Environmental Impact of Mutualized Mobility: Evidence from a life cycle perspective

Abstract: Today's urban transportation systems face increasing challenges such as greenhouse gas (GHG) emissions, urban air quality, and traffic congestion. In this context, various initiatives of mutualized mobility have emerged. However, notably lacking is assessing the environmental impacts of mutualized transportation modes from a life cycle perspective. Using the actual urban transportation big data and related product life cycle data, this study combined with the life cycle assessment methodology and a "bottom-up" approach to explore the effect of mutualized mobility on greenhouse gas emissions of urban transportation systems for both Beijing and Toronto. The results showed that mutualized mobility might positively affect the sustainability of urban transport systems, albeit in very different ways. In Toronto, the annual per capita greenhouse gas emissions in 2016 decreased by 2.8 kg of carbon dioxide equivalent (CO_2-eq) compared to 2011. Both carpooling and car-sharing displayed a higher curbing potential than ride-hailing. In a city characterized by higher population density like Beijing, ride-hailing created negative impacts. Deadheading (i.e., pulling an empty trailer) was the critical factor affecting ride-hailing's environmental performance, which accounted for about 30% of the total vehicle life cycle emissions. Counter-intuitively, greenhouse gas emissions of station-based bike-sharing (SBBS) were almost six times that of privately-owned bicycles and even higher than public transportation. This study's results can be used as a starting base for decision-makers to devise more appropriate strategies and programs to promote the sustainability of mutualized mobility and urban transportation systems. Meanwhile, it can also help the public at large to better understand the characteristics and environmental impacts of mutualized mobility to adopt more sustainable mutualized mobility alternatives.

Keywords: Mutualized mobility, Collaborative economy, Life cycle assessment, Greenhouse gas emission, Climate change, sustainability.

1. Introduction

Urban transportation systems are increasingly under operational and environmental pressure globally. In Toronto, 38% of greenhouse gas (GHG) emissions are generated by transportation, with 80% caused by personal vehicles (City of Toronto, 2017). Also, vehicles are the primary source of CO (85%), NOx (70%), and PM_{10} (40%) emissions within the Toronto area (Gower et al., 2014). Meanwhile, the capital of China, Beijing, has faced severe air pollution problems for years, and automobile pollution accounts for about 60% of total air pollution (Chen and He, 2014; Fan et al., 2017). In this context, mutualized transportation may contribute to improving and greening city transportation systems. Mutualized systems are access-based, emphasizing temporary use over ownership (Eckhardt et al., 2019), encompassing both "collaborative consumption" (CC) schemes and marketer-managed commercial systems. CC involves resources provided directly or indirectly (via an intermediary) by consumers (Ertz et al., 2019), such as ride-hailing or carpooling. Marketer-managed commercial systems differ from collaborative consumption in that resources originate from organizations rather than from consumers themselves (as in collaborative consumption). Such marketer-managed systems include bike-sharing (Lamberton and Rose, 2012) and car sharing (Bardhi and Eckhardt, 2012). Importantly, mutualized schemes are product-service systems that share commonalities with the circular economy since the value and the durability of transportation means are both maximized through lending, renting, leasing, sharing (Gaiardelli et al., 2014), corresponding to the "share" and "optimize" strategies of the ReSOLVE framework for the circular economy (Ellen MacArthur Foundation, 2015). The need for more collaborative production and consumption systems has been much emphasized in past literature to tackle global climate change problems (Kriegler et al., 2012; Brondizio et al., 2016).

Over the last decade, several studies have quantified the environmental benefits of mutualized mobility to various extents from different perspectives, but the results of varying transportation forms are fragmented across the literature (e.g., Martin and Shaheen, 2011; Chen and Kockelman, 2016; Nijland and Van Meerkerk, 2017). Besides, there are also mixed results regarding the environmental impact of specific mutualized mobility schemes such as ride-hailing (San Francisco County Transportation Authority, 2018; Clewlow and Mishra, 2017; Schmitt, 2019), while bike-sharing appears seemingly better for the environment (Qiu and He, 2018; Zhang and Mi, 2018). Finally, extant research provides "potential estimates," mainly based on assumptions, modeling, and scenario predictions instead of actual conditions and data. In contrast, real-world data show the result of behaviors and thus inform more accurate assessments. Finally, cities differ in their transportation policies, infrastructure, and cultural norms, which may influence the development and evolution of mutualized mobility. Yet, little research compares transportation systems across cities or countries.

