Environmental Impact of Free-floating Bike Sharing: From Life Cycle Perspective

Author's name and details

*Shouheng Sun, Myriam Ertz**

**Corresponding author*

Shouheng Sun, LaboNFC, Université du Québec à Chicoutimi, Saguenay, Quebec, Canada, e-mail: shouheng.sun1@uqac.ca

Myriam Ertz, LaboNFC, Université du Québec à Chicoutimi, Saguenay, Quebec, Canada, e-mail: Myriam_Ertz@uqac.ca

Abstract

Bike-sharing is becoming increasingly popular around the world. However, there is little empirical evidence of the emerging free-floating bike sharing (FFBS) system, and even less from a product life cycle. Based on actual urban transportation big data and related product life cycle data, this chapter takes Beijing FFBS system as a study case. By comparing the changes in the choice of transportation means of urban residents before and after the emergence of FFBS, and in combination with the evolution of the FFBS system, the real environmental impact of FFBS is dynamically observed and evaluated from a life cycle analysis (LCA) perspective. The results show that FFBS display desirable properties in reducing air waste in the form of greenhouse gas (GHG) emissions. This reduction effect is mainly achieved by connecting to the public transportation system, hence substituting for the use of private cars. Yet, in comparison to the period prior to the emergence of FFBS (i.e. 2016), the excessive supply of FFBS resulted in an average annual increase of 0.38 % in air waste as GHG emissions by daily transportation of urban residents in 2017 and 2018, with a cumulative increase of 0.102 million tons $CO_{2,\ e.}$ Since then, under increased government control, the scale of the FFBS system has gradually become reasonable and the operating efficiency has gradually improved. In 2019, air waste as GHG emissions were reduced by 0.065 million tons compared with 2016. Especially, according to the development plan of Beijing FFBS system, it is expected that the emission reductions will reach 0.16 million tons, a reduction rate of about 1.13%.

Keywords

bike sharing, sharing economy, life cycle assessment, greenhouse gas emission, climate change, sustainability.

Introduction

Collaborative mobility services have developed rapidly around the world over the past few years. Within the collaborative economy (CE), bike-sharing is a kind of urban collaborative mobility mode, and has become increasingly popular due to its convenience, low-cost, and ease of access (Parkes et al. 2013; Shaheen et al. 2010). Bike-sharing first appeared in the 1960s in Amsterdam with Witte Fietsen (White Bikes); the next generation, called coin-deposit system emerged in Denmark in the 1990s; the third generation is the station-based bike sharing (SBBS), which takes advantage of IT-based systems but requires the bikes to be placed at stations or docks (DeMaio 2009; El-Assi et al. 2017; Pal and Zhang 2017). With fast development of information technology and the rise of the CE, a variety of innovative mobility sharing services have emerged since the 2010s. In this context emerged the fourth generation of bike-sharing, known as free-floating bike sharing (FFBS). Unlike the station-based bike sharing, FFBS doesn't require docks or stations and can be picked up and left in any parking area at users' convenience (Pal and Zhang 2017). FFBS was originally launched in 2,000 on a small scale in Germany, and re-emerged on a much larger scale in China in 2016 (DeMaio 2009; Fannin 2017). In contrast to existing small-

scale, station-based bike sharing systems, FFBS are flexible, do not require tedious registration processes, and provide a practical solution to the 'first/last mile problem' for urban commuters using green transport (Ma et al. 2018). In light of this, FFBS have changed urban travel and potentially created a niche to transform the current unsustainable trajectory of the transport sector towards sustainability (Cohen et al. 2016).

Bike-sharing is widely viewed as a green and sustainable transportation mode. Its environmental benefits have been discussed in many literatures. For example, cycling instead of driving a car can reduce carbon dioxide (CO_2) emissions, traffic congestion and noise pollution, and bring health benefits to users (Shaheen et al. 2010; Caulfield et al. 2017; Shen et al. 2018). Rojas-Rueda et al. (2013) assessed the health impacts of replacing car trips with bicycling and confirmed that reducing car usage and increasing cycling in cities can reduce exhaust gas, and thus, air pollution while bringing health benefits for both travellers and citizens. Zhang and Mi (2018) estimated that bike-sharing in the process of riding saved 8, 358 tons of petrol and decreased CO_2 emissions by 25,240 tons in 2016. Luo et al. (2019) conducted a comparative life cycle assessment (LCA) of station-based and dock-less bike-sharing system in the U.S., and indicate that both station-based and dock-less systems are promising to serve as sustainable transportation modes, if they are well designed and operated. Cao and Shen (2019) qualitatively and quantitatively analyzed how both shared bikes and non-shared (privately owned) bikes differ in their environmental impact. They concluded that bike sharing could play comprehensive and positive roles for economy and environment. Qiu and He (2018) analyzed the impacts of bike-sharing on the economy, energy use, the environment in Beijing. They estimate that if 75% of the kilometers travelled by bicycle replaced that number of kilometers travelled by cars, Beijing's energy consumption would be reduced by nearly 0.225 million tons and road transportation CO_2 emissions would be reduced by nearly 0.616 million tons.

However, despite the numerous qualitative and quantitative analyses that have been made on the environmental impact of bike sharing, there are still some space that deserve further study, especially for the emerging FFBS mode. First, existing research mainly focuses on the environmental benefits of bike sharing in its use stage. Yet, little attention has been paid to the environmental impact of bike sharing from a life cycle perspective, that is, including bike production, use, recycling and disposal. Harmful waste and emissions are nonetheless generated throughout those different stages and need, therefore, to be better assessed in order to provide a more accurate estimation of the environmental impact of FFBS. In addition, with regards to the notion of "impact", the accuracy of the environmental impacts of bike-sharing is still unclear, as the existing research results are all the "potential value" based on a series of assumptions and scenario predictions rather than on the results that are based on actual conditions. Such conclusions are likely to be unreliable. For example, ride-sharing has long been claimed as a potential way to make cities better by improving traffic and reducing private car ownership. But there is a growing body of evidence that suggests the opposite is taking place (San Francisco County Transportation Authority 2018; Clewlow and Mishra 2017; Beijing Municipal Commission of Transport 2016a). Moreover, almost all the research hypothesis only considered the substitution of bicycle travel to other high emission-intensity transportation modes (e.g. private car), and didn't consider the potential impact of bike sharing on the overall urban travel volume (i.e. rebound effect), which may have a negative impact on the sustainability of urban transportation. Therefore, in order to better complement the existing research, this study investigate the actual net environmental impact brought by bike sharing to the overall urban transportation system from the perspective of life cycle. Besides, this study uses actual urban transportation data.

Based on the existing research results, the actual urban transportation big data and the operational data of bike sharing, this chapter presents a quantitative estimation of the real environmental impacts of free-floating bike sharing on the urban transportation system in Beijing from a life cycle perspective. The environmental impact of FFBS is considered from the perspective of air waste. When talking about waste, scholars, business developers and decision makers often think of material waste. However, multiple forms of waste exist, especially in the air and in the water. These two latter forms are probably much more dangerous and pervasive because they are much less visible and sensible than material waste. Yet, their effects on the environment, climate and human health are very real and oftentimes quite harmful. For example, air waste in the form of greenhouse gas emissions and volatile organic compounds have been associated to asthma and other respiratory and health problems. When speaking *of waste, it is therefore of utmost importance to consider air waste as well. In this chapter, the concept of air waste shall be explored in its most notorious and harmful for, namely greenhouse gas (GHG) emissions.*

To this authors' knowledge, this is the first study to assess the real environmental impact in terms of air waste as GHG emissions of FFBS. Therefore, this chapter aims to provide solid empirical evidence for businesspeople, policy-makers, and scholars alike to comprehensively understand the environmental impact in the form of air waste as GHG emissions of bike sharing. The chapter further provides some valuable suggestions for the governance of urban bike-sharing system, so as to promote the healthy and sustainable development of the bike-sharing system and the urban transportation system.

Main Text

Materials and Methods

Background: Collaborative Mobility Services in Beijing

Beijing is the capital city of the People's Republic of China (PRC) with about 22 million inhabitants. The city is the centre of China's railway network and is thus the major rail hub of the country. In addition, many national roads and highways converge to the city. The city is also served by long-distance buses, several subway lines, numerous bus routes, tens of thousands of taxis, and the more traditional rickshaw form of transport. The subway alone has some 678 km of lines spread between 394 stations through which about 18 million journeys take place daily, that is, more than 6.5 billion trips annually (Shuang 2017). This massive crowding and full-capacity working impacts not only the transportation infrastructure but also the environment. Therefore, due to the continuous deterioration of urban transportation and the environment, Beijing has been continuously exploring and developing green and sustainable development models for years. The recent development of collaborative consumption schemes and business models appeared as particularly desirable options in this regard. Collaborative consumption is defined as "the set of resource circulation schemes that enable consumers to both receive and provide, temporarily or permanently, valuable resources or services through direct interaction with other consumers or through an intermediary" (Ertz et al. 2019, p. 32). In the transportation domain, this refers to business models or exchange schemes that allow lay individuals to offer transportation resources (e.g., cars, bikes) or services (e.g., rides) to other individuals, either directly (i.e., in-person), or indirectly (i.e., via an intermediary such as a website, application, platform or organization) (Ertz et al., 2016a, 2016b; Ertz et al., 2017; Ertz and Leblanc-Proulx, 2018). The collaborative mode of transportation known as ride-hailing has therefore gained traction as a creative solution to cater to the growing transportation needs of Beijingers. In addition, albeit not a collaborative form of consumption, bike-sharing has also grown in prominence. The two major forms of bike-sharing in Beijing include SBBS and FFBS.

