Can shared micromobility programs reduce greenhouse gas emissions: Evidence from urban transportation big data

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Highlights

- The impact of global shared micromobillity programs on GHG emissions is estimated.
- Station-based and free-floating bikes, e-bikes, and e-scooters have been examined.
- Technological progress has not fostered desirable GHG benefits for shared micromobillity.
- Overcommercialized shared micromobillity causes adverse GHG impacts.
- The GHG impact of shared micromobillity shows regional differences.

Abstract: Shared micromobillity has been extensively developed globally in the past few decades, but its impact on the environment remains unclear. This study quantitatively estimates the effects of global shared micromobillity programs on greenhouse gas (GHG) emissions using a life cycle assessment (LCA) perspective. Specifically, it takes major countries and cities around the world as examples to empirically analyze the impact of station-based bike-sharing

(SBBS), free-floating bike-sharing (FFBS), free-floating e-bike sharing (FFEBS), and free-floating e-scooter sharing (FFESS) programs on the GHG emissions of urban transportation. The results show that, with the exception of SBBS, the other shared micromobillity programs have not achieved desirable GHG emissions reduction benefits. Contrarily to subjective expectations, although the rapid progress of technology in recent years has promoted the vigorous development of shared micromobility, it has brought negative impacts on the GHG emissions rather than the positive benefits claimed by related promoters and operators. The overcommercialization and low utilization rate makes shared micromobility more likely to be an environmentally-unfriendly mode of transportation. In addition, the regional differences in mode choice, operational efficiency, fleet scale, and market potential of shared micromobility and the corresponding impacts on GHG emissions vary greatly. Therefore, authorities should formulate appropriate shared micromobility plans based on the current conditions and goals of the region. This empirical study helps to better understand the environmental impact of the global shared micromobility program and offers valuable references for improving urban sustainability.

Keywords: Sustainability; Big data; Shared micromobility; Sustainable transportation; Life cycle assessment; Greenhouse gas emissions

1 Introduction

Increasingly severe urban traffic and environmental problems have prompted the continuous exploration, development, and diversification of green and sustainable transportation modes worldwide (Eisenack & Roggero, 2022; Ornetzeder & Rohracher, 2013; Pettifor et al., 2017; Sun & Ertz, 2021b). The COVID-19 outbreak further modified individuals' mobility behaviors due to telehealth, teleconferencing, e-learning, or e-shopping, which decreased (increased) the occurrence of long (shorter) trips (Mouratidis and Papagiannakis, 2021). However, knowledge of those modifications in travel behavior tends to be immature, especially regarding their impact on the environment (Benita, 2021). As an innovative transportation strategy, shared micromobility enables users to gain short-term access to transportation modes on an "as-needed" basis (Reck et al., 2021; Shaheen et al., 2020). Part of its sustainable aspect resides in the fact that micromobility refers squarely to vehicles that are smaller than cars, such as bicycles or scooters (Hosseinzadeh et al., 2021; Krauss et al., 2022; Reck et al., 2021). In addition, the integration of shared micromobilty into the extensive public transportation network can improve the last mile connectivity and facilitate the promotion of Mobility as a Service (MaaS), which is widely regarded as a promising way to improve urban sustainability (Le Pira et al., 2021; Mao et al., 2021; Reck et al., 2021; Shaheen et al., 2020). Shared micromobility is a specific part of the broader pseudo-sharing economy (Ertz, 2020), which has been proposed as a pathway to sustainability under certain conditions (Sun & Ertz, 2021c).

Driven by technological innovation and colossal venture capital, some new types of shared micromobility services have emerged and have experienced explosive growth in just a few years, such as free-floating bike-sharing (FFBS), free-floating e-bike sharing (FFEBS), and free-floating e-scooter sharing (FFESS) (Sun and Ertz, 2020; Hosseinzadeh et al., 2021; NABSA, 2021; Qxcu Industrial Research Institute, 2021; Reck et al., 2021), which are often operated and managed by privately-owned shared micromobility platforms (also known as transportation network companies [TNCs]). These profit-driven platforms have been actively expanding their market scale and rapidly updated products and services, making the traditional station-based bike-sharing (SBBS) program incomparable with emerging FFBBS, FFEBS, and FFESS in terms of market scale and development speed (CSIC, 2020; NABSA, 2021; World Resource Institute, 2019; Zhang, 2017). So, does the evolution from SBBS to FFBS, and then to FFEBS and FFESS, follow merely the capital market, or has technological progress spurred a sustainable tide across urban transportation and in favor of the environment? This is still debatable.

The potential environmental benefits of shared micromobility are mainly based on the premise of replacing car trips. Qiu & He (2018) estimated the impact of Beijing FFBS on urban road traffic emissions, arguing that if 75% of shared bike miles replaced car travel, the carbon dioxide (CO_2), carbon monoxide (CO), nitrogen dioxide (NO_2) and particulate matter (PM) can be reduced by nearly 616,040 tons, 1,587 tons, 59 tons and 21 tons, respectively. Kou et al. (2020) quantified the GHG emission reduction effects of bike-sharing programs in New York, Chicago, Boston, Philadelphia, Washington, D.C., Los Angeles, San Francisco, and Seattle in 2016 by using high rates of car trip replacement (i.e., approximately 65%–80% of bike-sharing trips replaced car trips), and the results show that annual reductions in GHG emissions for these different cities ranged from 41–5, 417 tons of CO_2-eq. Liu et al. (2022) estimated that if 1% of

Nanjing's resident population uses shared e-bikes instead of cars for commuting, the one-way CO_2 emission reduction can reach about 9.55 tons. However, a growing body of evidence suggests that estimates of the environmental benefits of shared micromobility may be overly optimistic. Some studies argue that the actual substitute rate of shared micromobility trips for car travel in many cities (e.g., Paris, Edinburgh, Washington D.C., Shanghai, Melbourne, New York, Minnesota, Seattle, and Brisbane) is not high, with only about 10%–30% (D'Almeida et al., 2021; de Bortoli & Christoforou, 2020; Fan & Harper, 2022; Teixeira et al., 2021; Zhu, 2021). Furthermore, shared micromobility may not be an environmentally-friendly mode of transport if viewed from a life cycle perspective, taking into account emissions during the manufacturing and maintenance phases (Saltykova et al., 2022; Teixeira et al., 2021) .Sun & Ertz (2021b) investigated the environmental impact of mutualized mobility in Beijing and Toronto from a life cycle perspective and found that emission intensity (CO_2-eq per passenger-kilometer) of SBBS is almost double that of public transit. In this case, if a large portion of shared mobility replaces an environmentally-friendly mode of transportation, there may be a negative impact on the environment (Bozzi & Aguilera, 2021). Reck et al. (2022) found that shared e-scooters and shared e-bikes in Zurich brought more CO_2 emissions than the modes of transport they replaced from a life cycle perspective. Moreau et al. (2020) conducted a life cycle assessment (LCA) on the environmental impact of the FFESS system in Brussels. Considering its substitution for other modes of transportation, the use of shared e-scooter generated an additional 21 g of CO_2-eq per passenger-kilometer on average. Similarly, de Bortoli & Christoforou (2020) used life cycle analysis to quantify the GHG emissions impact of FFESS in Paris. They found that 82% of skateboarding trips substituted for low-emission modes of transport (60% for public transit and 22% for walking) and estimated that 1 million FFESS users could generate an additional 13,000 tonnes of CO_2-eq per year.

Although extensive research has been conducted on the environmental impact of shared micromobility, there are still shortcomings. First of all, most studies lack a comprehensive and systematic consideration of actual operating characteristics and related life cycle factors of the shared micromobilty such as service life of the vehicle, utilization rate, trip distance, the substitution rates of various transportation modes in the urban transportation system, and the impact of manufacturing, rebalancing and collecting (Fishman, 2016; Fishman et al., 2014; Li et al., 2021; Teixeira et al., 2021; Zhang & Mi, 2018), which leads to deviations in research conclusions. Moreover, existing research only focuses on one or two modes of shared micrombility, and there is no research to compare and analyze all the shared micrombility modes simultaneously. In particular, these studies are only case studies in individual regions, and the related assumptions and conclusions are thus non-representative and not generalizable. Furthermore, due to differences in social, economic, cultural, demographic, geographical variables as well as urban road network construction, the operational characteristics and development status of shared micromobility vary significantly across different regions (CACTO, 2018; Hosseinzadeh, Algomaiah, et al., 2021; NACTO, 2020). As a result, there may be significant regional differences in the environmental impact of shared micromobility, which have not been studied so far. Overall, although shared micromobility is growing rapidly worldwide, there is a lack of a comprehensive understanding of its environmental impact globally. However, such an understanding appears crucial for improved governance and the development of shared micromobility, which is still in a nascent stage.

Therefore, considering these research gaps, this study combines the life cycle assessment (LCA) framework and actual shared micromobility operation data of major countries and cities worldwide. The overarching objective is to investigate the impact of shared micromobility programs on greenhouse gas emissions. In particular, this study compares and analyzes the impact of several typical shared micromobility programs on greenhouse gas emissions from the urban transportation system, including SBBS, FFBS, FFEBS, and FFESS. The research framework and findings have valuable theoretical and practical significance for improving the sustainability of shared micromobility markets and urban transportation systems.

2 Material and methods

The analysis process of this study can be divided into two steps. First, the LCA method calculated the GHG emission factors (EF) of shared micromobility based on the actual operational characteristics and data of specific shared micromobility schemes. Then, combining the EF of shared micromobility and other modes of transportation within the urban transportation system and the substitution rate of shared micromobility for different transportation modes, the GHG emissions reduction benefits (RB) of shared micromobility can be further compared and estimated.

Specifically, this study empirically analyzed and compared the GHG emissions reduction benefits of SBBS and FFBS programs in 39 cities worldwide. In terms of FFEBS and FFESS, the operational data for the city-level market are lacking due to the short operating history. Therefore, this paper takes the United States, the largest FFESS market, and China, the world's largest FFEBS market, as an example to conduct a comparative analysis of the impacts of FFEBS and FFESS on GHG emissions from transportation systems. In order to avoid analysis bias, this paper does not select the data of the shared micromobility system in a particular year for analysis but is based on the overall statistical characteristics of the system's multi-year operational data. The dataset in terms of shared micromobility type, temporal period, and spatial context is summarized in Table 1.

Table 1. The datasets involved in this study

Shared micromobility type	Statistical period (year)	Spatial context
Station-based bike sharing (SBBS)	2011– 2020	Vancouver, Montreal, Toronto, London, Melbourne, Antwerp, Paris, Milan, Barcelona, Vienna, Moscow, Shanghai, Beijing, Guangzhou, Hangzhou, Nanjing, Ningbo, Seattle, Los Angeles, Bay Area, Philadelphia, Boston, Washington D.C., Chicago, New York, Brisbane, Minneapolis
Free-floating bike sharing (FFBS)	2016 – 2020	Beijing, Shanghai, Hangzhou, Nanjing, Shenzhen, Guangzhou, Xi'an, Wuhan, Chengdu, Jinan, Seattle, Washington D.C.
Free-floating e-bike sharing (FFEBS)	2018 – 2020	China (The entire FFEBS market)
Free-floating e-scooter sharing (FFESS)	2018 – 2020	the United States (The entire FFESS market)

2.1. Life Cycle Assessments

LCA is a standardized method used to measure the environmental and energy impacts of a product or service throughout its life cycle (Escobar et al., 2020; ISO, 2006b, 2006a; Kjaer et al., 2018). The analysis framework and specific processes of LCA have been widely used to assess the energy and environmental impacts associated with particular transportation methods and the entire transportation system (D'Almeida et al., 2021; Hollingsworth et al., 2019; Kjaer et al., 2018; Sun & Ertz, 2021b). This study uses the world's leading LCA software SimaPro

9.0 and the life cycle inventories (LCI) database Ecoinvent 3.6 to conduct the LCA analysis. The specific analysis process follows the standardized LCA procedure provided by ISO (2006a, 2006b), as shown below.

2.1.1. Goal and scope definition

In the LCA analysis of transportation mode, the vehicle life cycle can be divided into three stages: manufacturing, use, and end-of-life (Dave, 2010; de Bortoli & Christoforou, 2020; ISO, 2006a, 2006b; Sun & Ertz, 2020), so the corresponding system boundaries for shared micromobility in this study are shown in Fig. 1. In the SBBS system, we need to consider the ancillary facilities (i.e., stations and docks). In order to improve the operating efficiency of shared micromobility systems, operators need to frequently relocate shared vehicles from overcrowded sites to shortage sites (Chiariotti et al., 2018; Hollingsworth et al., 2019). Therefore, these rebalancing activities are also an essential part of the system boundary for shared micromobility LCA analysis (Hollingsworth et al., 2019; Sun & Ertz, 2021b). As for the electricity-powered vehicles (i.e., e-bikes and e-scooters), the energy consumption and the collection and recharging processes (i.e., regularly recharging the battery) need to be included in the use phase.

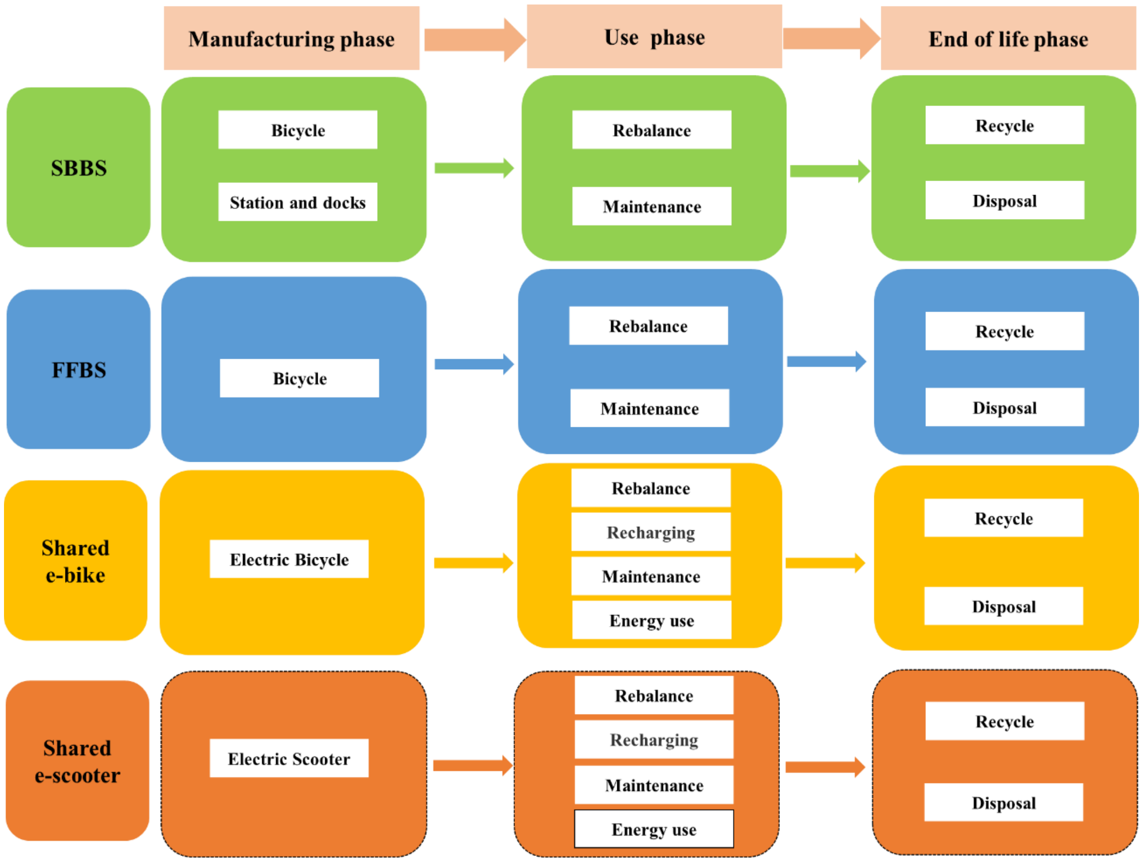

Fig. 1. LCA System boundary for shared micromobility

In order to facilitate comparison and analysis, the functional unit used in this study is passenger-kilometer (i.e., pkm) (Dave, 2010; Hollingsworth et al., 2019), and the measurement unit of the GHG emission factor (i.e., EF) of the transportation mode is g CO_2-eq/pkm. (Hollingsworth et al., 2019; Kjaer et al., 2018; Kou et al., 2020; Sun & Ertz, 2021b). Eq. (1) presents the expression for EF (Dave, 2010; Hollingsworth et al., 2019; Kjaer et al., 2018).

$$EF = TGHG / PKM \quad (1)$$

In Eq. (1), $TGHG$ refers to the total life cycle GHG emissions, which is the sum of the emissions in these three stages of the vehicle life cycle. PKM refers to the cumulative passenger-kilometers during the vehicle life cycle, which can be calculated by Eq. (2).

$$PKM = OPT \times DTR \times DPT \times SL \quad (2)$$

Where OPT refers to average vehicle occupancy per trip, DTR (i.e., daily turnover rate) refers to the average number of trips per vehicle per day. DPR refers to the average distance per trip. Finally, SL refers to the lifespan of the shared vehicle.