Consequently, there is no systematic research on the environmental impacts of the entire "mutualized mobility industry" in overall urban transportation systems and even less across cities. The life cycle analysis of a comprehensive set of mutualized transports may provide more depth and breadth on the global environmental implications of mutualized transportation (Cohen and Shaheen, 2018). Therefore, to address these abovementioned gaps in the literature, this study provides a close estimation of the net environmental impact brought by different forms of mutualized mobility, to the overall urban transportation system, from a life cycle assessment (LCA) perspective, by using actual urban transportation big data and the operational data of mutualized mobility. More precisely, it evaluates the environmental impact of mutualized mobility addressing the following research questions: What is the environmental impact of different forms of mutualized mobility? Which mutualized mobility forms provide the most neutral effect? How does this impact span across the life cycle of each mutualized transportation mode? How does this impact differ across major cities and countries?

2. Material and methods

2.1 Study areas and analysis framework

This study selects two representative cities for empirical analysis, the first being located in an Eastern economy, namely Beijing, China, and the second is a Western metropole, namely Toronto, Canada. To provide a scientifically-sound and reasonable basis for the comparative analysis, as well as considering the availability of accurate data, this paper selects the year 2011 and the year of 2016 as the comparison time nodes. From 2011 to 2016, mutualized mobility has developed well in both cities. In Beijing, the proportion of mutualized mobility travel in the total daily travel of urban residents has risen from 0% in 2011 to nearly 3% in 2016, with the lion's share being attributable to ride-hailing (2.5%) (Beijing Municipal Commission of Transportation, 2016; Beijing Transport Institute, 2017). Ride-hailing was introduced in Beijing in 2012 and developed rapidly. In 2016, the average daily order volume had reached 800,000 (Beijing Municipal Commission of Transportation, 2016; Sina, 2017; China State Information Center, 2018). Station-based bike sharing (SBBS) also emerged in Beijing in 2012. In 2016, the number of bikes for SBBS in Beijing was 81,000, and the annual number of SBBS trips had reached 50 million, accounting for 0.36% of the total daily trips made by urban residents (Beijing Transport Institute, 2017). Also, FFBS services first appeared in Beijing at the end of 2016, and the overall scale has grown exponentially after that (China State Information Center, 2018). The scale of FFBS in Beijing in 2016 was relatively small, and the trips provided by FFBS accounted for only 0.03% of the total bicycle trips in 2016 (Beijing Transport Institute, 2017). Considering the timeframe of this study, FFBS was thus excluded from the scope of this work.

The mutualized mobility landscape in Toronto is more diverse but revolves essentially around car-centric mutualizing schemes. The proportion of mutualized mobility travel in urban residents' total daily travel rose from about 6.0 % in 2011 to nearly 7.6% in 2016 (Statistics Canada 2011, 2016; Transportation Tomorrow Survey, 2014, 2018). Carpooling is the most extensive mutualized mode in Toronto. Its proportion of Toronto residents' total daily trips has risen from 5.9% in 2011 to nearly 7% in 2016 (Statistics Canada, 2011, 2016; Transportation Tomorrow Survey, 2014, 2018). There are two modes of car sharing in Toronto, station-based car sharing (SBCS) and free-floating car-sharing (FFCS). In the station-based car sharing mode, the user needs to pick up and return the shared car at the car-sharing operators' fixed stations (Shaheen and Chan, 2016; Cohen and Shaheen, 2018). As to the free-floating car-sharing mode, the shared cars are freely parked in public spaces within the designated operational area. The journey can start and finish in any location within this area (Shaheen and Chan, 2016; Cohen and Shaheen, 2018). Car sharing in Toronto also experienced rapid development between 2011 and 2016, and the size of the overall car-sharing fleet rose from 500 to about 1400. The FFCS fleet size is about 500 vehicles, and the SBCS fleet size is about 900 vehicles. In 2016, the daily average travel volume exceeded 14,000 (Habibi et al., 2016; Statista, 2019). Ride-hailing emerged in Toronto in 2012, and the market scale has surpassed car sharing. The average daily order volume in 2016 had exceeded 35,000 (Elliott, 2014; Transportation Tomorrow Survey, 2018). Toronto SBBS started in 2011 and has grown to 2,000 bicycles and 200 stations by 2016, with annual ridership reaching 0.83 million (Wikipedia, 2020). The share of SBBS has remained very modest and appears to be an epi-phenomenon compared to other modes of transportation.

The overall framework of this study is as follows. First, we use the LCA method to compare and analyze the GHG emission factors of the mutualized mobility modes and understand the key factors affecting each type of mutualized mobility's environmental performance. Then, combining the GHG emission factors of various transportation modes and the actual transportation data of urban residents (e.g., mode choice, trip volume, and average travel distance per trip), a "bottom-up" approach was used to evaluate the impact of mutualized mobility on the GHG emissions of the urban transportation system.

2.2. Life Cycle Assessments

In this study, LCA modeling and calculation were done by the SimaPro v. 9.0 software (PRé Consultants, 2019) and the Ecoinvent database v. 3.5 (Wernet et al., 2016). The methodology follows the standardized LCA procedure, which includes four primary stages of goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and result interpretation (ISO, 2006a, 2006b).

