Resources Conservation & Recycling

International Journal of Sustainable Resource Management and Environmental Efficiency

ScienceDirect®

Resources, Conservation and Recycling

Supports open access

20.3 CiteScore

13.2 Impact Factor

Submit your article

Guide for authors

Menu

Search in this journal

Volume 146

Pages 1-612 (July 2019)

Download full issue

Previous vol/issue

Next vol/issue

Receive an update when the latest issues in this journal are published

Set up journal alerts

FEEDBACK

Previous vol/issue

Next vol/issue

ISSN: 0921-3449

Resources, Conservation & Recycling 146 (2019) 180–189

Contents lists available at ScienceDirect

Resources, Conservation & Recycling

journal homepage: www.elsevier.com/locate/resconrec

Full length article

Comparative life cycle assessment of station-based and dock-less bike sharing systems

Hao Luo[a], Zhaoyu Kou[b], Fu Zhao[a,c], Hua Cai[a,b,*]

[a] Environmental and Ecological Engineering, Purdue University, West Lafayette, IN, 47907, USA
[b] Industrial Engineering, Purdue University, West Lafayette, IN, 47907, USA
[c] Mechanical Engineering, Purdue University, West Lafayette, IN, 47907, USA

ARTICLE INFO

Keywords:
Bike sharing
Life cycle assessment
Station-based
Dock-less

ABSTRACT

Bike sharing system (BSS) is growing worldwide. Although bike sharing is viewed as a sustainable transportation mode, it still has environmental footprints from its operation (e.g., bike rebalancing using automobiles) and upstream impacts (e.g., bike manufacturing). Thus, evaluating the environmental impacts of BSS from the life cycle perspective is vital to inform decision making for the system design and operation. In this study, we conducted a comparative life cycle assessment (LCA) of station-based and dock-less BSS in the U.S. The results show that dock-less BSS has a greenhouse gas (GHG) emissions factor of 118 g CO_2-eq/bike-km in the base scenario, which is 82% higher than the station-based system. Bike rebalancing is the main source of GHG emissions, accounting for 36% and 73% of the station-based and dock-less systems, respectively. However, station-based BSS has 54% higher total normalized environmental impacts (TNEI), compared to dock-less BSS. The dock manufacturing dominants the TNEI (61%) of station-based BSS and the bike manufacturing contributes 52% of TNEI in dock-less BSS. BSS can also bring environmental benefits through substituting different transportation modes. Car trip replacement rate is the most important factor. The results suggest four key approaches to improve BSS environmental performance: 1) optimizing the bike distribution and rebalancing route or repositioning bikes using more sustainable approaches, 2) incentivizing more private car users to switch to using BSSs, 3) prolonging lifespans of docking infrastructure to significantly reduce the TNEI of station-based systems, and 4) increasing the bike utilization efficiency to improve the environmental performance of dock-less systems.

1. Introduction

The Bike sharing system (BSS), as one type of shared urban mobility modes, has attracted more and more users in recent years, because of its convenience, low-cost, and easy accessibility (Bachand-Marleau et al., 2012; Davis, 2014; Fishman, 2016; Shaheen et al., 2013). In 2004, only 13 cities globally had introduced the bike sharing systems (Fishman, 2016). As of 2018, over 1500 bike sharing programs are in operation and the number keeps increasing rapidly (Meddin and DeMaio, 2018). The traditional bike sharing system is station-based, which includes bikes and the sharing infrastructures (i.e. stations and docks) for picking up and returning bikes (Shaheen et al., 2013). A station normally consists of a map stand, a kiosk, a solar panel system (including batteries for energy storage), and a docking system which includes a steel base and several docking racks to hold the bikes. The users of the station-based BSS are required to pick up/return bikes from/to the stations. As a result, the use of the station-based BSS is mostly limited to the regions where the station infrastructure is available.

In recent years, enabled by the wide adoption of smart phones, a newer generation of BSS, known as the dock-less bikes, station-less bikes, or floating shared bikes, has been launched in several cities (Fishman, 2016). The dock-less bikes are connected to the internet with mobile communication devices to help users locate the dock-less bikes for pickup (Shaheen et al., 2010). Without being constrained by the station infrastructure, the dock-less BSS allows the users to park the bikes almost anywhere within the service region. Removing the high initial capital investment required for the docking stations, the dock-less BSS can potentially help expand the bike sharing service with lower cost. However, many dock-less systems have low system efficiency, resulting from bike vandalism, lack of visibility of the program, or reluctance to use smartphone apps for transactions (Nieuwesteeg, 2018). While 44% of the shared bikes in the U.S. are dock-less bikes, they only contribute to 4% of the total bike sharing trips (NACTO, 2017). While more and more cities are planning to launch, expand, or modify their

* Corresponding author at: 315 N. Grant Street, West Lafayette, IN, 47907, USA.
E-mail address: huacai@purdue.edu (H. Cai).

https://doi.org/10.1016/j.resconrec.2019.03.003
Received 2 November 2018; Received in revised form 5 March 2019; Accepted 5 March 2019
Available online 02 April 2019
0921-3449/

BSSs to improve urban sustainability, two major questions are yet to be answered. First, how sustainable is BSS and what are the key factors impacting the environmental performances of the station-based and dock-less BSS? And second, which BSS, the station-based one or the dock-less one, is more sustainable?

If only considering the use phase of BSSs, bike sharing offers benefits to the cities and the public through substituting motorized vehicle usage and encouraging exercise. Fishman et al. (2014) evaluated the car trip replacement by BSSs using survey and trip data of bike sharing programs in different cities, considering the additional truck use for bike rebalance and maintenance. The results showed a significant reduction in annual vehicle usage: 243,291 km in Washington, D.C and around 90,000 km in Melbourne and Minneapolis/St. Paul. Qiu and He (2018) investigated the environmental benefits of the BSSs by calculating the emissions from the substituted personal vehicle trips and estimated a reduction of 616,036 tons of CO_2 emission in Beijing in 2020 compared to the 2015 value. The BSS in Shanghai, China was estimated to save 8358 tones gasoline and reduce 25,240 tons of CO_2 emissions in 2016, assuming that all the bike trips longer than 1 km were able to replace car usage (Zhang and Mi, 2018). An investigation of 12 BSSs in Europe estimated the potential of death avoidance because of the car trip substitution (Otero et al., 2018). A study modelling the human health impact of BSS in London based on the variations in physical activities, road traffic injuries, and exposure to air pollution showed overall positive effects of health impacts from BSSs, especially for men (Woodcock et al., 2014).

On the other hand, however, if considering the manufacturing and operation phases required for BSSs, BSS may also have negative impacts on the environment and public health. First, BSS operation requires bike rebalancing, which is usually done by using vehicles. For station-based BSS, the capacity of each station is limited by both the occupied docks (available bikes for checking out) and the unoccupied docks (available spots for returning bikes). During the day, especially in peak hours, certain stations may have no free docks to allow bike return or have no bikes available to be checked out. As a result, bike rebalancing is required to redistribute the bikes to meet service demands in different regions. Although the dock-less shared bikes are not constrained by the number of docks for bike returning, checking out the bikes is still constrained by the availability of nearby bikes. Therefore, bike rebalancing to redistribute the dock-less shared bikes around the city is still necessary to better meet the user demands.