2.1.2 Inventory analysis

The shared micromobility LCA inventory data are mainly from the Ecoinvent database, peer-reviewed published articles, industry statistical reports, and the operational reports released by shared micromobility platforms.

For the SBBS, the weight of the shared bicycle is about 18 to 23 kg, and the service life (i.e., lifespan) ranges from 5 to 8 years (Bonilla-Alicea et al., 2020; Chen et al., 2020a; NABSA, 2021; NACTO, 2019; Sun & Ertz, 2021a; Xu, 2018). In terms of the stations and docks for the SBBS system, the service life is set to 10 years (Bonilla-Alicea et al., 2020; Luo et al., 2019), and the associated GHG emissions during the lifespan will be evenly distributed to every kilometer of bike trips (Bonilla-Alicea et al., 2020; Sun & Ertz, 2021b). In addition, various commercial vehicles (e.g., small trucks and vans) are used to rebalance shared bicycles within the city, with an average GHG emission intensity of about 300 g CO_2-eq/km during the rebalance process (Chen et al., 2020a; Hollingsworth et al., 2019). As to the end-of-life stage, 90% of metal materials of stations and docks can be recycled, and the recycling rate of the metal materials for SBBS bikes ranges from 60% to 90% (CAICT, 2019; Luo et al., 2019; NABSA, 2021). In addition, other parts and materials (e.g., plastic, rubber, glass, and electronic components) are subjected to a series of disposal processes such as landfill, incineration and treated as solid waste and electronic waste (Chen et al., 2020b; Mao et al., 2021; Xu, 2018). The operating characteristics of SBBS are presented in Table 2 and Table 3. In addition, the primary inventory data and processes for SBBS and the supporting facilities are shown in Supplementary materials A and B.

Table 2. The operating characteristics of SBBS

	DTR (Triangular distribution)			**Docks per bike (Triangular distribution)**			**Bikes per station (Triangular distribution)**			**Distance per trip (km) (Normal distribution)**	
	Min	Avergae	Max	Min	Avergae	Max	Min	Avergae	Max	Mean	Standard Deviation
Vancouver	1.13	1.25	1.37	1.75	1.90	2.05	9.00	10.00	11.00	3.00	0.065
Montreal	2.16	2.25	2.33	1.85	2.02	2.20	11.58	11.80	12.00	2.70	0.068
Toronto	1.16	1.32	1.42	1.65	1.75	1.95	10.96	11.56	17.10	3.23	0.075
London	2.30	2.42	2.60	1.85	1.99	2.21	14.00	15.33	16.00	3.50	0.088
Melbourne	0.70	0.78	1.10	1.80	1.98	2.20	11.50	11.76	12.50	4.40	0.081
Antwerp	1.85	1.95	2.15	1.45	1.68	2.18	11.00	11.92	13.00	3.00	0.075
Paris	4.75	4.93	5.20	2.30	2.56	2.80	11.00	12.05	13.00	2.81	0.070
Milan	3.20	3.42	3.60	1.85	2.00	2.20	15.50	16.49	17.50	1.50	0.025
Barcelona	4.40	4.68	4.80	1.95	2.16	2.35	14.00	14.15	15.00	2.91	0.073
Vienna	1.70	1.87	2.10	1.70	1.95	2.20	12.00	13.50	15.00	2.36	0.059
Moscow	2.50	2.71	2.90	1.25	1.45	1.65	8.50	10.00	11.50	2.80	0.070
Shanghai	2.00	2.20	2.40	1.40	1.55	1.80	23.00	25.00	27.00	3.00	0.075
Beijing	1.25	1.46	1.70	1.40	1.51	1.73	27.00	29.50	32.00	2.20	0.055
Guangzhou	1.15	1.31	1.65	1.30	1.36	1.58	20.0	26	30.00	2.35	0.045
Hangzhou	3.50	3.75	4.00	1.40	1.46	1.60	22.00	24.00	26.00	1.39	0.028
Nanjing	1.10	1.27	1.50	1.40	1.46	1.65	34.00	36.31	38.00	2.40	0.060
Ningbo	1.40	1.57	1.80	1.40	1.48	1.71	22.00	23.92	26.00	3.90	0.098
Seattle	0.50	0.61	0.90	2.10	2.24	2.40	6.50	7.85	8.50	2.03	0.051
Los Angeles	0.55	0.66	1.00	1.65	1.77	1.85	10.00	11.92	14.00	1.97	0.049
Bay Area	1.05	1.26	1.50	2.90	3.22	3.38	4.50	5.69	7.00	2.50	0.063
Philadelphia	1.10	1.34	1.50	2.05	2.23	2.40	7.00	8.60	11.00	2.72	0.068
Boston	1.70	1.89	2.10	2.80	3.19	3.42	4.50	5.50	7.00	2.75	0.069
Washington D.C.	1.50	1.63	1.80	1.40	1.56	1.80	9.00	10.58	12.00	1.63	0.041
Chicago	1.50	1.72	1.90	1.50	1.74	1.90	8.50	9.89	11.50	2.74	0.055
New York	2.50	2.69	2.85	1.75	1.94	2.15	13.50	15.26	17.00	2.69	0.067
Brisbane	0.40	0.50	0.70	1.45	1.62	1.80	12.00	13.33	15.00	3.20	0.080
Minneapolis	0.70	0.90	1.20	1.85	2.06	2.20	8.00	10.00	12.00	3.50	0.088

Note: Source from Beijing Transport Institute (2016); Bike Share Research (2021); Bike Share Toronto (2020); CACTO (2018); Deng et al. (2017); Fishman et al. (2013, 2014); Kou et al. (2020); Liu et al. (2016); Mei et al. (2019); Morency et al. (2017); SURC & TDRI (2016, 2020); and Zheng and Zhu (2014).

Table 3. Parameters and distribution of uncertainty analysis for SBBS

	Distribution type	Distribution parameters
Service life (year)	Triangular	Mean =6.5 Min=5 Max=8
Weight of shared bike bicycle (kg)	Triangular	Mean =20 Min=18 Max=23
Recycle rate (%)	Triangular	Mean =60% Min=75% Max=90%
Rebalance distance (for serving one-kilometer SBBS trip) (km)	Normal distribution	Mean=0.04 Standard Deviation (SD) = 0.0042

Note: Source from Beijing Transport Institute (2016); Bike Share Research (2021); Bike Share Toronto (2020); Deng et al. (2017); Fishman et al. (2013, 2014); Kou et al. (2020); Liu et al. (2016); Mei et al. (2019); Morency et al. (2017); NACTO (2018); SURC & TDRI (2016, 2020); and Zheng and Zhu (2014).

As to the FFBS, the weight of the shared bicycle is about 18 to 23 kg, and the life span is about 2 to 3 years. (Bonilla-Alicea et al., 2020; Chen et al., 2020a, 2020b; CSIC, 2020; Luo et al., 2019; NACTO, 2020). Although FFBS does not require stations and docks, FFBS bicycles are equipped with additional photovoltaic panels, electronic components, and batteries (Bonilla-Alicea et al., 2020; Luo et al., 2019; Sun & Ertz, 2021a; Xu, 2018). In addition, the rapid expansion of the scale of FFBS in cities and the lack of adequate market supervision have brought about oversupply and resource waste (Gao & Li, 2020; Schellong et al., 2019; Shaheen & Cohen, 2021; Teixeira et al., 2021), the recycling rate of FFBS systems ranged from 30% to 75% (CAICT, 2019; Chen et al., 2020a, 2020b; CSIC, 2020; Hu, 2019; Mao et al., 2021; NACTO, 2020; Xu, 2018). The operating characteristics of FFBS are presented in Table 4 and Table 5. In addition, the primary inventory data and processes for FFBS are summarized in Supplementary material C.

Table 4. The operating characteristics of FFBS in different regions

	DTR (Triangular distribution)			Distance per trip (km) Normal distribution	
	Min	Average	Max	Mean	Standard Deviation
Beijing	0.9	1.42	2	1.650	0.133
Shanghai	1.1	1.35	1.5	1.840	0.046
Hangzhou	0.75	0.89	1.1	1.150	0.058
Nanjing	2.4	2.86	3.1	1.350	0.046
Shenzhen	1.45	1.77	2.2	1.550	0.039
Guangzhou	1.95	2.35	2.5	2.200	0.125
Xi'an	0.7	0.79	1	1.110	0.067
Wuhan	0.6	0.67	0.9	1.690	0.047
Chengdu	1.6	1.80	2.1	1.670	0.056
Jinan	0.9	1.06	1.34	1.680	0.042
Seattle	0.75	0.85	1.1	2.030	0.065
Washington D.C.	0.6	0.68	0.9	1.630	0.035

Note: Source from Chen et al. (2020a); CAICT (2019); CSIC (2020); Luo et al., 2019; Mao et al., 2021; NACTO, 2019; NACTO, 2018; World Resource Institute, 2019).

Table 5. Operating characteristics and the Parameter distribution of uncertain factors for FFBS

	Distribution type	Distribution parameters
Service life (year)	Triangular	Mean =2.0 Min=3.0 Max=4.0
Weight of shared bike bicycle (kg)	Triangular	Mean =18 Min=20 Max=23
Recycle rate (%)	Triangular	Mean =30% Min=50% Max=75%
Rebalance distance (serving one-kilometer FFBS trip) (km)	Normal distribution	Mean=0.10 Standard Deviation = 0.0075

Note: Source from Chen et al. (2020b); CAICT (2019); CSIC (2020); Luo et al. (2019); Mao et al. (2021); NACTO (2019); NACTO (2018); and World Resource Institute (2019).

For the FFEBS project, the weight of the shared e-bike is about 24 to 39 kg, and the life span is about 2 to 4 years (Aurora Mobile, 2021; CAICT, 2019; iiMedia Research, 2020; Qxcu Industrial Research Institute, 2021; WTDSRI, 2020). The energy consumption per 100 kilometers ranged from 1.45 kWh to 2.25 kWh (Aurora Mobile, 2021; CAICT, 2019; Hello Inc, 2021; iiMedia Research, 2020; Qxcu Industrial Research Institute, 2021; WTDSRI, 2020). The GHG emissions per kilowatt-hour of electricity produced and supplied in China are about 972 g CO_2-eq (China National Energy Administration, 2020). The rebalance, collection, and recharging distance for serving a 1 km FFEBS trip was about 0.103 – 0.262 km (Aurora Mobile, 2021; CAICT, 2019; Hello Inc, 2021; iiMedia Research, 2020; Qxcu Industrial Research Institute, 2021). The shared e-bike recycling rate in the FFEBS system ranged from 30% to 75% (CAICT, 2019; iiMedia Research, 2020; Qxcu Industrial Research Institute, 2021).

Regarding FFESS, the weight of shared e-scooter ranges from 10 to 19 kg, with an average of about 1 kg (Barnes, 2019; de Bortoli & Christoforou, 2020; Hollingsworth et al., 2019; Mobility Foresights, 2021; Moreau et al., 2020). The service life of shared e-scooters, in the early stages of development, was only 1-5 months (Mobility Foresights, 2021; Moreau et al., 2020). However, with improved manufacturing technology and process, the durability of shared e-scooters has been improved, and the life span has been increased from 9 to 18 months (de Bortoli & Christoforou, 2020; Hollingsworth et al., 2019; Moreau et al., 2020). The energy consumption per 100 kilometers ranged from 1.09 kWh to 2.15 kWh (Barnes, 2019; Hollingsworth et al., 2019; Mobility Foresights, 2021). The GHG emission intensity of U.S. electricity throughout its life cycle is approximately 203.5 g CO_2-eq/MJ (732.6 g CO_2-eq/kWh) (National Renewable Energy Laboratory, 2020). The rebalance, collection, and recharging distance for serving a 1 km FFESS trip was about 0.058 – 0.157 km (on average 0.102km) (de Bortoli & Christoforou, 2020; Hollingsworth et al., 2019; Moreau et al., 2020; Zou et al., 2020). The recycling rate of the shared e-scooter ranged from 30% to 75%, which is similar to FFBS

(Mobility Foresights, 2021; Moreau et al., 2020; NACTO, 2020; U.S. Department of Transportation, 2021). The characteristics and operational data of FFEBS and FFESS are presented in Table 6. In addition, the primary inventory data and processes for FFEBS and FFESS are shown in Supplementary materials D and E, respectively.

Table 6. The characteristics and operational data of FFEBS and FFESS

	FFESS in the United States		**FFEBS in China**	
	Distribution type	Distribution parameters	Distribution type	Distribution parameters
Lifespan (Months)	Triangular	First stage : Mean =2.5 Min=1.0 Max=5.0 Second stage : Mean =12.0 Min=9.0 Max=18.0	Triangular	Mean =36 Min=24 Max=48
Weight of shared vehicle (kg)	Triangular	Mean =10.0 Min=15.0 Max=19.0	Triangular	Mean =30 Min=24 Max=39
Recycle rate	Triangular	Mean =30% Min=50% Max=75%	Triangular	Mean =30% Min=50% Max=75%
Rebalance, collection, and recharging distance for serving 1 km shared mobility trip	Normal distribution	Mean=0.102 SD = 0.0164	Normal distribution	Mean=0.167 SD= 0.0266
DTR	Triangular distribution	Mean =1.78 Min=0.987 Max=5.85	Triangular distribution	Mean =1.52 Min=1.05 Max=3.45
Distance per trip (km)	Triangular distribution	Mean =1.95 Min=0.98 Max=3.10	Triangular distribution	Mean =2.50 Min=1.85 Max=3.40

Energy use (kWh/100km)	Normal distribution	Mean=1.55 SD= 0.1817	Normal distribution	Mean=2.10 SD= 0.1297

Note: Source from Aurora Mobile (2021); Barnes (2019); Bozzi and Aguilera (2021); CAICT (2019); de Bortoli and Christoforou (2020); Hello Inc (2021); Hollingsworth et al.(2019); iiMedia Research (2020); Mobility Foresights (2021); NABSA (2021); NACTO (2019, 2020); Qxcu Industrial Research Institute (2021); U.S. Department of Transportation (2021); WTDSRI (2020); and Zou et al., (2020).

2.1.3. Impact assessment

The hierarchist impact assessment method (i.e., ReCiPe 2016) was used in Simapro 9.0 to calculate the environmental impact indicator score, and the impact category “Global warming” was selected to quantitatively estimate the EF and GHG emissions reduction benefits of shared micromobility (Huijbregts et al., 2017; Sun & Ertz, 2021b). In addition, considering the potential bias resulting from the uncertainty of the input data, the corresponding uncertainty analysis was based on 10,000 Monte Carlo simulations.

2.2. GHG emissions reduction benefits of Shared Micromobility

The GHG emissions reduction benefit of shared micromobility can be obtained by Eq. (3)

$$RB = \sum(EF_i - EF_{SM}) \times S_i - EF_{SM} \times S_{NT} \quad (3)$$

With RB referring to the GHG emissions reduction benefit of the shared miromobility. A positive value of RB means that GHG emissions reduction benefit has been obtained, while a negative value indicates that it has increased GHG emissions. EF_{SM} refers to the EF of shared micromobility. S_i and EF_i refer to the share of shared micromobility trips used to replace another transportation mode *i* within the urban transportation system (i.e., car trip, public transit, privately-owned bike, and walking) and the EF of transportation mode *i*. S_{NT} refers to the share of new trips, which refers to the trips that would not be made if the shared micromobility mode were unavailable.

