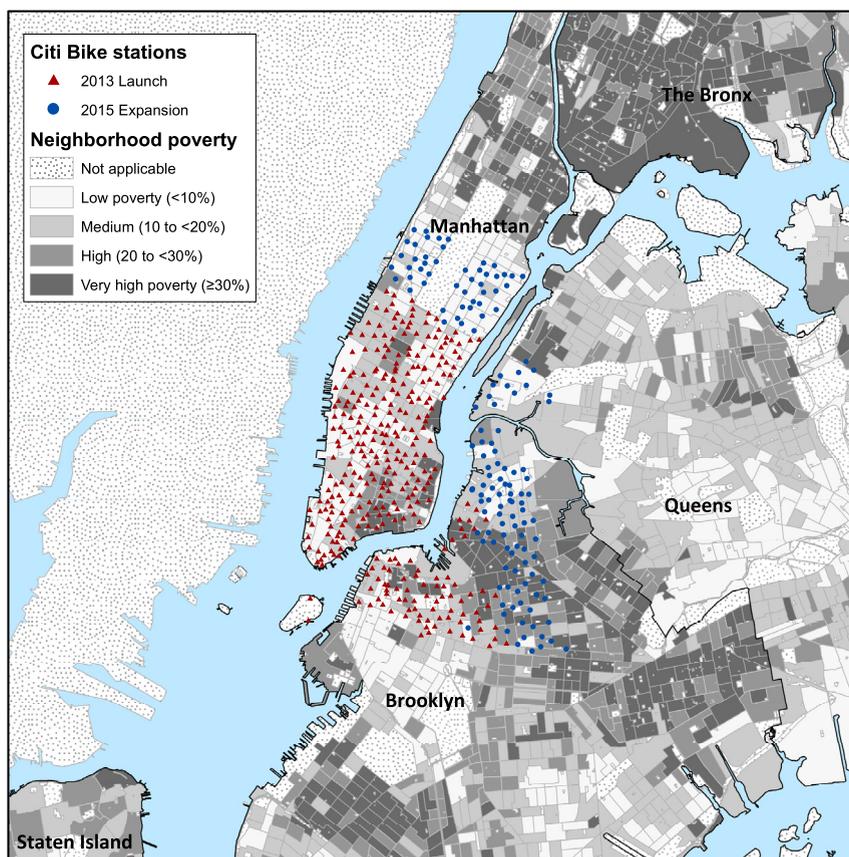
Fig. 2. Map depicting NYC Citi Bike station locations at the 2013 launch and after the 2015 expansion, and neighborhood poverty. Neighborhood poverty (based on CT) defined as percent of residents with incomes below 100% of the Federal Poverty Limit (FPL), per American Community Survey 5-Year Estimate for 2009–2013 (U.S. Census Bureau, 2009-2013b).

Fig. 3. The crude mortality rate for NYC by neighborhood poverty, and the distribution of NYC Citi Bike stations by neighborhood poverty at the 2013 launch, after the 2015 expansion, and for NYC overall.

Neighborhood poverty (based on CT) defined as percent of residents with incomes below 100% of the Federal Poverty Limit (FPL), per American Community Survey 5-Year Estimate f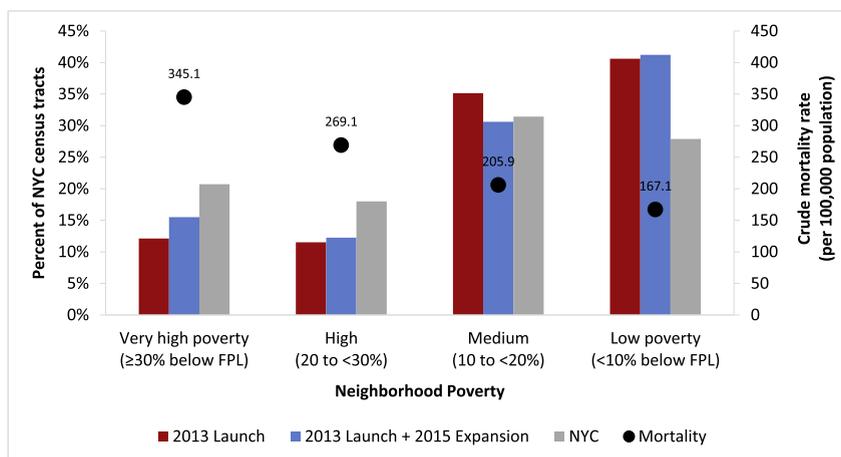or 2009–2013 (U.S. Census Bureau, 2009-2013b). Crude mortality rates for adults ages 20–64 years for NYC CTs, by neighborhood poverty (Bureau of Vital Statistics, 2013). Note: One NYC CT in both Citi Bike phases, and 42 NYC CTs were a park or cemetery so neighborhood poverty was not applicable.