Furthermore, if a BSS could not substitute enough automobile vehicle usage to compensate the extra vehicle trips for rebalancing, it will cause additional environmental impacts and traffic. London experienced additional 766,341 km of motor vehicle use annually after launching the bike sharing system, because the heavy rebalancing work outweighed the benefit from car trip substitution (Fishman et al., 2014). Wang and Zhou (2017) investigated 96 urban areas in the U.S. and concluded that the introduction of BSS could worsen the congestion in cities with higher income level. The bike sharing program may induce 'extra bike trips' (e.g., leisure and sightseeing trips) which would not be made without BSS. People in these cities tend to use cars as connectors to these 'extra trips', leading to more traffic. Moreover, manufacturing the bikes, electronic components, and sharing infrastructure requires resource and energy inputs and generates wastes and emissions (Berkhout and Hertin, 2001; Chester and Horvath, 2009; Coelho and Almeida, 2015). Producing too many bikes that exceed the demand could also lead to resource wastage and waste management problems. In Shanghai, more than 1.5 million dock-less bikes were in the street and the retired or abandoned bikes clogged the sidewalks and created huge piles of bike wastes (Benjamin, 2017).

To fully understand the sustainability of BSS, we need to quantify its net environmental impacts. The net impact is the difference between the environmental footprints in the life cycle of bikes and the sharing infrastructure, including manufacturing, system operation, and the end-of-life management, and the environmental benefits gained by substituting more emission and energy intensive modes. To the best of our knowledge, the only life cycle assessment study of BSSs is conducted by Amaya et al. (2014), analyzing the BSS in the city of Lyon, France as a case study to improve the design for product-service systems (PSS). However, this study only focused on the life cycle of the bikes, neglecting the impacts of the docking stations. Bike sharing stations and docks are a critical component of station-based BSS and should be included in the analysis.

Additionally, no study has yet compared the station-based and dock-less BSSs from the life cycle perspective. The stations required in the station-based BSS can be material and energy intensive. While the dock-less BSS removes the need of stations, electronic components are required to be installed in each bike to allow bike tracking and locking/unlocking. Given the large number of bikes required for the dock-less BSS, it is unclear which BSS can have better environmental performances. Moreover, the efficiency difference of the two systems also obscures the comparison result. A comparative LCA of both BSSs is needed to better understand their environmental impacts and inform decision making for BSS development.

To address the above discussed gaps, this study conducted a comparative LCA of station-based and dock-less BSS, covering all life cycle stages and infrastructure support required for each system. Compared to the existing studies, this research has two major unique contributions: first, analyzing the net environmental impacts of BSSs holistically (in terms of greenhouse gas emissions and the total normalized environmental impacts), considering both life cycle environmental impacts from system development and operations and environmental benefits from substituting motorized vehicle trips; and second, comparing the station-based and the dock-less BSSs. The results of this study are expected to: 1) provide the emission factors for both station-based and dock-less BSSs, which are needed information to support system analysis of urban transportation sustainability, 2) inform decision-makers on BSS design and development for more sustainable systems, and 3) identify potential strategies for bike sharing operators and city planners to improve the environmental contributions of the BSSs.

2. Method and data

LCA is a standardized method to analyze the environmental impacts of a product through its entire life cycle, including resource extraction, raw materials processing, product assembly, transport, packaging, use, maintenance, waste treatment, and disposal (Finnveden et al., 2009; Rebitzer et al., 2004). This 'cradle-to-grave' method has been broadly applied by researchers and companies since the 1990s and has been standardized by ISO-14040 and ISO-14044 (ISO, 2006a, 2006b). This study is conducted following the standard LCA procedure. In the following subsections, we will discuss the four steps of our LCA study, including goal and scope definition (Section 2.1), life cycle inventory analysis (Section 2.2), life cycle impact assessment (Section 2.3), and result interpretation (Section 2.4). Because the transportation modes replaced by bike sharing trips could be different from city to city, we evaluated several substitution scenarios to analyze the range of the net impacts (Section 2.5).

2.1. Goal and scope definition

The goal of this study is to compare the environmental impacts of generic station-based and dock-less bike sharing systems in the U.S. from the life cycle perspective, and to understand the key factors affecting the environmental performance of each type of BSS. The functional unit chosen for this study is traveling one kilometer by one bike (i.e. bike-km). The system boundary of the bike sharing systems includes: 1) raw material extraction, processing, and product assembly (referred to as the manufacturing phase), 2) use phase, and 3) end-of-life treatment (referred to as the end of life) (Fig. 1). The manufacturing phase includes the transportation from raw material processing

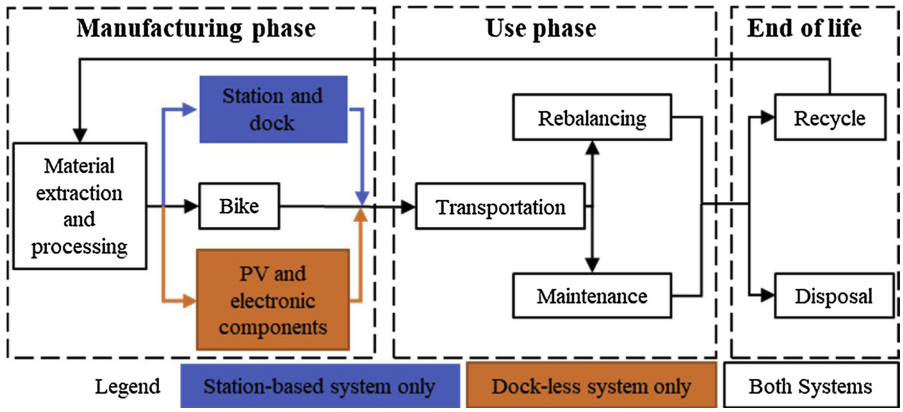

Fig. 1. System boundary of the station-based and dock-less bike sharing systems.

factories to the bike manufacturers, but ignores the packages used in this phase due to the lack of data. The major differences between the station-based and dock-less systems are that 1) the station-based system requires the manufacturing of the sharing infrastructure (i.e. stations and docks); and 2) the dock-less bikes require photovoltaic panel as the power supplier, and electronic equipment, such as Global Positioning System (GPS) devices, batteries, and electronic locks to enable bike locating, locking, and unlocking. In the use phase, all the bikes are distributed and rebalanced by vans among warehouses and stations/locations. The maintenance work includes components manufacturing, electricity and water consumption, and waste disposal. At the end of life, the metal parts in the system can be recycled before landfill. The environmental benefits from aluminum and steel recycling are credited for avoiding the use of virgin materials. The plastic and rubber wastes are assumed to be delivered to landfills.

2.2. Life cycle inventory (LCI) analysis

Life cycle inventory analysis builds an inventory of the natural resources use, energy inputs, and wastes and emission outputs involved in the system. All the process data of material inputs, energy consumption, and emission outputs are collected from the Ecoinvent 3 database (Wernet et al., 2016). The input data of the station-based system, including the docks and stations manufacturing, rebalancing, maintenance, recycling, and disposal, are collected from a bike sharing program in a large metropolitan area operated in the U.S. (Interview, 2018). Each bike weights about 20 kg. The inventory data of bike productions are scaled with bike mass, based on an LCA report of manufacturing a 17 kg urban-used bicycle (Leuenberger and Frischknecht, 2010). The lifespan of the bike and the sharing infrastructure are ten years. For the dock-less system, constrained by the available data, we assume that the components for the dock-less bikes are the same as the station-based bikes, except that dock-less bikes additionally require a photovoltaic panel, 0.15 kg rechargeable battery, and 0.35 kg electronic components, the data of which are collected from a bike supplier. Although dock-less bikes could potentially be more vulnerable to vandalism due to the inherent difficulties in managing the scattered bikes, the challenging bike management also motivates the dock-less system operators adopting more durable bikes which are designed to have a longer lifetime. Therefore, whether the dock-less bikes will have shorter or longer lifespan compared to the station-based docks are not apparent. In this study, we assume that the dock-less bikes have the same lifespan of 10 years as the station-based bikes, except for the batteries which have a 5-year lifetime (Texas Instruments, 2018). The material flows of stations and docks are also included and we assume that all these materials can sustain for 10 years except that the batteries need to be renewed every 5 years (Bernstein and Woods, 2013). Table 1 lists the detailed material consumption and the matched unit processes in the manufacturing phase.