2.2.1. Goal and scope definition

The life cycle of transportation means can be divided into three different phases: (1) manufacturing phase; (2) use phase; and (3) end-of-life phase (ISO, 2006a, 2006b): The *manufacturing phase* includes the raw material extraction and processing, the natural resources and energy inputs required to manufacture the vehicle. The *use phase* includes the operation and maintenance of the vehicle by one or multiple users, simultaneously or sequentially, over time. The *end-of-life* phase refers to the stage during which the product cannot be used for the primary purpose for which it was originally manufactured, namely transportation, and thus involves the partial or total recycling as well as the disposal of vehicles. The vehicles involved in mutualized mobility are bicycles and cars, and the corresponding system boundaries are shown in Fig. 1 and Fig. 2.

[INSERT FIGURE 1 ABOUT HERE]

[INSERT FIGURE 2 ABOUT HERE]

The bicycle system's system boundary is used for personal owned bikes (POB) trip and SBBS trip. The significant differences between the POB and SBBS are that the station-based bike-sharing system requires supporting facilities (i.e., stations and docks). Also, all the shared bikes need to be distributed and rebalanced by vans among stations in the use phase.

The car system's system boundary is used for six modes of car trip: private car (not involved in any mutualized mobility), SBCS, FFCS, carpooling, ride-hailing, and taxi. In the use stage of vehicles, it is necessary to consider the 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 fuel types considered in this paper were gasoline and electricity.

When studying the GHG emissions factor of a single transportation mode, the general approach divides the total carbon emissions of the vehicle's entire life cycle by the vehicle-kilometers-traveled (VKT) during the entire life cycle (Dave, 2010). But this is not an appropriate way to compare the transport modes with different carrying capacities. Therefore, to facilitate comparative analysis, we first convert VKT to passenger-kilometers-traveled (or passenger-miles-traveled) (Dave, 2010; Rui-Qiang et al., 2019), which is to multiply VKT by the average vehicle occupancy, as shown in Eq

(1):

$$PKT = \sum VKT_i \times O_i \tag{1}$$

Where VKT_i refers to the vehicle-kilometer -traveled at stage i. O_i refers to the average vehicle occupancy at stage i. PKT refers to the passenger-kilometers-traveled provided by a vehicle in the life cycle. According to (Beijing Transport Institute, 2017; City of Toronto Transportation Services, 2019; Ding et al., 2019; Henao and Marshall, 2019; Union of Concerned Scientists, 2020), the occupancy of a taxi, ride-hailing, bus, and streetcar does not include the driver, while the occupancy of a private car (not involved in any mutualized mobility), carpooling and car-sharing consists of the driver since drivers in these modes are also considered passengers. For example, a taxi with two passengers that travels 10 kilometers has completed 20 passengers-kilometers-traveled in a period. If a taxi travels 2 kilometers without passengers, the PKT at this stage is 0.

Therefore, the functional unit (FU) selected in this study is a passenger-kilometer (pkm) representing the transport of one passenger over one kilometer. The assessment results are expressed as gCO$_2$-eq/pkm, which can be used to compare and analyze the GHG emission factors of various transportation modes. GHG emission factors are specifically defined by Eq (2):

$$e_j = TGHG_j / PKT_j \tag{2}$$

Where j refers to the transport mode. $TGHG$ refers to the total GHG emissions of a vehicle during its lifespan. PKT_j refers to the total passenger-kilometers traveled provided by the vehicle during its lifespan. $TGHG_j$ can be obtained by adding the greenhouse gas emissions at each stage of the vehicle life cycle. As to the automobiles, the GHG emissions from fuel consumption during the use phase can be calculated by Eq. (3).

$$E_{fuel} = EFF \times FCR \times VKT \tag{3}$$

Where E_{fuel} refers to total GHG emissions from fuel consumption during the use phase. EFF refers to the WTW GHG emission factor of the fuel (i.e., gasoline and electricity in this study). FCR refers to the fuevehicle's fuel consumption rate: the amount of fuel used per unit distance (i.e., liters per 100 kilometers for gasoline vehicles and kWh per 100 kilometers for battery electric vehicles).

The VKT and occupancy of POB and private cars are set as fixed values to facilitate comparative analysis. The calculation of VKT and PKT for other different modes of transportation is described below.

(1) SBBS

Since only one person usually uses bicycles, VKT, and PKT are the same for bikes in this study and calculated by Eq. (4).

$$VKT_{SBBS} = DTR_{SBBS} \times d_{SBBS} \times L_{SBBS} \tag{4}$$

Where VKT_{SBBS} refers to the lifetime mileage of the shared bike, DTR_{SBBS} refers to average daily uses per bike, that is, the shared bike's daily turnover rate. d_{SBBS} refers to the average distance per SBBS trip, and L_{SBBS} is the lifespan of the shared bike.