The functional unit for the GHG emissions reduction benefit of the shared micromobility is set to passenger kilometer (pkm). Precisely, the decomposition of the substitution of shared micromobility to other transportation modes (or new trips) was calculated based on the weighted kilometer-based modal shifts, and the corresponding GHG emissions reduction benefit of the shared micromobility can be expressed as g CO_2-eq/pkm (de Bortoli & Christoforou, 2020; Sun & Ertz, 2021b). The decomposition of shared micromobility trips was calculated based on surveys and statistics reports of transportation departments in various regions. The EF of other transportation modes (non-shared micromobility) is presented in Supplementary material F. The details about the substitution rates of shared micromobility for traditional travel modes are shown in Supplementary materials G and H.

3 Results

Here, it first analyzed and compared the impact of pedal bike sharing on GHG emissions (i.e., SBBS and FFBS) and then estimated the effect of electric shared micromobility programs on GHG emissions (i.e., FFEBS and FFEES). For each type of shared micromobility, EF and RB were calculated sequentially, and a corresponding parameter uncertainty analysis and a sensitivity analysis were also performed.

3.1 GHG emissions reduction benefit of SBBS and FFBS

For the SBBS system, the average EF ranged from 30.01 to 187.27g CO_2-eq/pkm (see Fig.2). Due to the significant differences in the actual operating characteristics of SBBS systems in different cities, the EF values vary significantly across other regions. For example, the SBBS in Barcelona, Paris, London, Moscow, New York, Shanghai, Ningbo, and Hangzhou had lower

EF (about 30-40 CO_2-eq/pkm). In contrast, the EF of the SBBS system in Seattle, Los Angeles, Brisbane, and the Bay Area (San Francisco) was relatively high (over 100 g CO_2-eq/pkm). From the perspective of the decomposition value, it can be seen that the stations and docks, as well as the rebalance stage, account for the majority of the emissions.

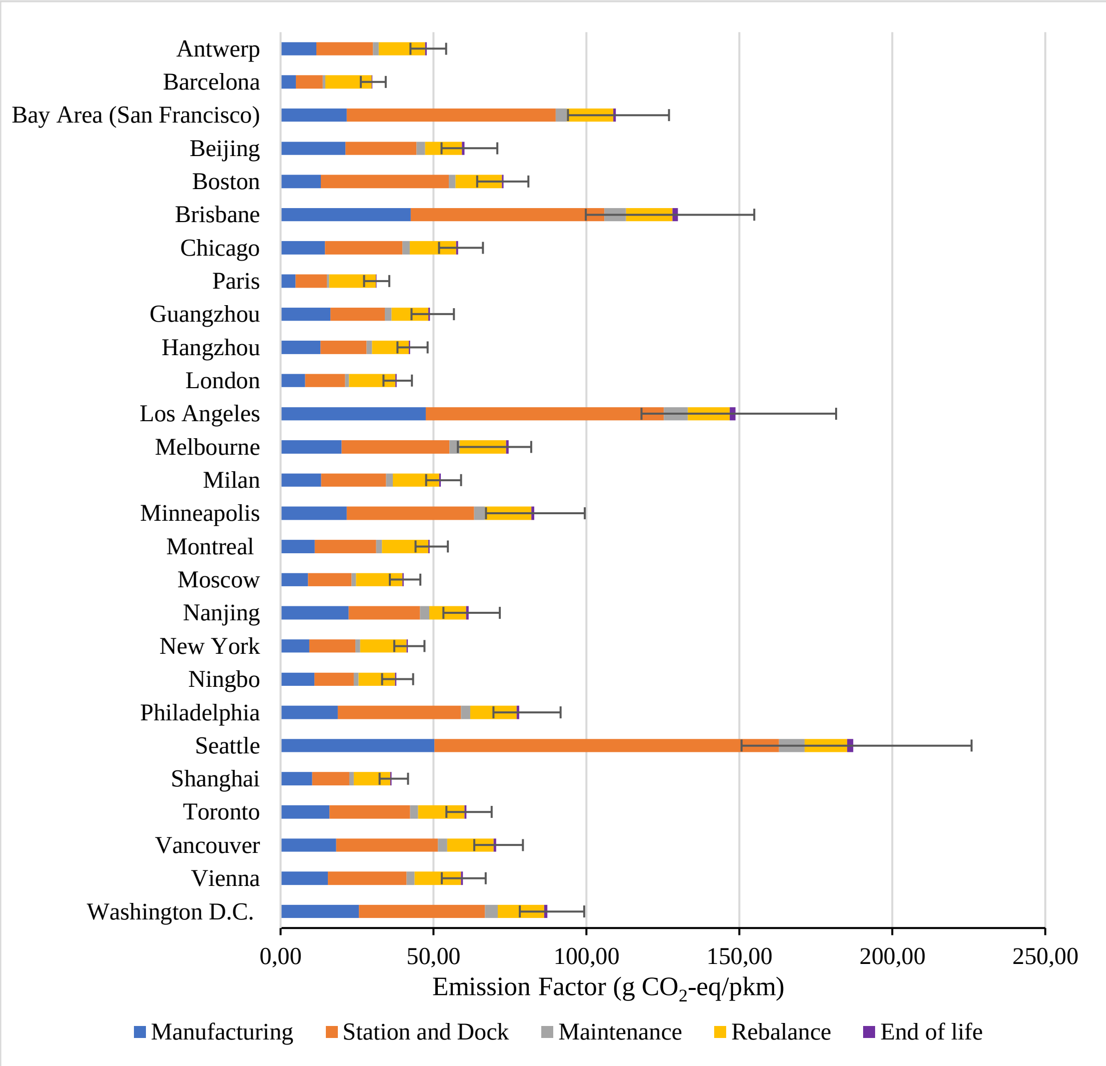

Fig. 2 The GHG emissions factors of SBBS

The FFBS system's EF ranged from 60.22 to 265.29 CO_2-eq/pkm (see Fig.3). The FFBS in Guangzhou, Chengdu, and Nanjing have lower GHG emission factors (about 60–90 g CO_2-eq/pkm). In contrast, the EF values of FFBS systems in Hangzhou, Xi'an, Seattle, and Washington D.C. were relatively high (over 200 g CO_2-eq/pkm). From the perspective of the decomposition value, it can be seen that the manufacturing and the rebalance processes account for the majority of the GHG emission of the FFBS system. It is worth noting that for the decomposition value of emission factors, the decomposition value of FFBS in the manufacturing stage was much higher than that of SBBS. This is mainly because the life cycle vehicle kilometers traveled (VKT) of FFBS was much lower than SBBS. Although there is not much difference in the amount of GHG emissions between manufacturing an SBBS bike and manufacturing an FFBS bike (FFBS=161.56 kg CO_2-eq vs. SBBS=183.57 kg CO_2-eq/pkm), the average life cycle VKT of the FFBS bike is only about a fifth of the SBBS bike (see Supplementary material I). Therefore, according to Eq. (1) (for shared micromobility systems, VKT is equivalent to passenger-kilometers traveled), on a per passenger-kilometer basis, the GHG emission of FFBS in the manufacturing stage was much larger than that of SBBS.

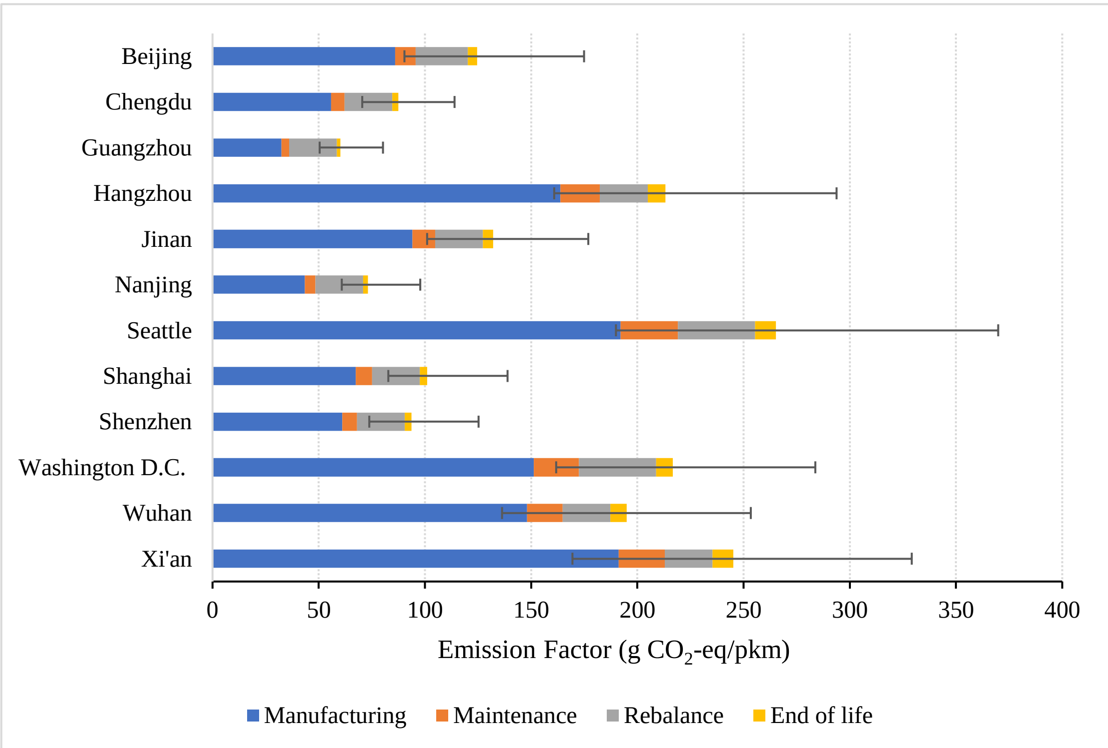

Fig. 3 The GHG emissions factors of FFBS

It can be found that the EF of FFBS was significantly higher than that of the SBBS system. This can be intuitively reflected in cities that have two types of shared bicycle systems, such as Beijing (FFBS=124.61 g CO_2-eq/pkm vs. SBBS=60.08 g CO_2-eq/pkm), Hangzhou (FFBS=213.27 g CO_2-eq/pkm vs. SBBS=42.40 g CO_2-eq/pkm), Nanjing (FFBS=73.12 g CO_2-eq/pkm vs. SBBS=61.45 g CO_2-eq/pkm), Seattle (FFBS=265.28 g CO_2-eq/pkm vs. SBBS=187.27 g CO_2-eq/pkm), Shanghai (FFBS=101.11 g CO_2-eq/pkm vs. SBBS=36.29 g CO_2-eq/pkm) and Washington D.C. (FFBS=216.64 g CO_2-eq/pkm vs. SBBS=87.27 g CO_2-eq/pkm) (see Supplementary material J).

Based on the CE value, the GHG emissions reduction benefits (RB) of shared micromobility can be further estimated and compared. As shown in Fig.4, SBBS has a significant GHG emission reduction potential compared with FFBS. Except for Seattle, Los Angeles, and Brisbane, the GHG emissions reduction benefits of SBBS systems in other cities range from 20.54 g CO_2-eq/pkm to 66.70 g CO_2-eq/pkm. However, the promotion of FFBS has not brought desirable GHG emissions reduction benefits. In particular, the FFBS systems in Seattle, Xi'an, Hangzhou, Washington, and Wuhan have increased GHG emissions by as much as 155.77 g CO_2-eq/pkm, 151.85 g CO_2-eq/pkm, 132.63 g CO_2-eq/pkm, 104.37 g CO_2-eq/pkm and 101.44 g CO_2-eq/pkm, respectively. Uncertainty analysis results (see Supplementary material K) show that neither SBBS nor FFBS can obtain GHG emissions reduction benefits in some cities, such as Seattle. Some cities with SBBS and FFBS systems have achieved GHG emissions reduction benefits, such as Guangzhou and Nanjing. However, the GHG emissions reduction benefits are not significant.

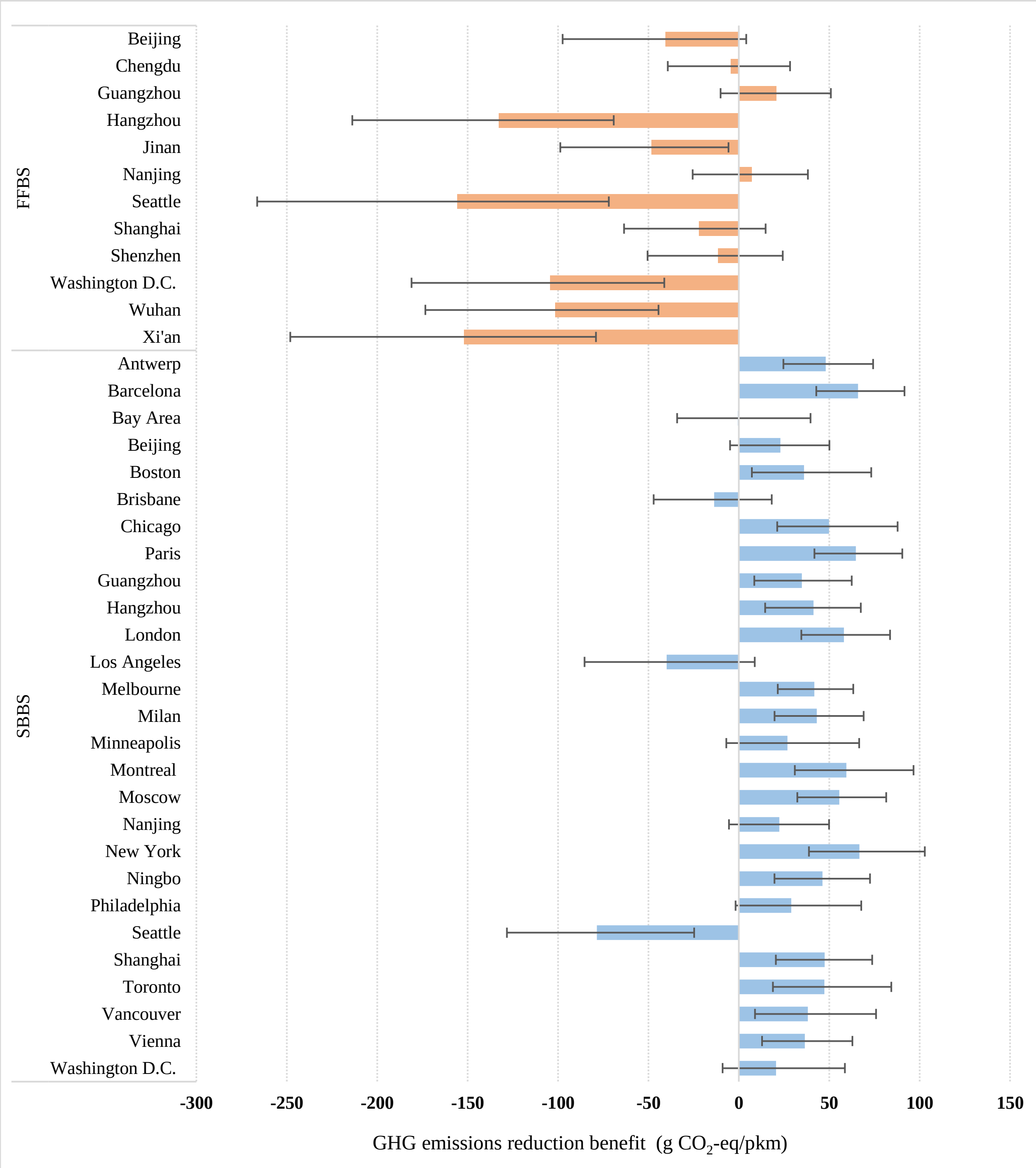

Fig. 4 The GHG emissions reduction benefits of SBBS and FFBS

A sensitivity analysis was also carried out to identify further and analyze the key factors affecting the GHG emissions reduction benefits of SBBS and FFBS. The variance contribution (VC) of uncertain variables in the FFBS and SBBS systems are presented in Supplementary materials L and M, respectively. It shows that the main factors affecting the GHG emission factor and GHG emissions reduction benefit of the SSBS system are DTR (VC = −72.1%), the distance per trip (VC = −11.6%), the rebalance distance (VC = 9.5%), and docks per trip (VC = 3.1%). The main factors affecting the GHG emission factor and GHG emissions reduction benefit of the FFBS system are DTR (VC = −73.3%), the rebalance distance (VC = 8.9%), service life (VC = −8.5%), and distance per trip (VC = −6.2%). It can be seen that the GHG emissions reduction benefits of these bike-sharing programs are mainly affected by the utilization of the shared bike, that is, the life cycle VKT, which is determined by DTR, lifespan, and distance per trip. Increasing DTR, life span, and distance per trip can significantly reduce the GHG emission factor, increasing the corresponding GHG emissions reduction benefits. The difference in GHG emissions reduction benefits between SBBS and FFBS is mainly due to the life cycle VKT. The life cycle VKT of FFBS is much lower than that of SBBS. In addition, the rebalancing process is also an important factor affecting the GHG emissions reduction benefit of FFBS and SBBS. Reducing the rebalancing and distribution distance can also increase the emission reduction potential of SBBS and FFBS.