The material consumption for bike maintenance is based on (Leuenberger and Frischknecht, 2010). On average, serving 1 km of bike trip needs 0.0275 km's van ($<$ 3.5 t) usage for bike rebalancing in the station-based system. We used the '*Transport, van < 3.5 t/US- US-EI U*' process to account for the life cycle impacts of the rebalancing fleet, including vehicle operation (i.e. fuel consumption), vehicle manufacturing, road construction, and waste disposal. We assume that the rebalancing demand for each bike stays constant for different systems. Although all the retired metal parts can be recycled, a recycling rate factor (95%) is applied to account for bike lost and material loss during the collection process. The 5% lost rate is based on our communication with a station-based system operator and this number is in line with other reported values for station-based systems in the U.S. (Lazo, 2019). Due to the lack of data, we assumed that the dock-less systems have the same bike lost rate in this study. Considering the possibility that dock-less systems may have higher bike lost rates, we have tested the sensitivity of results with 20% bike lost rates. As expected, higher bike lost rates increase the environmental impacts, but the conclusions are not affected (Section SI.2). A recycling efficiency of 90% was applied during the recycling process, which means that 90% of the recycled metals can be reused as primary metals (Haupt et al., 2018). The recycling efficiency is highly dependent on the treatment processes. We also investigated the impact of a lower efficiency (70%). While the lower recycling efficiency increase the environmental impacts of the BSS, it does not change the main conclusions (Section SI.3).

The BSS system size (the total number of stations, docks, and bikes) and ridership (the total number of trips and trip distances) can also impact the LCA results significantly. The BSS system size in the U.S. varies from city to city, ranging from 500 bikes with 60 stations to more than 10,000 bikes with 687 stations (NACTO, 2017). So does the ridership. As a result, the environmental performance of a BSS at the program level is highly case specific. Therefore, to allow comparison among different systems, we calculated the system setup based on the functional unit, to find out the number of stations, docks, and bikes the system uses to serve 1 bike-km, represented as #station/bike-km, #dock/bike-km, and #bike/bike-km, respectively. We evaluated the operation information for eight station-based BSSs in the U.S. (Table 2) (Kou and Cai, 2018) and developed a base station-based scenario using the average values as a reference system. The BSSs in New York City and Seattle were the two systems we chose, to create the best and worst scenarios for accessing the ranges of different BSSs' environmental impacts, because these two have the highest and lowest efficiency. For the dock-less system, we used the same scenario building strategy to acquire the base, best, and worst cases. Table 3 summaries the operation parameters of all the scenarios we created.

Table 1
Material inventory and manufacturing processes for making one bike, station, and dock.

Component	Value	Unit	Material[c]	Ecoinvent unit process
Station-based bike	1.18[a]	p	–	Bicycle, at regional storage/US-/I US-EI U
Dock-less bike	1.18[a]	p	–	Bicycle, at regional storage/US-/I US-EI U
	0.35	kg	Electronic equipment	Electronics for control units/US- US-EI U
	0.15	kg	Battery (5yrs.lifetime)	Battery, Li-ion, rechargeable, prismatic, at plant/GLO US-EI U
	0.02	m^2	Photovoltaic Panel	Photovoltaic panel, single-Si wafer {GLO}| market for | APOS, U
Station[b]	1.5	m^2	Photovoltaic Panel	Photovoltaic panel, single-Si wafer {GLO}| market for | APOS, U
	45.36	kg	Steel	Chromium steel 18/8, at plant/US- US-EI U
	38.5	kg	Aluminum	Aluminum alloy, AlMg3, at plant/US- US-EI U Sheet rolling, aluminum/US- US-EI U
	6.8	kg	Glass	Flat glass, uncoated, at plant/US- US-EI U
	81.5	kg	Battery (5yrs.lifetime)	Battery, Li-ion, rechargeable, prismatic, at plant/GLO US-EI U
	10	kg	Electronic components	Electronics for control units/US- US-EI U
Dock[b]	13.6	kg	Aluminum	Aluminum alloy, AlMg3, at plant/US- US-EI U Sheet rolling, aluminum/US- US-EI U
	2.72	kg	Electronic components	Electronics for control units/US- US-EI U
	67.8	kg	Steel	Chromium steel 18/8, at plant/US- US-EI U

Notes:
[a] Scaling coefficient based on mass.
[b] Only for the station-based system.
[c] Unless noted, the component lifespan is considered as 10 years.

2.3. Life cycle impact assessment (LCIA)

The LCIA quantifies the environmental impacts based on the developed inventory (Pennington et al., 2004). Because the systems are based in the U.S., we used the Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI 2.1) developed by the U.S. EPA in this study to conduct the LCIA (EPA, 2012). TRACI covers eight impact categories: Ozone depletion, Climate change, Acidification, Eutrophication, Smog formation, Human health impacts (Cancer, Non-cancer and Respiratory effects), Ecotoxicity, and Resource use. Each characterized impact category can be normalized to calculate the total normalized environmental impacts (TNEI) (Ryberg et al., 2014).

2.4. Result interpretation

To evaluate the environmental impacts, we first analyzed the GHG emissions of the two systems. Additionally, we investigated the TNEI to attain the overall impact, considering all the impact categories. Due to the uncertainties in the input data, especially for the dock-less BSS, we conducted sensitivity analysis to evaluate how different system setup and operation would impact the GHG emissions and TNEI values. Additionally, in order to better evaluate these two systems to inform BSS development, we analyzed the break-even points to identify key parameter values that will make the two systems have the same environmental impacts.

2.5. Transportation mode substitution

The BSSs can provide environmental benefits if they can replace more energy and resource intensive transportation modes. However, different cities may have very different mode substitution scenarios. Martin and Shaheen (2014) compared the public transit mode (bus and rail) change before and after employing the BSSs in two U.S. cities and found totally different modal shifts in these cities. Therefore, to capture the ranges of potential environmental benefits from BSSs, we conducted scenario analysis to evaluate how different transportation modal shift patterns due to BSSs can impact the overall system GHG emissions and TNEI values. The transportation modes that can be replaced by bike sharing include car, bus, personal bike, and walking in this study. We used Ecoinvent to obtain the emission results for these transportation modes. The dataset we choose are: 'Transport, passenger car/US- US-EI U', 'Transport, regular bus/US* US-EI U', 'Transport, electric bicycle/US* US-EI U', and 'Transport, bicycle/US* US-EI U'. The SimaPro 8.4 software was used to perform the inventory analysis. The mode substitution rates are based on BSS user survey in Melbourne, Brisbane, Washington, D.C., Minneapolis/St. Paul, and London, which are listed as Scenarios 1–5, respectively, in Table 4 (Fishman, 2016). The survey asked the participants to "Thinking about your last bike share trip, which transportation mode you would take if BSS not existed". Scenario

Table 2
Operation parameter of 10 BSS programs.