Table 1

Citi Bike utilization characteristics.

	T1 08/01/2013–07/31/2014	T2 08/01/2015–07/31/2016
Average number of trips per day	20,997	30,015
Average trip duration (minutes)	12.83	14.07
Estimated average distance per trip (miles)	1.59	1.75

Table 2

HEAT model user inputs and model calculations.

	T1 08/01/2013–07/31/2014	T2 08/01/2015–07/31/2016	Notes and Data sources
User Inputs			
Amount cycled per person per day (minutes)	2.735	3.843*	Total trip duration in year (Citi Bike, 2017) divided by average number of annual Citi Bike members per month (NYC Bike Share, 2017). * Only NYC trip data used.
Cyclist population	95,228	96,142	Average number of annual Citi Bike members per month (NYC Bike Share, 2017).
Temporal and spatial adjustment (percent)	0	0	HEAT requires long-term average input on active travel (Kahlmeier et al., 2017). No adjustment was needed as all Citi Bike system user inputs were calculated with annual data, and for members citywide.
Proportion of cycling in traffic (percent)	50	50	Adjusts air pollution levels to which assessed cyclists are exposed. Default value (Kahlmeier et al., 2017).
Proportion of cycling for transport (percent)	50	50	Assigns air pollution concentrations, assuming trips for transport replace modes of transport and therefore time in higher air pollution concentrations. Recreational trips are assumed to replace time in background air pollution concentrations. Default value (Kahlmeier et al., 2017).
Cycling as substitution of physical activity (percent)	25	25	Estimate treating 75% of all Citi Bike cycling as new physical activity, as informed by the default value of 0% (Kahlmeier et al., 2017) and a study finding as much as 38% of Citi Bike rides might be substituting for other physical activity (Yu et al., 2018).
Value of a statistical life (USD)	$9,200,000	$9,200,000	Economic value recommended for use by the United States Department of Transportation to quantify the benefit of avoiding a fatality in 2013 (Rogoff and Thomson, 2014).
Crude all-cause mortality rate per 100,000 population	160.69	168.63†	All-cause mortality rate for adults aged 20–64 years, based on NYC death records (Bureau of Vital Statistics, 2013). † Mortality rates for Jersey City CTs are not reflected in T2.
PM$_{2.5}$ concentration (micrograms per cubic meter)	11.64	9.56	Averaged CT average PM$_{2.5}$ concentration values in NYC CTs with Citi Bike stations present, to estimate air pollution exposure (New York City Department of Health and Mental Hygiene et al.).
Cyclist fatalities per 100 million kilometers cycled	2.286	2.376	Cyclist fatalities in all NYC crashes (New York City Department of Transportation, 2013, 2015) divided by the product of the default bicycle trip length (Kahlmeier et al., 2017) multiplied by estimated number of annual cycling trips in NYC (New York City Department of Transportation, 2018).
Model Calculations			
Relative risk of all-cause mortality among cyclists compared to non-cyclists	0.899	0.899	Value set by HEAT model (Kahlmeier et al., 2017).
Relative risk between all-cause mortality per 10 µg per cubic meter increase in PM$_{2.5}$ among cyclists compared to non-cyclists	1.07	1.07	Value set by HEAT model (Kahlmeier et al., 2017).
Number of premature deaths prevented per year	2	3	
Estimated annual mortality impact value (USD)	$18,800,000	$28,300,000	

T2 is estimated to value $28,300,000 per year (Table 2).

3.2.1. Sensitivity analyses

Overall, with our sensitivity tests we found the estimated annual health benefit to be substantial. The health benefits were most influenced by proportion cycling estimated to be a substitution of physical activity and the mortality rate of members.

