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Quantifying greenhouse gas emissions reduction from bike share systems: a model considering real-world trips and transportation mode choice patterns

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ABSTRACT

The emerging bike share systems provide convenient mobility to short-distance travelers for both leisure and commuting purposes. Many cities are rolling out bike share programs. However, few studies have evaluated how bike share systems (BSS) are used to quantify their sustainability impacts. This study proposes a Bike Share Emission Reduction Estimation Model (BS-EREM) to quantify the environmental benefits from bike share trips and compare the greenhouse gas (GHG) emission reductions from BSS in eight cities in the United States, including New York, Chicago, Boston, Philadelphia, Washington D.C., Los Angeles, San Francisco, and Seattle. The BS-EREM model stochastically estimates the transportation modes substituted by bike share trips, considering factors such as trip distance, trip purpose, trip start time, the accessibility of public transits, and historical distributions of transportation mode choices. Based on average life cycle emission factors of different transportation modes, our analysis reveals that the annual GHG emission reductions contributed by the eight BSSs in year 2016 range from 41 tons of CO_2-eq (Seattle) to 5417 tons of CO_2-eq (New York City), while the emission reductions per trip range from 283 to 581 g CO_2-eq. The total annual emission reduction is linearly correlated to the number of trips, bikes, and docks. The bike share stations located in the center of a city contributed to more total GHG emission reductions due to the high trip volumes, while the stations that are further away have higher emission reductions on a per trip basis due to longer trips and higher car substitution rate.

1. Introduction

Bike share is becoming an increasingly popular alternative transportation mode in many countries, including the United States. The year 2017 witnessed 35 million bike share trips in the U.S., a 25% increase since 2016 (NACTO, 2017). There are mainly two types of bike share systems (BSS): station-based systems and dockless systems. In a station-based system, the users check out a bike at a docking station and then return it to the same or another station after the trip. In a dockless bike share system, because all the necessary electronic devices are incorporated into the bikes instead of in the docks, the users can locate and unlock a bike with a smartphone application and then park and lock the bike without the restriction of docking stations. Currently, station-based bike share systems are still the dominant players, despite the large number of bikes launched by dockless bike share systems. In 2017, 56% of the bikes and 96% of the bike share trips in the U.S. are from station-based systems (NACTO, 2017). Therefore, this study focuses on station-based bike share systems.

Evaluating the benefits from bike share systems is important for the cities to make decisions on supporting the development of bike share programs. Bike share can potentially bring several social and environmental benefits such as saving transportation time (faster than walking and even driving in highly congested areas) and expenses, alleviating traffic congestion, reducing greenhouse gas (GHG) emissions and air pollutants, and improving multimodal transport connections (Shaheen et al., 2010; Drynda, 2014). Jäppinen et al. (2013) evaluated the spatial impacts of a hypothetical BSS on public transit travel time and estimated that bike share can reduce public transit travel time by an average of 10% in the Greater Helsinki area in Finland. Faghih-Imani et al. (2017) analyzed bike share trips and taxi trips in New York City and found that, for short trips (less than 3 km), traveling by bike share is either as fast as or faster than traveling by a taxi. Bullock et al. (2017) conducted a survey of bike share users in Dublin, Ireland and showed that the BSS contributed to the urban economy because the journey

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time savings and improved connectivity from bike share increased the productivity of local economic activities. They found that these benefits are more significant than those of modal shift from cars to bicycles. Using causal inference models, Hamilton and Wichman (2018) proved that the introduction of a bike share system reduced traffic congestion by about 4% in Washington. DC. Fuller et al. (2013) analyzed the data from a telephone survey about people's biking behaviors and concluded that there is a higher likelihood of cycling for people who live in areas where bike share is available, compared to people who have privately owned bicycles but have no access to bike share programs. Buehler and Hamre carried out a survey of bike share users and local businesses near the bike share stations in Washington DC, U.S. (Buehler and Hamre, 2015). They found that 73% of the users chose bike share to save travel time, while 25% of the users were motivated by cost savings.

Among the abovementioned benefits, this study focuses on the environmental benefit, which is one of the major drivers that motivate the decision makers to introduce BSS into the cities. Understanding the modal shift is important to evaluate the net environmental benefits of BSS. Whether bike share reduces transportation energy use depends on the transportation mode replaced by the bike share trips. If bike share trips replace personal vehicle or taxi trips, the bike share systems will reduce transportation fuel use and emissions. On the other hand, however, if the bike sharing trips replace walking trips, they may actually increase transportation energy use, due to the energy consumption required to build the stations, manufacture the bikes, and operate the system (e.g., transporting the bikes between stations to rebalance the bike availability). Therefore, in order to estimate the environmental benefits of bike share systems, it is critical to consider the transportation mode substitution by bike share trips. In existing literatures, there are limited studies trying to quantify the environmental benefits of BSS, in which the mode substitution is either based on simplified assumptions (Zhang and Mi, 2018; Anderson, 2015) or shifted concepts (e.g., using the percentage of users information from bike share user surveys as the percentage of travelled miles values) (Fishman et al., 2014). The environmental benefits estimated using these methods may lead to biased result (more details are provided in the Literature Review part of this paper). Therefore, better methods that consider the heterogeneity of bike share trips are needed.

In this study, we proposed a Bike Share Emission Reduction Estimation Model (BS-EREM), which quantifies the greenhouse gas (GHG) emission reductions from BSS with consideration of the detailed bike share trip information, such as trip distance, trip purpose, and time of the day for the trips. Mode substitution of bike share trips is simulated based on historical travel patterns learned from trip data in National Household Travel Survey (NHTS). The proposed model is then applied to compare the GHG emission reductions of eight bike share systems in the United States, including New York, Chicago, Boston, Philadelphia, Washington D.C., Los Angeles, San Francisco, and Seattle.

The rest of the paper is structured as follows: Section 2 discusses the relevant literature, research gaps, and the contributions made by this study; Section 3 provides detailed information about the input data and methodology of the proposed BS-EREM; In Section 4, the overall and unit (such as per trip and per bike) GHG emission reduction, as well as the spatial patterns of different bike share stations' contributions to GHG emission reduction are analyzed by applying the proposed model to real-world trip data; a sensitivity analysis is carried out in Section 5 to discuss the impacts of key parameters and assumptions of the BS-EREM; lastly, Section 6 summarizes the findings, then discusses the limitations of this work and future research directions.

2. Literature review

In order to estimate the replaced modes for bike share trips, researchers have tried to collect modal shift information through user surveys. Martin and Shaheen (2014) collected bike share user survey data in Washington, D.C. and Minneapolis. They analyzed the geospatial distribution of the modal shift due to bike share and concluded that higher proportion of bike share trips replaced public transit in urban periphery than in urban areas with high population density. The analysis from Nair et al. (2013) shows that bike share stations closer to public transit facilities often exhibit higher utilization. Shaheen et al. (2013) analyzed the modal shift of bike share by conducting user surveys for BSS in four cities: Montreal, Toronto, Twin Cities, and Washington, D.C. The survey results showed that bike share users shifted from all transportation modes and the modal shifts vary in different cities. About 40% to 50% of the respondents reported that their use of bike share reduces their bus and rail usage in Montreal, Toronto and Washington D.C., while in Twin Cities, 15% of the respondents reported increasing rail usage. In all four cities, bike share was found to reduce car and taxi usage. However, such survey results only provide qualitative information but not quantitative data for the changes (e.g., it shows the trend on whether bike sharing increases/decreases the use of other modes but does not quantify the changes). Similarly, another study also reveals that bike share reduced the usage of personal automobiles among about 50% of the bike share users in five cities: Twin Cities, Salt Lake City, Montreal, Toronto, and Mexico City (Susan et al., 2014). Two surveys were conducted for the BSS in Washington, DC, separately targeting the subscription members (users who purchase monthly/annual plans) (LDA Consulting and Capital Bikeshare, 2016) or casual users (those who only used the service with one-day or five-day plans) (Borecki et al., 2012). The survey results show that 39% of the members and 53% of the casual users who responded to the surveys used bike share to replace walking trips for their last bike share trips.

Few studies quantified the environmental benefits of bike share programs using mode substitution information. The research of Fishman et al. (2014) was one of the studies that first analyzed the bike share benefits with consideration of mode substitution. They used the bike share user survey data to estimate the mode substitution. In these user surveys carried out by the BSS operators, the BSS users were asked about their alternative travel modes, if not using bike share, to calculate the aggregated substitution rate (percentage) of different transportation modes. For instance, if 40% of the survey participants chose vehicles as their alternative mode, it is assumed that 40% of the bike share trips substituted vehicle trips. Based on the substitution rates, the authors estimated and compared the car travel distance reduction by BSS in Melbourne, Brisbane, Washington, D.C., Minnesota, and London. The substituted car travel at each BSS is calculated as the car substitution rate multiplied by the total annual trip distance, which is estimated using the bike share trip duration and an assumed biking speed of 12 km/h. However, this approach assumes that 1) the transportation mode substitution is independent of the trip distance and trip purpose, 2) the percentage of trip substitution is equivalent to the percentage of travel distance substitution, and 3) the trip distance is linearly correlated to the trip duration. These assumptions could lead to biased results in estimating the environmental benefits of bike share programs. First, trip distance and purpose do affect people's transportation mode selection. For instance, for long-distance trips, people are more likely to prefer car or public transit to walking. Additionally, the transportation mode choice would be different if the trip is for sightseeing instead of commuting (USDOT, 2009). The user survey data doesn't include information for trip distance and purpose. Therefore, assuming that all the bike share trips follow the same mode substitution rates could lead to inaccurate results. Second, because the travel distance from trip to trip could vary significantly, the percentage of trip substitution (information asked in the survey) is not equivalent to the percentage of travel distance substitution (information the calculation is based on). Third, while the trip distance is linearly related to the trip duration for some trips (e.g., when the riders go direct from point A to point B, such as commuting), the distance of trips with detours or multiple stops (e.g., leisure trips) cannot be accurately estimated using the trip duration (Kou and Cai, 2019). Therefore, to better understand the transportation emission reduction contributed by bike share programs, the analysis needs to consider transportation mode substitution integratedly with trip distance and trip purpose. In another study which estimated the environmental benefits of the BSS in Shanghai, China, Zhang and Mi (2018) set a distance threshold of 1 km to divide the bike share trips into two groups: trips that are shorter than 1 km, which were assumed as not replacing car travel and therefore generating zero environmental benefits, and trips that are longer than 1 km, which were assumed as replacing car trips and providing environmental benefits. The environmental benefits from these trips were calculated by multiplying the total trip distance with impact factors (e.g., energy saving per km or emission reduction per km). Although this study considered trip distance in the analysis, the 1 km distance threshold is set arbitrarily. Trips that are less than 1 km could also replace a car trip while trips longer than 1 km could also substitute public transit trips or even walking trips. Anderson (2015) assessed a proposed bike share program in Portland, Maine in the United States, and concluded that the potential bike share program can improve air quality and rates of physical activity for bike share users. The analysis is based on several assumed parameters such as annual trips, average trip distance, and average minutes of physical activity per trip. The estimated benefits still need to be further verified with real-world data.