	Station-based systems[a]								Dock-less systems[b]	
City	Seattle	L.A.	Bay Area	Philadelphia	Boston	D.C.	Chicago	NYC	Seattle	D.C.
Total number of bikes	463	766	422	1023	1802	4308	5748	10,495	10,000	2000
Total number of stations	55	63	37	103	172	400	568	572	–	–
Total number of docks	787	1302	717	1739	3063	7324	9772	17,842	–	–
Annual trip counts	1.03E+05	1.84E+05	1.94E+05	4.99E+05	1.24E+06	2.56E+06	3.60E+06	1.03E+07	9.36E+05	4.92E+05
Average trip distance (km)	2.03	1.97	2.50	2.72	2.75	1.63	2.74	2.69	2.03	1.63
Total trip distance (km)	2.08E+06	3.63E+06	4.83E+06	1.36E+07	3.40E+07	4.18E+07	9.84E+07	2.76E+08	1.90E+07	8.03E+06
#bikes/bike-km	2.22E-04	2.11E-04	8.74E-05	7.53E-05	5.30E-05	1.03E-04	5.84E-05	3.80E-05	5.26E-04	2.49E-04
#stations/bike-km	2.64E-05	1.74E-05	7.66E-06	7.58E-06	5.06E-06	9.56E-06	5.77E-06	2.07E-06	–	–
#docks/bike-km	3.78E-04	3.59E-04	1.49E-04	1.28E-04	9.00E-05	1.75E-04	9.93E-05	6.47E-05	–	–

Notes:
[a] Station-based systems data are based on (Kou and Cai, 2018).
[b] Dock-less system data on Seattle and Washington, D.C. are based on (Lloyd, 2018; Lucas, 2018).

Table 3
Base, worst, and best scenarios.

Parameter	Base scenario		Worst scenario		Best scenario	
	Station-based	Dock-less	Station-based	Dock-less	Station-based	Dock-less
#bike/bike-km[a]	1.06E-04	3.87E-04	2.22E-04	5.26E-04	3.80E-05	2.49E-04
#station/bike-km[b]	1.02E-05	–	2.64E-05	–	2.07E-06	–
#dock/bike-km[c]	1.80E-04	–	3.78E-04	–	6.47E-05	–
rebalance distance (km/bike-km)[d]	2.75E-02	1.00E-01	5.76E-02	1.36E-01	9.87E-03	6.46E-02

Notes:
[a] '#bike/bike-km' refers to the average number of bikes serving 1 km's trip, which is calculated as the total bike count divided by the total trip distance in a program.
[b] '#station/bike-km' refers to the average number of stations serving 1 km's demand, which is calculated as the total station count divided by the total trip distance.
[c] '#dock/bike-km' refers to the average number of docks serving 1 km's demand, which is calculated as the total dock count divided by the total trip distance.
[d] For the station-based system, the 'rebalance distance (km/bike-km)' refers to the motor vehicle usage per km of bike trip, which is estimated as the total annual van mileages divided by total annual trip distance. Lacking rebalancing data for the dock-less system, we assume that the rebalancing demand for each bike is the same as that in the station-based systems.

Table 4
Transportation mode substitution scenarios.

	New trip	Mode substitute rate			
		Car	Bus	Bike	Walk
Scenario 1	1%	20%	40%	9%	30%
Scenario 2	2%	24%	44%	8%	22%
Scenario 3	4%	14%	45%	6%	31%
Scenario 4	13%	22%	20%	8%	37%
Scenario 5	3%	6%	57%	8%	25%
Scenario 6[a]	3%	20%	44%	8%	25%
Scenario 7-10[b]	3%	TBD	44%	8%	TBD

Notes:
[a] Median value selected from Scenarios 1–5 for car, bus, and bike substitution and new trips. The rest of the share is allocated to walking substitution.
[b] Based on scenario 6, these scenarios modify the car and walk substitution rates to identify the breakeven car trip substitution rates to achieve neutral GHG emissions or zero TNEI for each of the station-based and dock-less system.

6 was built as a representative case, where all parameters except for walking are the median values from Scenarios 1–5. In addition, Scenarios 7–10 use Scenario 6 as the basis and adjust the car trip and walking substitution rates to find the minimum level of car substitution to achieve neutral impacts from each of the GHG emission and TNEI value perspective for each of the station-based and dock-less system.

3. Results and discussions

This section first presents the LCIA results of the station-based and dock-less bike sharing systems, without considering the transportation mode substitution by bike sharing trips (Section 3.1). Due to the limited space, we will focus our discussion on the environmental impacts of each system from two aspects: greenhouse gas emissions and TNEI. The detailed results of each category are available in Table SI-1 in the Supplementary Information. Additionally, to analyze how system setup and operation changes impact the results, we also discuss the breakeven points of the two BSSs and the sensitivity of key parameters. Then, in Section 3.2, we add the potential environmental benefits from transportation mode substitution into our analysis, evaluating how different substitution scenarios change the overall system GHG emission and TNEI results.

3.1. BSS environmental footprints (without considering mode substitution)

3.1.1. Greenhouse gas (GHG) emissions

GHG emission impacts are obtained through the LCIA procedure. The station-based system has a carbon emission factor of 65 g CO_2-eq per bike-km in the base scenario (Fig. 2). The range of this emission rate is between 26 and 147 g CO_2-eq per bike-km from the best-and-worst case scenarios, respectively. For the dock-less system, the base emission rate is 118 g CO_2-eq per bike-km, with a range of 78–160 g CO_2-eq per bike-km. The overlap between the two systems implies that, if not designed and operated efficiently, the station-based system may not be more environmentally friendly than the dock-less system. The bike rebalancing using automobiles is the main source of GHG emissions for both systems, contributing 36% and 73% of the total GHG emissions, respectively (Fig. 2). Because we assumed that the rebalancing need for each bike would remain the same, the larger number of bikes required for the dock-less system also leads to high rebalancing demand compared to the station-based system.

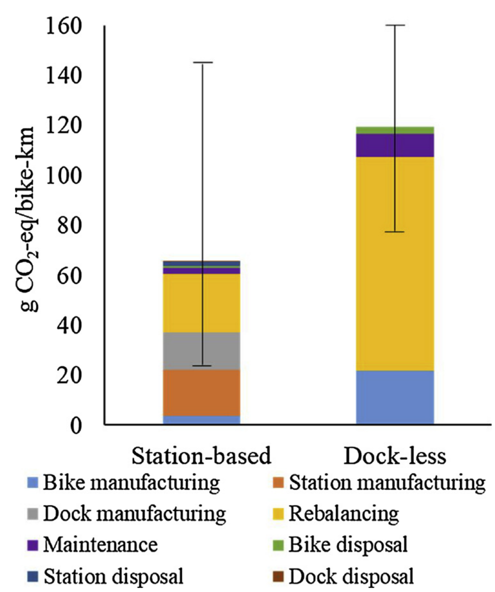

Fig. 2. Life cycle GHG emissions of the station-based and dock-less BSSs, with values breakdown by life cycle stages.