Ride-hailing *Ride-hailing was introduced in Beijing in 2012. Due to the advantage of convenience and affordable price, ride-hailing services are popular among city residents. Moreover, considering that ride-sharing was recognized as having the potential to make cities better by improving traffic conditions and reducing private car ownership, the government initially adopted relatively loose regulations. Therefore, ride-hailing has grown rapidly in Beijing. However, ride-hailing did not realize the green and sustainability promise that it originally claimed to fulfill. Instead, it appeared as a counterproductive form of transportation. In fact, ride-hailing has not reduced the number of private cars in the city or the demand for car purchases by urban residents. As shown in Fig.1, private car ownership of Beijing and the urban residents' demand for car purchases are still increasing year by year. In addition, because Beijing has been implementing the policies of restricting car travel (i.e. odd-and-even license plate rule) and car purchase (i.e. a license plate lottery system) for many years, residents' car travel needs are far from being met. The emergence of ride-hailing services has continuously stimulated and released the demand* *for urban residents to travel by car. The average daily order volume has reached 700,000 in 2016, which has seriously worsened the already serious road congestion problem in Beijing (Beijing Municipal Commission of Transport 2016a). Considering the actual impact of ride-hailing on urban transportation, Beijing has adopted strict regulatory policies on ride-hailing since 2016 to control the growth of ride-hailing. Since then, the overall scale of the Beijing ride-hailing market has been stable at around 700,000 orders per day (Beijing Municipal Commission of Transport 2016b; Sina 2017).*

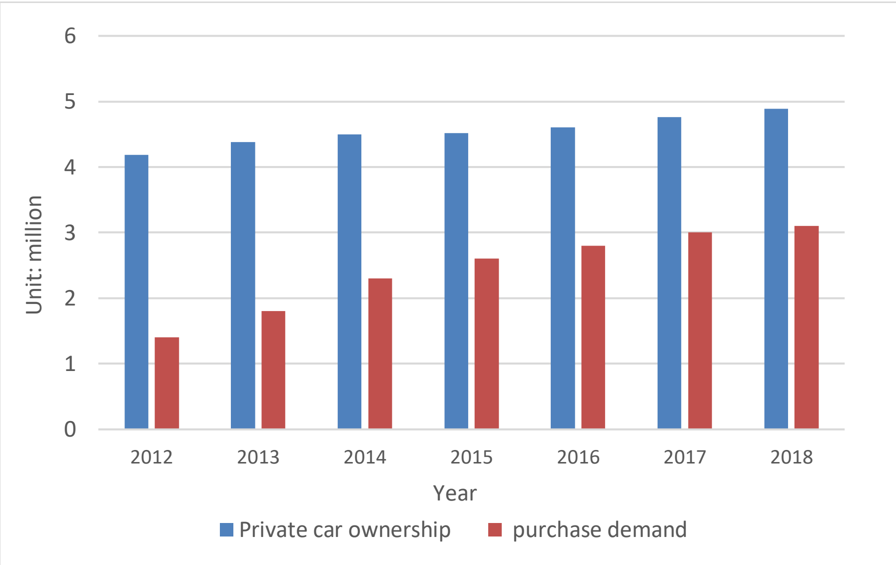

Fig. 1 *Private car ownership and purchase demand in Beijing (Beijing Transport Institute 2019)*

Station-based Bike Sharing *Since 2012, public bicycle, as a pollution-free, low-energy and health-promoting means of transportation, has emerged in Beijing. The Beijing municipal government regards bicycle as an indispensable part of the development of public transportation, especially attaches great importance to the function of bicycle to connect other transportation modes. But the development of SBBS in Beijing is not very smooth, as shown in Fig. 2. The SBBS program is operated and managed by the Beijing municipal government, the construction, operation and maintenance of SBBS all depend entirely on financial subsidies from governments. The expansion of SBBS not only increases the difficulty of operation and sustainable renewal, but also increases the financial burden of the government. Especially, the construction of SBBS system needs to find suitable station locations, which is very difficult in an already crowded urban space. Therefore, the Beijing government has set limits on the scale of public bicycles in various regions. According to the "Transportation development and construction plan of Beijing during the 13th five-year plan period" (Beijing Municipal Commission of Transport 2016c), the total number of SBBS will be about 100,000 by 2020. In recent years, the annual number of SBBS trips in Beijing has stabilized at around 50 million, accounting for only 0.34% of the total daily trips made by urban residents (Beijing Transport Institute 2017, 2018, 2019). Due to the limitation of development scale, SBBS will not contribute much to the sustainability of Beijing transportation system.*

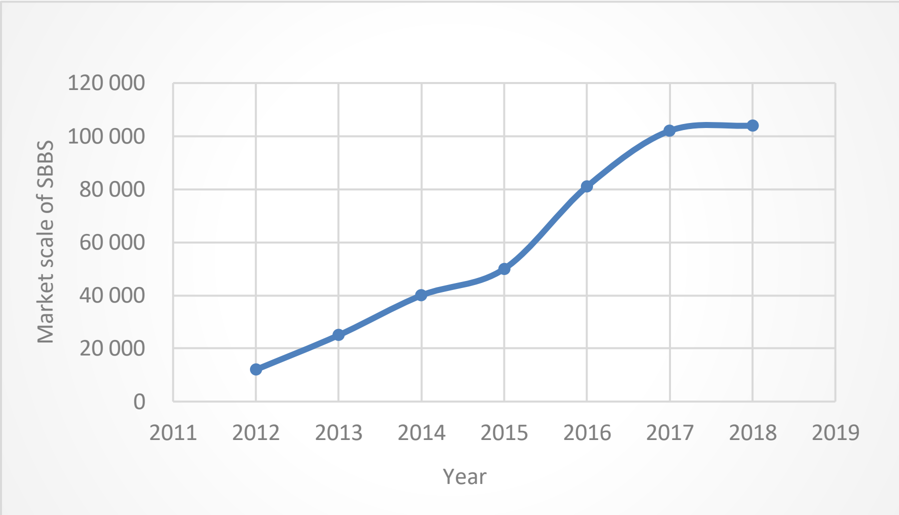

Fig. 2 *The development of station-based bike sharing in Beijing (Beijing Transport Institute 2017, 2018, 2019)*

Free-floating Bike Sharing *Free-floating bike-sharing services first appeared on Beijing Street at the end of 2016, and the overall scale has grown explosively thereafter. At the end of 2016, only 10,000 bikes were put on the market. In February 2017, the number has increased to 200,000. In May 2017, the market scale of FFBS in Beijing exceeded 2 million, making it the world's largest and hottest bike sharing market. After three years of development, the FFBS market in Beijing has developed relatively mature, as shown in Fig.3.*

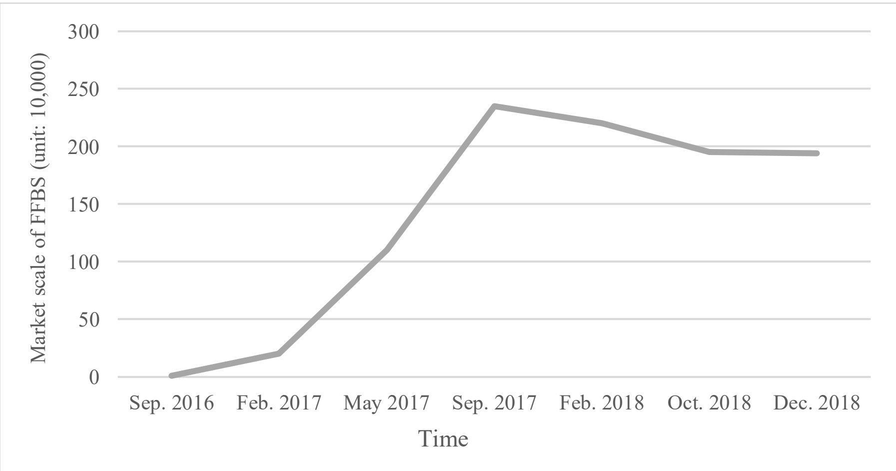

Fig. 3 *The development of FFBS in Beijing (Beijing Transport Institute 2017, 2018, 2019)*

Although the rapid development of free-floating bike sharing in the early days also brought some urban management problems such as disorderly parking and excessive supply which resulted in excessive waste also, it can well connect to the public transportation system and solve the "last kilometer" problem of urban travel (CBNData 2017). In addition, compare to SBBS, FFBS doesn't need to build stations and docks, and can, therefore, save more urban space resource, avoid potential waste production, and is thus easier to be implemented on a large scale by authorities than SBBS. Most importantly, it appears more flexible and convenient than SBBS, and more likely to be widely accepted and adopted by consumers and possibly. Therefore, Beijing regards FFBS as a promising way to promote the green and sustainable *development of urban transportation. The government has formulated relevant policies and measures to encourage and regulate the healthy and orderly development of FFBS such as control the number of bikes, improve use efficiency and parking order (Beijing Municipal Commission of Transport 2017), in order to better achieve the development goals of building a friendly city for walking and cycling (Beijing Municipal Commission of Transport 2016c).*

The aim of this paper is to quantitatively estimate the real environmental impacts of free-float bike sharing on the urban transport system in Beijing from the life cycle perspective. Therefore, we need to compare the situation before and after the emergence of FFBS. The scale of FFBS in Beijing in 2016 was relatively small, and the trips provided by FFBS volume accounted for only 0.03% of the total bicycle trips in 2016 (Beijing Transport Institute 2017). The impact of FFBS on the total volume and structure of urban residents' trips in 2016 was minimal and can be ignored. Therefore, we set 2016 as the base year and named it "before", that is, before the emergence of FFBS. In addition, the FFBS market in Beijing developed rapidly in 2017 and 2018, and the market size fluctuated greatly, which did not stabilize until the end of 2018. Therefore, in order to more scientifically and rationally evaluate the impact of FFBS on the air waste as GHG emissions of urban residents' daily trips, this paper takes the average of Beijing urban residents' travel statistics in 2017 and 2018, and named it "after", that is, after the emergence of FFBS. Then, based on the life cycle assessment, we compare the total air waste as GHG emissions form the urban residents' trips of these two time periods to evaluate the impact of FFBS.