In summary, existing studies quantifying the environmental benefits of BSS have two major limitations. First, the calculation of emission reduction from bike share trips is based on simplified assumptions (for example, “all bike share trips longer than 1 km will replace car trips” (Zhang and Mi, 2018)). Second, existing studies often replace the concept of “percent of miles” with “percent of users”, when mode substitution data from user surveys are used in the calculation. While user surveys can provide useful information about mode substitution, existing user surveys only reported the share of respondents claiming that they use bike share to replace a certain mode. However, not all users take the same number of bike share trips and not all trips have the same length. It could lead to biased results if we directly applied such “percent of users” information as if they were “percent of miles” data to quantify the environmental benefits. A user who take more trips and longer trips should be given a higher weight. Ideally, the historical bike share trips made by each survey participant should be used to link the detailed trip information with mode substitution. However, because the trip data and the user survey data are collected separately and anonymously, such linked data is not available at a large scale. Additionally, because user surveys are self-reported data, the accuracy of the data is always a concern (Cohen and Shaheen, 2018). Therefore, better modeling approaches are needed to evaluate the environmental benefits of BSS using real-world data and holistically evaluate the transportation mode substitution by bike share trips, considering detailed trip information such as trip distance, purpose, and start time.

To address the above discussed gaps, this study proposes a Bike Share Emission Reduction Estimation Model (BS-EREM) to quantify the greenhouse gas emission reductions by bike share trips through probabilistically simulating bike share trips’ mode substitution based on trip distance, trip purpose, time of the day for the trip, and historical travel patterns (mode choice distributions) before launching bike share programs. We applied the model to compare the life cycle greenhouse gas emission reduction from bike share programs in eight U.S. cities and also evaluated the spatial patterns of reduced GHG emissions at the station level in different cities. Compared to the existing literature, the unique contributions made by this study are: 1) we proposed a model to estimate the mode substitution of bike share trips, with the consideration of trip distance, trip purpose, trip start time, and the public transit accessibility near bike share stations; 2) the mode substitution estimation is based on travel survey data and real-world bike share trip data, thus, the proposed method can be generally applied to all cities that have such data available; and 3) the analysis not only quantifies the overall environmental benefits at the system level, but also evaluated the environmental benefits for unit distance travelled and the spatial distribution of the environmental benefits at the bike share station level, which provides insights for BSS station siting and planning. Results from this study can inform decision makers, city planners, and BSS operators to better develop, deploy, and operate BSS programs to improve transportation sustainability.

3. Data and methods

3.1. Input data

The proposed BS-EREM model integrates data from multiple sources to estimate the environmental benefits of BSS. The input data includes (1) bike share trip data (Section 3.1.1), (2) National Household Travel Survey (NHTS) data (Section 3.1.2), which provides historical transportation mode choice information prior to launching BSS programs, (3) public transit stations/stops near bike share stations (checking whether it is possible for a bike share trip to substitute a public transit trip, Section 3.1.3), and (4) GHG emission factors used for the calculation of trip environmental benefits given different mode substitution by BSS trips (Section 3.1.4). This section explains each type of data while the BS-EREM model is presented in Section 3.2.

3.1.1. Bike share trips in eight U.S. cities

Our study analyzed the bike share trip data from programs located in eight cities: Seattle (Pronto Cycle Share), Los Angeles (Metro Bike Share), Bay Area (Ford Gobike), Philadelphia (Indego Bike Share), Boston (Hubway, now rebranded as Blue Bikes), Washington D.C. (Capital Bike Share), Chicago (Divvy), and New York City (Citi Bike Share). To compare all eight BSSs, we used the trip data in year 2016, because Seattle’s Pronto Cycle Share was closed after March 2017. All eight systems are station-based. These bike share programs have made their trip data publically available, which include the timestamps and locations of the origin and destination of each trip. Because neither trip distance nor detailed bike trajectory data is provided, we estimated the trip distance between each pair of origin and destination stations using Google Maps Distance Matrix API, which could more accurately estimate the distance travelled by bike on urban street networks. Many of previous studies used trip displacement (e.g., the Great Circle Distance) to measure human movements (Rhee et al., 2011; González et al., 2008). However, in an urban transportation system, the movement of bikes is restricted by the street networks. The distance estimated by the API can better reflect the bike share trip along the pathways suitable for biking. Comparing to driving, bike travels are less affected by congestion (Alter, 2008; Lobo, 2013). Therefore, in this study, we assumed that the travel distance and duration between the same pair of start and end stations stay constant in spite of the trip start time. Round trips, which have the same origin and destination station, are excluded in our analysis due to the difficulty in estimating trip distance. Such round trips only make up 2% to 10% of the total trips in the eight systems. For the overall emission reduction estimation, we scaled up the results based on the total count of trips, assuming that these round trips share the same pattern as the one-way trips. Because this is an arbitrary assumption, we have also reported the emission reduction values excluding the round trips.

3.1.2. National household travel survey (NHTS)

The National Household Travel Survey (NHTS) (USDOT, 2009) is a nation-wide survey conducted by the U.S. Federal Highway Administration, which records the personal and household travel behaviors of local residents in the United States. Although more recent NHTS data has become available, in this study, we used the 2009 NHTS data to generate the mode substitution rate distributions, because it could better reflect people’s transportation mode choice when bike share service was not available (most of the BSSs in the United States were established after the year 2010). There are near 1.05 million trips recorded in NHTS 2009 data, which contains the detailed trip information

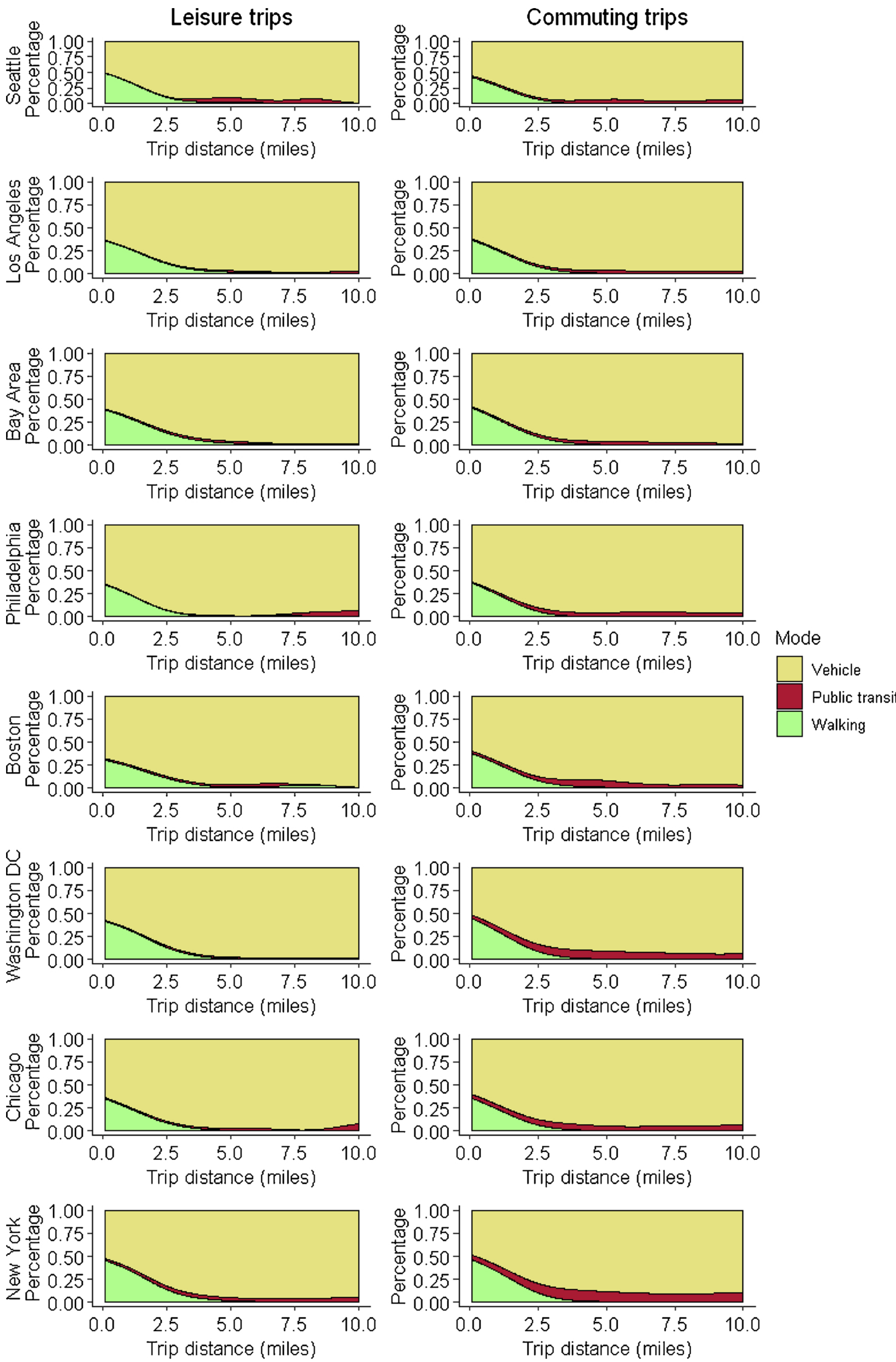

Fig. 1. Distributions of transportation mode choice regards to different trip distance for commuting trips and leisure trips.

and the characteristics of the people who are travelling. We extracted the attributes such as transportation modes, trip purpose, travel time, and travelled distance (in miles) of those trips taken in urban areas (typically with a population density of more than 1000 persons per square mile) (USDOT, 2009) for each of the eight cities. With such information, we can develop the distributions of people's transportation

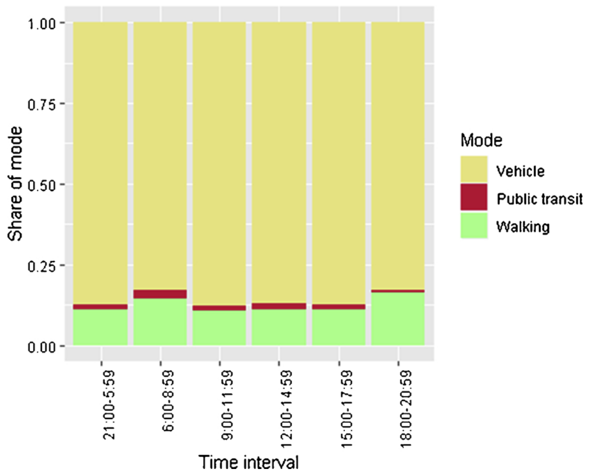

Fig. 2. Share of transportation mode choice in different time of the day in Los Angeles.

mode choice for a specific trip distance, travel time, and purpose. We only used NHTS records in the urban area because the bike share stations analyzed in this study are all located in urban areas as defined in the 2016 Topologically Integrated Geographic Encoding and Referencing system (TIGER) data from the U.S. Census Bureau (Thompson et al., 2016), which is also the data source that NHTS used to define urban areas (USDOT, 2009). In the case that a bike share system/station is located in rural area, the mode distribution should be generated using the NHTS trips from rural areas. Fig. 1 shows the mode choice distributions from the NHTS trip data for all time periods of the day with varied trip distance for commuting and leisure trips in each city. These distributions show that people are more likely to choose walking for short-distance trips (e.g., less than 2 miles) than for long-distance trips (e.g., 10 miles). For the same distance range, less people will choose public transit for leisure trips than for commuting trips. Fig. 2 depicts the share of different transportation modes in different periods of the day in Los Angeles. The 24 h of a day are separated into six time intervals. We group 21:00 to 5:59 as one period because the number of trips during this period is relatively low. For other time of the day, a three-hour interval is used. The mode share varies within a day, especially in the morning and evening. For example, during the period between 6 a.m. and 8:59 am, higher proportion of trips are taken by walking and public transit than other periods such as from 9 a.m. to 5:59 pm. These observations demonstrate the need to include trip distance, purpose, and time of the day in the analysis of trip mode substitution. Therefore, for each city, a total of 12 distributions are developed (2 trip purposes× 6 time intervals).