To account for the uncertainties in the input data and identify key factors that impact the GHG emissions, we conducted a sensitivity analysis of having different number of stations, docks, bikes, and rebalancing needs to serve the same demands. Fig. 3 shows the sensitivity analysis results and GHG emission breakeven points of the two systems. The slops of the lines show how sensitive the result is to the change of the parameter, with a steeper slop indicating higher sensitivity. As shown in Fig. 3a, the rebalancing needs (rebalance distance/bike-km) is the factor that the station-based system is most sensitive to. The GHG

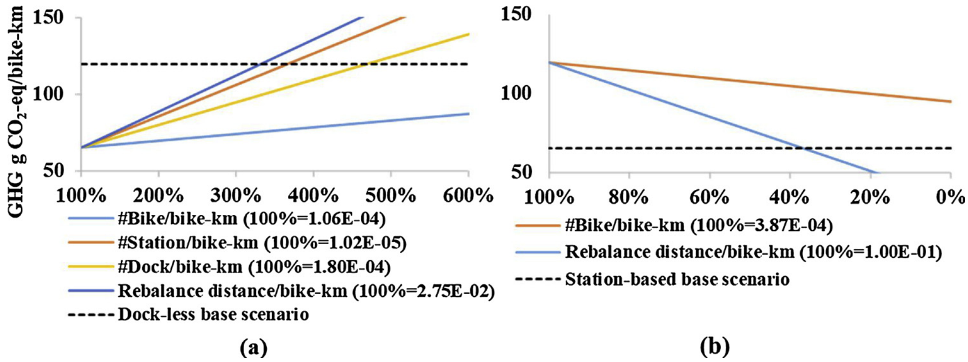

Fig. 3. GHG emission break-even points and parameter sensitivities. (a) changing parameters in station-based BSS; (b) changing parameters in dock-less BSS.

emission factors of the two systems could be the same when the rebalancing need becomes 325% of the base scenario. These results show that, when station-based BSSs require much more rebalancing to meet the same demands, they may lose their GHG emission reduction advantages over the dock-less systems. The station-based systems may also have a higher carbon footprint than the dock-less systems, if the system requires 2.5 times stations or 3.5 times number of docks more than the base scenario. Frequent replacement of the sharing infrastructure (e.g., due to change of contractors, improper maintenance of the stations, or redundant station siting) may lead to these scenarios (Chrisafis, 2018). For the dock-less system (Fig. 3b), the GHG emissions rate can be improved to the same level as in the station-based system, when the 'rebalance distance/bike-km' is decreased to 35% of the base scenario value. Optimizing the distribution of the dock-less bikes is an effective approach to reduce the rebalancing impacts.

3.1.2. Total normalized environmental impact (TNEI)

To allow comparisons across different systems with different types of environmental impacts, the impacts in different categories are normalized and summed into a single score to calculate the TNEI. Fig. 4 shows that the TNEI of the station-based system (2.30E-04 unit/bike-km) is 54% higher than that of the dock-less system (1.49E-04 unit/bike-km), in the base scenario. The potential human health impacts from carcinogenic compounds dominate the TNEI of the station-based system. The main source of carcinogenicity is from Chromium (Cr) VI, a strong carcinogen, emitted during the aluminum and steel smelting processes. Compared to the dock-less bike sharing system, the station-based system consumes significantly more aluminum and steel materials for the stations (38.5 kg aluminum and 45.4 kg steel per station) and docks (13.6 kg aluminum and 67.8 kg steel per dock) manufacturing. The contributions of each life cycle stage to the TNEI are summarized in Fig. 4b. For the station-based system, the sharing facility (docks and stations) manufacturing accounts for 61% and 23% of the overall environmental impacts due to the carcinogenic materials discharged. Bike manufacturing is the major TNEI contributor (52%) for the dock-less system because of the high volume of bikes used to meet the trip service. The additional PV panel and electronic components installed on each dock-less bike also increase the TNEI impacts for dock-less bikes. The rebalancing stage accounts for 39% of the TNEI for the dock-less system due to the smog, ozone depletion, SO_2, and other impact categories.

The value of TNEI ranges from 7.75E-05 to 5.09E-04 for the station-based system and from 1.10E-04 to 2.02E-04 for the dock-less system when considering the best and worst scenarios. The overlap implies that the station-based system may potentially have lower TNEI if the service can be provided with less number of stations and docks. Hence, the different BSS setup and operation practices in different cities may result different conclusions on whether the station-based or dock-less system has lower TNEI.

Similar to the GHG emission analysis, we analyzed the sensitivity of key parameters and the break-even points where the two systems are able to obtain the same TNEI values. For the station-based system (Fig. 5a), TNEI is the most sensitive to the number of docks in the system (#dock/bike-km). If the number of docks can be reduced by 40% without sacrificing the service, the station-based system would have less TNEI than the dock-less system. This improvement is attainable through several methods. First, design the system with the consideration to minimize underutilized docks. Second, prolong the service time of the docking infrastructure (#dock/bike-km value can be reduced by increasing the total trip distances served by these docks). Most of the station-based systems are still relatively new, and none of the existing programs have gone through replacing the stations and docks. Proper maintenance may be able to extend the use life of the sharing infrastructure beyond the estimated 10-years life time to 15-years. In terms of the dock-less system (Fig. 5b), its TNEI can be higher than the station-based system, when it needs twice the bikes as in the base scenario. Because the dock-less bikes may be more vulnerable to vandalism than the station-based bikes (O'Kane, 2018), it is possible that the dock-less bikes have a shorter lifetime and need more frequent bike replacement. In this case, the operator will need to continuously add more bikes into the system to maintain its service, requiring a larger #bike/bike-km value.

3.2. Net environmental impacts with consideration of mode substitution

The results discussed above only include the negative environmental impacts caused by establishing and operating the BSS. However, BSS may also make positive environmental benefits by substituting more emission intensive transportation modes. In this section, we analyze the net impacts of BSS under different transportation mode substitution scenarios in terms of GHG emissions and TNEI value.

Fig. 6 summaries the GHG emission and TNEI results of different transportation modes. Traveling by passenger car has the highest impacts for both GHG emissions rate and TNEI value. According to the base scenario results of BSSs, BSSs are not necessarily the more sustainable transportation modes compared to bus, electric bikes, and personal bikes. Hence, to counteract the environmental footprints from the BSSs, car trip substitution rate is the primary concern. Table 5 lists the GHG emission and TNEI values for 10 mode substitution scenarios. The method of setting the scenarios has been discussed in Section 2.5 and the emission rates presented in the Fig. 6 are used as inputs to calculate the results.

The results in Table 5 suggest that the station-based system has a greater potential in contributing to GHG emission reduction in the real-world scenarios. In the scenarios with real-world transportation mode substitution data (Scenarios 1–5), the station-based system shows the ability of reducing GHG emissions (-3 to −34 g CO_2-eq/km). Only 7% of the bike sharing trips are required to substitute car trips to reach neutral GHG emission (Scenario 7), on the basis of the median scenario (Scenario 6). On the other hand, however, under the current operation