LCA Framework

Life cycle assessment (LCA) is a standardized method for sustainability assessment and a scientific method of accounting for environmental impacts that is often applied to products (ISO 2006a, 2006b). It measures the impact of products and services 'cradle to grave', covering the phases of resource extraction, manufacture, distribution, use, and disposal (ISO 2006a, 2006b). LCA is widely be used during the evaluation of climate change (also referred to as Global Warming Potential) measured in greenhouse gas emissions (Dave 2010; Helin et al. 2013; Chen and Kockelman 2016).

This paper used the LCA framework to explore the effect of FFBS on GHG emission for urban transportation, it covers almost all the daily transportation modes adopted by urban residents, including POB, FFBS, SBBS, electric bicycle, electric motorcycle, private car, taxi, ride-hailing, bus, subway. The life cycle of transport means can be divided into different phases: manufacturing phase, use phase and end of life phase. The manufacturing phase includes the nature resource and energy inputs required to manufacture the vehicle, raw material extraction and processing, and manufacture and assembly of vehicles. The use phase includes the operation and maintenance of the vehicle. The end of life phase refers to the recycle and disposal of vehicles. Due to the differences in the characteristics and operation modes of vehicles, this paper constructs two LCA frameworks. One is for vehicles that operate without energy (i.e. electricity or fuel), including private owned bikes (POB), free-floating shared bikes and station-based shared bikes. The other framework is suitable for other energy-powered vehicles, including cars, motorcycles, elec-tric bicycles, buses and subways. The specific LCA frameworks for energy-powered vehicles and non-energy-powered vehicles are shown in Fig. 4 and Fig. 5 respectively.

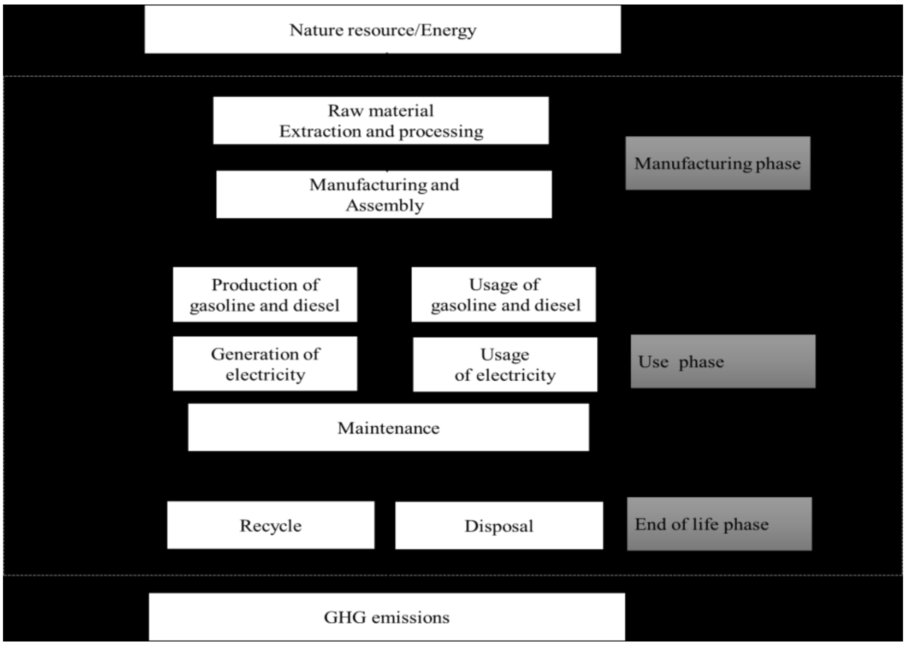

Fig. 4 *The LCA frameworks for energy-powered vehicles*

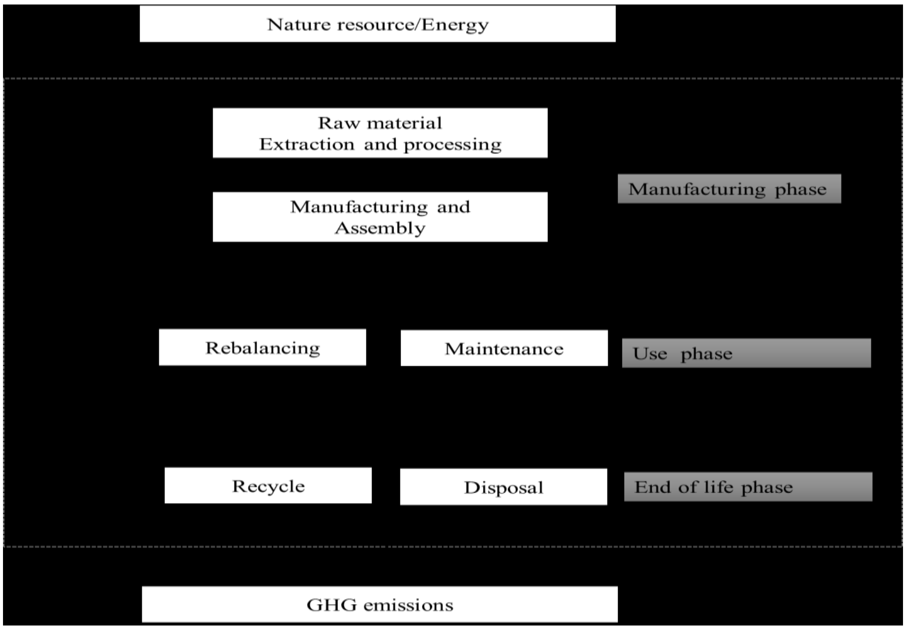

Fig. 5 *The LCA frameworks for non-energy-powered vehicles*

As can be seen from Fig. 4 and Fig. 5, the difference between the two frameworks is reflected in the use phase. Energy-powered vehicles need to consider the fuel life cycle, that is, fuel production and utilization. For non-energy-powered vehicles, we need to take into account the air waste as GHG emissions generated during the rebalancing the bikes for FFBS and SBBS. In addition, the maintenance includes all activity required to keep a vehicle as safe as possible on the road.

Another thing to note is that this study does not include infrastructure. Due to the complexity of the construction process and the lack of reliable and effective data on GHG emission, infrastructure is usually not included in the life cycle assessment of transportation modes (Blondel et al. 2011). Therefore, all related infrastructure such as bus stations, subway stations, stations and docks for SBBS, roads for cars and bicycles are excluded from the scope of this study.

Estimation Model for air waste as GHG Emissions

The goal of this LCA study is to evaluate the impact of FFBS on the air waste as GHG emissions of urban residents' daily transportation. Therefore, it is important to accurately calculate the air waste as GHG emissions from the daily transportation of the entire city residents. According to the mobile emission source measurement methods in the IPCC (2006), urban transport air waste as GHG emissions are generally estimated with top-down or bottom-up approach. The "top-down" approach is to estimate CO_2 emissions using aggregate data for total energy consumed or the size of the vehicle fleet and average kilometers traveled per vehicle (IPCC 2006). In contrast, the "bottom-up" approach is to estimate emissions from fewer aggregate travel attributes, including trip frequency, mode choice, and vehicle kilometers traveled for each trip (IPCC 2006). Bottom-up approach requires relatively more detailed data and allows further analysis of results such as evaluation of emission reduction strategies, and thus, is commonly applied in the estimation of city level transport emission (Bhave et al. 2014; Rui-Qiang et al 2019). According to the purpose of this study and the practicality of data acquisition, our estimation model for carbon emissions is established using a bottom-up approach based on the GHG emission factor, average trip distance, and travel frequency of different travel modes. The specific estimation model is shown in Eqs.1-2.

$$E_i = N_i \times D_i \times e_i \tag{1}$$

$$E_{total} = \sum E_i \tag{2}$$

where i represents the transport mode, E_i refers to the GHG emission of transportation mode i. N_i refers to the travel frequency of urban residents by transportation mode i, D_i refers to the average distance traveled per trip by transportation mode i. e_i refers to the GHG emission factor of transportation mode i. E_{total} refers to the total air waste as GHG emissions of the urban residents' daily transportation.

When studying the air waste as GHG emissions factor of a single transportation mode, the general approach is to divide the total carbon emissions of the vehicle's entire life cycle by the vehicle-kilometers-traveled (VKT) during the entire life cycle. But this is not an appropriate way to compare the transport modes with different carrying capacities. For example, the production and operation of a bus and subway will generate more air waste in the form of GHG emissions than a car, but they have higher occupancy (i.e. passenger capacity). Therefore, in order to facilitate comparative analysis, we first convert VKT to passenger-kilometers-traveled (PMT), which is to multiply VKT by the average occupancy of the vehicle, as shown in Eq.3

$$PKT_i = VKT_i \times AO_i \tag{3}$$

Where VKT_i refers to the average vehicle-kilometers-traveled of each vehicle in the life cycle in transport mode i. AO_i refers to the average occupancy per vehicle in mode i. PKT_i refers to the average passenger-kilometers-traveled provided by each vehicle in the life cycle in transport mode i. For example, a subway with 200 people that travels 1 million kilometers has completed 200 million passenger- kilometers -traveled. Since bicycles are only used by one person at a time, a bicycle that travels 20,000 kilometers has only completed 20,000 passenger- kilometers -traveled.

And then we can obtain the GHG emission factor of different transportation mode by using the Eq.4.

$$e_i = \frac{TGHG_i}{PKT_i} \tag{4}$$

Where $TGHG_i$ refers to the total life cycle GHG emissions of per vehicle in transport mode i, which can be calculated by using the LCA framework.

Thus, functional unit of air waste as GHG emissions is uniformly defined as "g $CO_{2,e}$ /pkt" (i.e. g $CO_{2,e}$ /per passenger-per kilometer-traveled) in this study. It can be seen that the bottom-up approach adopted in this paper can well include the impact of FFBS on changes in traffic structure and total travel volume, so that the impact of FFBS on air waste in the form of GHG emissions of urban transportation can be assessed more systematically and accurately.