The model was not sensitive to the input size of the cyclist population (#1) given the linear dose-response curve the model applies to estimate benefits from time cycling. Halving the cyclist population in turn increased the average cycling time per person and therefore did not change the annual impacts for mortality and economic value input (data not shown). Even if the proportion of annual member who are actual users is even more skewed (e.g. if 10% of users are making 50% of the trips), given the model assumptions intrinsic to HEAT of a linear dose-response curve, the overall estimated benefits would be the same, just distributed differently across users.

To examine the effect of proportion of cycling estimated to be a substitution of physical activity (#2), we input 50% of cycling through bike share as replacing other physical activity which decreased the number of premature deaths prevented per year for each time period by one-third. Assuming half of bike share use accounted for activity substitution decreased our estimated annual mortality impact value by approximately 36% for each time period (data not shown).

When we tested model sensitivity to mortality rate (#3a) by first inputting all T2 values with the T1 mortality rate, the estimated number of premature deaths prevented remained the same (due to HEAT's rounding of this output), and we found a 5% decrease to the annual economic value (data not shown). This small change is due to the relatively small difference between T1 and T2 mortality rates. Therefore, the major contributor of the increase in health benefit from T1 to T2 is the increased cycling amount, rather than the higher mortality rate of the cycling population in T2.

We then examined the health benefit if Citi Bike reached residents from higher poverty neighborhoods (#3b) by using the Citi Bike-related physical activity in T2 with the crude mortality rate of high-poverty (269.1 deaths per 100,000 population) and very high-poverty NYC CTs (345.1 deaths per 100,000). Using these alternative area-based mortality rates, five and six premature deaths would be prevented, respectively, with an annual economic value of $45,500,000 and $58,500,000. These benefits are incrementally greater than the benefits we originally calculated for T2, underscoring the significant increases in health and economic impact possible with expansion of the bike share system to populations in higher poverty neighborhoods.

In the simultaneous adjustment (#4), the lower bound, estimated for T2 by varying the proportion of cycling in traffic, proportion of cycling for transport, proportion of physical activity substitution, all-cause mortality rate, $PM_{2.5}$ concentration, and cyclist fatality rate by plus or minus 25% in the appropriate direction, was one premature death prevented, valued at $12,600,000. The upper bound was five deaths prevented, valued at $49,200,000. Despite adjusting our estimated and extrapolated measures for uncertainty the estimated annual health benefits remain substantial (Table 3).

4. Discussion

Citi Bike stations are located disproportionately in wealthier neighborhoods, and the proportion of higher-poverty neighborhoods with Citi Bike stations did not increase significantly during the expansion examined in this study. Although Citi Bike stations are not geographically equitably located, the estimated economic value of reduced mortality is substantial and has increased over time. The observed increase in benefit was primarily due to increased utilization, as the average duration of daily Citi Bike utilization in NYC by annual members increased 41% after system expansion to additional neighborhoods. The number of premature deaths prevented per year increased from two to three which corresponded with an increase in economic value from $18,800,000 to $28,300,000 annually, underscoring the mortality benefit effect of such active transportation infrastructure.

Given the context of neighborhood racialized economic and health disparities in NYC, and the potential of bike share systems to increase cycling, overall physical activity, and improve health outcomes (Buck et al., 2013; Midgley, 2011; Shaheen et al., 2010), and the influence of station proximity on utilization (Bachand-Marleau et al., 2012; Fuller et al., 2013), this study highlights the

Table 3
Upper and lower bounds for HEAT model user inputs and model calculations for T2.

	T2 Lower bounds 08/01/2015–07/31/2016	T2 Upper bounds 08/01/2015–07/31/2016
User Inputs		
Amount cycled per person per day (minutes)	3.843	3.843
Cyclist population	96,142	96,142
Temporal and spatial adjustment (percent)	0	0
Proportion of cycling in traffic (percent)	*75*	*25*
Proportion of cycling for transport (percent)	*25*	*75*
Cycling as substitution of physical activity (percent)	*50*	*0*
Value of a statistical life (USD)	$9,200,000	$9,200,000
Crude all-cause mortality rate per 100,000 population	*126.47*	*210.79*
$PM_{2.5}$ concentration (micrograms per cubic meter)	*11.95*	*7.17*
Cyclist fatalities per 100 million kilometers cycled	*2.970*	*1.782*
Relative risk of all-cause mortality among cyclists compared to non-cyclists	0.899	0.899
Model Calculations		
Relative risk between all-cause mortality per 10 μg per cubic meter increase in $PM_{2.5}$ among cyclists compared to non-cyclists	1.07	1.07
Number of premature deaths prevented per year	1	5
Estimated annual mortality impact value (USD)	$12,600,000	$49,200,000

Italicized user inputs were varied by plus or minus 25%.

importance of examining spatial equity in the planning and expansion of bike share systems. While our approach cannot disaggregate geographically, we used an observed and hypothetical shift in baseline mortality rate as a proxy to understand the actual and potential shift in benefit from locating the bike stations in census tracts with higher neighborhood poverty. We illustrate how the public health benefit is enhanced, and underlying inequities diminished, depending on who a program such as Citi Bike reaches.