3.1.3. Public transit accessibility

Another factor that could affect people's mode choice is the accessibility of public transit. If there's no public transit facilities (e.g., bus stops, subway stations) near the origin and destination stations of a trip, it is less possible that the bike share trip replaced public transit. Using Google Maps Places API, we counted the number of public transit facilities within a 200-m (0.12 miles, about 3–4 minutes' walk) buffer zone around each bike share station in each of the eight cities. The impact of choosing 200 m as the public transit accessible zone is tested in the sensitivity analysis (Section 5). The details on how we use the data are described in Section 3.2.

3.1.4. GHG emission factors

We use life cycle GHG emission factors from Dave (2010) to calculate the emission reduction associated with each bike share trip (note that, in the life cycle analysis, emissions from the upstream processes besides the trips, such as road constructions, are also allocated in the emission factor calculation). We adopted the emission factors from this study because this study evaluated the emission factors of different transportation modes based on the same analysis scope and assumptions, making the emission factors more comparable to each other than factors drawn from different studies which may be generated based on different assumptions. Because the emission factors developed in this study include multiple types of public transit (e.g., bus and subway) and vehicles (e.g., car, SUV, and pickup), we take the weighted average of the emission factors in each transportation mode category to simplify our analysis to include only four transportation modes: walking, bicycling, vehicle, and public transit (Table 1). The weighting factors are the corresponding miles travelled using each mode in the NHTS 2017 data (here we used the 2017 data because it can better reflect the distance travelled by different modes in year 2016; NHTS 2017 and 2009 are the two most recent NHTS survey datasets available). Because it is difficult to find more fine-grained emission factor data for all the analyzed cities, we use the weighted average emission factors described above as the emission factors for the analysis of all eight cities.

Table 1
Emission factors used for the GHG emission reduction calculation.

Mode	Sub-category	Emission factor (g CO_2-eq/passenger mile travelled) (Dave, 2010)		Miles travelled in 2017 NHTS (U.S.DOT, 2017)	Weighted average of the emission factor
Walking	Walking	33			33
Bicycling	Bicycling	33			33
Vehicle	Sedan	382		3,843,053	441
	SUV	446		2,278,726	
	Pickup	619		1,230,229	
Public transit	Bus Average	326		170,342	299
	BART[1]	136	Average of three light rail/ subway: 177.7	39,207	
	MUNI[1]	173			
	Green Line[1]	224			

Note: 1 BART: Bay Area Rapid Transit System; MUNI: San Francisco Municipal Railway; Green Line: subway system in Boston; since we do not have the emission factors for all the light rail/subway systems in the eight cities, we used the average emission factors of BART, MUNI and Green Line to represent the unit emission of light rail/subway.

The difference between the life cycle emission factors of the substituted transportation mode and biking is then used to calculate the GHG emission reduction. For example, if a bike share trip substituted a vehicle trip, the emission reduction for this trip would be 408 g CO_2-eq/mile (biking generates 408 g CO_2-eq less than vehicles per passenger mile travelled) multiplied by the trip distance (in miles). How to determine the substituted transportation mode will be discussed in Section 3.2.

3.2. Bike share emission reduction estimation model (BS-EREM)

Using the above mentioned data as inputs, we propose a Bike Share Emission Reduction Estimation Model (BS-EREM) to estimate the GHG emissions reduction from a bike share trip (Fig. 3). The BS-EREM model includes two major components: bike share trip purpose estimation and bike share trip mode substitution simulation.

From the NHTS data, the historical trips are first separated into six time groups as specified in Section 3.1.2 based on the trip start time. Then for each time group, we developed the historical mode choice distributions for commuting and leisure trips separately. To differentiate between commuting and leisure trips, we compare the trip speed to the average speed of all trips in this city as a way to infer trip purpose. Trips whose speeds are lower than the average speed are considered as leisure trips (e.g., stop at different locations, take detours to visit different places-of-interest, and not in a hurry to get from the

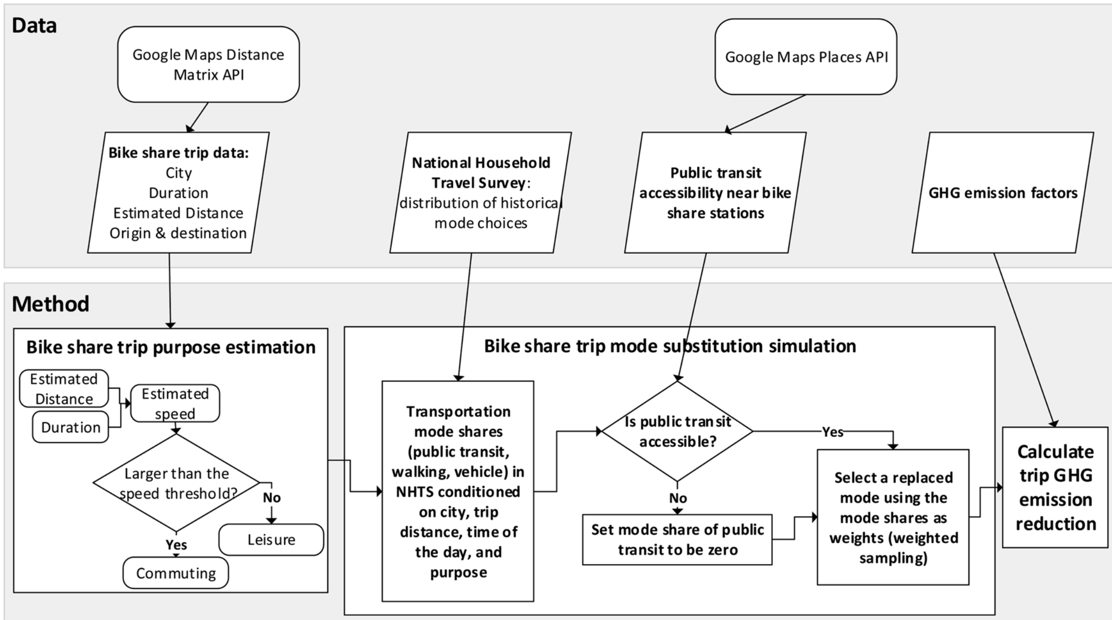

Fig. 3. Overview of the BS-EREM.

origins to the destinations), while the others are considered as commuting trips (e.g., directly going from the origins to the destinations). The impact of using the average speed as the threshold for trip purpose estimation is tested in the sensitivity analysis (Section 5). Given the distance of each bike share trip, the estimated trip purpose, time period of the day, and the corresponding historical distribution of mode choice regarding the specific trip distance, purpose, and time period, we can obtain the probability of the bike share trip replacing vehicles, walking, or public transit to determine the replaced mode in the simulation process. Using the mode choice distributions from NHTS data to simulate the displaced mode by bike share assumes that an average BSS user is the same as an average person in the city. It is possible that BSS users are a self-selected group which has different travel patterns (e.g., having lower percentage of vehicle trips than an average person). The influence of this assumption is tested in the sensitivity analysis (Section 5). If there's no public transit facility available near the location of the bike share trip's origin or destination, it is unlikely that this bike share trip replaces public transit. In this case, the mode share of public transit will be set to zero. The pseudo code describing the detailed algorithm to determine the replaced mode in the simulation is provided in the Appendix A. After determining the replaced mode, we can then calculate the GHG emission reduction from the trip using the emission factors and trip distance. We used the trips in the entire year of 2016 for our simulation and compared the results among different cities.

3.3. Evaluating the emission reduction from BSS in the context of the transportation sector emissions

After obtaining the total GHG emission reduction using BS-EREM, we compared the results with the total GHG emissions from the transportation sector in these cities. This reflects the BSS's relative GHG emission reduction contribution to its local transportation systems. The data of GHG emission from the transportation sector is collected from the most recent greenhouse gas inventory report of these cities. The cities do not release such data every year but the data from adjacent years can reflect the general level of transportation sector's GHG emissions in these cities (Table 2). The transportation sector's GHG emissions have been staying relatively stable based on historical data (for instance, the transportation sector's GHG emissions for City of Chicago in the year 2005, 2010, 2015 are 8.20, 7.95, and 8.05 million MT, respectively (Report, 2017). The changes for 2010 and 2015 compared to 2005 are only −3% and −2%, respectively.

4. Results and discussions

To understand the GHG emission reduction contributions of BSS in different cities, we analyzed the modeling results from two perspectives: the total GHG emission reduction from a BSS in each city and the unit emission reduction by trip, dock, bike, and mile travelled (Section 4.1), as well as the spatial distribution of the reduced GHG emissions (Section 4.2).

4.1. Overall environmental benefits of the BSS

Table 3 listed the basic statistics and modeling results of the bike share trips for each city. The BSS in New York, Chicago, Boston, and Washington, DC are the four largest station-based systems in the United States (NACTO, 2017). In year 2016, these systems generally have more than 150 stations and generated more than one million bike share trips. These larger systems also have a greater system diameter (indicating spatial coverage), which is defined as the longest Euclidian distance between any two of the bike share stations in a BSS. The total GHG emission reduction in 2016 in these four larger systems are much higher than those in the other four smaller systems (Fig. 4a). New York city has the largest amount of total GHG emissions reduction: with 10,262,649 bike share trips taken in 2016, New York's BSS contributed to 5417 tons of GHG emission reduction (in CO_2-eq). In contrast, Seattle's BSS only reduced 41 tons of GHG emissions. One thing to note is that, we estimate the emission reduction of round trips based on the assumption that these trips have the same emission reduction per trip. Take New York as an example, excluding the round trips would change the total GHG emission reduction to 5305 tons CO_2-eq. Although the round trips only take up a very small portion (2% in New York), this part of estimation could be improved if the detailed trajectory data is available.

The emission reduction per trip ranges from 280 to 590 g CO_2-eq (Table 3). The total GHG emission reduction is found to correlate linearly to the ridership (total count of trips) in each city with an R squared of 0.998 (Fig. 4b). The linear regression also shows that the marginal emission reduction of one additional trip is 533 g CO_2-eq. Similar linear relationship is also found between the total GHG emission

Table 2
GHG emissions from the transportation sector in the eight evaluated cities.