Data Sources

In our study, GHG emission is estimated through a bottom-up approach. During the specific calculation process, it mainly involves the behavior characteristics of urban residents' daily trips, the operation conditions of all kinds of transport modes, some statistics data on the vehicle life cycle and fuel life cycle etc. These data have been obtained from the following sources.

The data about behavior characteristics of urban residents' daily trips comes from the "Beijing traffic development annual report" (Beijing Transport Institute 2017, 2018, 2019), which is a professional statistical analysis report based on Beijing traffic big data officially released by the Beijing government. With the help of transportation big data, we can calculate the daily travel structure, travel frequency and average travel distance of urban residents.

The data about the operation conditions of transport modes are partly from "Beijing statistical yearbook" and "Beijing traffic development annual report" (Beijing Municipal Bureau of Statistics 2019; Beijing Transport Institute 2019). It includes vehicle population, annual mileage travelled, passenger volume, average trip distance of some transport modes such as private car, bus, subway, taxi, SBBS, etc. In addition, the operation data of ride-hailing and FFBS were obtained from the statistical announcement of Beijing Municipal Commission of Transport, real operation data of FFBS and ride-hailing company, publicly available data and investigation data.

The vehicle life cycle and fuel life cycle data in this article mainly comes from vehicle manufacturing industry, some published industry statistics reports and peer-reviewed journal articles. In addition, carbon emission factors of materials and fuels were converted by data obtained from IPCC (2006) and other officially published reports such as "China energy statistical yearbook" (National Bureau of Statistics of China 2016) and "China electric power statistical yearbook" (China electric power development promotion association 2016).

Therefore, with the help of the LCA framework and the bottom-up approach, we analyze the impact of FFBS on the air waste as air waste in the form of GHG emissions of urban residents' daily trips.

Results and Discussions

Life Cycle GHG Emission Factors for Transportation Modes

Energy-powered Vehicles

Energy-powered vehicles refer to cars (includes cars for ride-hailing), taxis, buses, subways, electric bicycles and electric motorcycles. The air waste as GHG emissions of these vehicles are mainly in their operation phase, that is, the fuel consumption phase (Dave 2010; Chen and Kockelman 2016). In estimating the air waste as GHG emissions impact of the transport mode, it is necessary to account for the air waste as GHG emissions from the perspective of fuel life cycle. Fuel life cycle also known as "Well-To-Wheel (WTW)", which refers to the entire process of energy flow, from the upstream energy production to tailpipe exhaust (Yang et al. 2019). The main energy sources used by vehicles in Beijing are electricity, gasoline, diesel and compressed natural gas (CNG). According to (China electric power development promotion association 2015), the air waste as GHG emissions intensity for electricity production on national average is about 715g $CO_{2,e}$ /kWh. Considering the efficiency of power *transmission and the actual situation of Beijing, the comprehensive WTW GHG emission factor of electricity in Beijing was 0.920 kg $CO_{2,e}$ /kW h (China electric power development promotion association 2015). As to other three type fuel, we used the carbon emission factor of IPCC and converted to the WTW GHG emission factor which applicable to the Beijing area. The details are shown in Table 1.*

Table 1 *WTW GHG emission factor for different types of fuels (IPCC 2006; National Bureau of Statistics of China 2016)*

Fuel type	carbon emission factor in IPCC	Chinese net calorific value	Chinese fuel density	The proportion of combustion phase emissions to total fuel life cycle emissions	WTW GHG emission factor
Gasoline	69300 kg/TJ	43040 kJ/kg	0.725 kg/L	77.0%	2.81 kg/L
Diesel	74100 kg/TJ	42652 kJ/kg	0.850 kg/L	80.2%	3.35 kg/L
CNG	56100 kg/TJ	38931 kJ/m^3	0.654 kg/m^3	79.0%	2.76 kg/m^3

Therefore, the vehicle's air waste as GHG emissions during the operation phase can be calculated by Eq.5.

$$E_{operation} = EFE \times ECR \times TKT \quad (5)$$

Where $E_{operation}$ refers to the air waste in the form of GHG emissions of vehicle during its operation phase. EFE refers to the WTW GHG emission factor of the energy used by vehicle. ECR refers to the energy consumption rate of the vehicle, and the units are L/100km, kwh/100km or m^3/100km, respectively . TKT refers to the total kilometers traveled during the vehicle life cycle. The energy type, ECR and TKT of different type of vehicles in Beijing are shown in Table 2.

Table 2 *The energy type, energy consumption rate and life cycle kilometers traveled of different type of vehicles in Beijing (Beijing Transport Institute 2017,2018, 2019; Yang et al. 2019; Ding et al. 2019)*

Types of vehicles	Fuel type	EFE	Energy consumption rate Per 100 km	TKT
Subway	Electricity	0.92 kg $CO_{2,e}$/ kWh	2,800 kWh	3,251,274 km
Bus	Diesel	3.35 kg $CO_{2,e}$/ L	40 L	471,192 km
	CNG	2.76 kg $CO_{2,e}$/ m^3	50 m^3	471,192 km
Taxi	CNG	2.76 kg $CO_{2,e}$/ m^3	8–10 m^3	446,796 km
Private owned car	Gasoline	2.81 kg $CO_{2,e}$/ L	8.5 L	200,000 km
Ride-hailing car	Gasoline	2.81 kg $CO_{2,e}$/ L	8.5 L	300,000 km
Electric-bicycle	Electricity	0.92 kg $CO_{2,e}$/ kWh	1.2 kW h	50,000 km
Electric-motor	Electricity	0.92 kg $CO_{2,e}$/ kWh	2 kW h	60,000 km

According to the Table 2 and Eq.5, we can calculate the air waste in the form of GHG emissions of each type vehicles during the operation. Combining air waste as GHG emissions data from vehicle manufacturing, maintenance, and end of life stages, we can further calculate the life cycle air waste as GHG emissions of each transportation mode. The details are shown in Table 3.

***Table 3** The life cycle GHG emissions of each energy-powered transport mode (Cherry et al. 2009; Liu 2014; Ding et al. 2019)*

Types of vehicles	manufacturing phase (kg $CO_{2,e}$)	use phase (kg $CO_{2,e}$)	end of life phase (kg $CO_{2,e}$)	Total (kg $CO_{2,e}$)
Subway	10,656.4	83,768,802.8	85.3	83,779,544
BUS-Diesel	40,928.3	639,582.9	327.4	680,838
BUS-CNG	40,928.3	658,430.6	327.4	699,686
Taxi	6,567.2	101,281.4	52.6	107,901
Ride-hailing car	6,567.2	74,283.9	52.6	80,904
Private car	6,567.2	50,398.9	52.6	57,019
Electric-bicycle	603.0	590.5	4.8	1,198
Electric-motor	875.0	1,159.8	7.0	2,042

Based on the data in Table 3, according to the Eqs.3-4， we can calculate the Life cycle GHG emission factors for each transportation mode. The details are shown in Table 4.

***Table 4** The life cycle GHG emissions factor of each energy-powered transport mode (Beijing Transport Institute 2017,2018, 2019; Yang et al. 2019; Ding et al. 2019)*

Types of vehicles	Total GHG emission (kg $CO_{2,e}$)	Average occupancy (person)	TKT (km)	GHG emission Factor ($gCO_{2,e}$/pkt)
Subway	83779544.4	800	3251274	32.21028
BUS-Diesel	680838.666	70	471192	20.64183
BUS-CNG	699686.346	70	471192	21.21326
Taxi	107901.214	1.41	446796	171.2766
Ride-hailing car	80903.6576	1.33	300000	202.7661
Private car	57018.6576	1.26	200000	226.2645
Electric-bicycle	1198.2954	1	50000	23.96591
Electric- Motorcycle	2041.825	1.1	60000	30.93674

Note: The occupancy of motorcycles is also usually 1, but sometimes two people use it at the same time. This article assumes that 80% of the cases are used by one person and 20% of the cases are used by two people, so the weighted average occupancy rate is 1.1, which is more in line with the actual situation. The occupancy of taxi and ride-hailing car does not include the driver, while the occupancy of private cars includes the driver.

Non-energy-powered Vehicles

In terms of the manufacture of bicycles, the main components are similar across FFBS, SBBS and POB, since there are no major differences in the main raw materials and quantities required for manufacturing each type of bicycle (Blondel et al. 2011; Ding et al. 2018). The inventory data of bike productions are scaled with bike mass, based on an LCA report of the manufacturing of a 17 kg urban-used bicycle (Leuenberger and Büsser 2010). Combined with the research results related to bicycle manufacturing, this study assumes that an average bicycle weights 17 kg and the main raw materials for manufacturing a bike we calculated in this study, are aluminum, steel, rubber and plastic. To be specific, it takes an average of 9 kg aluminum, 5.5 kg steel, 1.5 kg plastic and 1 kg rubber to manufacture an urban-used POB, and the average air waste in the form of GHG emissions during manufacturing phase is about 86.5 kg $CO_{2,e}$ (Ding et al. 2018; Cherry et al. 2009; Zheng et al. 2019; Bonilla-Alicea et al 2020). The bike for SBBS can be considered the same as the POB. Howerver, the free-floating shared bike additionally require a 0.015m^2 photovoltaic panel, 0.2kg rechargeable battery, and 0.3kg electronic components (e.g. printed circuit board), which makes the air waste as GHG emissions of free-floating shared bike in the *manufacturing stage about 30 kg higher than that of POB (IPCC 2006; Finnegan et al. 2018; Ma et al. 2018; Luo et al. 2019; Bonilla-Alicea et al 2020).*

According to the (Ding et al. 2018; Bonilla-Alicea et al. 2020; Luo, 2019), the GHG emissions of POB during the maintenance stage and end of life stage are about 8.15kg and 6.33kg respectively.

As to the SBBS, the GHG emissions during the maintenance, rebalancing and end of life stage are about 23.26 kg, 58.8 kg and 6.33 kg respectively (Bonilla-Alicea et al. 2020; Luo 2019).