3.2 GHG emissions reduction benefit of FFEBS

The average EF of FFEBS in China was about 145.19 g CO_2-eq/pkm (Standard Deviation= 26.33, Coefficient of Variation= 0.1813, 95% CI= 102.91– 204.96) (see Fig.5). The manufacturing stage and rebalancing process were the main sources, accounting for about 40.64% and 32.12% of GHG emissions, respectively. The average GHG emissions reduction benefit of FFEBS in China was about −19.46 g CO_2-eq/pkm (standard deviation= 31.72, Coefficient of Variation= 1.63, 95% CI= −37.66– 88.31 g CO_2-eq/pkm) (see Fig.5), which means that the per kilometer FFBS trip increased GHG emissions by 19.46 g CO_2-eq. Therefore, the probability that FFEBS can obtain GHG emissions reduction benefits is approximately 27.79%. The sensitivity analysis results (see Supplementary material N) show that the GHG emissions reduction benefits of FFEBS are mainly affected by the utilization rate of the shared e-bike (i.e., life cycle VKT). Increasing DTR, life span, and distance per trip can significantly increase the GHG emissions reduction benefits of FFEBS. Similarly, reducing the rebalancing and distribution distance (VC = 15.0%) and the bike weight (VC=5.6%) can also increase the GHG emissions reduction potential of FFEBS.

Since expanding the utilization (life cycle VKT) of the shared e-bike is the key to improving the GHG emissions reduction benefit of FFEBS, we estimated the GHG emission factors and GHG emissions reduction benefit of FFEBS under different life cycles VKT (see Fig.6).

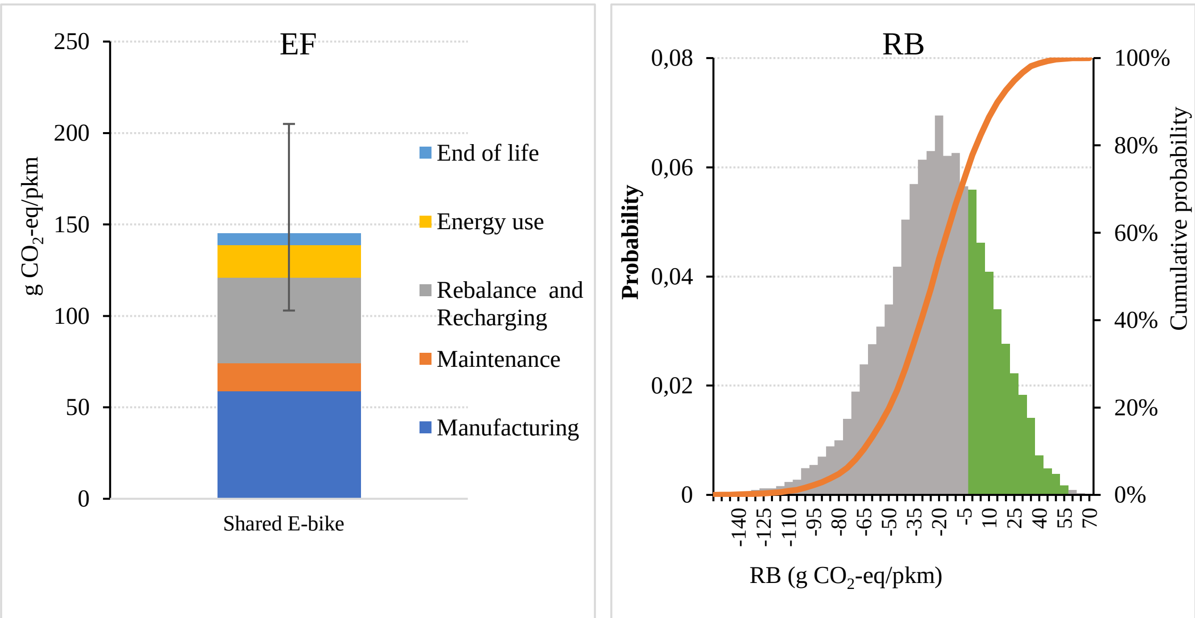

Fig. 5 EF and RB of FFEBS. The uncertainty analysis results were based on statistics of 10,000 simulations.

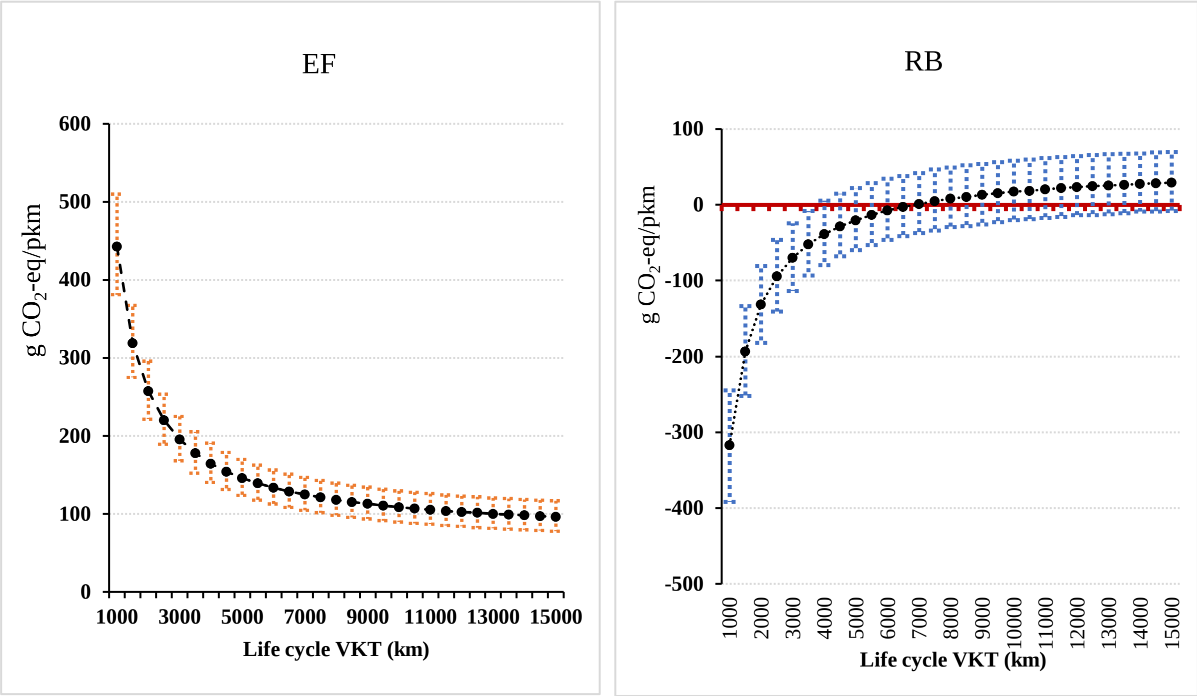

Fig. 6 EF and RB of FFEBS under different life cycle mileage

It can be found that the EF and GHG emissions reduction benefits of FFEBS significantly depend on its life cycle mileage. The inflection points of the emission factor curve and the GHG emissions reduction benefit curve are about 4,000 km. When VKT is less than 4,000 kilometers, as VKT increases, the emission factor and GHG emissions reduction benefit of FFEBS will drop sharply. When VKT is greater than 4,000 kilometers, its sensitivity to GHG emission factors and GHG emissions reduction benefits will gradually weaken. Therefore, it is found that the life cycle VKT of shared e-bikes needs to exceed 7,000 km to obtain GHG emissions reduction benefits. When the life cycle VKT reaches 8000 kilometers, the average GHG emission factor and GHG emissions reduction benefit are about 117.86 g CO_2-eq/pkm (95% CI: 98.20 –139.51 g CO_2-eq/pkm) and 8.22 g CO_2-eq/pkm (95% CI: −29.34– 49.10 g CO_2-eq/pkm), respectively. For example, if the life cycle VKT reaches 10,000 kilometers, the average GHG emission factor and GHG emissions reduction benefit could be about 108.61 g CO_2-eq/pkm

(95% CI: 89.59– 129.47 g CO_2-eq/pkm), and 17.37 g CO_2-eq/pkm (95% CI: −20.24– 58.19 g CO_2-eq/pkm), respectively. In particular, when the life cycle VKT reaches 15 000 kilometers, the GHG emission factor can be reduced to 96.37 g CO_2-eq/pkm (95% CI: 77.79– 116.81 g CO_2-eq/pkm), and the average GHG emissions reduction benefit could be increased to 29.17 g CO_2-eq/pkm (95% CI: −8.08– 69.74 g CO_2-eq/pkm).

3.3 GHG emissions reduction benefit of FFESS

The development of FFESS can be divided into two stages. In the first stage of the development of FFESS, the service life of the shared e-scooter was only about 1–5 months. The average EF of FFESS in the US was about 599.75 g CO_2-eq/pkm (standard deviation= 321.26, Coefficient of Variation= 0.5357, 95% CI= 221.98– 1417.85g CO_2-eq/pkm) (see Fig.7). The manufacturing stage was the primary source, accounting for approximately 76.51% of GHG emissions. In the second phase of the development of FFESS, the service life of the shared e-scooter has increased to 9–18 months. The average EF of shared e-scooter was about 158.58 g CO_2-eq/pkm (standard deviation= 59.14, Coefficient of Variation= 0.3729, 95% CI= 84.05– 309.91g CO_2-eq/pkm) (see Fig.7). From the perspective of the decomposition value, the manufacturing stage and rebalancing process were the primary sources, accounting for about 57.57% and 19.25 % of the total lifecycle GHG emissions, respectively.

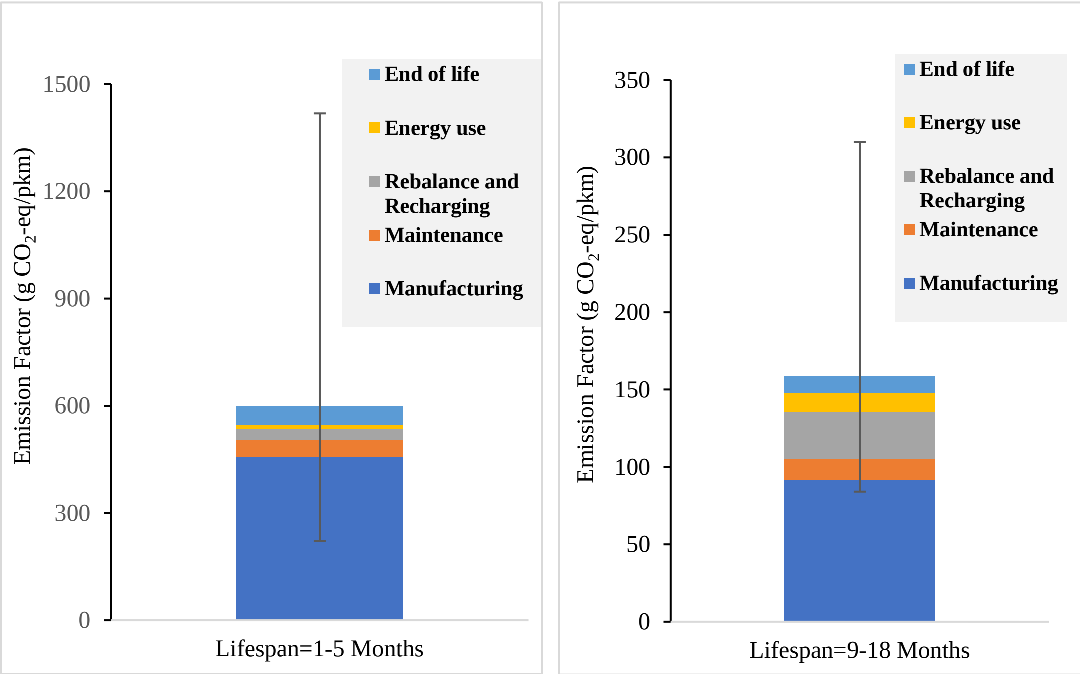

Fig. 7 GHG emission factors of FFESS

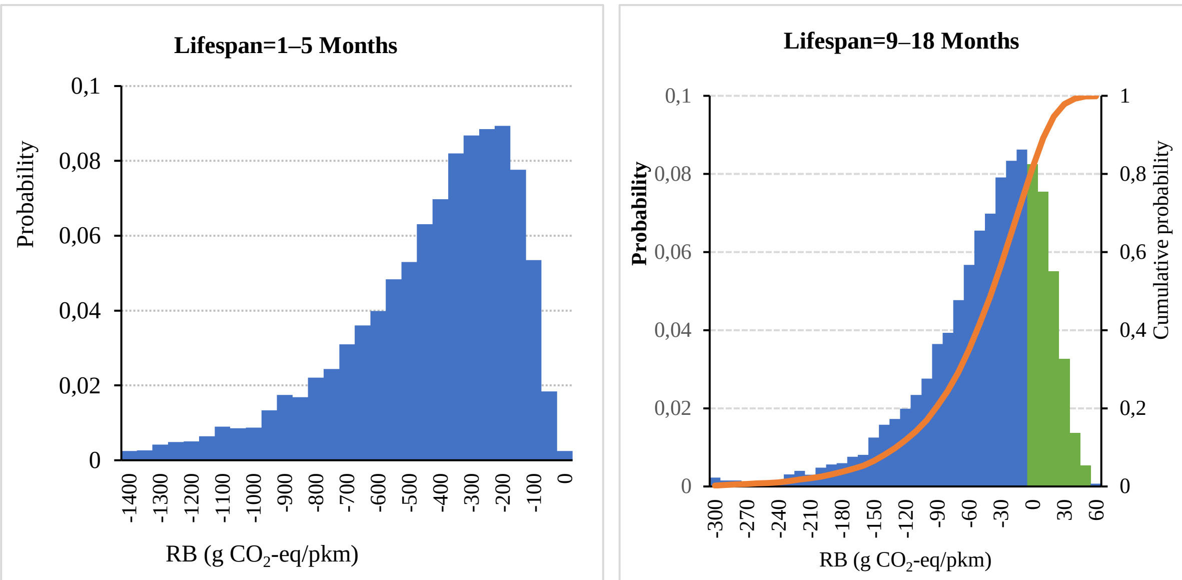

Fig. 8 GHG emissions reduction benefit of FFESS.

It can be found that the promotion of FFESS has not achieved a desirable GHG emission reduction effect. As shown in Fig. 8, in the first stage of the development of FFESS, the service life of the shared e-scooter was only about 1–5 months, and the average GHG emissions reduction benefit (RB) of FFESS was about −482.05 g CO_2-eq/pkm (standard deviation= 321.46, Coefficient of Variation= 0.6669, 95% CI= −1303.14 – −105.81g CO_2-eq/pkm), which means that per kilometer FFESS trip increased GHG emissions by 482.05 g CO_2-eq. Therefore, at this stage, FFESS can hardly obtain positive GHG emissions reduction benefits (the probability was about 0). However, when the lifespan of the shared e-scooter was increased to 9 –18 months, the average RB value of FFESS in the US rose to −40.87g CO_2-eq/pkm (standard deviation= 60.09, Coefficient of Variation= 1.47, 95% CI= −192.84–37.96 g CO_2-eq/pkm), which means that per kilometer FFESS trip increased GHG emissions by 40.87 g CO_2-eq. Moreover, the probability of FFESS achieving a positive GHG emissions reduction benefit was about 26.52%.

The sensitivity analysis results show that the utilization (life cycle VKT) of the shared e-scooter was the primary factor affecting the GHG emissions reduction benefit of FFESS (see Supplementary material O), and the GHG emission factors and GHG emissions reduction benefit of FFESS under different life cycle VKT are presented in Fig.9.