Previous data has shown that cycling rates have increased in recent years across racial and ethnic groups and across all neighborhood poverty levels in NYC (Crossa et al., 2016). However, bike share stations are typically placed in densely populated urban areas, assuming density is a proxy for demand (Institute for Transportation Development Policy, 2018). Since the Citi Bike system has been concentrated in wealthier neighborhoods which remain highly segregated due to historic discriminatory housing practices and systematic racialized disinvestment, bike share services may not be reaching Blacks or Latinos and residents in higher-poverty neighborhoods proportional to the population of the city (Stewart et al., 2013). As shown in sensitivity analyses, health and economic impacts are proportional to the mortality rate of the benefiting population; therefore, assuming sustained or increased system utilization, there is potential for even greater health and economic benefits with further expansion to higher-poverty neighborhoods.

Other research has found that bike share systems are not equally accessible to all residents, resulting in bike share membership not reflecting the resident composition (Buck et al., 2013; Shaheen et al., 2010; Ursaki and Aultman-Hall, 2016). Ogilvie and Goodman (2012) found that although fewer residents from higher poverty neighborhoods were bike share members, after adjusting for spatial accessibility, residents from higher-poverty neighborhoods utilized the bike share system more than residents from lower-poverty neighborhoods. Who uses the program is not determined solely by where stations are located. While our study focused on spatial equity, factors such as cost, a required credit or debit card, and a lack of familiarity with bike share additionally influence bike share accessibility (Howland et al., 2017; Stewart et al., 2013). To increase Citi Bike membership and utilization, the NYC Better Bike Share Partnership, a collaboration of multi-sectoral stakeholders, was launched in 2015 (National Association of City Transportation Officials, 2017). The partnership currently includes representatives from community-based organizations, hospitals, public housing, the NYC Departments of Transportation and Health, and Citi Bike, working together to diversify bike share riders through inclusive programs, policies, and approaches.

Our study has several key strengths. We overlaid Citi Bike station locations onto neighborhood poverty to provide important context for the system and its potential to impact health. Our economic assessment used the WHO HEAT 4.1 model to both estimate the benefits of bike share in NYC and to demonstrate the importance of spatial equity of bike share systems in high-poverty neighborhoods. The tool has been applied internationally to assess physical activity and health impacts for past and planned investments (Kahlmeier et al., 2010), as it provides an easy to use assessment of the health and economic benefit of infrastructure that encourages active transport. To the best of our knowledge, the NYC bike share system has not previously been assessed using HEAT, and therefore ours is the first estimate of associated mortality and economic value benefits.

Our analysis takes into account the positive health effects of active transport, as well as the negative effects of air pollution and cyclist crash fatalities. Since HEAT only accounts for the effects of cycling on all-cause mortality, it is a conservative estimate. The model does not account for a reduction in morbidity from increased physical activity among annual Citi Bike members or other benefits, such as improved cognitive function and productivity (Castelli et al., 2015) and increased access to jobs and education resources. Further, our analysis focused solely on the benefit of cycling by annual Citi Bike members, but casual bike share users benefit from cycling too. Even non-participants in the bike share system may also benefit, as studies have found there to be an increased uptake of cycling (Buck et al., 2013; Fuller et al., 2013) as bike share systems normalize the image of cycling (Goodman et al., 2014), and everyone may benefit from reduced air pollution and traffic congestion. Though cycling has inherent risks, research shows that the benefits outweigh the risks of air pollution and road crashes (Doorley et al., 2015; Mueller et al., 2015), and there is a safety-in-numbers effect (Elvik and Bjørnskau, 2017; Jacobsen, 2003).