In terms of FFBS, it is a commercial project after all, the FFBS platform pay more attention to market development and corporate image in the early stage. Therefore, the operators made a lot of efforts in vehicle maintenance and rebalancing to ensure the quality and reasonable distribution of bikes, so that users can use bikes safely and conveniently. According to the (Ding et al. 2018), the average annual air waste as GHG emissions of each bicycle of FFBS in Beijing during the maintenance and rebalancing are about 20 kg and 17 kg, respectively. In addition, the air waste as GHG emissions of FFBS in the end of life stage is about 7.5 kg (Luo 2019; Bonilla-Alicea et al. 2020). The life cycle GHG emissions of three types of bicycle are shown in Fig. 6.

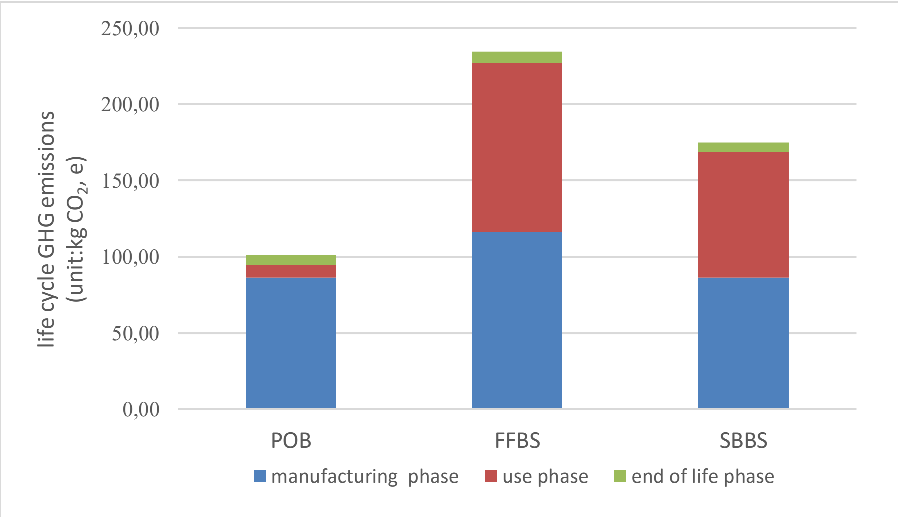

Fig. 6 *Life cycle GHG emissions of the POB, FFBS, SBBS*

As can be seen from Fig. 6, the air waste in the form of GHG emissions of FFBS in the manufacturing phase and in the use phase is both significantly higher than those of the other two types of bicycles. Then, combining the life cycle GHG emissions and the life cycle TKT of the bicycle, we can calculate the GHG emission factor for each type of bikes through Eq. 4.

According to the (Liu 2014; Bonilla-Alicea et al. 2020), the TKT of the POB is estimated to12,000 km and. According to the (Beijing Transport Institute 2017,2018, 2019; Bonilla-Alicea et al. 2020), the TKT of the SBBS in Beijing is estimated to 8000 km. As to the TKT of FFBS, we need to calculate according to its actual operation data. The result can be calculated by Eq.6.

$$TKT_{FFBS} = L \times DTR \times D \tag{6}$$

Where TKT_{FFBS} *refers to the total kilometers traveled during the life cycle of FFBS bike.* DTR *refer to the average daily turnover rate of FFBS bike.* D *refers to the average distance traveled per trip. L refers to the average life span of FFBS bike.*

As to the lifespan, the life span of a shared bicycle for FFBS is mandated by the government to be 3 years (Beijing Municipal Transportation Commission 2017). According to the (Beijing Transport Institute 2019), the average DTR of FFBS in Beijing in 2017 and 2018 was about 0.875. As to the average distance traveled per FFBS trip, according to the actual operating data of FFBS in Beijing (mainly from the FFBS *company Mobike and OFO), we drew a statistical graph of frequency distribution for travel distance of FFBS, as shown in Fig.7.*

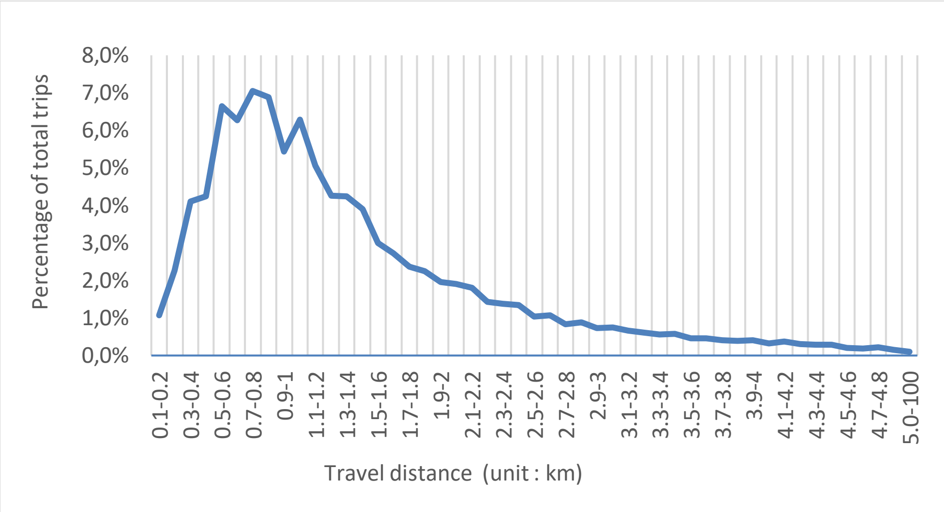

Fig. 7 *Travel distance distribution statistics of FFBS trips*

As can be seen from the Fig. 7, FFBS trips are mainly concentrated in the range of 0.3km to 1.5km, accounting for about 50% of the total FFBS trips. The average distance traveled per trip of FFBS in Beijing in 2017 and 2018 was about 1.2km.

Therefore, we can obtain the life cycle GHG emissions factors for all transportation modes in Beijing. The specific results are shown in Fig. 8, and the breakdown values by life cycle stages are shown in Fig. 9.

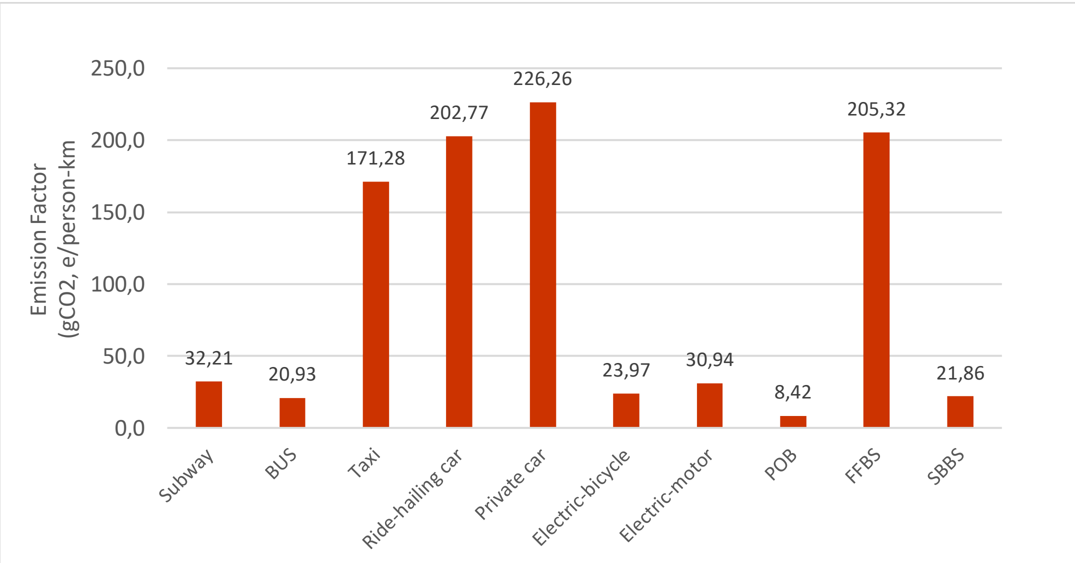

Fig. 8 *Greenhouse gas emission factors for various modes of transportation in Beijing, the GHG emission factor of the bus is calculated based on the weighted average of the number of two different types of buses.*

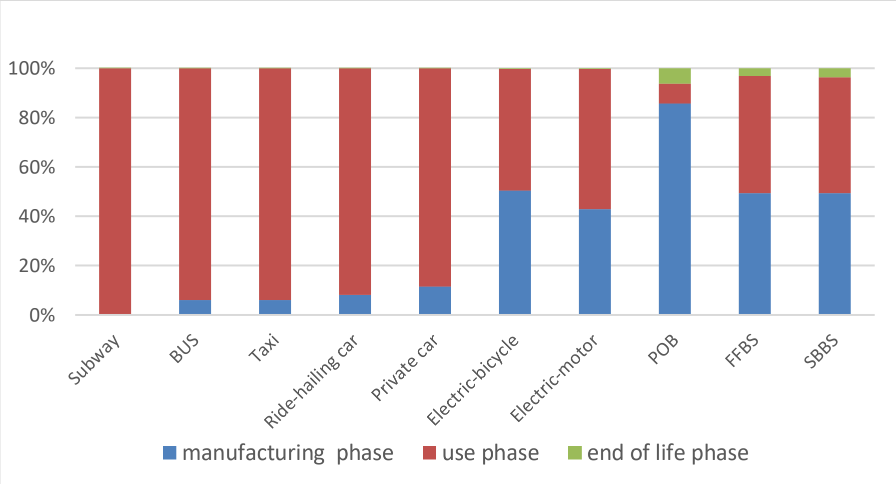

Fig. 9 *The proportion of air waste as GHG emissions at each stage of the life cycle*

It can be seen from the Fig. 8 that among the various modes of transportation in Beijing, private car has the highest greenhouse gas emission factor, followed by FFBS, ride-hailing and taxi, while POB and other public transportation have lower emissions. The emission factor of FFBS is only lower than that of private cars, and is almost equivalent to that of ride-hailing. This is mainly due to its short lifespan and low usage rate, which makes the total mileage traveled throughout the life cycle very small. According to Eq. 6, the total life-cycle mileage of per bike of FFBS is only 1,143 kilometers, which is far less than other modes of transportation. The emission reduction effect of FFBS can only be achieved by directly or indirectly (combined with other transportation modes) instead of private-car trips. In addition, as can be seen from Fig. 9, the air waste as GHG emissions of energy-powered transportation modes are mainly concentrated in the use phase, that is, the fuel consumption phase, and the air waste as GHG emissions for bicycles are mainly concentrated in the production stage. As to the shared bike, the proportion of greenhouse gas emissions during the use phase is also large, which is mainly due to more maintenance and rebalancing activities.