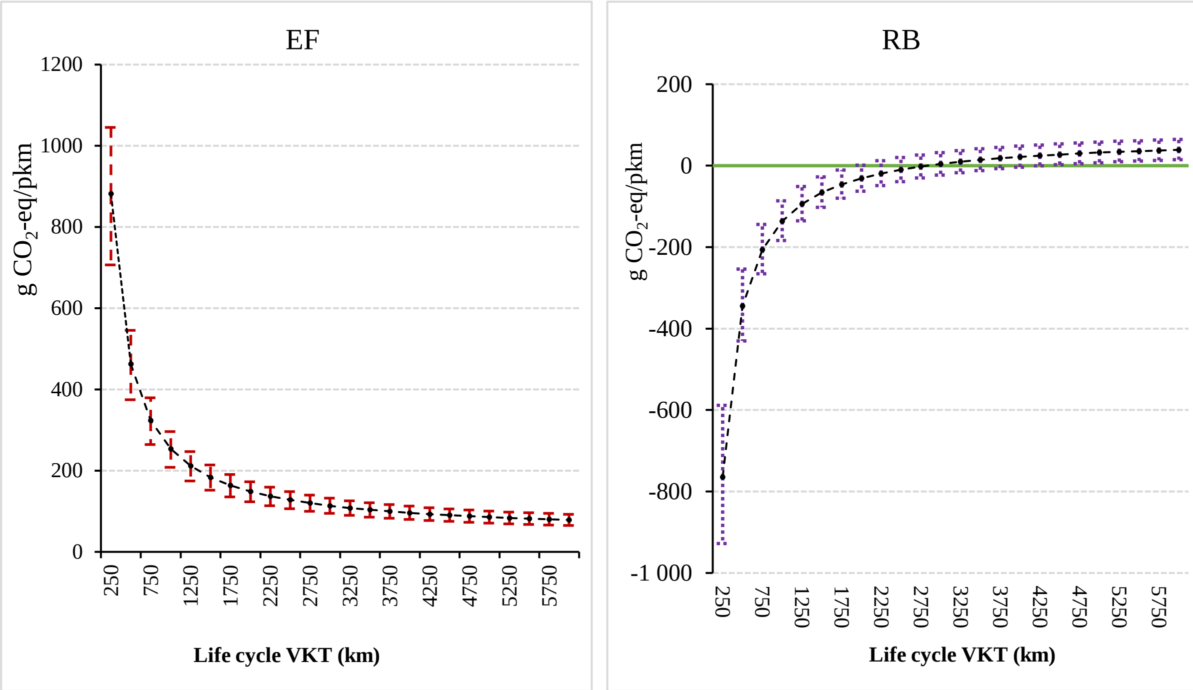

Fig. 9. EF and RB of FFESS under different life cycle VKT

It can be found that the GHG emission and GHG emissions reduction benefits of FFESS significantly depend on its life cycle mileage. The inflection points of the emission factor curve and the GHG emissions reduction benefit curve of FFESS are about 1000 km. When VKT is less than 1000 kilometers, as VKT increases, the emission factor and GHG emissions reduction benefit of FFESS will drop sharply. When VKT is greater than 1,000 kilometers, its sensitivity to emission factors and GHG emissions reduction benefits will gradually weaken. Therefore, it is found that the life cycle mileage of a shared e-scooter needs to exceed 3,000 kilometers to obtain GHG emissions reduction benefits. When the life cycle VKT reaches 4,000 kilometers, the average emission factor and GHG emissions reduction benefit are about 96.14 g CO_2-eq/pkm (95% CI: 79.92 –112.79 g CO_2-eq/pkm) and 21.65 g CO_2-eq/pkm (95% CI: −3.86–48.07g CO_2-eq/pkm), respectively. For example, if the life cycle VKT reaches 5,000 kilometers, the average GHG emission factor and GHG emissions reduction benefit could be about 85.61 g CO_2-eq/pkm (95% CI: 70.85 –100.48 g CO_2-eq/pkm), and 32.13 g CO_2-eq/pkm (95% CI:

−7.03– 57.76 g CO_2-eq/pkm), respectively. In particular, when the life cycle mileage of an E-scooter reaches 6000 kilometers, the GHG emission factor can be reduced to 78.70 g CO_2-eq/pkm (95% CI: 65.05 –92.50 g CO_2-eq/pkm), and the average GHG benefit can be increased to 38.96g CO_2-eq/pkm (95% CI: 14.79– 64.41 g CO_2-eq/pkm).

4 Discussion

This study estimates the impact of global shared micromobillity programs on GHG emissions from the LCA perspective. In contrast to previous studies focused on one or two modes of shared micromobility (Bieliński et al., 2021; Bonilla-Alicea et al., 2020; J. Chen et al., 2020a; Hollingsworth et al., 2019; Luo et al., 2019), this study focuses simultaneously on all the primary modes of shared micromobility. Specifically, it empirically compares and analyzes the GHG emissions impact of traditional shared micromobility modes (i.e., SBBS) and emerging shared micromobility modes (i.e., FFBS, FFEBS, and FFESS) on urban areas' transportation systems. In particular, it presents regional differences in the operating characteristics and development status of global shared micromobility programs. This might be the first study to provide a comprehensive perspective of the GHG emissions reduction benefits of global shared micromobility.

The GHG emissions reduction benefits of shared micromobility were calculated using the LCA method based on the actual operating characteristics and traffic big data of shared micromobility (see Fig.10). Compared with previous exploratory studies only based on the assumption that the usage of shared micromobilty substitute (or reduce) car travel during the vehicle use stage (Fishman, 2016; Fishman et al., 2014; Li et al., 2021; Teixeira et al., 2021; Zhang & Mi, 2018), this study adopts a more robust and systematic approach, so that the conclusions drawn are characterized by greater accuracy and credibility. This paper partially supports the view that shared micromobility has particular GHG emission reduction potential in previous studies (Fishman, 2016; Fishman et al., 2013, 2014; Luo et al., 2019; Teixeira et al., 2021), but only for SBBS. SBBS has achieved desirable GHG reduction benefits in several cities across Europe, North America, and China (over 20 cities in this study). However, the emerging modes driven by the technology progress and the sharing economy have not brought the claimed GHG emissions reduction benefits. Neither FFBS and FFEBS, which have been widely promoted in China, nor FFESS, which has been widely developed in Europe and the US, have lived up to the GHG emissions reduction expectations.

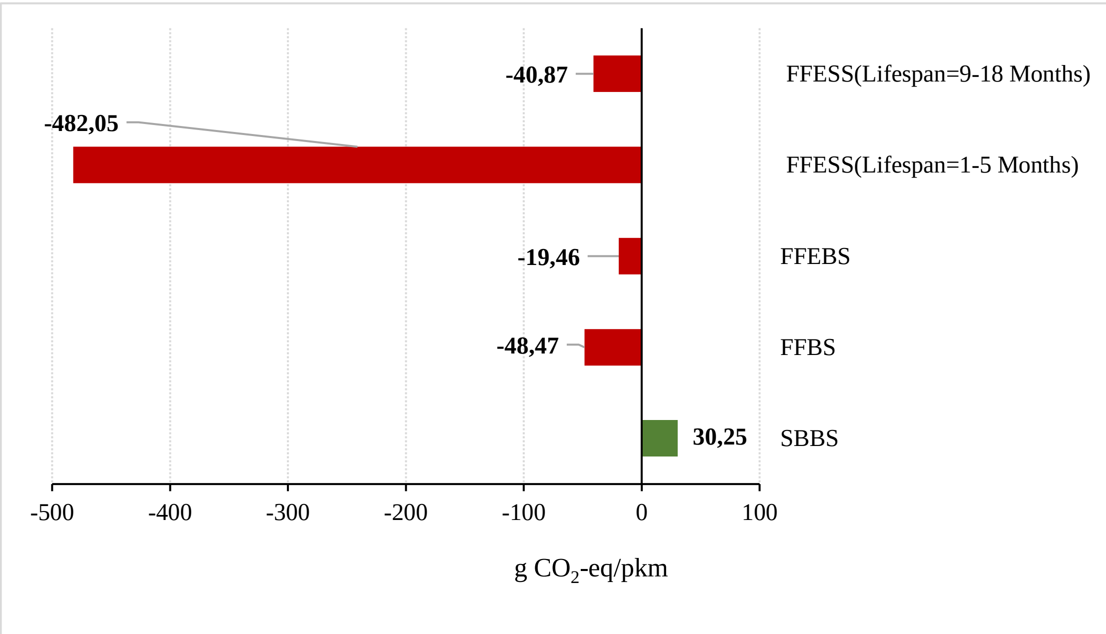

Fig. 10 Average GHG emission reduction benefits of different shared micromobility modes

The results of this study suggest that the environmental benefits of shared micromobility may have been overestimated in previous studies. One of the main reasons for this difference is that the substitute rate of shared micromobility trips for car travel within the cities was overestimated. For example, Qiu and He (2018) estimated the environmental impact of FFBS in Beijing using a 75% substitute rate. As another example, Kou et al. (2020) quantified the GHG emission reduction effects of bike-sharing programs in New York, Chicago, Boston, Philadelphia, Washington, D.C., Los Angeles, San Francisco, and Seattle in 2016 by using the assumption that approximately 65%–80% of bike-sharing trips replaced car trips, Yet, this study uses statistical substitute rates based on actual transportation data that are much lower than these assumptions.

Furthermore, although some studies have corrected the substitute rate of car trips, they have ignored the negative impact of shared micromobility in the manufacturing and maintenance phases (Li et al., 2021; Teixeira et al., 2021; Yi & Yan, 2020). GHG emissions from the manufacturing and maintenance phases account for most of the total GHG emissions in the shared mircomobility lifecycle. According to Eq. (1), if the life cycle mileage of a shared micromobility vehicle is too short, it may become a high-emission mode of transportation. When shared micromobility replaces other more environmentally-friendly ways of transportation (e.g., public transit and walking), its GHG emission reduction benefits will be further diminished. Some studies on China's FFBS market augured that the low service life and utilization rate of shared vehicles makes the GHG emission factor of FFBS much higher than that of public transit and privately-owned bicycles, thus making the promotion of FFBS have a negative environmental impact (Chen et al., 2020; Sun & Ertz, 2020). The latest research on shared e- scooters in the European and US markets also indicated that a too short lifespan can cause the use of shared electric scooters to generate more CO_2 emissions than the mode of transportation they replace (de Bortoli & Christoforou, 2020; Hollingsworth et al., 2019; Moreau et al., 2020; Reck et al., 2022). Similarly, the results of this study also indicate that shared micromobility maybe not be an environmentally-friendly transportation mode. As shown in Fig. 11, the utilization rate of emerging shared micromobility modes (i.e., FFBS, FFEBS, and FFESS) is much lower than traditional shared micromobility modes (i.e., SBBS). The average life cycle VKT of the shared bike in SBBS was about 16245.71 km (95% CI: 5072.60– 32953.22 km), while the average life cycle VKT of the FFBS bike, shared e-bike, and shared e-scooter were about 2799.04 km (95% CI: 990.05–5333.03 km), 5555.99 km (95% CI: 2900.05– 9614.77 km), and 493.73 (95% CI:153.93– 1143.00 km)– 2274.11 km (95% CI: 810.49–4851.33km), respectively. As a result, the average EF of SBBS, FFBS, FFEBS, and FFESS were about 50.79 g CO_2-eq/pkm, 125.57 g CO_2-eq/pkm, 145.19 g CO_2-eq/pkm, and 158.58–599.75 g CO_2-eq/pkm, respectively (see Supplementary material P). The EF of FFBS, FFEBS, and FFESS are significantly higher than those of public transport and private bicycles.

The rapid development of shared micromobility driven by technological progress provides a new potential path for improving the sustainability of urban transportation. However, many transportation network companies have fierce market competition driven by venture capital and commercial interests. To seize market share as soon as possible, they continued to put vehicles into the market and quickly updated products, resulting in an oversupply and severe resource waste. This over-sharing phenomenon has been detrimental to the sustainability of shared micromobility. It reduces the overall utilization and the GHG emissions reduction potentials of the emerging shared micromobility fleet and even worsens the sustainability of the entire transportation system.

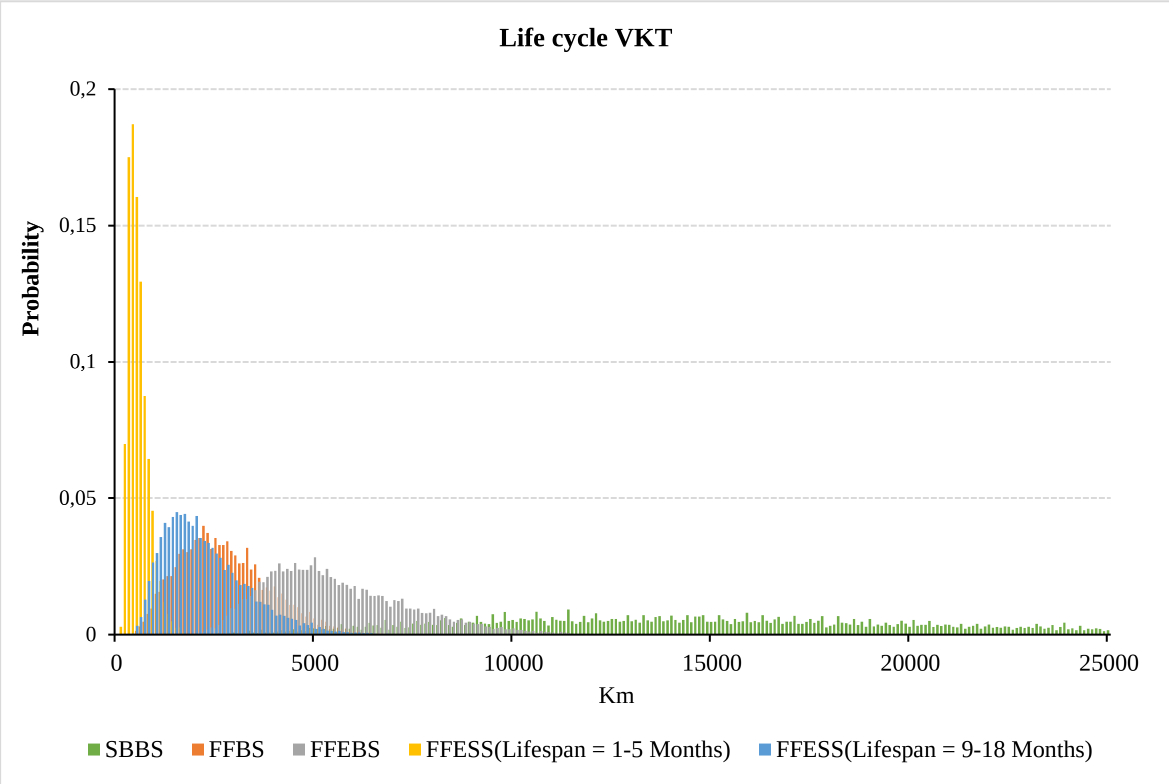

Fig. 11. Life cycle VKT of shared micromobility

In order to better achieve the GHG benefits, authorities and operators should take a series of practical measures to improve the efficiency of the shared micromobility system, such as building more reasonably-sized fleets, optimizing the distribution and rebalancing process, and improving the DTR. In addition, operators should strengthen cooperation with manufacturers and recycling organizations to actively participate in the complete life cycle management of the products in shared micromobility (from design, manufacturing, to recycle). Such cooperation following a cradle-to-cradle philosophy might better realize the closed-loop management of a shared transportation mode, extend its service life, and improve resource utilization, thus contributing to the circular economy (Ertz et al., 2019a, 2019b). Moreover, the public should be encouraged to actively use these systems for daily transport to increase the utilization of shared vehicles and the proportion of green travel in urban traffic.

Driven by technological innovation, better product design and more durable materials can be applied to shared micromobility to extend the service life of the shared transportation mode. This would further contribute to promote the improved design strategy for extending product lifetimes, a strategy that remains very marginal in comparison to others (e.g., distribution, maintenance, recovery) (Ertz et al., 2019a, 2019b). Moreover, with the application and promotion of intelligent management based on machine learning, big data, and the Internet of Things, the operation efficiency of the entire shared micromobility system can be significantly improved (Ertz et al., 2022). All these can help increase the resource utilization rate of the city's shared micromobility system, thereby increasing the future sustainability of the shared micromobility.