City	GHG emissions from transportation sector (million MT CO_2-eq/year)	Year of the data	Data Source
Seattle	3.58	2014	2014 Seattle Community Greenhouse Gas Emissions Inventory (E.P and Kevin, 2014)
Los Angeles	33.74	2010	2015 Environmental Report Card for Los Angeles (Gold et al., 2015)
San Francisco	1.98	2016	2016 San Francisco Geographic Greenhouse Gas Emissions Inventory at a Glance (Program, 2015)
Philadelphia	3.96	2012	Philadelphia Citywide Greenhouse Gas Inventory, 2012 (Spring, 2015)
Boston	1.64	2013	City of Boston Community Greenhouse Gas Inventory 2005-2013 (Boston, 2014)
Washington DC	1.74	2013	District of Columbia Greenhouse Gas Inventory Update 2012-2013 (I. Of, 2012)
Chicago	8.05	2015	City of Chicago Greenhouse Gas Inventory Report, 2015 (Report, 2017)
New York	15.48	2015	Inventory of New York City Greenhouse Gas Emission in 2015 (Pasion et al., 2017)

Table 3
Basic statistics and analysis results of the bike share systems.

City	Seattle	Los Angeles	Bay Area	Philadelphia	Boston	Washington D.C.	Chicago	New York
Total trips in 2016	102,606	184,345	193,506	499,306	1,236,199	2,562,718	3,595,383	10,262,649
Total stations	59	64	74	119	327	407	581	687
Total docks[a]	1,038	1,352	1,357	2,280	5,729	6,720	9,987	20,390
Docks per station[a]	17.59	21.12	18.34	19.16	17.52	16.51	17.19	29.68
Percentage of stations with public transit access	57.63%	67.19%	93.24%	100.00%	96.94%	71.01%	98.28%	57.79%
Percentage of trips used for simulation[b]	91.64%	89.40%	97.58%	91.90%	96.87%	95.36%	95.73%	97.94%
NHTS trips used for simulation[c]	1,619	49,427	29,284	3,350	3,293	14,199	6,096	40,631
Total number of bikes[d]	463	763	421	1,023	1,797	4,305	5,746	10,486
System diameter (miles)[e]	4.71	2.85	2.33	5.06	8.57	14.28	23.29	11.17
Average number of trips per station	1,739	2,880	2,615	4,196	3,780	6,297	6,188	14,938
Average number of trips per dock	99	136	143	219	216	381	360	503
Average number of trips per bike	222	242	460	488	688	595	626	979
Median of trip distance (miles)	1.16	1.2	1.39	1.46	1.43	0.91	1.39	1.31
Average trip distance (miles)	1.27	1.23	1.56	1.7	1.72	1.02	1.71	1.68
Average speed of bike share trips (miles/hour)	6.87	6.24	7.97	7.28	8.21	7.55	7.71	7.92
Percentage of commuting trips	51.92%	48.45%	52.30%	54.37%	52.57%	52.85%	52.88%	46.95%
Total GHG emission reduction (without round trips, ton CO_2-eq)	37.21	46.56	67.43	234.83	668.11	1,275.88	2,000.89	5305.13
Total GHG emission reduction (including round trips, ton CO_2-eq)[f]	40.60	52.08	69.10	255.51	689.66	1,338.00	2,090.05	5,416.68
Percentage of GHG emission reduction from commuting trips (without round trips)	57.70%	53.93%	60.89%	60.50%	60.14%	61.49%	60.93%	57.16%
Average emission reduction (g CO_2-eq) per mile travelled	324.57	286.59	298.75	340.89	345.02	329.69	352.66	329.48
Average emission reduction (g CO_2-eq) per trip	395.73	282.50	357.12	511.73	557.89	522.10	581.32	527.81
Average emission reduction (ton CO_2-eq) per station	0.69	0.81	0.93	2.15	2.11	3.29	3.60	7.88
Average emission reduction (ton CO_2-eq) per dock	0.04	0.04	0.05	0.11	0.12	0.20	0.21	0.27
Average GHG emission reduction (ton CO_2-eq) per bike	0.09	0.07	0.17	0.26	0.35	0.28	0.37	0.49

Notes:
a. For Seattle, Bay Area, Boston, and Chicago, the station capacity (number of docks of each station) information is extracted from the station information data (year 2016) released by the system operator; while such data is not available for other four cities: for Los Angeles, Philadelphia, and New York, the station capacity information is obtained from a station status snapshot (real-time station status) in Oct. 15, 2017 from the operators' website; for Washington, DC, the station capacity information is extracted from the bike share station information (Aug. 20, 2018) in Open Data of Washington, DC government[1] . Although the information for the latter four cities mentioned is not exact the station information for year 2016, it can reflect the general level of station capacity of these systems.
b. Round trips are excluded in the simulation.
c. Only NHTS survey records in the urban area of the corresponding city were used in our analysis.
d. All bikes that showed up in the trip data in year 2016.
e. The system diameter is the longest Euclidian distance between any two bike share stations of a BSS at the end of year 2016. Data is collected from (Kou and Cai, 2019).
f. Emission reduction for those round trips is calculated by number of trips multiplied by emission reduction per trip of the those one-way trips.

reduction and the total number of bikes (R squared: 0.970, Fig. 4c). Each bike can contribute to an average of 0.07 to 0.49 tons of GHG emission reduction depending on the system (Table 3), while the marginal emission reduction of adding one more bike into the system is 0.51 tons CO_2-eq in a year. In the same way, we can observe a linear relationship between the total GHG emission and the total number of docks (R squared: 0.984, Fig. 4d). The marginal emission reduction of adding one more dock into the system is 0.28 tons CO_2-eq in a year. Also note that in the fitted linear models, the marginal emission reduction (gradient) is mainly influenced by the four larger systems. For the smaller systems such as Seattle and Los Angeles which have less bikes and docks, they also exhibit much lower per-bike (less than 0.1 ton CO_2-eq per bike) and per-dock (less than 0.1 ton CO_2-eq per dock) emission reduction than those larger systems (more than 0.2 ton CO_2-eq per bike and 0.25 ton CO_2-eq per dock). The bikes and docks are utilized less efficiently in these smaller systems. Each bike/dock in these smaller systems on average served less trips compared with that in larger systems, as shown in Table 3. For example, each bike and dock in Seattle on average served 99 trips and 222 trips in 2016, respectively; while the trips per bike and trips per dock could be as high as 503 trips

[1] Capital Bike Share Locations, Open Data of Washington, DC, http://opendata.dc.gov/datasets/capital-bike-share-locations.

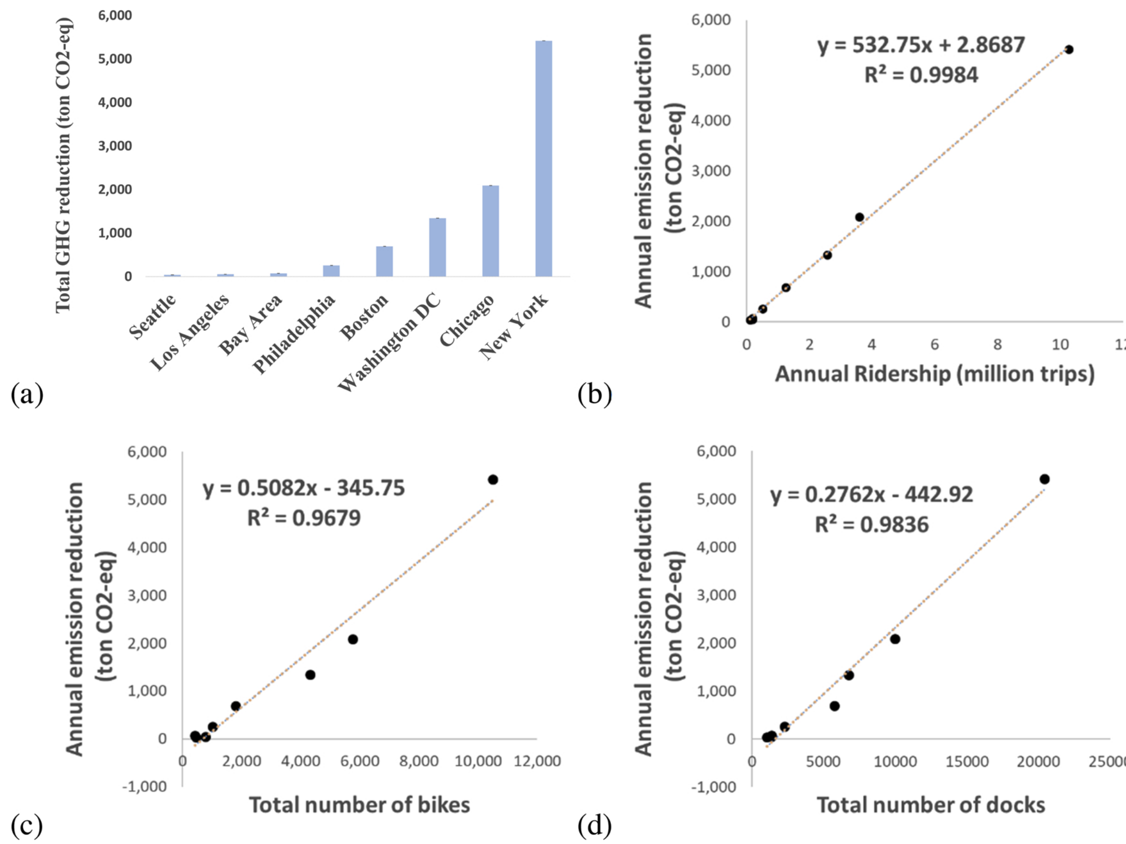

Fig. 4. Total GHG emission reduction in 2016 of the eight systems (a) and its relationship with (b) annual ridership (count of trips), (c) total number of bikes, and (d) total number of docks.

and 979 trips, respectively in New York. The reasons for this need to be further investigated in future research. Regarding trip purpose, commuting trips take up about half of the total trips in the eight cities, ranging from 47% to 54% (Table 3). However, the GHG emissions reduction from commuting trips takes up a higher share (54%–61%) than that from leisure trips, due to combined reasons of travel distance and mode share distribution. Take Los Angeles as an example, the average distance of commuting trips is 1.08 miles, while that of leisure trips is only 0.90 miles. On the other hand, higher proportion (64.3%) of commuting bike share trips are car-replacing trips than that of leisure trips (60.3% car-replacing trips).

In order to understand the relative environmental benefits of BSS contributed to these cities, we also compared the emission reduction from BSS to the total emission from the transportation sector in each city (Fig. 5a). Generally, the emission reduction from BSS only makes up a small part of the total GHG emission from the transportation sector, which ranges from 0.0002% to 0.007% for the four smaller systems and 0.026% to 0.077% for the four larger systems. Among these cities, Los Angeles has the lowest ratio because it has high transportation sector emissions but a relatively small BSS.