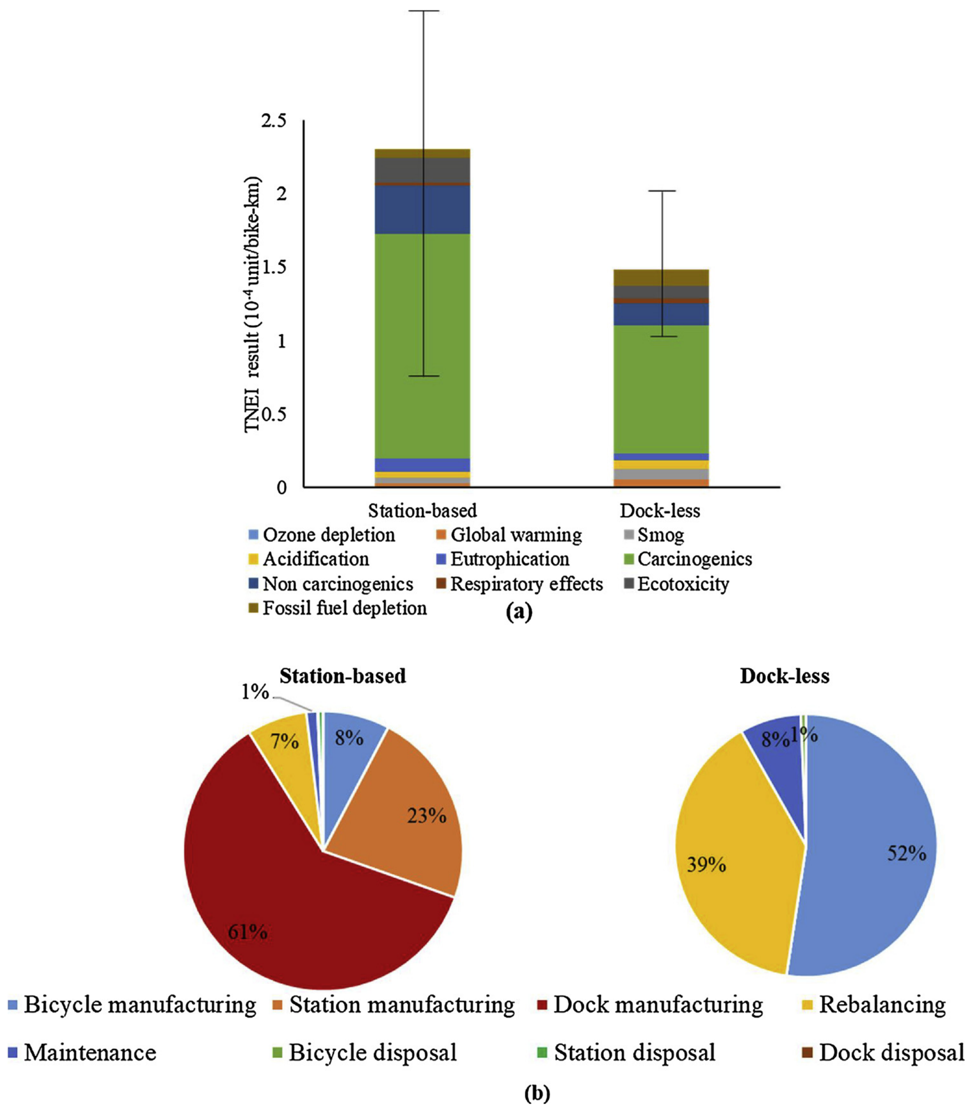

Fig. 4. TNEI results of station-based and dock-less BSSs. (a) aggregated impacts from different impact categories; (b) contributions to TNEI from different life cycle stages.

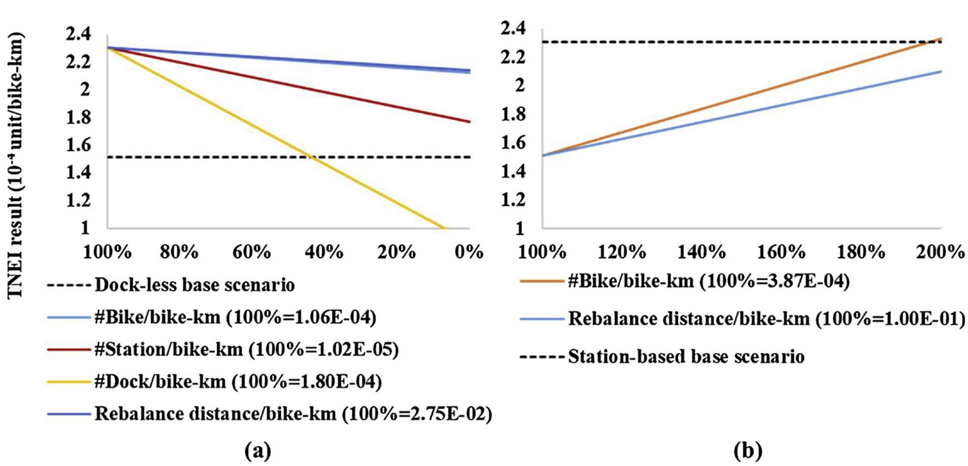

Fig. 5. TNEI break-even points and parameter sensitivities: (a) changing parameters in the station-based BSS to achieve the same TNEI as the base dock-less BSS; (b) changing parameters in the dock-less BSS to achieve the same TNEI as the base station-based BSS.

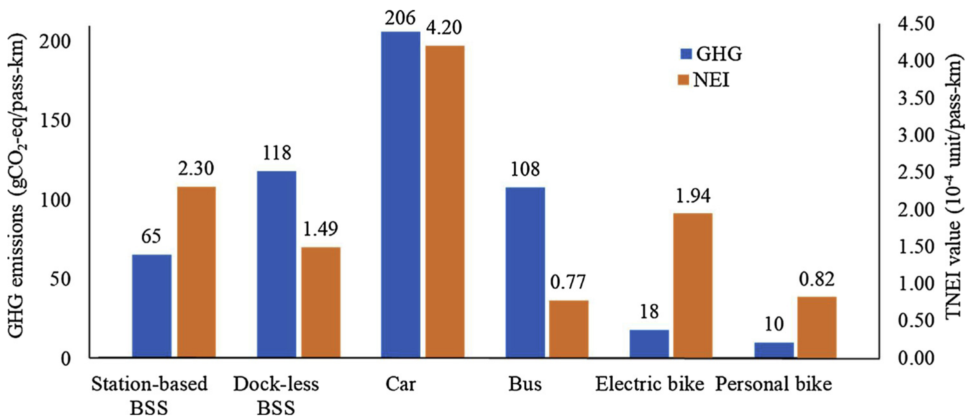

Fig. 6. GHG emission rates and TNEI values per passenger-km of different transportation modes.
Notes: The data of station-based and dock-less BSSs are from the base scenario of this study. The data of car, bus, electric bike, and personal bike are from Ecoinvent (Wernet et al., 2016).

efficiency, dock-less system may not be able to serve as a GHG abatement mode. At least 34% of the bike sharing trips need to substitute car usage for dock-less BSS to achieve GHG emission reduction, which is much higher than the currently reported level. Hence, if the bike share trips cannot replace a higher ratio of car trips, the current dock-less system may increase the GHG emission burden to a city. An effective way to lower the breakeven car trip substitution rate is to lighten the GHG emission rate of the dock-less system. Based on the sensitivity analysis in section 3.1.1, increasing the dock-less BSS efficiency through more strategic rebalancing and higher bike utilization can reduce the emission factor for the dock-less BSS.

In terms of TNEI, none of the five real-world substitution scenarios have positive TNEI values, regardless of being station-based or dock-less BSS. At least 45% and 26% of the bike sharing trips need to replace car trips in order to obtain TNEI benefits for the station-based and the dock-less system, respectively. This result shows that it may not be feasible for BSS to have positive TNEI benefits only through increasing the car trip substitution rate, because the thresholds are much higher than the survey results in Scenarios 1–5. Thus, it is necessary to combine car trip replacement with other improvements we discussed in Section 3.1.2 to reduce the unit TNEI impact per bike-km of BSS.

4. Conclusions

This study compared the life cycle environmental impacts of the station-based bike sharing system and the dock-less system. The base scenario results show that the dock-less bike sharing system has a higher GHG emission factor than the station-based system, mainly due to the more intensive rebalancing demands. The analyses of break-even points and parameter sensitivity further support this point. Rebalancing need is the most sensitive parameter for the GHG emission performance in both BSSs.

The TNEI analysis of the two systems shows that, taking all the impact categories into account, the station-based system has a higher TNEI value than the dock-less system in the base scenarios. The additional environmental impact is mainly due to the upstream impacts of aluminum and steel components used for docking infrastructure manufacturing, especially the carcinogenic emissions in metal processing. For the dock-less system, bike manufacturing and rebalancing work are the two major contributors of the environmental impacts. The results of breakeven points and parameter sensitivity test suggest that the number of docks and bikes needed to serve the same demand are the key determinants of the TNEI performance for the station-based and dock-less system.