City-dwellers worldwide are shifting lifestyles due to the COVID-19 pandemic, especially in daily transport (Bert et al., 2020; Tiako & Stokes, 2021; Wang & Noland, 2021). During the pandemic, shared micromobility has become a resilient and safe ways to move around for essential needs, as it promotes social distancing and helps cities to not rely exclusively on private cars to replace public transit trips, especially for short-distance travel within the city (Awad-Núñez et al., 2021; Dias et al., 2021; Li et al., 2020; Tokey, 2020). In particular, when public transit is considered dangerous or disrupted, shared micromobility can provide resilience to the entire transportation system during public health emergencies and disasters (Jiang et al., 2021; Schwedhelm et al., 2020; Wang & Noland, 2021). Covid-19 has, is, and will continue to shape urban mobility. Cities worldwide have responded to this shift by formulating various policies and plans (Awad-Núñez et al., 2021; Combs & Pardo, 2021). Shared micromoblity is viewed as a more attractive and safe mobility option and contributes to the city's resilience and sustainability (Jobe & Griffin, 2021; Nikiforiadis et al., 2020; Tokey, 2020). Urban planners and designers are rethinking urban, and transport infrastructure planning and construction as cities worldwide reopen to adapt to a post-pandemic world. Shared micromobility systems can become an option for building urban resilient infrastructure architecture.

5 Conclusions

This study combines the life cycle assessment (LCA) framework and the actual shared micromobility operation big data of major countries and cities worldwide to investigate the real impact of shared micromobility programs on urban transportation and the environment. Furthermore, it compares and analyzes the GHG emissions reduction benefits of multiple types of shared micromobility such as SBBS, FFBS, FFEBS, and FFESS. The main conclusions of this study are as follows.

Shared micromobility has particular potentialities for GHG emissions reduction, but it needs to achieve a specific utilization rate. On average, an SBBS trip can reduce about 32.25g CO_2-eq per kilometer, while an FFBS trip may increase it by approximately 48.47g CO_2-eq. As for electric free-floating shared micromobility modes, an FFEBS trip may increase about 19.46 g CO_2-eq per kilometer, and an FFESS trip may increase approximately 40.87g– 482.05 g CO_2-eq per kilometer on average. The emerging shared micromobilty modes (i.e., FFBS, FFEBS, and FFESS) seem less environmentally-friendly than the traditional shared micromobility mode (SBBS). This is mainly because the utilization rate of the emerging shared micromobility modes was much lower than that of the conventional shared micromobility mode. The average life cycle VKT of these new shared micromobility modes was only about one-third to one-fifth of the average life cycle VKT of SBBS.

Contrary to subjective expectations, although the rapid progress of technology in recent years has promoted the vigorous development of shared micromobility, it has not yet brought the GHG emissions reduction benefits claimed by related promoters and operators. In addition to the substitution rate of shared micromobility trips for cars, trips were generally overestimated. Another important reason is that the low utilization rate (i.e., short life cycle mileage) makes shared micromobility more likely to be an environmentally-unfriendly mode of transportation. Considering that the operating characteristics and development status of the shared micromobility market vary considerably, authorities should rethink the shared micromobility program and formulate appropriate plans based on the current conditions and goals of the region to better improve the utilization rate of the shared micromobility and promote the sustainability of the urban transportation system.

This empirical study helps to better understand the environmental impact of the global shared micromobility programs. Furthermore, the analysis framework and findings offer valuable references for researchers and managers committed to improving urban sustainability. As what is likely the first study to provide a comprehensive picture of the GHG emissions reduction benefits of global shared micromobility, this research not only fills the academic gap that lacks empirical evidence for the environmental impact of shared micromobility, but also constitutes a new approach for further research on the sustainability of emerging shared micromobility.

This study also has several limitations that pave the way for future research. First, this article only studies GHG emissions in terms of environmental analysis. It does not include broader impacts such as air pollution, terrestrial acidification, resource scarcity, water consumption, land use, and so on. In addition to the environmental impact, the social and economic effects of shared micromobility deserve further exploration and research. Besides, this study did not consider the substitution rate among different shared micromobility modes due to the lack of available data. This may affect the GHG emissions reduction benefits of the shared micromobility to a certain extent, and it needs to be further improved based on more sufficient data in the future. Finally, the quantitative analysis in this study is based on the overall statistical characteristics of the system's multi-year operational data. Although multi-year aggregation can mitigate some data biases, this operation will eliminate the signals reflecting time-series changes of shared micromobility industrial development. Therefore, future research will further analyze the evolution of the industry development of shared micromobility and the corresponding environmental impacts from a dynamic perspective.

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Supplementary materials

Supplementary material A. Main inventory data and processes for a shared bike in the SBBS system.

Process	Inputs from the Technosphere/Outputs to the Technosphere		unit	value
Manufacturing stage	Inputs from the technosphere	polyurethane, flexible foam	kg	3.50E-02
		chromium steel removed by turning, average, conventional	kg	1.88E-01
		heat, district, or industrial, other than natural gas	MJ	2.28E-01
		wire drawing, steel	kg	3.99E-01
		powder coat, aluminum sheet	m2	4.13E-01
		synthetic rubber	kg	6.64E-01
		tap water	kg	8.78E-01
		welding, arc, aluminum	m	8.85E-01
		steel, chromium steel 18/8, hot rolled	kg	1.88E+00
		injection molding	kg	2.31E+00
		road vehicle factory	unit	1.12E-09
		polyethylene, high density, granulate	kg	2.31E+00
		section bar extrusion, aluminum	kg	4.45E+00
		steel, low-alloyed, hot rolled	kg	5.78E+00
		electricity, medium voltage	kWh	8.13E+00
		aluminum, wrought alloy	kg	8.89E+00
		heat, district or industrial, natural gas	MJ	1.60E+01
	Outputs to technosphere, wastes	municipal solid waste	kg	5.31E+00
		used bicycle	unit	1.00E+00
		wastewater	m^3	1.00E-03
Use stage	Inputs from the technosphere	aluminum alloy, AlMg3	kg	4.45E-01
		chromium steel removed by turning, average, conventional	kg	2.69E-01
		injection molding	kg	1.16E+00
		polyethylene, high density, granulate	kg	1.16E+00
		polyurethane, flexible foam	kg	3.50E-02
		road	my	5.81E-05
		section bar extrusion, aluminum	kg	4.45E-01
		steel, low-alloyed, hot rolled	kg	2.69E-01
		synthetic rubber	kg	1.99E+00
		tap water	kg	8.80E-02
	Outputs to the technosphere, wastes	waste plastic, mixture	kg	1.19E+00
		waste rubber, unspecified	kg	9.96E-01
End of life	Outputs to	Transport	km	2.25E+00

stage(Recycling)	technosphere	waste plastic, mixture	kg	2.35E+00
		waste rubber, unspecified	kg	3.32E-01
End of life stage (Leaving a shared bicycle without disposal options)	Outputs to technosphere	aluminum treatment of waste aluminum, sanitary landfill	kg	8.89E+00
		Polyethylene treatment of waste polyethylene, sanitary landfill	kg	2.31E+00
		Polyurethane treatment of waste polyurethane, sanitary landfill	kg	3.50E-02
		Steel treatment of scrap steel, inert material landfill	kg	8.18E+00
		Synthetic rubber treatment of waste rubber, unspecified, municipal incineration	kg	6.64E-01
		Transport	km	2.15E+00

Note: 1) The data presented in the table is for a 20kg SBBS bicycle. Considering that there is no significant difference in materials and components of various SBBS bicycles, the inventory data in the manufacturing stage is scaled with bike mass.

2) Data comes from Bike Share Research (2021); Bike Share Toronto (2020); Bonilla-Alicea et al. (2020); Deng et al. (2017); Kou et al. (2020); Liu et al. (2016); Mei et al., 2019; Morency et al., (2017); NACTO (2018); Sun and Ertz (2021a); Wernet et al. (2016); Zheng and Zhu (2014).

Supplementary material B. Main material consumption for making one station and one dock.

Component	Material / Ecoinvent unit process	Unit	Value
Station	Aluminum alloy, AlMg3	kg	3.85E+01
	Battery, Li-ion, rechargeable, prismatic	kg	8.15E+01
	Electronics, for control units	kg	1.00E+01
	Flat glass, uncoated	kg	6.80E+00
	Photovoltaic panel, multi-Si wafer	m2	1.50E+00
	Steel, chromium steel 18/8	kg	4.54E+01
Dock	Steel, chromium steel 18/8	kg	3.00E+01

Note : Source from Bonilla-Alicea et al.(2020); Luo et al.(2019); Sun and Ertz (2021a, 2021b)

Supplementary material C. Main inventory data and processes for a shared bike in the FFBS system.

Process	Inputs from the Technosphere/Outputs to the Technosphere		unit	value
Manufacturing stage	Inputs from the technosphere	section bar extrusion, aluminum	kg	4.40E+00
		Printed circuit board	kg	3.00E-01
		aluminum, wrought alloy	kg	8.75E+00
		Battery	kg	2.00E-01
		wire drawing, steel	kg	3.99E-01
		chromium steel removed by turning, average, conventional	kg	1.88E-01
		steel, chromium steel 18/8, hot rolled	kg	1.88E+00
		Electronic equipment	kg	3.00E-01
		polyethylene, high density, granulate	kg	2.31E+00
		tap water	kg	8.78E-01
		polyurethane, flexible foam	kg	3.50E-02
		synthetic rubber	kg	6.64E-01
		injection molding	kg	2.31E+00
		steel, low-alloyed, hot rolled	kg	5.78E+00
		electricity, medium voltage	kWh	8.13E+00
		welding, arc, aluminum	m	8.85E-01
		Photovoltaic panel	m2	2.00E-02
		powder coat, aluminum sheet	m2	4.13E-01
		heat, district, or industrial, other than natural gas	MJ	2.28E-01
		heat, district or industrial, natural gas	MJ	1.60E+01
		road vehicle factory	unit	1.12E-09
	Outputs to technosphere, wastes	municipal solid waste	kg	5.31E+00
		wastewater	m3	1.05E-03
		used bicycle	unit	1.00E+00
Use stage	Inputs from the technosphere	road	my	5.81E-05
		polyurethane, flexible foam	kg	3.50E-02
		tap water	kg	8.80E-02
		steel, low-alloyed, hot rolled	kg	2.69E-01
		chromium steel removed by turning, average, conventional	kg	2.69E-01
		aluminum alloy, AlMg3	kg	4.45E-01
		section bar extrusion, aluminum	kg	4.45E-01
		polyethylene, high density, granulate	kg	1.16E+00
		injection molding	kg	1.16E+00
		synthetic rubber	kg	1.99E+00
	Outputs to the technosphere, wastes	waste plastic, mixture	kg	1.19E+00
		waste rubber, unspecified	kg	9.96E-01

End of life stage(Recycling)	Outputs to technosphere	Used Li-ion battery	kg	2.50E-01
		waste rubber, unspecified	kg	3.32E-01
		Waste electric and electronic equipment	kg	6.00E-01
		Transport	km	2.25E+00
		waste plastic, mixture	kg	2.35E+00
End of life stage (Leaving a shared bicycle without disposal options)	Outputs to technosphere	aluminum treatment of waste aluminum, sanitary landfill	kg	8.885
		Used battery	kg	2.00E-01
		Polyurethane treatment of waste polyurethane, sanitary landfill	kg	3.50E-02
		Waste electric and electronic equipment	kg	6.00E-01
		Synthetic rubber treatment of waste rubber, unspecified, municipal incineration	kg	6.64E-01
		Transport	km	2.00E+00
		Polyethylene treatment of waste polyethylene, sanitary landfill	kg	2.31E+00
		Steel treatment of scrap steel, inert material landfill	kg	8.18E+00

Note: 1) The data presented in the table is for a 20kg FFBS bicycle. Considering that there is no significant difference in materials and components of various types of FFBS bicycles, the inventory data in the manufacturing stage is scaled with bike mass.

2) Data comes from Bonilla-Alicea et al.(2020); Chen et al.(2020a); Chen et al.(2020b); CSIC (2020); Luo et al.(2019); NACTO (2020) ; Sun and Ertz(2021a); Wernet et al.(2016).

Supplementary material D. Main inventory data and processes for a shared e-bike in the FFEBS system.

Process	Inputs from the Technosphere/Outputs to the Technosphere		unit	value
Manufacturing stage	Inputs from the technosphere	Aluminum, cast alloy	kg	3.01E+00
		Aluminum, wrought alloy	kg	6.40E+00
		Battery, Li-ion, rechargeable, prismatic	kg	4.77E+00
		Chromium steel is removed by turning	kg	1.99E-01
		Electric motor,	kg	5.50E+00
		Electricity, medium voltage	kWh	8.61E+00
		Heat, district or industrial,	MJ	1.72E+01
		Injection molding	kg	2.45E+00
		Polyethylene, high density, granulate	kg	2.45E+00
		Polyurethane, flexible foam	kg	3.75E-02
		Powder coat, aluminium sheet	m2	4.37E-01

		Road vehicle factory	p	1.65E-09
		Section bar extrusion, aluminium	kg	4.71E+00
		Steel, chromium steel 18/8, hot rolled	kg	1.99E+00
		Steel, low-alloyed, hot rolled	kg	6.13E+00
		Synthetic rubber	kg	7.03E-01
		Tap water	kg	9.30E-01
		Welding, arc, aluminium	m	9.37E-01
		Wire drawing, steel	kg	4.22E-01
		Printed circuit board	kg	3.50E-01
		Electronic control unit	kg	3.50E-01
		Photovoltaic panel	m^2	2.00E-02
	Outputs to technosphere, wastes	used e-bike	unit	1.00E+00
		municipal solid waste	kg	5.63E+00
		wastewater	m^3	1.00E-03
Use stage	Inputs from the technosphere	Aluminum alloy, AlMg3	kg	3.49E-01
		Battery, Li-ion, rechargeable, prismatic	kg	4.77E+00
		Chromium steel is removed by turning,	kg	2.11E-01
		Injection moulding	kg	9.06E-01
		Polyethylene, high density, granulate	kg	9.06E-01
		Polyurethane, flexible foam	kg	2.78E-02
		Section bar extrusion, aluminium	kg	3.49E-01
		Steel, low-alloyed, hot rolled	kg	2.11E-01
		Synthetic rubber	kg	1.56E+00
		Tap water	kg	6.90E-02
	Outputs to the technosphere, wastes	waste rubber, unspecified	kg	7.81E-01
		Used Li-ion battery	kg	4.77E+00
		waste plastic, mixture	kg	9.34E-01
End of life stage(Recycling)	Outputs to technosphere	waste plastic, mixture	kg	2.48E+00
		waste rubber, unspecified	kg	3.15E+00
		Waste electric and electronic equipment	kg	6.00E-01
		Used Li-ion battery	kg	4.77E+00
		Transport	km	2.00E+00
End of life stage (Leaving a shared bicycle without disposal options)	Outputs to technosphere	aluminum treatment of waste aluminum, sanitary landfill	kg	1.35E+01
		Waste electric and electronic equipment	kg	7.00E-01
		Used electric motor, vehicle	kg	5.49E+00
		Rubber treatment of waste rubber, unspecified, municipal incineration	kg	3.15E+00
		Transport	km	2.00E+00

	Used Li-ion battery	kg	4.77E+00
	waste plastic, mixture treatment of waste plastic, sanitary landfill	kg	2.48E+00
	Steel treatment of scrap steel, inert material landfill	kg	8.45E+00

Note: 1) The data presented in the table is for a 30kg shared E-bicycle. Considering that there is no significant difference in materials and components of various types of shared E-bicycles, the inventory data in the manufacturing stage is scaled with the mass of shared E-bicycle.

2) Data comes from Aurora Mobile (2021); CAICT(2019); iiMedia Research (2020); Qxcu Industrial Research Institute (2021);Wernet et al.(2016); WTDSRI (2020).

Supplementary material E. Main inventory data and processes for a shared e-scooter in FFEES system.