The GHG emission reduction per mile travelled varies among different cities (Fig. 5b): Chicago, Boston, and Philadelphia have the best performance, which reduced 352.7 g, 345.0 g and 340.9 g CO_2-eq for each mile of bike share trip travelled, respectively. From Fig. 5c, we can observe that in these three cities, higher percentage of bike share trips replaced car trips (74% for Chicago, 75% for Boston, and 75% for Philadelphia), which is the main reason that they have better GHG emission reduction per mile travelled. However, the GHG emission reduction per bike share trip in Chicago is slightly higher because Chicago's larger bike share station network allows the users to travel longer distance. Generally, the majority of the GHG emission reduction are contributed by relatively short trips (less than 5 miles, Fig. 5d). As shown in Table 3, the average and median of bike share trip distance are both less than 2 miles for all the cities. However, in larger systems which have a larger spatial coverage of bike share stations, higher proportion of emission reduction was from trips within 2–5 miles instead of 0–2 miles, compared to those smaller systems. Therefore, the bike share station network plays an important role in affecting the users' travel pattern and the BSS's ability to reduce GHG emissions.

4.2. Spatial distributions of GHG emission reduction

To better understand how locations of the bike share stations affect the GHG emission reductions, we also analyzed the spatial patterns of station level emission reduction (to save the computation time, the analysis in this part is based on the trip data in August 2016 instead of the entire year's data). This information could potentially help the decision making in siting future bike share stations. The GHG emission reduction also exhibits geographic variances within a bike share system. We allocated the GHG emission reduction of each trip to its start station (since the origin of a trip generally reflects the demand of travel) and plotted the GHG emission reduction by station on the map. In the case of Los Angeles and Philadelphia, stations located in the center of the city reduced more GHG emissions (Fig. 6(a1) and (b1)), because of the larger ridership (count of trips) at these stations. The GHG emission reduction per trip exhibits the reverse pattern: each trip reduced less GHG emission if they started from the city center (Fig. 6(a2) and (b2)). This is because trips originated from the city center are mostly short and more likely to replace walking, while trips made from areas away from city center are relatively longer. Fig. 6(a3) and (b3) shows that higher proportion of bike share trips replaced vehicle trips in the stations that are away from the city center. Generally, all the eight cities show similar spatial patterns regarding GHG emission reduction (see Fig. B1 in the Appendix A for the figures of the other

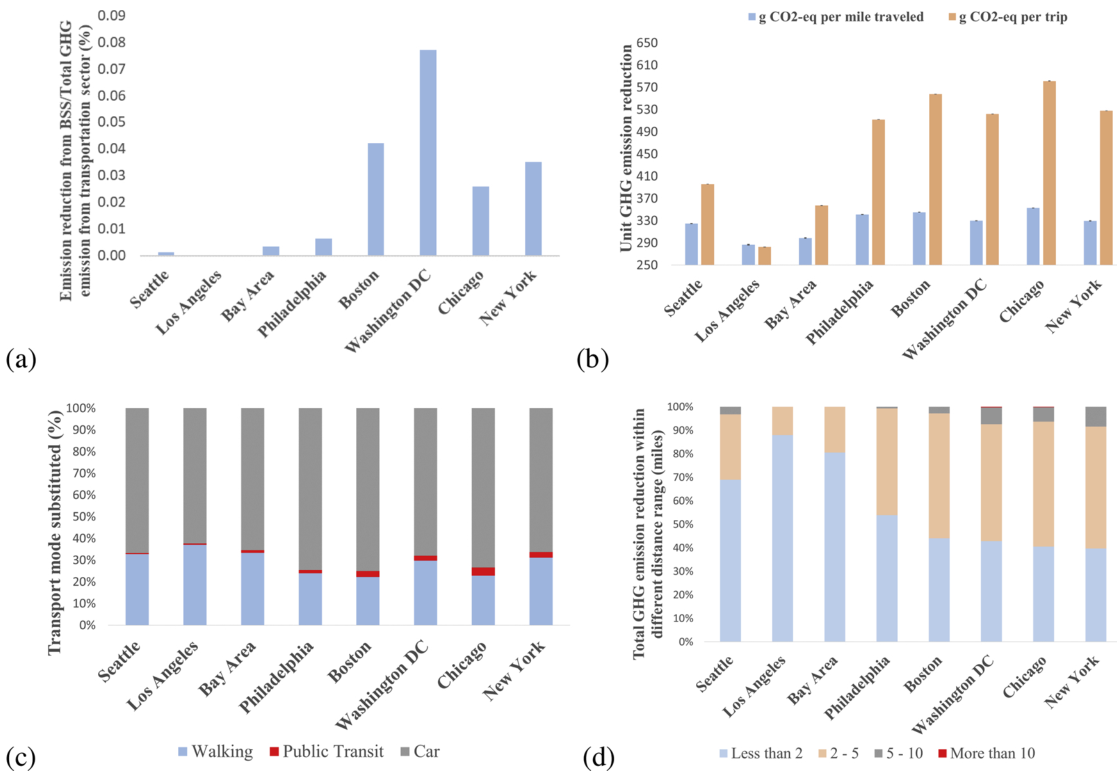

Fig. 5. GHG emission reduction in the eight cities: (a) GHG emission reduction from BSS/Total GHG emission from the transportation sector (%), (b) emission reduction per mile travelled and per trip, (c) percentage of trips replaced by bike share, (d) emission reduction of BSS in different distance range.

cities). These results show that, although the city center has more BSS users than areas away from city center, a higher proportion of these users adopt bike share as a substitution of walking. In order to improve the environmental benefits from the BSS, BSS operators needs to either attract more vehicle users in the city center to switch to bike share, or strategically locate and install more stations in the areas that are away from the center of the city.

5. Sensitivity analysis

In our model, there are several major factors or assumptions that may impact the results: speed threshold to determine the trip purpose, buffer zone radius for the public transit accessibility, transportation mode distribution from the NHTS data, and the emission factors used in our analysis. Therefore, we conducted a sensitivity analysis to evaluate how sensitive the results are to these factors. For the speed threshold, buffer zone radius, and transportation mode distribution, we varied the parameters from 70% to 130% of the values used in the original model, and compared the total emission reduction from the BSSs in Bay Area and Philadelphia (Fig. 7). For the emission factors, we used the lowest and the highest values for vehicle and public transit in Table 1 to generate the lower and upper bounds for the emission reduction. Additionally, since the emission factor of bicycling in (Dave, 2010) does not consider the emissions generated from bike share station (including docks) manufacturing and bike rebalance, we also add the unit emissions from bike share stations and rebalance from the work of Luo et al. (2019) to evaluate the influence from station infrastructure and operation.

In the original model, we used the average trip speed as the speed threshold to determine whether a trip is for commuting or leisure purposes. So the sensitivity analysis tested the result variations using a speed threshold that ranges from 70% to 130% of the average speed in each city (as listed in Table 3, the average speed varies by city). A buffer zone radius of 200 m was originally used to extract the public transit accessibility information. Accordingly, the sensitivity analysis tested the result variations using a buffer zone radius ranging from 140 m to 260 m. For the distributions of transportation mode choices, we modified the probability of the car trips by −30% to +30% of the original value, and then evenly distributed the changes to walking and public transit (for example, if the mode distribution for a trip at given distance is 60% by car, 30% by walking, and 10% by public transit, the −30% scenario will decrease the car trip probability to 42% and increase the probability of walking and public transit to 39% and 19%, respectively). These scenarios will represent cases where the bike share users take less or more vehicle trips than an average person. The focus of these different scenarios is on vehicle trips because the vehicle trips dominate the potential GHG emission reduction (Fig. 5c). For the emission factors, we used the travelled mileage as the weights to calculate the weighted average for vehicle and public transit. In this part, instead of using the weighted average, we use the lowest value (sedan – 382 g $CO_{2\text{-eq}}$/passenger mile travelled (PMT) for vehicle, and BART – 136 g $CO_{2\text{-eq}}$/PMT for public transit) and the highest value (pickup – 619 g $CO_{2\text{-eq}}$/PMT for vehicle, and Bus average – 326 g $CO_{2\text{-eq}}$/PMT for public transit) to calculate the emission reduction in two extreme cases (Table 4). In addition, in order to evaluate the influence of the emissions from stations and rebalance, we add the unit emission of 95 g $CO_{2\text{-eq}}$/PMT (from Luo et al., 2019) for bike share stations (57 $CO_{2\text{-eq}}$/PMT, including docks) and rebalance (38 $CO_{2\text{-eq}}$/PMT) to the original emission factor of 33 g $CO_{2\text{-eq}}$/PMT (from (Dave (2010)) for the emissions from bike, road, and human breath, which results in a modified emission factor of 128 g $CO_{2\text{-eq}}$/PMT for bicycling using shared bikes from station-based BSS. It is notable that the emission factors from Luo et al. (2019) reflect the average operational conditions of a station-based system in the U.S.. Because the modified bicycling emission factor is the sum of emission factors from two studies, which may rely on different data source and assumptions, we only consider emissions from station and rebalance in the sensitivity analysis. In the sensitivity analysis, we use the same emission factors of walking, public transit, and vehicles as stated in Table 1.