Next, using the emission factors of various modes of transportation, we will analyze the changes brought about by the emergence of FFBS to the total air waste in the form of GHG emissions of urban residents' daily transportation.

Air waste as GHG Emissions Impact of FFBS to Urban Transportation

Based on the actual transportation data of Beijing in 2016-2018, we first analyze the changes brought by the emergence of FFBS to urban residents' daily traffic volume and structure. The results are shown in Fig.10. For the convenience of comparison, we combine electric bicycles and electric motorcycles into one group and name them as "Others", combine FOB, FFBS and SBBS into one group and name them as "Bicycle", and combine private cars and online taxi into one group and name them as "Car". The detailed changes for each mode of transportation are shown in Fig.11.

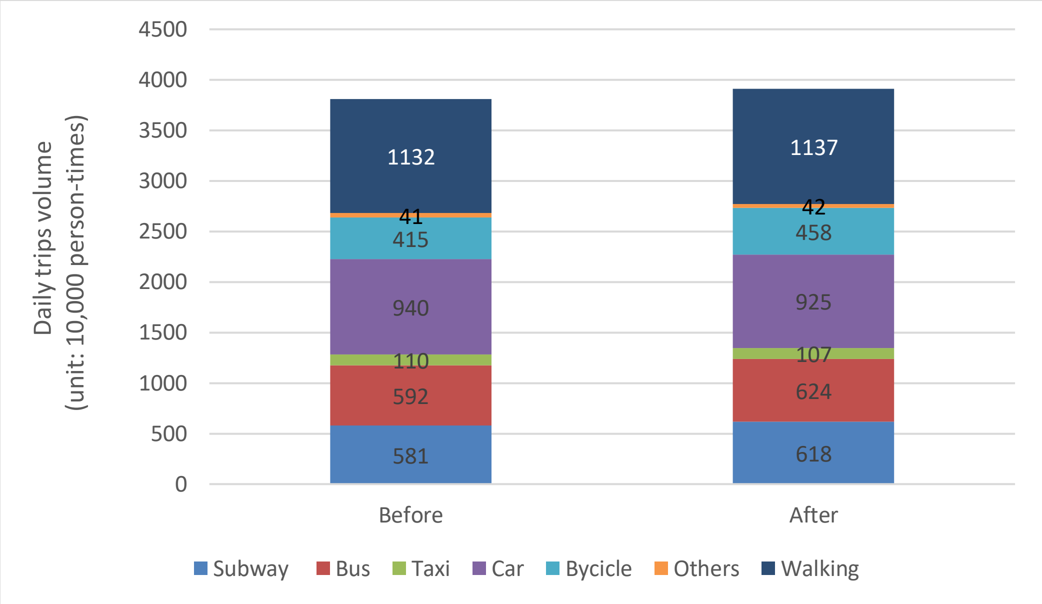

Fig. 10 *Changed in average daily traffic volume and structure of Beijing*

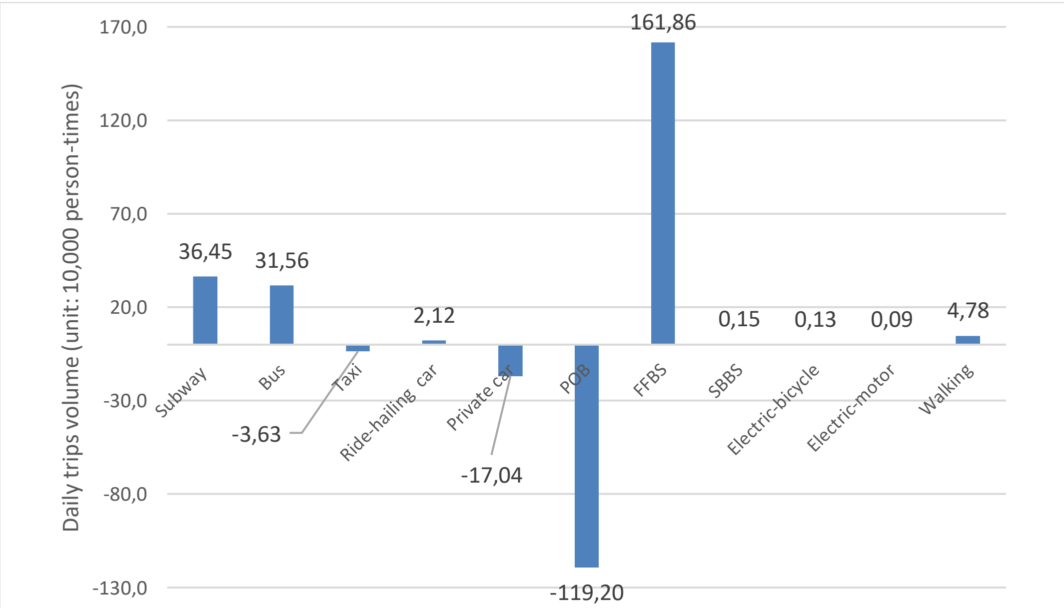

Fig. 11 *Changes brought by FFBS to urban residents' daily transportation*

It can be seen from Fig. 10 that the emergence of FFBS has increased the daily traffic volume of urban residents in Beijing in 2017 and 2018 by an average of 2.55%. In addition, the daily traffic structure of urban residents has also changed. As can be seen from Fig.7, the average daily travel volume of subways and buses increased by 0.36 million and 0.31 million respectively, with growth rates of 6.3% and 5.3%. The average daily trip volume of FFBS increased by 1.6 million, while the average daily trip volume of POB decreased by 1.2 million. Taking into account the changes in SBBS travel volume, the overall bicycle travel volume increased by 0.428 million on average per day, an increase of 10.32%. In addition, the daily travel volume of private cars and taxis decreased by 149,000 and 36,000, respectively, and the reduction rates were 1.8% and 3.3%, respectively. This demonstrate that FFBS can promote bicycle travel in the city and can be well connected with the public transportation system to reduce the use of cars.

Based on the GHG emission factors of transportation modes, we can calculate the total air waste as GHG emissions of urban transportation system through Eqs.2-3. The results are shown in Table 5.

Table 5 *The impact of FFBS on the total air waste as GHG emissions from daily transportation of urban residents in Beijing*

	Before (10,000 tons $CO_{2,e}$)	After (10,000 tons $CO_{2,e}$)	Change (10,000 tons $CO_{2,e}$)	Rate of change
Subway	121.83	129.47	7.64	6.27%
BUS	49.94	52.60	2.66	5.33%
Taxi	64.26	62.14	-2.12	-3.30%
Car	1,091.22	1,073.76	-17.80	-1.60%
Bicycle	4.48	18.83	14.71	320.55%
Others	2.02	2.03	0.01	0.53%
Sum	1,333.74	1,338.83	5.09	0.38%

As can be seen from Table 5, the air waste as GHG emissions of daily trips by urban residents in 2017 and 2018 increased by 0.38% on average compared with that of 2016, with a total increase of 101,800 tons $CO_{2,e}$. Among them, the emissions of subways and buses increased by 6.27% and 5.33%, respectively, with an increase of approximately 76,400 tons $CO_{2,e}$ and 26,600 tons $CO_{2,e}$. In particular, emissions form bicycles increased by 320%, an increase of about 143,600 tons $CO_{2,e}$. This is mainly due to the large GHG emission factor of FFBS and the significant increase in FFBS trips. However, the air waste as GHG emissions of car trips and taxi trips decreased by 1.63% and 3.30%, respectively, and the reductions were 174,600 tons $CO_{2,e}$ and 21,200 tons $CO_{2,e}$, respectively. Therefore, combined with the changes in the urban residents' traffic travel structure, we can find that FFBS can indeed replace part of car use by connecting public transportation, but the excessively high GHG emission factor limits its potential for reducing emissions. The high emission factor is mainly due to the low utilization rate of bicycles of FFBS, which caused by the oversupply of bikes in the city. In the early stage of the FFBS development, in order to seize market rapidly, almost all the FFBS platforms have constantly put bikes into the city, resulting in a serious oversupply problem. In 2017 and 2018, the average bicycle ownership in Beijing was 1.91 million, which leads to a relative low vehicle utilization (Beijing Transport Institute 2019).

In order to optimize the operation of shared bicycles and increase the daily turnover rate， Beijing has strengthened the management of the shared bicycle market since 2019, and has achieved some positive results.

The average DTR of FFBS has increased to 1.2 in 2019, while keeping the travel structure unchanged from 2018 (Beijing Municipal Transportation Commission 2019). Moreover, according to the development plan of Beijing government, the DTR is expected to rise to 1.5 by 2020 and gradually increase to 4 times in the future (Beijing Municipal Transportation Commission 2019).

In order to better understand the relationship between DTR and air waste as GHG emission factors of FFBS, we drew a picture to observe the change in GHG reduction emission factors of FFBS as the turnover rate continues to increase (see Fig. 12).