Process	Inputs from the Technosphere/Outputs to the Technosphere		unit	value
Manufacturing stage	Inputs from the technosphere	Aluminum alloy, AlMg3	kg	6.74E+00
		Aluminium, cast alloy	kg	3.01E-01
		Battery, Li-ion, rechargeable, prismatic	kg	3.25E+00
		Charger, for electric scooter	kg	4.53E-01
		Electric motor, for electric scooter	kg	1.40E+00
		Light emitting diode	kg	1.88E-02
		Polycarbonate	kg	3.22E-01
		Printed wiring board, surface mounted, unspecified, Pb containing	kg	6.94E-02
		Steel, low-alloyed	kg	1.59E+00
		Synthetic rubber	kg	1.39E+00
		Tap water	kg	8.75E-01
		Transistor, wired, small size, through-hole mounting	kg	7.29E-02
		Powder coat, aluminium sheet	m2	4.12E-01
		Welding, arc, aluminium	m	8.82E-01
		Electronic control unit	kg	3.00E-01
		Electricity, medium voltage	kWh	7.63E+00
		Heat, district or industrial, natural gas	MJ	1.51E+01
		Heat, central or small-scale, other than natural gas	MJ	2.14E-01
	Outputs to technosphere, wastes	used e-scooter	unit	1.00E+00
		municipal solid waste	kg	2.74E+00
		wastewater	m^3	1.00E-03
Use stage	Inputs from the technosphere	Aluminum alloy, AlMg3	kg	2.79E-01
		Chromium steel removed by turning, average, conventional	kg	1.69E-01
		Injection moulding	kg	7.25E-01

		Polyethylene, high density, granulate	kg	7.25E-01
		Polyurethane, flexible foam	kg	2.20E-02
		Section bar extrusion, aluminium	kg	2.79E-01
		Steel, low-alloyed, hot rolled	kg	1.69E-01
		Synthetic rubber	kg	1.25E+00
		Tap water	kg	5.50E-01
	Outputs to the technosphere, wastes	waste rubber, unspecified	kg	6.30E-01
		waste plastic, mixture	kg	7.50E-01
End of life stage(Recycling)	Outputs to technosphere	waste plastic, mixture	kg	2.74E-01
		waste rubber, unspecified	kg	1.19E+00
		Waste electric and electronic equipment	kg	3.50E-01
		Used Li-ion battery	kg	3.27E+00
		Transport	km	2.00E+00
End of life stage (Leaving a shared bicycle without disposal options)	Outputs to technosphere	aluminum treatment of waste aluminum, sanitary landfill	kg	5.98E+00
		Waste electric and electronic equipment	kg	7.45E-01
		Used electric motor for electric scooter	kg	1.19E+00
		Rubber treatment of waste rubber, unspecified, municipal incineration	kg	1.19E+00
		Transport	km	2.00E+00
		Used Li-ion battery	kg	3.27E+00
		waste plastic, mixture treatment of waste plastic, sanitary landfill	kg	2.74E-01
		Steel treatment of scrap steel, inert material landfill	kg	1.47E+00

Note: 1) The data presented in the table is for 15kg shared E-scooters. Considering that there is no significant difference in materials and components of various types of shared E-scooters, the inventory data in the manufacturing stage is scaled with the mass of E-scooters.
2) Data comes from Barnes (2019); de Bortoli and Christoforou (2020); Hollingsworth et al.(2019); Mobility Foresights(2021); Moreau et al. (2020); National Renewable Energy Laborator (2020); U.S. Department of Transportation(2021); Wernet et al.(2016); Zou et al.(2020).

Supplementary material F. EF of non-shared micromobility modes in the urban transport system

Transportation mode	**GHG Emission factor (g CO_2-eq/pkm)**
Public transit trip	89.5
Car trip	256.8
Privately-owned bike (POB)	15.4
Walk	0.0

Note: Source from Hollingsworth et al.(2019), Luo et al. (2019), and Wernet et al.(2016).

Supplementary material G. Substitution rates of shared micromobility for pedal bike sharing (SBBS and FFBS)

City	**Transportation mode substitution rate**				**City**	**Transportation mode substitution rate**			
Antwerp		min	max	mean	Minneapolis		min	max	mean
	car	6%	44%	25%		car	13%	57%	26%
	Public transit	58%	13%	27%		Public transit	45%	11%	29%
	POB	8%	27%	28%		POB	6%	9%	7%
	Walk	25%	13%	13%		Walk	32%	14%	32%
	new trip	4%	3%	6%		new trip	4%	9%	6%
Barcelona		min	max	mean	Montreal		min	max	mean
	car	7%	41%	27%		car	15%	52%	24%
	Public transit	56%	15%	28%		Public transit	43%	15%	34%
	POB	7%	29%	24%		POB	10%	8%	7%
	Walk	27%	13%	15%		Walk	28%	12%	26%
	new trip	3%	2%	6%		new trip	4%	13%	9%
Bay Area (San Francisco)		min	max	mean	Moscow		min	max	mean
	car	14%	56%	26%		car	5%	42%	26%
	Public transit	41%	17%	29%		Public transit	52%	18%	31%
	POB	8%	9%	7%		POB	10%	23%	19%
	Walk	30%	15%	32%		Walk	25%	15%	18%
	new trip	7%	3%	6%		new trip	8%	2%	6%
Beijing		min	max	mean	Nanjing		min	max	mean
	car	6%	35%	16%		car	5%	34%	17%
	Public transit	35%	31%	43%		Public transit	37%	30%	42%
	POB	30%	9%	21%		POB	29%	6%	16%
	Walk	13%	12%	11%		Walk	15%	15%	14%
	new trip	17%	13%	9%		new trip	14%	15%	11%
Boston		min	max	mean	New York		min	max	mean
	car	13%	57%	26%		car	11%	56%	24%
	Public transit	45%	11%	29%		Public transit	46%	16%	32%
	POB	6%	12%	7%		POB	8%	11%	9%
	Walk	32%	10%	32%		Walk	31%	10%	29%
	new trip	4%	11%	6%		new trip	4%	7%	6%
Brisbane		min	max	mean	Ningbo		min	max	mean
	car	21%	42%	29%		car	7%	31%	16%
	Public transit	41%	26%	36%		Public transit	32%	37%	38%
	POB	9%	21%	13%		POB	22%	8%	21%
	Walk	25%	10%	21%		Walk	19%	9%	13%
	new trip	4%	1%	1%		new trip	20%	15%	12%
Chengdu		min	max	mean	Philadelphia		min	max	mean
	car	5%	35%	17%		car	14%	54%	25%
	Public transit	37%	30%	42%		Public transit	43%	16%	29%

	POB	29%	5%	21%		POB	7%	9%	7%
	Walk	15%	15%	11%		Walk	31%	10%	29%
	new trip	14%	15%	9%		new trip	5%	11%	9%
Chicago		min	max	mean	Seattle		min	max	mean
	car	13%	53%	26%		car	13%	57%	26%
	Public transit	38%	18%	31%		Public transit	45%	11%	29%
	POB	9%	7%	8%		POB	6%	11%	7%
	Walk	33%	11%	29%		Walk	32%	11%	32%
	new trip	7%	11%	6%		new trip	4%	11%	6%
Paris		min	max	mean	Shanghai		min	max	mean
	car	7%	41%	25%		car	7%	35%	17%
	Public transit	57%	19%	27%		Public transit	34%	28%	42%
	POB	8%	25%	28%		POB	29%	5%	21%
	Walk	24%	12%	13%		Walk	15%	17%	11%
	new trip	4%	3%	6%		new trip	15%	15%	9%
Guangzhou		min	max	mean	Shenzhen		min	max	mean
	car	8%	33%	16%		car	5%	35%	19%
	Public transit	33%	40%	39%		Public transit	37%	30%	40%
	POB	24%	5%	20%		POB	27%	5%	21%
	Walk	19%	10%	12%		Walk	15%	15%	11%
	new trip	16%	12%	13%		new trip	16%	15%	9%
Hangzhou		min	max	mean	Toronto		min	max	mean
	car	6%	35%	18%		car	12%	50%	23%
	Public transit	39%	35%	42%		Public transit	41%	20%	32%
	POB	26%	7%	17%		POB	6%	11%	7%
	Walk	12%	14%	11%		Walk	32%	9%	29%
	new trip	17%	9%	11%		new trip	9%	10%	9%
Jinan		min	max	mean	Vancouver		min	max	mean
	car	5%	35%	17%		car	14%	55%	26%
	Public transit	37%	30%	42%		Public transit	42%	13%	30%
	POB	29%	5%	21%		POB	10%	13%	12%
	Walk	15%	15%	11%		Walk	28%	12%	26%
	new trip	14%	15%	9%		new trip	6%	7%	6%
London		min	max	mean	Vienna		min	max	mean
	car	6%	44%	25%		car	8%	40%	22%
	Public transit	58%	13%	27%		Public transit	54%	17%	33%
	POB	8%	27%	28%		POB	10%	29%	23%
	Walk	25%	13%	13%		Walk	22%	10%	16%
	new trip	4%	3%	6%		new trip	6%	4%	6%
Los Angeles		min	max	mean	Washington D.C.		min	max	mean
	car	11%	49%	26%		car	13%	56%	29%
	Public transit	39%	20%	29%		Public transit	43%	17%	27%
	POB	7%	11%	7%		POB	6%	13%	9%

	Walk	32%	11%	32%		Walk	30%	10%	28%
	new trip	11%	9%	6%		new trip	8%	4%	7%
Melbourne		min	max	mean	Wuhan		min	max	mean
	car	21%	42%	29%		car	5%	35%	17%
	Public transit	41%	26%	36%		Public transit	37%	30%	42%
	POB	9%	21%	13%		POB	29%	5%	21%
	Walk	25%	10%	21%		Walk	15%	15%	11%
	new trip	4%	1%	1%		new trip	14%	15%	9%
Milan		min	max	mean	Xi'an		min	max	mean
	car	6%	44%	25%		car	7%	31%	16%
	Public transit	58%	13%	27%		Public transit	31%	36%	35%
	POB	8%	27%	28%		POB	24%	10%	18%
	Walk	25%	13%	13%		Walk	17%	13%	15%
	new trip	4%	3%	6%		new trip	21%	10%	16%

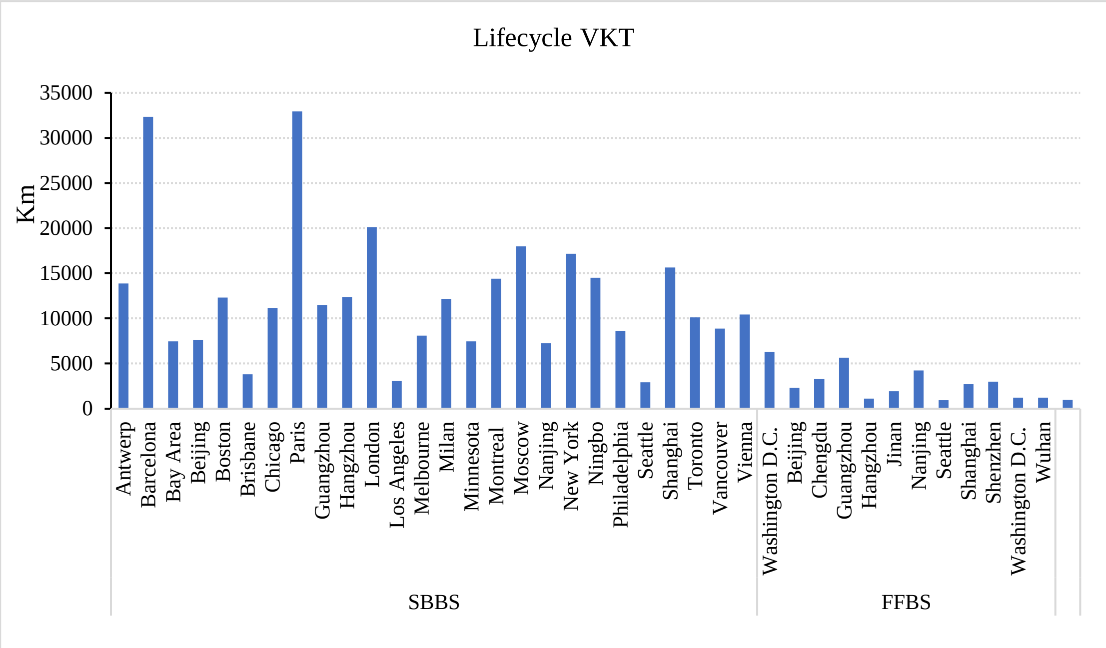
Note: Source from CSIC (2018); Fishman (2016); Fishman et al. (2014, 2013); Fitch et al.(2020); Jiang et al., (2021); Kou et al. (2020); Link et al. (2020); Mao et al. (2021); Morency et al.(2017); NACTO(2019); Qxcu Industrial Research Institute (2021); Shaheen and Cohen (2021); SURC & TDRI (2020); Teixeira et al. (2021); and U.S. Department of Transportation (2021).

Supplementary material H. Transportation mode substitution rate of FFEBE and FFESS

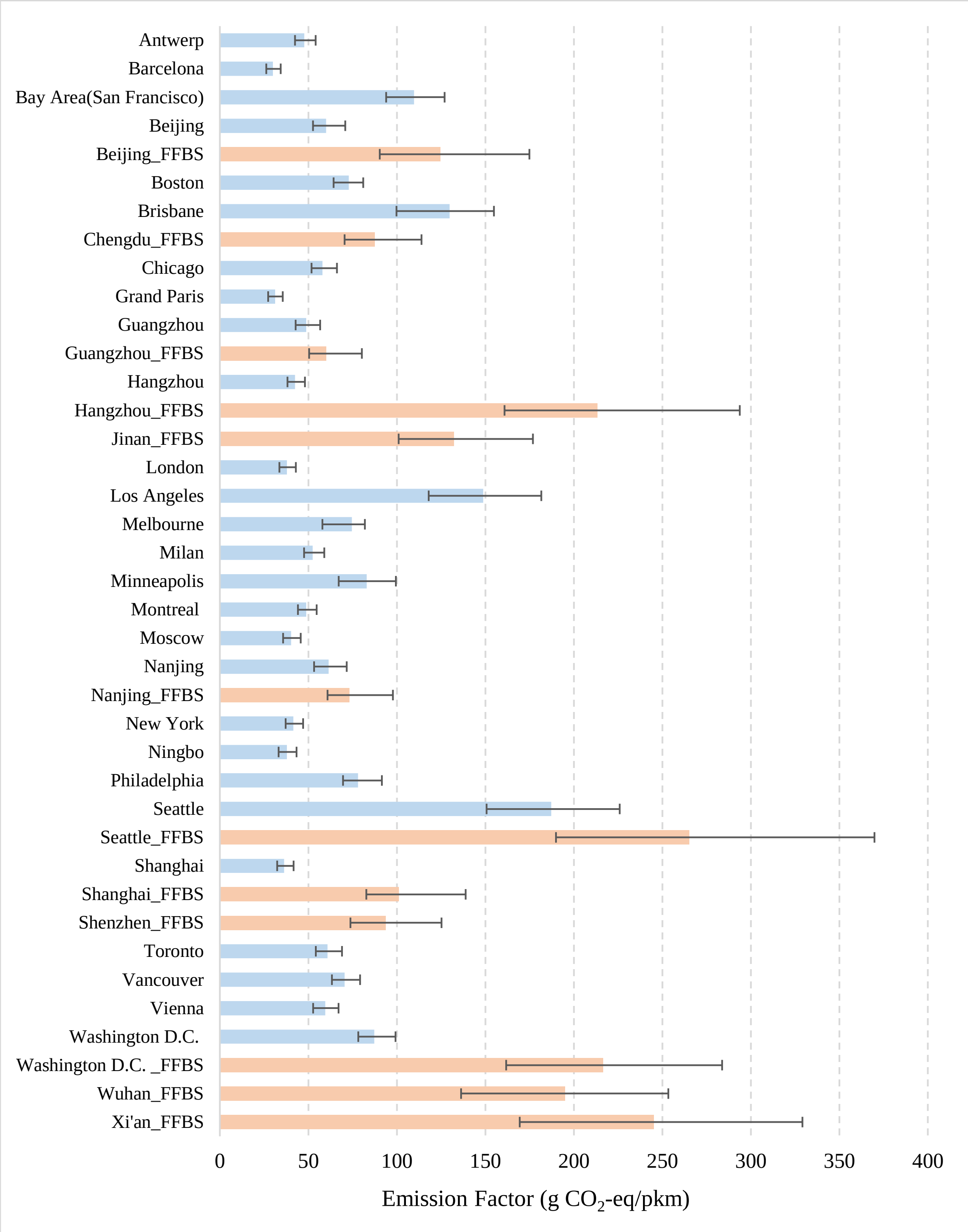
	FFEBS in China (Triangular Distribution)			FFESS in the United States (Triangular Distribution)		
	min	mean	max	Min	mean	max
Car	21%	31%	57%	23%	40%	52%
Public	38%	41%	28%	36%	13%	11%
POB	21%	13%	5%	17%	8%	8%
Walk	11%	9%	6%	19%	37%	30%
New trip	9%	6%	4%	5%	2%	0%
Sum	100%	100%	100%	100%	100%	100%

Note: Source from Barnes (2019); Bozzi and Aguilera (2021); Chicago Department of Transportation (2021); Liu et al. (2019); NABSA (2021); NACTO (2020); Qxcu Industrial Research Institute (2021); U.S. Department of Transportation (2021); WTDSRI (2020); Yan et al. (2021); and Zou et al. (2020).