The sensitivity analysis shows that the total emission reduction is

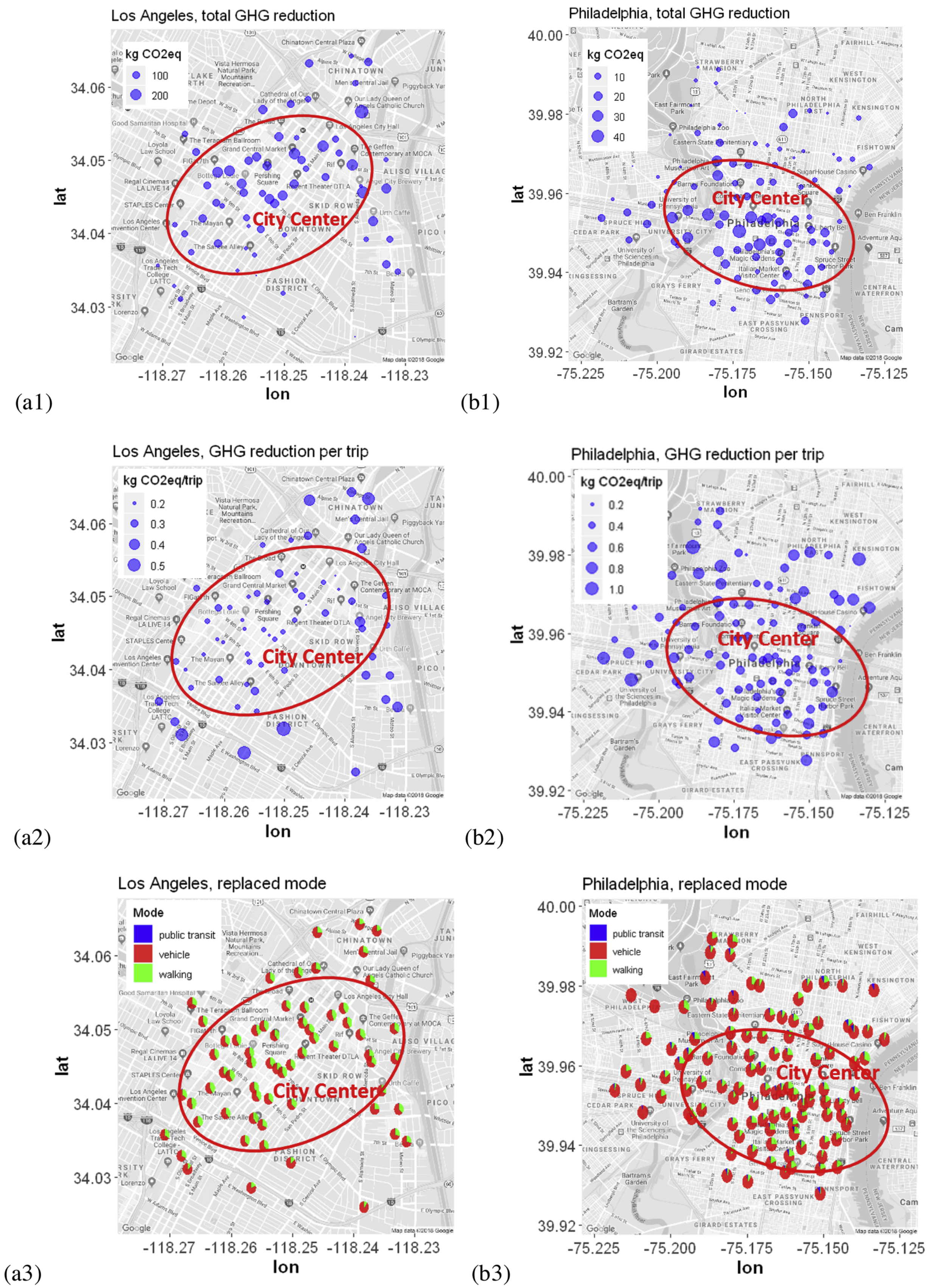

Fig. 6. Geographic distribution of GHG emission reduction and mode substitution in (a) Los Angeles and (b) Philadelphia: 1. Total emission reduction of each station in Aug. 2016, 2. Emission reduction per trip, 3. Pie chart of mode substitution of each station.

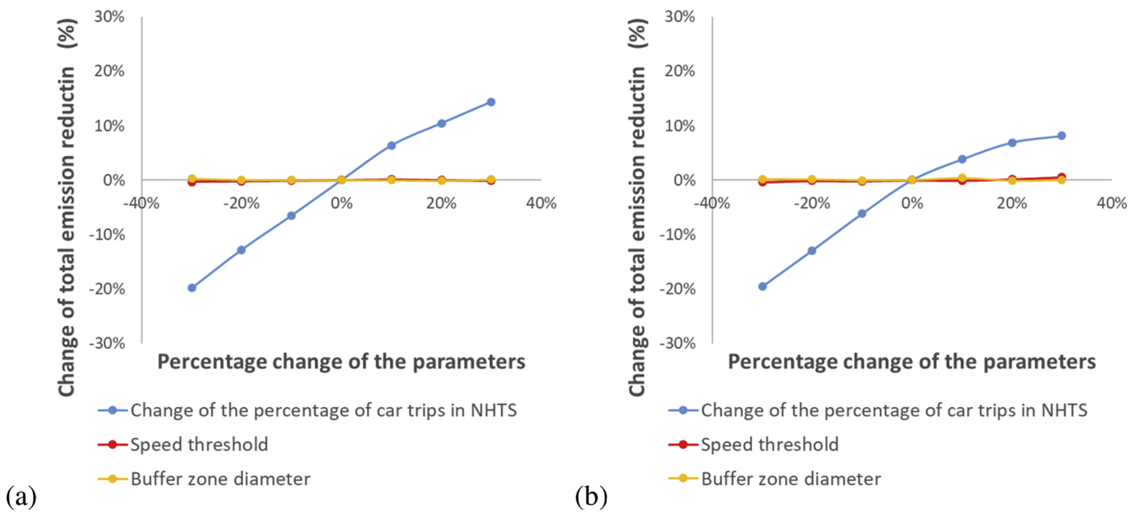

Fig. 7. Change of total emission reduction by varying parameters in the model: (a) Bay Area, (b) Philadelphia.

the most sensitive to the emission factors and mode choice distribution change, but stays relatively stable when we change the speed threshold and buffer zone diameter. Therefore, it is critical to obtain more accurate information about BSS user's transportation choice to refine the estimated environmental benefits of BSS. It is notable that, for longer trips (e.g., over 5 miles), driving is the dominant mode (e.g., with a probability of 90%). When we evaluate the +30% scenario, the probability of driving would exceed 100%. In these cases, we capped the probability of vehicle trips to be 100% and all trips would replace vehicle trips). This is why the line for the mode distribution change is not linear in Fig. 7 (the positive side is curved due to the capped 100% probability). When we only consider changing the percentage of vehicle trips by −30%–0% and fit a linear regression, the linear trend line has a gradient of 0.6567 in Bay Area (R squared 0.9994) and a gradient of 0.6542 in Philadelphia (R squared 0.9996). These results show that, if the bike share users take 10% less vehicles trips than an average person (whose travel pattern is captured in the NHTS data), the total emission reduction of the system will decrease by 6.6% and 6.5% in Bay Area and Philadelphia, respectively.

When we change the emission factors in the analysis (Table 4), the total emission reduction of all the studied cities decreased by 14–16% for the low emission factor case and increased by 41–43% for the high emission factor case. This provides a lower and upper bound of the total emission reduction given the uncertainty of the emission factors in different cities. It is worth mentioning that it is unlikely that we can expect the high emission factor case to happen, which assumes that all the replaced vehicle trips used pickups. When we use the modified emission factor for bicycling (adding emissions of stations and rebalance from Luo et al. (2019)), the total emission reductions are lowered by around 30% (Table 4). Therefore, the emissions from bike share stations and rebalance operation also play an important role for the environmental performance of a BSS.

6. Conclusions and limitations

We proposed a Bike Share Emission Reduction Estimation Model (BS-EREM) to evaluate the environmental benefits of bike share systems in eight cities in the United States. The BS-EREM model considers the trip distance, trip purpose, trip start time, public transit accessibility around each bike share station, as well as the historical distributions of transportation mode choices in different cities. Although our analysis only focused on the reduction of GHG emissions, the same approach can be applied to quantify other environmental impacts (e.g., NOx, PM2.5), using appropriate emission factors as inputs.

The total annual GHG emission reduction in the eight systems evaluated in this study shown linear relationships with the overall system size and ridership. According to our modeling result, as the largest bike share program in the United States, New York's Citi Bike Share contributed to 5417 tons of GHG emission reduction in year 2016. In contrast, Seattle's BSS only reduced 41 tons of GHG emissions in 2016. However, the emission reduction contribution from BSS currently is still relatively limited (less than 0.1%) in the context of the total GHG emissions from the entire transportation sector in these cities. Expanding the BSS system size (e.g., building more stations and docks, launching more bikes) can help increase the GHG emission reduction by generating more bike share trips. Another thing to note is that, for Los Angeles, even though the overall traffic volume is at the top level in the U.S. (Gold et al., 2015), the usage intensity (trips per bike, per station, and per dock) of its bike share system is relatively low, which means that bike share is not as popular there as in New York City. Improving biking infrastructures such as bike lanes can potentially help improve the use of bike share (United Nations Environment Programme (UNEP), 2018).

In addition, the environmental benefit is also influenced by the mode substitution, i.e., which transportation mode does the bike share

Table 4
Change of total emission reduction by varying the emission factors for public transit, vehicles and.

Change (%) of total GHG emission reduction	Seattle	Los Angeles	Bay Area	Philadelphia	Boston	Washington DC	Chicago	New York
Using lower bound of the emission Factors for public transit and vehicles	−14.7%	−14.7%	−15.0%	−15.2%	−15.7%	−15.6%	−15.9%	−15.7%
Using upper bound of the emission Factors for public transit and vehicles	43.2%	43.3%	42.8%	42.5%	41.8%	41.9%	41.4%	41.7%
Using modified emission factor for bicycling	−29.3%	−33.1%	−31.8%	−27.9%	−27.5%	−28.8%	−26.9%	−28.8%

trip replace. In our analysis, the bike share is mainly replacing trips made by vehicles and walking, while the distribution of replaced modes varies among different cities. The percentage of bike share trips replacing car trips is higher in Philadelphia and Chicago, compared to other cities, leading to higher GHG emission reduction per mile travelled. Such variation is mainly due to the difference of transportation mode choice preferences in these cities and the spatial coverage of the BSS, which impacts trip distances.

Furthermore, the bike share system layout matters. The GHG emission reduction is mainly contributed by short bike share trips (less than 5 miles). Bike share stations in the center of a city generally have higher total GHG emission reduction but lower unit GHG emission reduction (per trip travelled). The replaced transportation modes also exhibit spatial variations: a higher proportion of bike share trips replaced car trips in areas further away from city center than in the downtown area. Therefore, the unit emission reduction potential (per mile) from BSS could also be influenced by its bike share station network (i.e., how many stations are located in downtown versus areas away from city center, in the business centers versus leisure areas etc.). In order to improve the unit environmental benefit of bike share (per trip or per mile travelled), the system operators need to attract more vehicle users in the city center to switch to bike share, and also attract more users in the areas away from the city center. In order to achieve these goals, the cities need to improve biking safety (for instance, having more bike lanes) and the convenience of using bike share (such as simplifying the process of checking out and returning bikes), which would make bike share a more competitive transportation mode. The stations that are further away from city center are often distributed less densely than in city center, which can be observed in Fig. 6. The difficulty of finding a nearby bike share stations in areas away from city center may discourage users to choose bike share. Installing more stations in these regions could help increase bike share usages but will increase the emissions from the station manufacturing. Having a dockless system in areas with less demand can reduce the need of stations and the associated emissions but may increase emissions from rebalancing dispersed bikes. Future study considering these factors at the station level is needed to further quantify the tradeoffs and assess the net benefits of different approaches. In addition, as indicated by Luo et al. (2019) and our sensitivity analysis results, improving the rebalance efficiency can further improve the sustainability of a BSS. This can be achieved by optimizing the station location and capacity (Park and Sohn, 2017; García-Palomares et al., 2012; Romero et al., 2012), applying more efficient rebalance vehicle routing algorithms (Chiariotti et al., 2018; Alvarez-Valdes et al., 2016), and using more environmental-friendly vehicles (e.g., electric vehicles) instead of internal combustion engine vehicles for bike rebalancing.

In the case of a dockless BSS or hybrid BSS (combining dockless and station-based BSS in the same system), the proposed BS-EREM can still be applied. To reduce the computational intensity due to the dispersed bikes, the service area can be partitioned into small grids. Then the center of each grid can be modelled as a pseudo station. All trips starting (ending) within a grid can be marked as starting (ending) at the corresponding pseudo station. We can also check whether there are public transit facilities within the grid to determine the public transit accessibility. The grid size should be similar to the spatial coverage of an existing bike share station. Such map gridding method has also been used in existing studies (such as in Zhang and Mi (2018), Pan et al. (2018)) to model a dockless system.