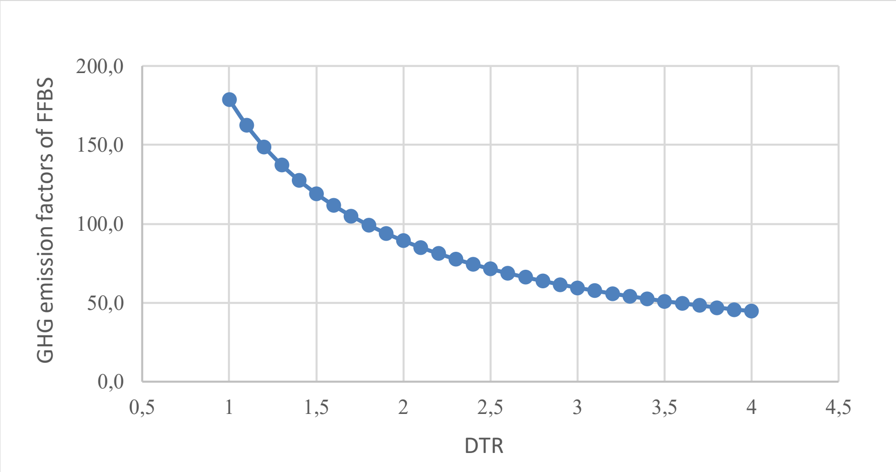

***Fig. 12** Relationship between daily turnover rate and GHG emission factors*

As can be seen from Fig. 5, with the increase of DTR, the air waste as GHG emission factor of FFBS will be gradually lower. In 2019, the GHG emission factor of FFBS in Beijing was about 162.4 g $CO_{2,e}$/pkt (DTR was 1.2), which is a decrease of 43 g $CO_{2,e}$ compared to the average emission factors of 2017 and 2018, with a decrease rate of about 21%. In addition, in 2020, the turnover rate is expected to rise to 1.5, and the corresponding air waste as GHG emission factor of bicycles will be further reduced to about 162.4 g $CO_{2,e}$/pkt, the reduction rate will reach to 42%. In particular, when the DTR of FFBS is reduced to 4, the air waste as GHG emission factor of FFBS will be about 40 g $CO_{2,e}$, which is close to the emission factor of the Beijing subway. By then, FFBS will play an important role in the air waste as GHG emission reduction of the urban transportation system. In order to better understand the potential of FFBS in reducing greenhouse gas emissions for the Beijing transportation system, we keep the current transportation structure unchanged to observe the air waste as GHG emissions reduction effect of FFBS under different DTR. The detailed results are shown in Fig. 13.

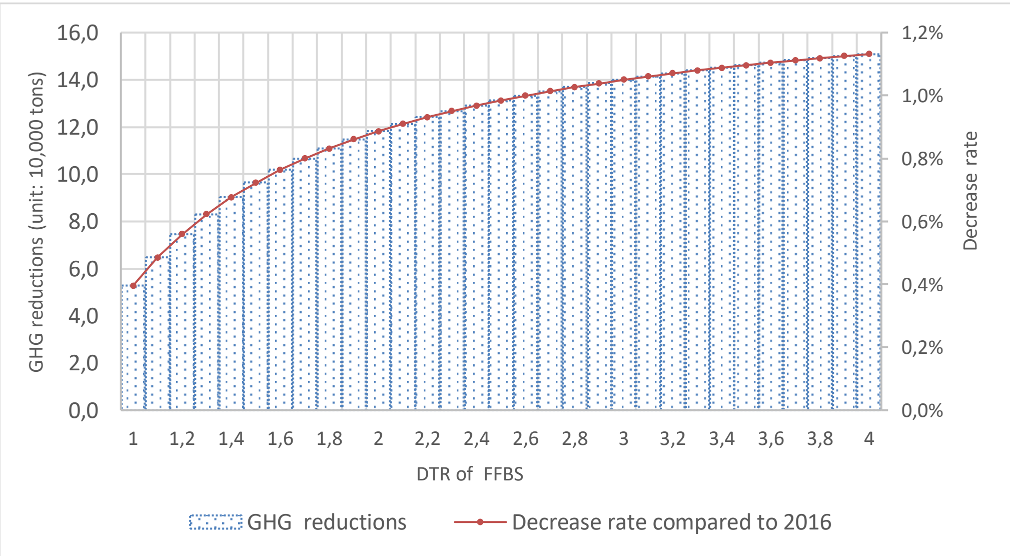

***Fig. 13** Air waste as GHG emissions reduction effect under different daily turnover rate of FFBS*

As can be seen from the Fig. 13, the total air waste in the form of GHG emissions of urban residents' daily trips in 2019 were 64,700 tons $CO_{2,e}$ lower than that of 2016, with a reduction rate of 0.49%. On the premise of keeping the current travel structure unchanged, it is expected to reduce emissions by 96,400 tons $CO_{2,e}$ in 2020 compared with 2016, with an emission reduction rate of 0.72%. In particular, when the turnover rate reaches the government's optimal target, that is, 4 times per day per bike, the GHG emission reduction will reach 159,900 tons $CO_{2,e}$, and the emission reduction rate can reach 1.13%. Thus, *it can be seen that FFBS does have the potential to reduce greenhouse gas emissions, but only through effective governance of the FFBS market and continuous improvement of the operational efficiency of the FFBS system can this potential be well realized. Beijing is a very typical case. The rapid and chaotic development of bicycle sharing in the early stage brought certain negative impacts on the city's traffic and environment. For example, the air waste as GHG emissions of the entire urban residents' daily trips increased by 0.38% compared with before the emergence of FFBS. Under the effective governance of the government, the operating efficiency of the FFBS system has gradually improved. FFBS begun to achieve some good results in reducing greenhouse gas emissions of urban transportation in 2019. Air waste in the form of GHG emissions of urban residents' daily trips decreased by 0.49% compared to 2016. Therefore, the authorities and relevant parties should take appropriate measures to continuously improve the overall operating efficiency of FFBS system, so as to give full play to the environmental benefits of FFBS.*

Conclusion

This study employs the LCA framework and the bottom-up method to quantitatively estimate the real environmental impacts of free-float bike sharing on the urban transport system in Beijing. Based on the actual urban transportation big data and the operational data of bike sharing, changes in GHG emissions form urban daily traffic before and after the emergence of FFBS in Beijing has been compared and analyzed. The main contributions of this study are as follows.

The emergence of FFBS has significantly promoted the transformation of urban traffic structure towards sustainability. Specifically, due to the promotion of FFBS, the bicycle trips of urban residents increased by 10.32 %, the subways and buses trips increased by of 6.3% and 5.3%, respectively. In contrast, the cars and taxis trips decreased by 1.8% and 3.3%, respectively. This shows that FFBS can be well connected with the public transportation system to reduce the use of cars. Therefore, it does have the potential to reduce greenhouse gas emissions.

The low vehicle utilization rate caused by oversupply largely limits the emission reduction potential of FFBS. The average scale of the FFBS in Beijing was 1.9 million in 2017 and 2018, far exceeding the size of vehicles required by the city. The oversupply directly led to an average daily turnover rate of only about 0.87. The life cycle GHG emission factor of the bicycle was 205.32 $CO_{2,\,e}$ *g/pkt, only lower than that of private car. In comparison to the period prior to the emergence of FFBS (i.e. 2016), GHG emissions by daily transportation of urban residents increased by an average of 0.38% in 2017 and 2018, with a cumulative increase of 0.102 million tons* $CO_{2,\,e}$*. Under increased government control, the operating efficiency of FFBS in Beijing continues to improve. In 2019, the average DTR of FFBS has risen to 1.1, the total air waste as GHG emissions of urban residents were 64,700 tons* CO_2*, e lower than that of 2016, with a reduction rate of 0.49%. Especially, according to the development plan of Beijing FFBS system, under the premise of keeping the current transportation structure unchanged, the maximum air waste as GHG emission reduction potential of FFBS is about 0.16 million tons* CO_2*, e (compared to 2016), and the emission reduction rate can reach 1.13%*

Although the rapid development of FFBS has brought some urban governance issues, it is undeniable that this new type of bike sharing also provide a new potential path for the sustainable development of urban transportation. In order to better realize the emission reduction potential of FFBS, the authorities should take appropriate measures to continuously improve the overall operating efficiency of the FFBS, such as improving the average DTR through more reasonable vehicle size, more efficient resource allocation, and faster maintenance and rebalancing. In addition, FFBS companies can cooperate with bicycle manufacturers to develop more durable and easier to repair vehicles to extend the service life. Moreover, the government should actively encourage the public to travel by bike, so as to continuously increase the proportion of green travel in urban transportation. All these will significantly improve the bicycle utilization and enhance the environmental benefits of FFBS.

This study contributes to a better comprehension of the environment impact of FFBS. As what is likely the first study to verify the real environment impact of FFBS based on actual urban transportation big data and FFBS operational data, this paper fills an academic gap in the absence of empirical evidence on the sustainability of FFBS by providing a grounded analysis. In addition, the research work in this paper constitutes a new approach for the further studies of the sustainability of the emerging mobility sharing, as well as a valuable reference for better improving the sustainable development of urban transportation.

However, there also exist some limitations in the study. Due to the lack of more relevant data support, this article only considers the impact of free-floating bike-sharing on greenhouse gas emissions, and does not consider other environmental impact factors such as atmospheric pollutants and solid waste. Similarly, due to the lack of sufficient evidence, this paper does not specifically analyse the impact of FFBS on other modes of transportation. All of these limitations require more research in the future. In addition, the study also opens up a host of questions for future research. The main avenues for future research are as follows. First, in order to better promote the sustainable development of urban transportation, a comprehensive and systematic assessment of the energy and environmental impact of bike sharing is very necessary. Second, as FFBS have only been developed for a short time in Beijing, its environmental impact on the urban transportation needs further observation and verification. Specifically, the real impact of FFBS might be changing with the development of the whole urban transportation systems, it is necessary to assess the impact of FFBS dynamically for a long time. Moreover, With the continuous promotion and development of FFBS, it is a very worthy research direction to analyse the impact of FFBS on the bicycle ownership of the entire city and the production of the whole bicycle industry from a longer period of time.