Additionally, our use of real-world membership and utilization data for annual Citi Bike members, alongside local economic and geographic data (e.g. census tract-level poverty) to explore a health equity lens, is a strength of our study. Our estimated and extrapolated inputs were comparable to other countries and cities. Further, our findings were robust across sensitivity analyses. Regardless of how we adjusted our inputs, the estimated annual mortality and economic value benefits of Citi Bike in NYC were substantial and showed potential to increase.

Regarding limitations to our study, since Citi Bike membership data does not include race, ethnicity, or health status, we had to rely on existing literature to corroborate our assumptions. In estimating the health economic benefits, the model uses population-level mortality data for adults aged 20–64 years to estimate how many adults in the target population would normally be expected to die. Our analysis does not account for possible differences in individual characteristics of Citi Bike members compared to the underlying population that may influence the mortality rate. However, we used mortality data only from NYC neighborhoods containing Citi Bike stations, and the 20–64 year age range reflects annual Citi Bike member ridership. Furthermore, local data indicates that approximately 75% of Citi Bike members reside within NYC ZIP codes containing Citi Bike stations, and approximately 84% of Citi Bike members reside within NYC ZIP codes (Crossa, 2017). While Jersey City trip data is available, our analysis is limited to NYC because of the availability of local mortality rates, air pollution levels, and crash fatality rate data. The inclusion of Jersey City trip data would have added 2.4 s cycling per person per day in T2, which had negligible effects to HEAT outputs (data not shown).

Because local data on modal share and shifts was limited, we did not assess effects on carbon emissions. Whereas the HEAT default for proportion of substituted activity is 0%, our main models assume 25% of the activity is substituted, treating three-quarters of the activity associated with the Citi Bike system as newly added physical activity. Studies have found that bike share can encourage new cyclists and can support increasing the bicycling mode share overall (Buck et al., 2013; Yu et al., 2018). We assumed that cycling levels are independent of the number of bike share stations in a given CT. We chose to use the full registered annual membership population as we did not have data on which subset of annual members were habitual cyclists. While not all registered annual

members bike equivalent amounts, we confirmed that changing the cyclist population size did not affect our output.

In relation to crashes, HEAT only considers fatalities and not injuries. Additionally, the tool assumes a linear dose-response relationship between the amount of cycling and mortality risk and between air pollution exposure and mortality risk, and therefore uses a single relative risk for each. However, these model simplifications have been previously justified in detail (Kahlmeier et al., 2017).

A recent study by Yu et al. (2018) found that expanding Citi Bike to lower-income communities is a cost-effective means of encouraging exercise and reducing pollution in NYC, offering good value relative to most health interventions. A cost-benefit analysis was outside the scope of our study. However, HEAT complements existing tools for economic valuations of transport interventions or infrastructure projects and can provide input into cost-benefit analyses (Kahlmeier et al., 2017) and prospective health impact assessments (Rojas-Rueda et al., 2011). Future proposals of bike share systems and expansion of existing system networks would benefit from input from such tools and from the systematic collection of race and ethnicity data from bike share users. Although neighborhood populations are constantly changing, and many high-poverty urban neighborhoods are rapidly gentrifying, proactively utilizing these tools and data can help identify inequities in both spatial access and health benefits. Future health impact assessments and research should use data on bike share membership characteristics, neighborhood representativeness and utilization, as well as more complex models that further account for bike share benefits on morbidity, air quality and injury risk.

5. Conclusion

At the launch of Citi Bike in 2013, and through expansion in 2015, we found that Citi Bike stations were inequitably distributed, with a greater presence in wealthier neighborhoods. Nonetheless, as calculated by the HEAT model, the annual mortality and economic value benefits of Citi Bike in NYC are substantial. The increased benefits observed after expansion were due to greater system utilization by annual members. Our findings underscore the potential for even greater benefits with the expansion of Citi Bike into neighborhoods with higher poverty and communities of color.

Our findings highlight the importance of the built environment in shaping health, and the need for a health equity lens to consider the social and political processes that perpetuate inequities. Our study can be used to support planning and expansion for bike share systems, including dockless bike share programs, as well as complete streets infrastructure, such as bike lanes. Collaboration between community partners, city agencies (transportation, planning, and health), and bike share operators is needed to expand bike share to higher-poverty neighborhoods and communities of color and to address other barriers to bike share access and safe cycling in general. Additional work is needed to develop a more comprehensive understanding of the effect of transportation infrastructure, particularly bike share systems, on population health and equity issues.

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