We also considered the environmental benefits that the BSS could bring through transportation mode substitution. To achieve environmental benefits and contribute to GHG emission reduction, the bike sharing trips need to substitute car trips. With the current system setup and operation efficiency, station-based system can better help reduce GHG emissions than the dock-less system. For the dock-less system, to realize carbon reduction, at least 34% of the bike sharing trips need to replace car usage. Besides increasing the car mode substitution rate, the system efficiency of BSS also needs to be improved through prolonging service time of docks and improving bike utilization level in order to achieve positive TNEI.

The results from this study provide several insights for the city decision-makers and bike sharing operators to improve the sustainability of bike sharing systems. The most efficient way to decrease the GHG emission rates for the two systems is alleviating the rebalancing needs. This can be achieved by optimizing the bike distribution and rebalancing scheme and a lot of effort has been put into this field. Liu et al. (2016) applied a heuristic algorithm to optimize the station site

Table 5
BSS environmental impacts with different mode substitution scenarios.

	New trip	Mode substitute rate				GHG Emission (g CO_2 eq/km)		TNEI (10^{-4} unit/km)	
		Car	Bus	Bike	Walk	Station-based	Dock-less	Station-based	Dock-less
Scenario 1	1%	20%	40%	9%	30%	−21	34	1.08	0.28
Scenario 2	2%	24%	44%	8%	22%	−34	21	0.89	0.09
Scenario 3	4%	14%	45%	6%	31%	−14	41	1.32	0.52
Scenario 4	13%	22%	20%	8%	37%	−3	52	1.16	0.36
Scenario 5	3%	6%	57%	8%	25%	−11	44	1.54	0.74
Scenario 6	3%	20%	44%	8%	25%	−25	30	1.06	0.26
Scenario 7	3%	**7%**	44%	8%	**38%**	**0**	55	1.58	0.78
Scenario 8	3%	**34%**	44%	8%	**11%**	−55	**0**	0.45	−0.35
Scenario 9	3%	**45%**	44%	8%	**0%**	−77	−22	**0.00**	−0.80
Scenario 10	3%	**26%**	44%	8%	**19%**	−38	17	0.80	**0.00**

allocation. The improved station sites could help reduce the unbalanced demand and improve the bike usage, compared with the existing system. Shui and Szeto (2018) minimized the unmet trip demand and CO_2 emission cost via optimizing the vehicle loading/unloading and route planning problem with a dynamic approach. Another way to reduce the environmental cost of rebalancing work is to change the rebalancing strategy. The BSS in Portland employed the financial incentives to encourage users to help rebalancing. Also, the staffs could ride electric cargo bikes instead of driving vans, to perform the rebalancing work (Maus, 2016). Through these innovative rebalancing strategies, the automobile usage and the system operation costs can be decreased significantly. However, riding the e-cargo bikes would require higher labor cost and extend the rebalancing time which may impact ridership. Additionally, incentivizing car users to switch to use bike sharing is critical. Setting stations and bikes in regions with higher demands or coordinating BSS with public transport infrastructure can help make it easier for bike sharing to substitute car use. Developing less car-centered and more bike friendly cities could also encourage the trip mode switch and increase bike share use. Furthermore, prolonging the service time of the docks and stations in station-based systems can significantly mitigate the impacts in the manufacturing phase. This can be realized via careful maintenance on these infrastructures. Developing dock designs that use less metals is another way to reduce the impacts. For the dock-less system, increasing the utilization rate of existing bikes (each bike serving more trips) is an effective method to reduce the environmental footprints. To achieve this, careful planning and design are crucial. Another emerging operation strategy is to only allow users to check in/out the dock-less bikes inform/to specific areas marked by signs or geo-fences. These areas can serve as ‘virtual stations’ to increase the system efficiency, reduce the rebalancing demand, and avoid consuming metals for building physical stations and docks.

Although this study has the merit of being the first comparative LCA of station-based and dock-less bike sharing systems, there are several limitations need to be noted. First, the input data for the station-based system was based on our communication with one bike share program in a large metropolitan area. Many factors can impact the BSS operation (such as weather, local culture, spatial layout of the city, management strategies etc.) City-to-city variations or program-to-program differences may exist. When BSS operation data from multiple programs or cities become available, comparisons across cities and different programs will help us better understand the life cycle environmental impacts of BSS. Second, because dock-less systems are still very new in most cities, very few data can be obtained, which makes the uncertainty of our dock-less system analysis high. Dock-less BSS may have different bike lifespan, the number of bikes in operation, bike lost rate, and rebalancing needs. Although we have identified the breakeven points between the two systems to capture the potential changes due to different input data, better operation data from the dock-less system can improve the accuracy of the results. Third, we still omit some stages in the life cycle, including component packages, paving bike lanes and roads, construction of material extraction and bike manufacture factories, etc. Additionally, depending on the locations of the stations, the solar panels may not be able to provide sufficient energy to meet all the demands at each station. In this case, the batteries need to be recharged using grid power. Due to the limited data on this, we did not include this additional electricity consumption in the analysis. In terms of the environmental benefit, we only consider the emission reduction from mode substitution. We did not account for the reduced ownership of bikes and private cars as a result of the shared economy. Additionally, the bike sharing system could encourage users to switch from car trips to multi-modal trips with the shared bikes serving as the first and/or last mile mode and public transportation as the middle leg. This can further increase the potential emission reduction contributed by BSSs. A survey on the car, bike, and electric bike ownership change due to having access to bike sharing, and more detailed data on travel mode change can provide the relevant data to fill these gaps. Furthermore, system expansion of BSS is not considered in the analysis. Putting in more bikes in the system can change the rebalance needs, and at the same time influence the usage rate and maintenance frequency. A model captures the dynamics of system evolution can bring additional insights.

In summary, the BSSs, both station-based and dock-less systems, are promising to serve as sustainable transportation modes, if they are well designed and operated. When determining which system is greener for developing new BSS or modifying the existing system, the decision makers should consider two key factors. First, from the GHG emission's perspective, an optimal distribution of stations and bikes can significantly decrease the rebalancing demand and increase the car trip replacement rate, thereby alleviate the carbon emission for both systems. Second, from the perspective of TNEI, how to prolong the service life of stations and how to increase bike utilization rates are the crucial determinants for the station-based and dock-less system, respectively.

Declaration of interests

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

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.resconrec.2019.03.003.

References

Amaya, J., Lelah, A., Zwolinski, P., 2014. Design for intensified use in product–service systems using life-cycle analysis. J. Eng. Des. Technol. 25, 280–302. https://doi.org/10.1080/09544828.2014.974523.

Bachand-Marleau, J., Lee, B.H.Y., El-Geneidy, A.M., 2012. Better understanding of factors influencing likelihood of using shared bicycle systems and frequency of use. Transp. Res. Rec. J. Transp. Res. Board. https://doi.org/10.3141/2314-09.

Benjamin, H., 2017. Chinese Bike Share Graveyard a Monument to Industry's “arrogance.”. (Access on 10/10/2018). https://www.theguardian.com/uk-news/2017/nov/25/chinas-bike-share-graveyard-a-monument-to-industrys-arrogance/.

Berkhout, F., Hertin, J., 2001. Impacts of Information and Communication Technologies on Environmental Sustainability : Speculations and Evidence.

Bernstein, M., Woods, M., 2013. Understanding the Life of Lithium Ion Batteries in Electric Vehicles American Chemical Society. (Accessed on 02/01/19. https://www.acs.org/content/acs/en/pressroom/newsreleases/2013/april/understanding-the-life-of-lithium-ion-batteries-in-electric-vehicles.html.