Although this study has the merit of proposing a more detailed model to quantify the environmental benefits of BSS programs, there are three major limitations that we would like to point out. First, our results are based on the assumption that the BSS users have the same travel pattern as an average person in the urban area of each city. The sensitivity analysis has showed that the results are very sensitive to the transportation mode distribution. Therefore, future research collecting more detailed transportation mode distribution specifically from the BSS users can help improve the results accuracy. Additionally, other factors, such as weather and user demographics may also impact the mode substitution decisions. For example, we only evaluated whether public transit stations and stops are available near the bike share stations in the model but did not consider the actual schedule and routes of the public transit networks. It is possible that the users may have to wait for a long time or have to make too many transfers between two bike share stations having access to public transit, making the substitution of public transit less feasible. When surveying BSS users on mode substitutions by bike share trips, it is important to focus the question on a specific trip, so mode substitution can be linked to trip distance, purpose, start time, origin, and destination, etc. Such information would also benefit the system operators and city planners to optimize the system and attract more vehicle users to switch to bike share. Second, the emission factor we used in this study may overestimate the environmental benefits of bike share trips since emissions from other system infrastructure and operations such as bike share station and bike rebalancing are not included. Our sensitivity analysis showed that the emissions from bike share stations and rebalance could decrease the overall GHG emission reduction by around 30%. Emission factors from a more comprehensive life cycle assessment for different transportation modes, including bike share, tailored to each city would help improve the estimation using BS-EREM. Also, the system operators of BSS may apply different rebalancing schedules and use different vehicles (e.g., trucks, vans, or electric tricycles). Therefore, to obtain more accurate estimation, more detailed data on system operations in different cities are required. In addition, there could be other factors affecting the emission factors, such as the increased emission from extensive usage of air conditioning in vehicles in certain seasons, different driving behaviors, and vehicle ages etc., which are not reflected in our study. Furthermore, different BSS may use bikes and stations that are manufactured with different materials or processes and apply different maintenance and disposal practices. These factors will also affect the system's GHG emissions and require more detailed data to be further addressed. Third, this study only considers the cases that bike sharing can substitute the entire trip. Because the data only record trip start and end stations, we have no information on the actual trip origin and destinations. Bike share could also serve as the "last mile" solution and contribute to substituting a one-mode trip (e.g., car trip) with a multi-modal trip (e.g., bike-train-bike mobility chain as mentioned in (United Nations Environment Programme (UNEP), 2018). Due to the lack of data to support such analysis, the multi-modal trip substitution is not considered, which could underestimate the environmental benefits of bike share. Data that tracks trips across different transportation modes (e.g., smart cards that can be used for both public transit and bike share) and more targeted survey questions could help further analyze these trips.

Declaration of Competing Interest

The authors have no financial conflict of interest to declare.

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Appendix A

Detailed procedures of BS-EREM

The BS-EREM involves the following variables

Detailed procedures of BS-EREM

The BS-EREM involves the following variables:

T: Bike share trip data in a city C in the study period (with n trips in total);
T_i (ST_i, $Dist_i$, Dur_i, P_i, $transit_{Oi}$, $transit_{Di}$): Trip information of the ith trip in T, i= 1, 2, … , n;
N (ST_N, $Dist_N$, P_N, $Mode_N$): a set of NHTS trips in the same city C;

where

ST: trip start time interval, indicates the time slots (out of the 6 time intervals) that the trip start time lies in;
Dur: duration;
$Dist$: distance;
$Transit_O$: public transit accessibility around bike share trip origin (True/False);
$Transit_D$: public transit accessibility around bike share trip destination (True/False);
P: trip purpose (Commuting/Leisure);
$Mode$: transportation mode of the NHTS trip (Walking/Vehicle);

$Speed_i$: The speed of the ith bike share trip;

$SpeedThreshold$: The speed threshold to determine the trip purpose (commuting/leisure) of a bike share trip (in this study, the speed threshold is the average speed of all bike share trips T);

N_{subset}: A subset of the NHTS trips that meets a certain condition;

$N_{subset,\ Mode\ =\ M}$: NHTS trips in N_{subset} with $Mode_N$=M;

E_M: Emission factor for transportation mode M, where $M \in$ {Biking, PublicTransit, Walking, Vehicle};

S_M: Mode share of transportation mode M in N_{subset}, where $M \in$ {PublicTransit, Walking, Vehicle};

$ReplacedMode_i$: Replaced mode of the ith bike share trip in the simulation;

R: A random number generated in the simulation process ($0 \leq R \leq 1$);

ER_i: Emission reduction of the ith bike share trip in the simulation;

ER_{Total}: Emission reduction of all bike share trip T;

The algorithm below describes the details of BS-EREM in one round of simulation

Algorithm for bike share trip mode substitution simulation

/* First read in the data and parameters. */
READ NHTS trips N
READ bike share trips T
READ $SpeedThreshold$
READ emission factors E_{Biking}, $E_{PublicTransit}$, $E_{Walking}$, $E_{Vehicle}$

/* Simulate the mode replacement for each trip and determine the emission reduction. */
FOR each trip T_i (i= 1, 2, … , n)
    COMPUTE $Speed_i = Dist_i/Dur_i$
    IF $Speed_i \geq$ SpeedThreshold **THEN**
        P_i = Commuting
    ELSE
        P_i = Leisure
    END

    SUBSET NHTS trip data N that trips in N_{subset} have $ST_N = ST_i$, int($Dist_N$) = int($Dist_i$), and $P_N = P_i$
    /* The NHTS trip subset N_{subset} have identical trip information (time interval, distance, and purpose with bike share trip T_i; this study uses a 1-mile distance interval to subset NHTS trips. */

    SUBSET $N_{subset, Mode = M}$ from N_{subset} where all trips in $N_{subset, Mode = M}$ have $Mode_N$=M|, for M in {PublicTransit, Walking, Vehicle}
    COMPUTE the transportation mode share: $S_M = |N_{subset, Mode = M}| / |N_{subset}|$, for M in {PublicTransit, Walking, Vehicle}
    /* $|N_{subset, Mode = M}|$ and $|N_{subset}|$ are the number of the trips in dataset $N_{subset, Mode = M}$ and N_{subset}, respectively.*/
    IF $transit_{Oi}$= False **OR** $transit_{Di}$ = False **THEN**
        $S_{PublicTransit} = 0$
        $S_M = |N_{subset, Mode = M}| / (|N_{subset}| - |N_{subset, Mode = PublicTransit}|)$, for M in {Walking, Vehicle}
    /* When there is no public transit facilities around trip origin or destination, adjust the mode share of public transit to be zero so the bike share trip cannot replace a public transit trip.*/
    END

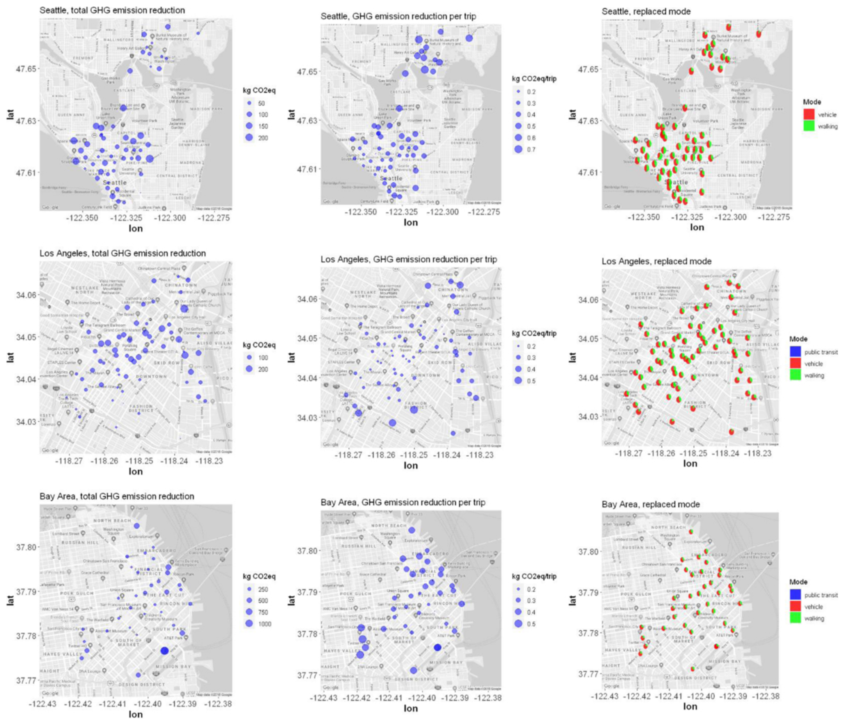
    GENERATE a random number R ($0 \leq R \leq 1$)
    IF $R \leq S_{PublicTransit}$ **THEN**
        $ReplacedMode_i$ = PublicTransit
    ELSE IF $S_{PublicTransit} \leq R \leq S_{PublicTransit} + S_{walking}$ **THEN**
        $ReplacedMode_i$ = Walking
    ELSE
        $ReplacedMode_i$ = Vehicle
    END

    COMPUTE $ER_i = (E_{ReplacedModei} - E_{Biking}) \times Dist_i$ /* Calculate emission reduction of trip T_i */
END

COMPUTE $ER_{total} = \sum_{i=1}^{n} ER_i$, i= 1, 2, … , n /* Calculate the total emission reduction of all trips T. */