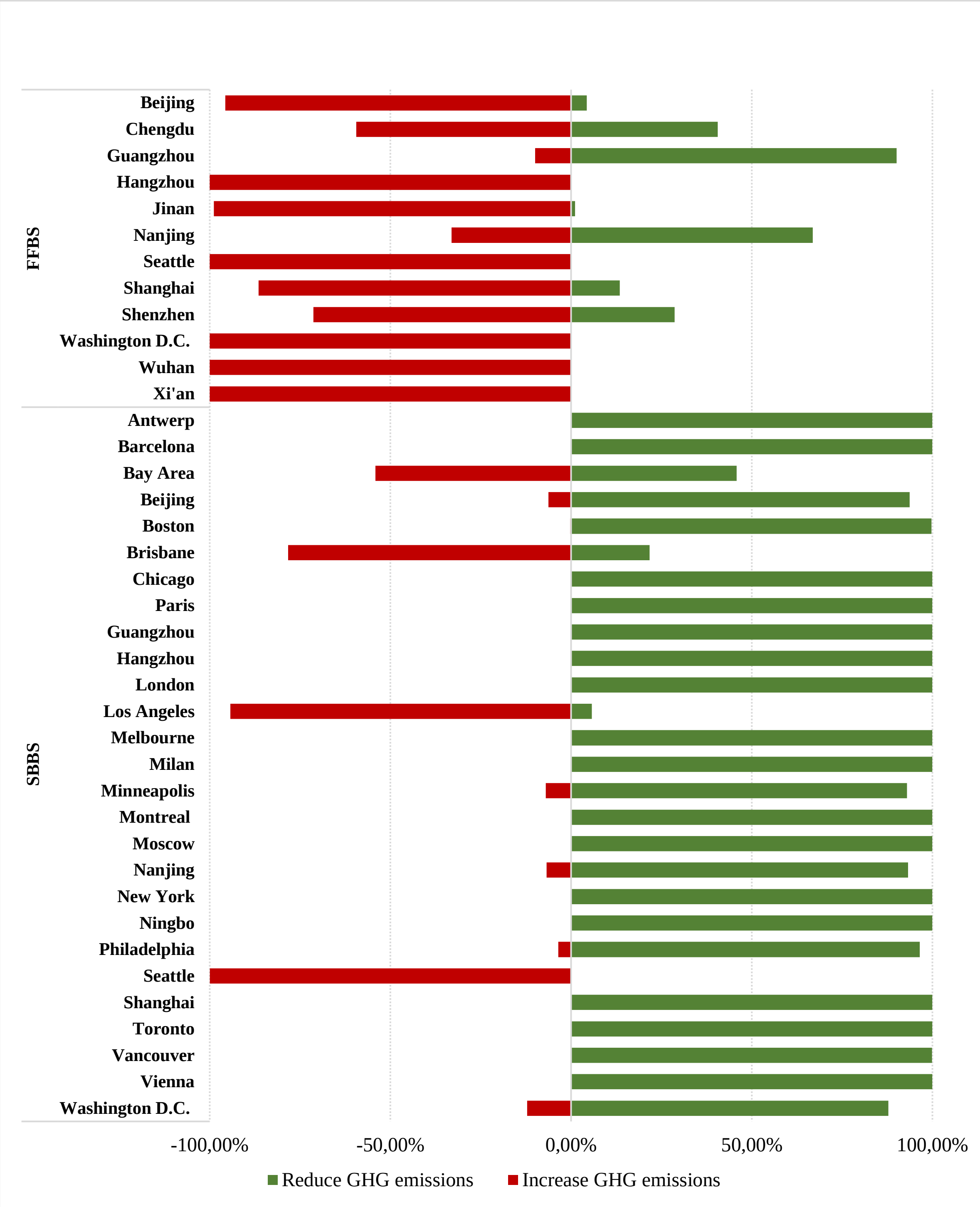
Supplementary material I. The life cycle VKT of the SBBS and FFBS



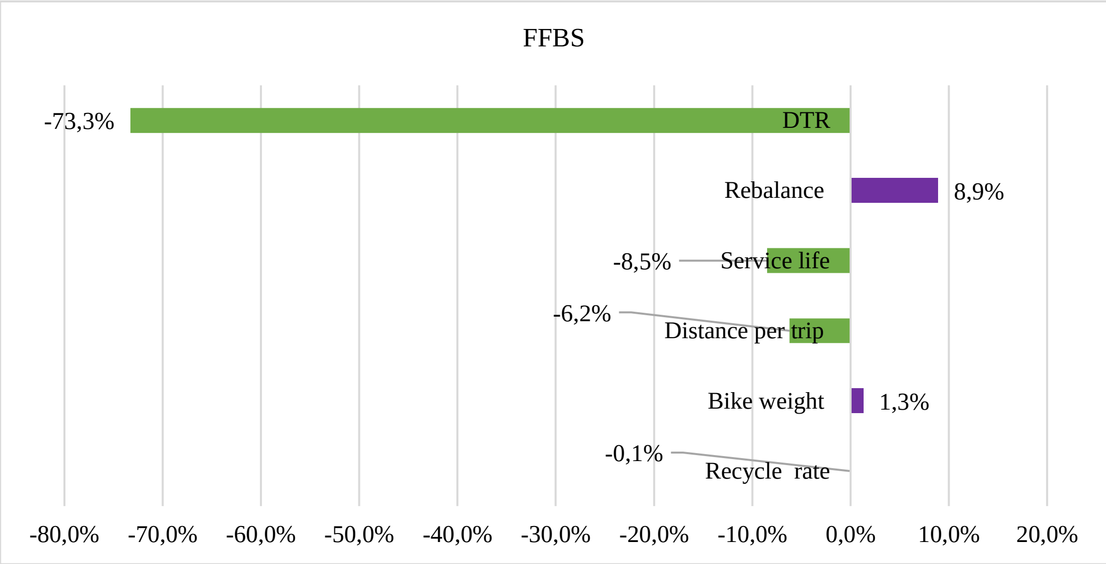
Supplementary material J. Comparison of GHG emission factors between SBBS system and FFBS system



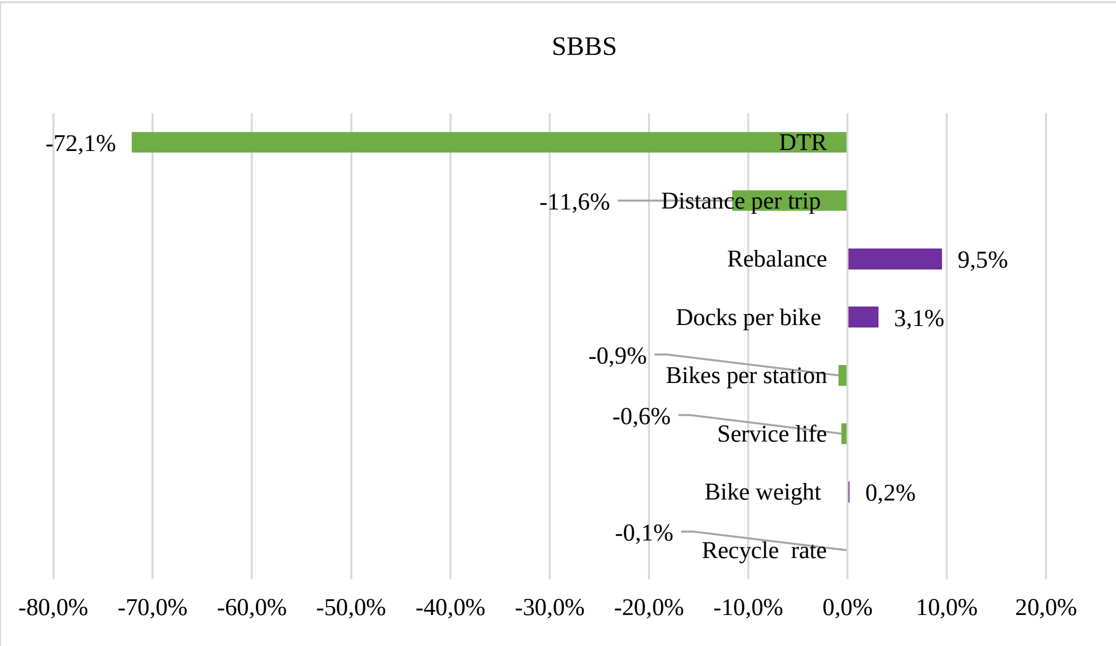
Supplementary material K. Uncertainty analysis of GHG emissions reduction benefits of SBBS and FFBS. The green bar represents the probability of obtaining GHG emissions reduction benefits, while the red bar represents increasing GHG emissions.



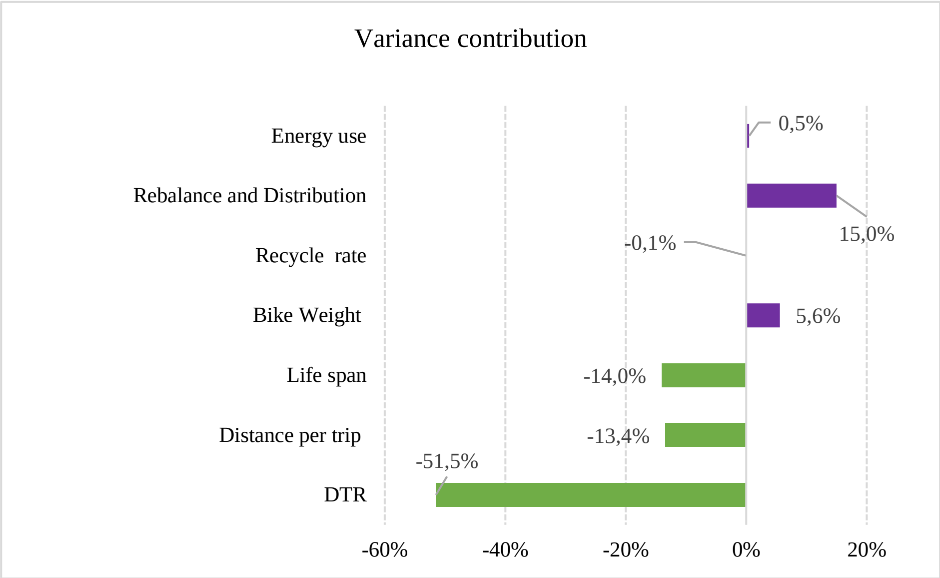
Supplementary material L. Variance contribution of uncertain variables in FFBS system



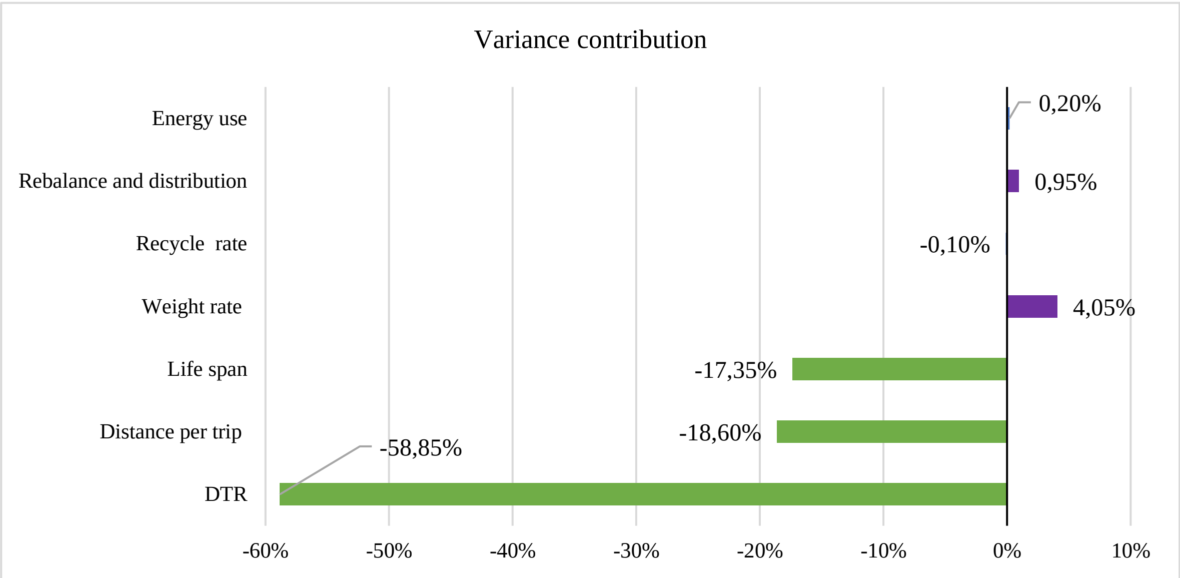
Supplementary material M. Variance contribution of uncertain variables in SBBS system



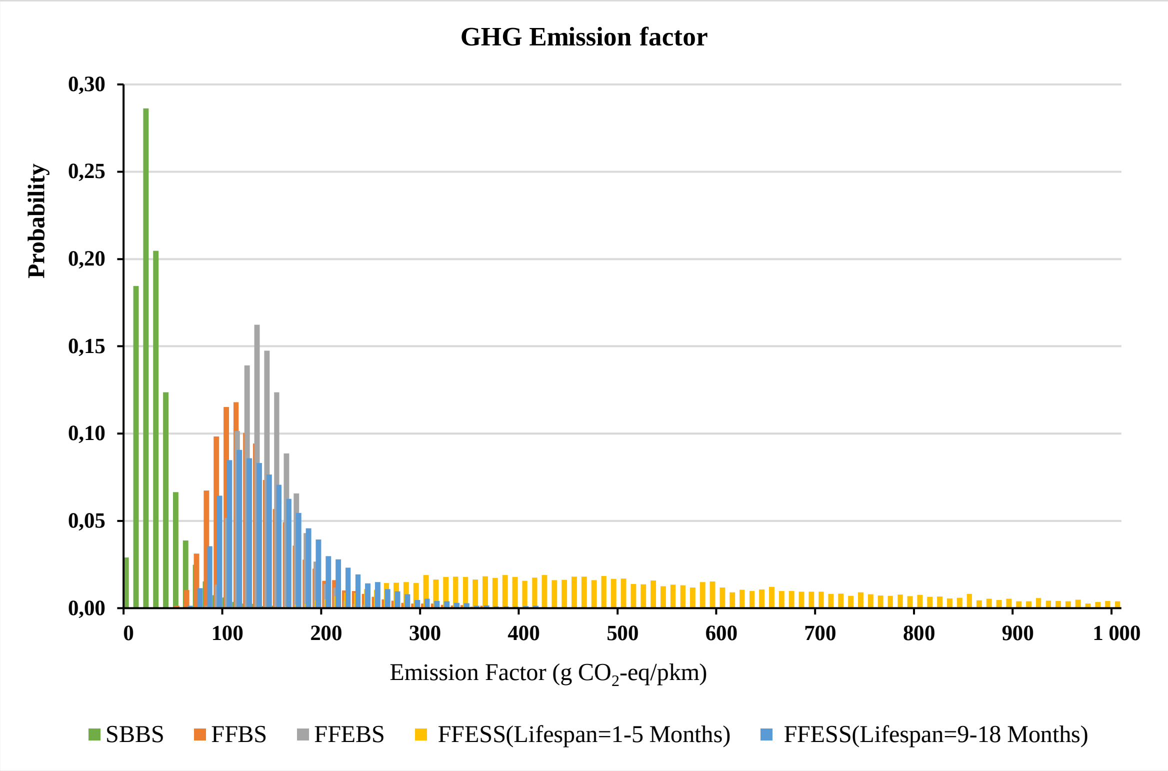
Supplementary material N. The sensitivity analysis results for FFEBS



Supplementary material O. The sensitivity analysis results for FFESS



Supplementary material P. Average GHG Emission factors of shared micromobility



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