Chester, M.V., Horvath, A., 2009. Environmental assessment of passenger transportation should include infrastructure and supply chains. Environ. Res. Lett. 4. https://doi.org/10.1088/1748-9326/4/2/024008.

Chrisafis, A., 2018. Wheels Come Off Paris Bike-share Scheme After Hi-tech Upgrade. (Accessed 01/02/19). https://www.theguardian.com/world/2018/may/04/paris-bike-share-scheme-velib-hi-tech-upgrade-problems.

Coelho, M.C., Almeida, D., 2015. Cycling mobility - A life cycle assessment based approach. Transp. Res. Procedia 10, 443–451. https://doi.org/10.1016/j.trpro.2015.09.094.

Davis, L.S., 2014. Rolling along the last mile: bike-sharing programs blossom nationwide. Planning 80 (5), 11–16.

EPA, 2012. Tool for the Reduction and Assessment of Chemical and O Ther Environmental Impacts (TRACI) User's Guide. U.S. Environmental Protection Agency.

Finnveden, G., Hauschild, M.Z., Ekvall, T., Guinée, J., Heijungs, R., Hellweg, S., Koehler, A., Pennington, D., Suh, S., 2009. Recent developments in life cycle assessment. J. Environ. Manage. 91, 1–21. https://doi.org/10.1016/j.jenvman.2009.06.018.

Fishman, E., 2016. Bikeshare: a review of recent literature. Transp. Rev. 36, 92–113. https://doi.org/10.1080/01441647.2015.1033036.

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. Part D Transp. Environ. 31, 13–20. https://doi.org/10.1016/j.trd.2014.05.013.

Haupt, M., Kägi, T., Hellweg, S., 2018. Life cycle inventories of waste management processes. Data Br. 19, 1441–1457. https://doi.org/10.1016/j.dib.2018.05.067.

Interview, 2018. Interview With Staffs of a Station-Based Bike Sharing Program Operated in a Large Metropolitan Area in the U.S.Interview With Staffs of a Station-Based Bike Sharing Program Operated in a Large Metropolitan Area in the U.S.

ISO, 2006a. Environmental Management-Life Cycle Assessment-Principles and Framework. International Ogranization of Standardization.

ISO, 2006b. Environmental Management — Life Cycle Assessment — Requirements and Guidelines. International Ogranization of Standardizationhttps://doi.org/10.1007/

s11367-011-0297-3.
Kou, Z., Cai, H., 2018. Understanding bike sharing travel patterns: an analysis of trip data from eight cities. Phys. A Stat. Mech. its Appl. https://doi.org/10.1016/j.physa.2018.09.123.
Lazo, L., 2019. Bike-share Debacle Isn't Unique to Baltimore. (Accessed on 01/08/2019). https://www.washingtonpost.com/local/trafficandcommuting/theres-no-shame-in-baltimores-bike-share-theft-problem-it-happened-in-new-york-and-paris/2017/10/04/f3758a2a-9d5b-11e7-9c8d-cf053ff30921_story.html?utm_term=.8a9770e21a26.
Leuenberger, M., Frischknecht, R., 2010. Life Cycle Assessment of Two Wheel Vehicles. ESU-services Ltd.
Liu, J., Li, Q., Qu, M., Chen, W., Yang, J., Xiong, H., Zhong, H., Fu, Y., 2016. Station site optimization in bike sharing systems. Proc. - IEEE Int. Conf. Data Mining. https://doi.org/10.1109/ICDM.2015.99.
Lloyd, S.A., 2018. How Did Seattle's Bike-share Pilot Go? (Accessed 10.10.18). https://seattle.curbed.com/2018/6/19/17479724/seattle-dockless-bike-share-data.
Lucas, K., 2018. Dockless in D.C. District Department of Transportation.
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.
Maus, J., 2016. Portland Now Using Pedal-powered Trikes to Help Rebalance Bike Share Stations - BikePortland. (Accessed on 10/10/2018). https://bikeportland.org/2016/09/07/portland-now-using-pedal-powered-trikes-to-help-rebalance-bike-share-stations-191007.
Meddin, R., DeMaio, P., 2018. The Bike-sharing World Map. (Accessed on 10/10/2018). http://www.bikesharingworld.com.
NACTO, 2017. Bike Share in the U.S.: 2017. National Association of City Transportation Officials.
Nieuwesteeg, T., 2018. Dockless Bikes Promise the Future of Transportation, but Litter the City of Dallas. (Accessed on 02/01/2019). https://www.nbcnews.com/tech/innovation/dockless-bikes-promise-future-transportation-litter-city-dallas-n866351.
O'Kane, S., 2018. Dockless Bike-share Service Leaves France After 'mass Destruction' of Its Fleet. (Accessed on 10/10/2018). https://www.theverge.com/2018/2/26/17053408/gobee-bike-sharing-france-belgium.
Otero, I., Nieuwenhuijsen, M.J., Rojas-Rueda, D., 2018. Health impacts of bike sharing systems in Europe. Environ. Int. 115, 387–394. https://doi.org/10.1016/j.envint.2018.04.014.
Pennington, D.W., Potting, J., Finnveden, G., Lindeijer, E., Jolliet, O., Rydberg, T., Rebitzer, G., 2004. Life cycle assessment Part 2: current impact assessment practice. Environ. Int. 30, 721–739. https://doi.org/10.1016/j.envint.2003.12.009.
Qiu, L., He, L., 2018. Bike sharing and the economy, the environment, and health-related externalities. Sustainability 10, 1145. https://doi.org/10.3390/su10041145.
Rebitzer, G., Ekvall, T., Frischknecht, R., Hunkeler, D., Norris, G., Rydberg, T., Schmidt, W.P., Suh, S., Weidema, B.P., Pennington, D.W., 2004. Life cycle assessment Part 1: framework, goal and scope definition, inventory analysis, and applications. Environ. Int. 30, 701–720. https://doi.org/10.1016/j.envint.2003.11.005.
Ryberg, M., Vieira, M.D.M., Zgola, M., Bare, J., Rosenbaum, R.K., 2014. Updated US and Canadian normalization factors for TRACI 2.1. Clean Technol. Environ. Policy 16, 329–339. https://doi.org/10.1007/s10098-013-0629-z.
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., Cohen, A., Martin, E., 2013. Public bikesharing in North America. Transp. Res. Rec. J. Transp. Res. Board 2387, 83–92. https://doi.org/10.3141/2387-10.
Shui, C.S., Szeto, W.Y., 2018. Dynamic green bike repositioning problem – a hybrid rolling horizon artificial bee colony algorithm approach. Transp. Res. Part D Transp. Environ. 60, 119–136. https://doi.org/10.1016/j.trd.2017.06.023.
Texas Instruments, 2018. Smart Lock Reference Design With Extended Flash Memory Enabling More Than Five Years of Life on Four AA Batteries.
Wang, M., Zhou, X., 2017. Bike-sharing systems and congestion: evidence from US cities. J. Transp. Geogr. 65, 147–154. https://doi.org/10.1016/j.jtrangeo.2017.10.022.
Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., Weidema, B., 2016. The ecoinvent database version 3 (part I): overview and methodology. Int. J. Life Cycle Assess. 21, 1218–1230. https://doi.org/10.1007/s11367-016-1087-8.
Woodcock, J., Tainio, M., Cheshire, J., O'Brien, O., Goodman, A., 2014. Health effects of the London bicycle sharing system: health impact modelling study. BMJ 348, 1–14. https://doi.org/10.1136/bmj.g425.
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.