Appendix B

Spatial distribution of the GHG emission reduction for all the eight cities



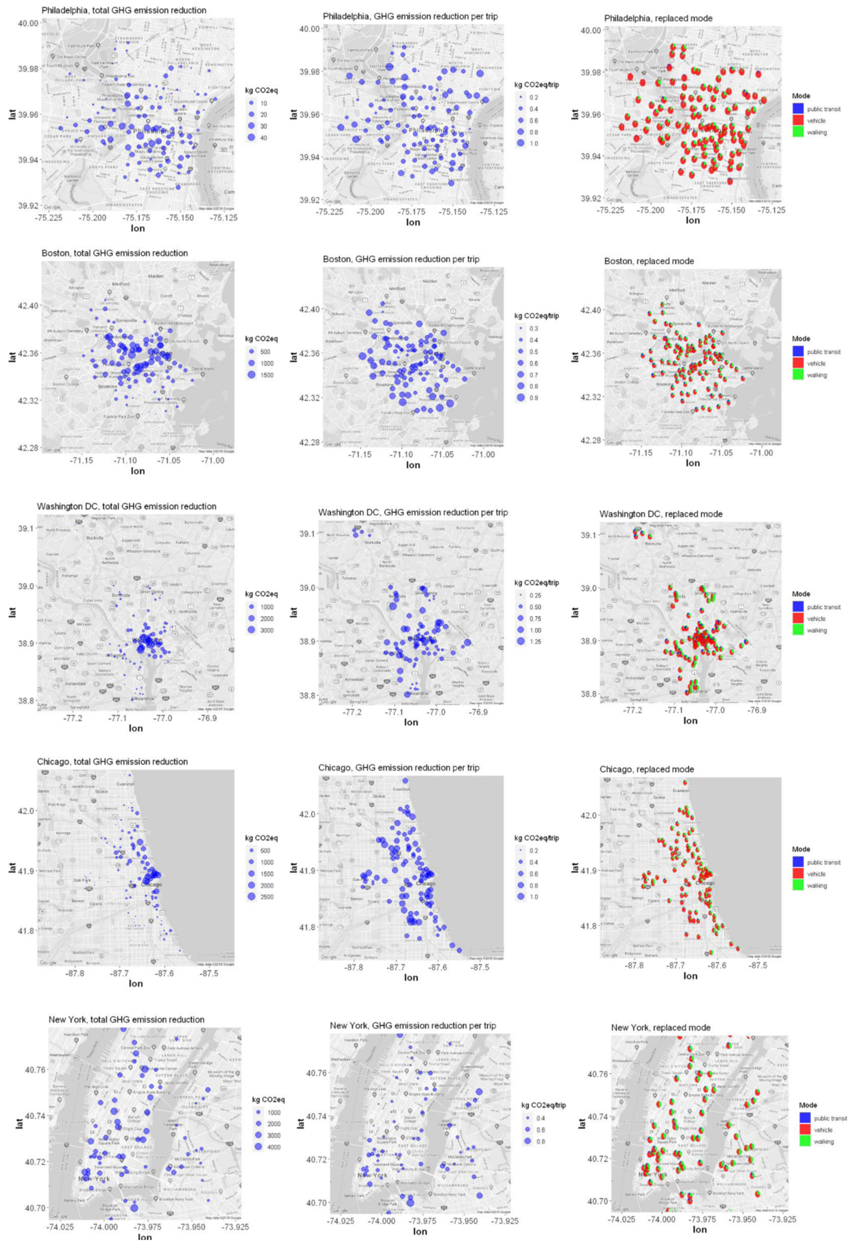


Fig. B1 Spatial distribution of the emission reduction in different cities (100 stations are randomly selected and visualized in the four larger systems to avoid overlap in visualization).

References

Alter, L., 2008. Bikes Faster Than Subway or Car, Seven Years Running, TreeHugger. https://www.treehugger.com/bikes/bikes-faster-than-subway-or-car-seven-years-running.html. (Accessed 18 November 2017).
Alvarez-Valdes, R., Belenguer, J.M., Benavent, E., Bermudez, J.D., Muñoz, F., Vercher, E., Verdejo, F., 2016. Optimizing the level of service quality of a bike-sharing system. Omega (United Kingdom) 62, 163–175. https://doi.org/10.1016/j.omega.2015.09.007.
Anderson, N.A., 2015. Portland Bicycle Share Health Impact Assessment.
Borecki, N., Rawls, B., Buck, D., Reyes, P., Al, E., 2012. Virginia Tech Capital Bikeshare Study.
Boston, G., 2014. GHG Change 2012-2013.
Buehler, R., Hamre, A., 2015. Business and bikeshare user perceptions of the economic benefits of capital bikeshare. Transp. Res. Rec. J. Transp. Res. Board. 2520, 100–111. https://doi.org/10.3141/2520-12.
Bullock, C., Brereton, F., Bailey, S., 2017. The economic contribution of public bike-share to the sustainability and efficient functioning of cities. Sustain. Cities Soc. 28, 76–87. https://doi.org/10.1016/j.scs.2016.08.024.
Chiariotti, F., Pielli, C., Zanella, A., Zorzi, M., 2018. A dynamic approach to rebalancing bike-sharing systems. Sensors (Switzerland) 18, 1–22. https://doi.org/10.3390/s18020512.
Cohen, A., Shaheen, S., 2018. Planning for Shared Mobility. https://doi.org/10.7922/G2NV9GDD.
Dave, S., 2010. Life Cycle Assessment of Transportation Options for Commuters. pp. 1–16.
Drynda, P., 2014. Development of bike share systems and their impact on the sustainability of urban transport. Case study of Opole Bike. Cent. East. Eur. J. Manag. Econ. 2, 199–215.
E.P, Kevin, T., 2014. 2012 Seattle Community Greenhouse Gas Emissions Inventory. . http://www.seattle.gov/Documents/Departments/OSE/2012GHG_inventory_report_final.pdf.
Faghih-Imani, A., Anowar, S., Miller, E.J., Eluru, N., 2017. Hail a cab or ride a bike? A travel time comparison of taxi and bicycle-sharing systems in New York City. Transp. Res. A Policy Pract. 101, 11–21. https://doi.org/10.1016/j.tra.2017.05.006.
Fishman, E., Washington, S., Haworth, N., 2014. Bike share's impact on car use: evidence from the United States, Great Britain, and Australia. Transp. Res. D Transp. Environ. 31, 13–20. https://doi.org/10.1016/j.trd.2014.05.013.
Fuller, D., Gauvin, L., Kestens, Y., Daniel, M., Fournier, M., Morency, P., Drouin, L., 2013. Impact evaluation of a public bicycle share program on cycling: a case example of BIXI in Montreal, Quebec. Am. J. Public Health 103, 85–92. https://doi.org/10.

2105/AJPH.2012.300917.
García-Palomares, J.C., Gutiérrez, J., Latorre, M., 2012. Optimizing the location of stations in bike-sharing programs: a GIS approach. Appl. Geogr. 35, 235–246. https://doi.org/10.1016/j.apgeog.2012.07.002.
Gold, M., Pinceti, S., Federico, F., 2015. 2015 Environmental Report Card for Los Angeles County. pp. 99. www.environment.ucla.edu.
González, M.C., Hidalgo, C.A., Barabási, A.-L., 2008. Understanding individual human mobility patterns. Nature. 453, 779–782. https://doi.org/10.1038/nature06958.
Hamilton, T.L., Wichman, C.J., 2018. Bicycle infrastructure and traffic congestion: evidence from DC's capital bikeshare. J. Environ. Econ. Manage. 87, 72–93. https://doi.org/10.1016/j.jeem.2017.03.007.
I. Of, 2012. District of Columbia Greenhouse Gas Inventory Update 2012-2013. https://doee.dc.gov/sites/default/files/dc/sites/ddoe/service_content/attachments/2013_Greenhouse_Gas_Inventory_Update_web.pdf.
Jäppinen, S., Toivonen, T., Salonen, M., 2013. Modelling the potential effect of shared bicycles on public transport travel times in Greater Helsinki: an open data approach. Appl. Geogr. 43, 13–24. https://doi.org/10.1016/j.apgeog.2013.05.010.
Kou, Z., Cai, H., 2019. Understanding bike sharing travel patterns: an analysis of trip data from eight cities. Phys. A Stat. Mech. Appl. 515, 785–797. https://doi.org/10.1016/j.physa.2018.09.123.
LDA Consulting, Capital Bikeshare, 2016. Member Survey Report, 2016.
Lobo, A., 2013. Bikes Are Faster Door-to-door Than Cars or Public Transport Within 5-10km, Better by Bicycl. http://www.betterbybicycle.com/2013/12/bikes-are-faster-door-to-door-than-cars.html. (Accessed 18 November 2017).
Luo, H., Kou, Z., Zhao, F., Cai, H., 2019. Comparative life cycle assessment of station-based and dock-less bike sharing systems. Resour. Conserv. Recycl. 146, 180–189. https://doi.org/10.1016/j.resconrec.2019.03.003.
Martin, E.W., Shaheen, S.A., 2014. Evaluating public transit modal shift dynamics in response to bikesharing: a tale of two U.S. Cities. J. Transp. Geogr. 41, 315–324. https://doi.org/10.1016/j.jtrangeo.2014.06.026.
NACTO, 2017. Bike Share in the U. S.: 2017. https://nacto.org/bike-share-statistics-2017/.
Nair, R., Miller-hooks, E., Hampshire, R.C., Bušić, A., Nair, R., Miller-hooks, E., Hampshire, R.C., Bušić, A., 2013. Large-scale Vehicle Sharing Systems: Analysis of Vélib Large-Scale Vehicle Sharing Systems: Analysis. https://doi.org/10.1080/15568318.2012.660115. 8318.
Pan, L., Cai, Q., Fang, Z., Tang, P., Huang, L., 2018. Rebalancing Dockless Bike Sharing Systems. pp. 1. http://arxiv.org/abs/1802.04592.
Park, C., Sohn, S.Y., 2017. An optimization approach for the placement of bicycle-sharing stations to reduce short car trips: an application to the city of Seoul. Transp. Res. A 105, 154–166. https://doi.org/10.1016/j.tra.2017.08.019.
Pasion, C., Oyenuga, C., Gouin, K., LLC, C., 2017. Inventory of New York City Greenhouse Gas Emissions in 2015. pp. 1–56.
Program, C., 2015. 2015 San Francisco Geographic Greenhouse Gas.
Report, F., 2017. City of Chicago greenhouse gas inventory report calendar year 2015, Chicago. . https://www.cityofchicago.org/content/dam/city/progs/env/GHG_Inventory/CityofChicago_2015_GHG_Emissions_Inventory_Report.pdf.
Rhee, I., Rhee, I., Shin, M., Shin, M., Hong, S., Lee, K., Hong, S., Kim, S.J., Lee, K., Chong, S., Chong, S., 2011. On the levy-walk nature of human mobility: do humans walk like monkeys? IEEE/ACM Trans. Netw. 19, 630–643. https://doi.org/10.1109/TNET.2011.2120618.
Romero, J.P., Ibeas, A., Moura, J.L., Benavente, J., Alonso, B., 2012. A simulation-optimization approach to design efficient systems of of bike-sharing. Procedia 54, 646–655. https://doi.org/10.1016/j.sbspro.2012.09.782.
Shaheen, S., Guzman, S., Zhang, H., 2010. Bikesharing in Europe, the Americas, and Asia. Transp. Res. Rec. J. Transp. Res. Board 2143, 159–167. https://doi.org/10.3141/2143-20.
Shaheen, S., Martin, E., Cohen, A., 2013. Public bikesharing and modal shift behavior: a comparative study of early bikesharing systems in North America. Int. J. Transp. 1, 35–54. https://doi.org/10.14257/ijt.2013.1.1.03.
Spring, P., 2015. Philadelphia Citywide Greenhouse Gas Inventory, 2012 Table of Contents.
Susan, S., Elliot, M., Nelson, C., Adam, C., Mike, P., 2014. Public Bikesharing in North America During a Period of Rapid Expansion : Understanding Business Models, Industry Trends and User Impacts.
Thompson, J., Potok, N., Blumerman, L., 2016. TIGER/Line® Shapefiles Technical Documentation.
U.S.DOT, 2017. 2017 National Household Travel Survey. http://nhts.ornl.gov.
United Nations Environment Programme (UNEP), 2018. The Weight of Cities: Resource Requirements of Future Urbanization. www.internationalresourcepanel.org.
USDOT, 2009. Summary of Travel Trend: 2009 National Household Travel Survey. http://nhts.ornl.gov.
Zhang, Y., Mi, Z., 2018. Environmental benefits of bike sharing: a big data-based analysis. Appl. Energy 220, 296–301. https://doi.org/10.1016/j.apenergy.2018.03.101.