References

Beijing Municipal Bureau of Statistics (2019) Beijing statistical yearbook. China Statistics Press, Beijing

Beijing Municipal Commission of Transport (2016a) Ride-hailing is the main reason for the increase in road congestion. Available via Sohu. https://www.sohu.com/a/58517842_119674. Accessed 20 March 2020

Beijing Municipal Commission of Transport (2016b) Detailed rules for the operation and service management of online taxi booking in Beijing. Available via Baidu. https://baike.baidu.com/item/. Accessed 20 March 2020

Beijing Municipal Commission of Transport (2016c) Transportation development and construction plan of Beijing during the 13th five-year plan period. http://www.beijing.gov.cn/gongkai/guihua/wngh/sjzdzxgh/201907/t20190701_100237.html. Accessed 25 March 2020

Beijing Municipal Commission of Transport (2017) Technical and service specification for bicycle sharing system. http://jtw.beijing.gov.cn/xxgk/flfg/r764/201709/t20170921_187532.html. Accessed 25 March 2020

Beijing Municipal Transportation Commission (2019) Public announcement on the operation, management and supervision of the Internet rental bicycle industry in the first half of 2019. Beijing. http://jtw.beijing.gov.cn/. Accessed 25 March 2020

Beijing Transport Institute (2017) Beijing Transport Annual Report 2017. http://www.bjtrc.org.cn/List/index/cid/7.html. Accessed 25 March 2020

Beijing Transport Institute (2018) Beijing Transport Annual Report 2018. http://www.bjtrc.org.cn/List/index/cid/7.html. Accessed 28 March 2020

Beijing Transport Institute (2019) Beijing Transport Annual Report 2019. http://www.bjtrc.org.cn/List/index/cid/7.html. Accessed 25 March 2020

Bhave AG, Mishra A, Raghuwanshi NS (2014) A combined bottom-up and top-down approach for assessment of climate change adaptation options. Journal of Hydrology 518:150-161

Blondel B, Mispelon C, Ferguson J (2011) CyCle more often Cool down the planet! Quantifying CO_2 savings of Cycling. European Cyclists' Federation ASBL, Brussels.

Bonilla‐Alicea RJ, Watson BC, Shen Z et al (2020) Life cycle assessment to quantify the impact of technology improvements in bike‐sharing systems. Journal of Industrial Ecology 24(1):138-148

Cao Y, Shen D (2019) Contribution of shared bikes to carbon dioxide emission reduction and the economy in Beijing. Sustainable Cities and Society 51: 101749

Caulfield B, O'Mahony M, Brazil W et al (2017) Examining usage patterns of a bike-sharing scheme in a medium sized city. Transportation Research Part A: Policy and Practice 100:152-161

CBNData (2017). Bike sharing is the best choice for short trips and short distance connections. Available via Sohu. https://www.sohu.com/a/154936058_267106. Accessed 25 March 2020

Chen TD, Kockelman KM (2016) Carsharing's life-cycle impacts on energy use and greenhouse gas emissions. Transportation Research Part D: Transport and Environment 47: 276-284

Cherry CR, Weinert JX, Xinmiao Y (2009) Comparative environmental impacts of electric bikes in China. Transportation Research Part D: Transport and Environment 14(5): 281-290

China electric power development promotion association (2016) China Electricity Statistics Yearbook 2016. China Statistics Press, Beijing.

Clewlow RR, Mishra GS (2017) Disruptive transportation: The adoption, utilization, and impacts of ride-hailing in the United States. University of California. https://escholarship.org/uc/item/82w2z91j. Accessed 28 March 2020

Cohen B, Almirall E, Chesbrough H (2016) The city as a lab: Open innovation meets the collaborative economy. California Management Review 59(1): 5-13

Dave S (2010) Life cycle assessment of transportation options for commuters. Massachusetts Institute of Technology. http://seeds4green.org/sites/default/files/Pietzo_LCAwhitepaper_0.pdf. Accessed 25 March 2020

DeMaio P (2009) Bike-sharing: History, Impacts, Models of Provision, and Future. Journal of Public Transportation 12(4): 3

Ding N, Yang J, Lu X et al (2018) Life cycle assessment of bike sharing and the its effects on greenhouse gas emissions of urban transport- A case study of Beijing. Acta Scientiae Circumstantiae: 1–14

El-Assi W, Salah Mahmoud M, Nurul Habib K (2017) Effects of built environment and weather on bike sharing demand: a station level analysis of commercial bike sharing in Toronto. Transportation 44(3):589-613

Ertz, M., Durif, F., & Arcand, M. (2016a). Collaborative consumption: Conceptual snapshot at a buzzword. Journal of Entrepreneurship Education, 19(2), 1-23.

Ertz, M., Durif, F., & Arcand, M. (2016b). Collaborative consumption or the rise of the two-sided consumer. International Journal of Business and Management, 4(6), 195-209.

Ertz, M., Lecompte, A., & Durif, F. (2017). Dual roles of consumers: towards an insight into collaborative consumption motives. International Journal of Market Research, 59(6), 725-748.

Ertz, M., & Leblanc-Proulx, S. (2018). Sustainability in the collaborative economy: A bibliometric analysis reveals emerging interest. Journal of Cleaner Production, 196, 1073-1085.

Ertz, M, Durif, F, Arcand, M (2019) A conceptual perspective on collaborative consumption. AMS Review 9(1-2): 27-41.

Fannin R (2017). Bike sharing apps in China pop up as latest startup and unicorn craze. Available via Forbes. https://www.forbes.com/sites/rebeccafannin/2017/03/28/bike-sharing-apps-in-china-pop-up-as-latest-startup-and-unicorn-craze/#774298581bcc. Accessed 28 March 2020

Finnegan S, Jones C, Sharples S (2018) The embodied CO_2 of sustainable energy technologies used in buildings: A review article. Energy and Buildings 181: 50-61

Helin T, Sokka L, Soimakallio S et al (2013) Approaches for inclusion of forest carbon cycle in life cycle assessment– a review. Gcb Bioenergy 5(5): 475-486

Higgins PAT, Higgins M (2005) A healthy reduction in oil consumption and carbon emissions. Energy Policy 33(1):1-4

ISO (2006a) International Standard 14040. Environmental Management Life Cycle Assessment. Principles and Framework, International Organization for Standardization.

ISO (2006b). International Standard 14040. Environmental Management Life Cycle Assessment Requirements and Guidelines, International Organization for Standardization.

IPCC (2006) Guidelines for National Greenhouse Gas Inventories. Prepared by the National Greenhouse. Gas Inventories Programme. Tokyo, Japan: Institute for Global Environmental Strategies.

Leuenberger M, Büsser S (2010) Life Cycle Assessment of Two Wheel Vehicles. https://treeze.ch/fileadmin/user_upload/downloads/Publications/Case_Studies/Mobility/leuenberger-2010-TwoWheelVehicles.pdf. Accessed 28 March 2020

Liu D (2014) The research on low-carbon transport development mode in Tianjin city. Dissertation, Hebei university of technology

Luo H, Kou Z, Zhao F et al (2019) Comparative life cycle assessment of station-based and dock-less bike sharing systems. Resources, Conservation and Recycling 146:180-189

Ma Y, Lan J, Thornton T et al (2018) Challenges of collaborative governance in the sharing economy: The case of free-floating bike sharing in Shanghai. Journal of Cleaner Production 197: 356–365

National Bureau of Statistics of China (2016) China energy statistical yearbook 2016. China Statistics Press, Beijing

Pal A, Zhang Y (2017) Free-floating bike sharing: Solving real-life large-scale static rebalancing problems. Transportation Research Part C: Emerging Technologies 80: 92-116

Parkes SD, Marsden G, Shaheen SA et al (2013) Understanding the diffusion of public bike sharing systems: Evidence from Europe and North America. Journal of Transport Geography 31: 94-103.

Qiu LY, He LY (2018) Bike sharing and the economy, the environment, and health-related externalities. Sustainability10(4): 1145

Rojas-Rueda D, de Nazelle A, Teixidó O et al (2013) Health impact assessment of increasing public transport and cycling use in Barcelona: A morbidity and burden of disease approach. Preventive Medicine 57(5): 573-579

Yuan RQ, Tao X, Yang XL (2019) CO_2 emission of urban passenger transportation in China from 2000 to 2014. Advances in Climate Change Research 10(1):59-67

San Francisco County Transportation Authority (2018) TNCs and Congestion. https://uknowledge.uky.edu/cgi/viewcontent.cgi?article=1000&context=ce_reports. Accessed 28 March 2020

Shaheen SA, Guzman S, Zhang H (2010) Bike sharing in Europe, the Americas, and Asia. Transportation Research Record 2143(1):159-167

Shen Y, Zhang X, Zhao J (2018) Understanding the usage of dockless bike sharing in Singapore. International Journal of Sustainable Transportation 12(9):686-700

Shuang L (2017) Beijing's subway is going full bore., Available via China Daily. http://www.chinadaily.com.cn/china/2017-01/12/content_27931764.htm. Accessed 12 July 2020.

Sina (2017) Beijing is limiting the total scale of ride-hailing markets. Available via Sina. https://finance.sina.com.cn/roll/2017-08-16/doc-ifyixcaw5077090.shtml. Accessed 28 March 2020

Yang L, Wang Y, Han S et al (2019) Urban transport carbon dioxide (CO_2) emissions by commuters in rapidly developing Cities: The comparative study of Beijing and Xi'an in China. Transportation Research Part D: Transport and Environment 68: 65-83

Zhang Y, Mi Z (2018) Environmental benefits of bike sharing: A big data-based analysis. Applied Energy 220, 296-301

Zheng F, Gu F, Zhang W et al (2019) Is bicycle sharing an environmental practice? Evidence from a life cycle assessment based on behavioral surveys. Sustainability 11(6):1550

Index Keywords

bike sharing, sharing economy, life cycle assessment, greenhouse gas emission, climate change, sustainability.