(2) Ride-hailing and taxi

With regards to ride-hailing and taxis, deadheading needs to be considered.

Deadheading is mostly used for the taxi industry and refers to distance traveled without passengers (e.g., driving to the next ride or driving from dispatch to pick-up location). Therefore, each ride-hailing or taxi trip length can be divided into two parts: passenger trip length (i.e., with a passenger) and deadheading length (i.e., without passenger). The VKT and PKT of the taxi and ride-hailing vehicles can be calculated by Eq. (5) and Eq. (6).

$$VKT_{R\_T} = \frac{DTR_{R\_T} \times d_{R\_T} \times L_{R\_T}}{(1-\alpha)} \tag{5}$$

$$PKT_{R\_T} = DTR_{R\_T} \times d_{R\_T} \times L_{R\_T} \times O_{R\_T} \tag{6}$$

Where VKT_{R_T} refers to the lifetime mileage of the vehicle, DTR_{R_T} refers to the number of trips provided per vehicle per day. d_{R_T} refers to the average passenger trip length. L_{R_T} is the lifespan of the vehicle. O_{R_T} refers to average vehicle occupancy for the passenger trip length. α refers to the average deadheading rate, that is, the deadheading length ratio to the entire trip length (passenger trip length and deadheading length).

(3) SBCS and FFCS

As for SBCS and FFCS, the GHG emissions generated during the rebalancing of the shared vehicles need to be considered, which refers to relocating cars from overcrowded stations to those with a shortage of cars to improve system effectiveness (Chiariotti et al., 2018). Therefore, the lifetime mileage of vehicles used for SBCS and FFCS consists of two parts: passenger driving mileage (i.e., passenger trip length). The other part is the mileage driven for redistribution purposes (by the mutualized mobility operator). The VKT and PKT of the vehicles used for SBCS and FFCS can be calculated by Eq.

(7) and Eq. (8).

$$VKT_{CS} = \frac{DTR_{CS} \times d_{CS} \times L_{CS}}{(1-\beta)} \tag{7}$$

$$PKT_{CS} = DTR_{CS} \times d_{CS} \times L_{CS} \times O_{CS} \tag{8}$$

Where VKT_{CS} refers to the lifetime mileage of the vehicle, DTR_{CS} refers to the average number of trips provided per vehicle per day. d_{cs} refers to the average distance per trip. L_{CS} is the lifespan of the shared vehicle. O_{cs} refers to average vehicle occupancy per trip. β refers to the percentage of the mileage used for rebalancing to the total lifetime mileage of the vehicle.

(4) Carpooling

The vehicle refers to the privately-owned car in the carpooling mode and does not belong to the mutualized mobility operator. Carpooling primarily meets the private vehicle owner's requirement and meets the others' needs on an occasional basis, so that only a fraction of the travel distance - in the lifetime of a private car - is used for carpooling purposes. Although the destination is similar for the vehicle owner and other carpoolers, different distances traveled to reach different pick-up and drop-off points. The VKT and PKT of the vehicles used for carpooling can be calculated by Eq. (9) and Eq. (10) and described in Supplementary material A.

$$VKT_{CP} = VKT_P \times (1-\gamma) + VKT_P \times \gamma \times (1+\delta) \tag{9}$$

$$PKT_{CP} = VKT_p \times (1-\gamma) \times O_p + \gamma \times VKT_P \times O_{Cp} \tag{10}$$

Where VKT_P refers to the lifetime mileage of a private car without participating in carpooling. VKT_{CP} refers to the lifetime mileage of the vehicle which participates in carpooling. O_{cp} The average vehicle occupancy during the carpooling, γ refers to the percentage of mileage used for carpooling in the lifetime of a private car. O_p refers to the average vehicle occupancy of private car trips. δ refers to the proportion of different distances traveled during carpooling. This is because the origin and destination points of other carpoolers may be some distance away from the private car owner's destination, which makes the private car owner need to drive some extra distance.

2.2.2 Life cycle inventory (LCI) analysis

Life cycle inventory analysis builds an inventory of the natural resources used, energy inputs, and waste and emission outputs involved in the system. The process data of material information, energy consumption, waste, and emission outputs related to the manufacture, maintenance, and disposal of the vehicles are mainly collected from the Ecoinvent database v. 3.5 (Wernet et al., 2016). The data about the operating characteristics of mutualized mobility are collected from the peer-reviewed journal articles and the statistical report of the transportation department and the mutualized mobility operators (Beijing Transport Institute, 2017; Bonilla-Alicea et al., 2020; City of Toronto, 2019; City of Toronto Transportation Services, 2019; Ding et al. 2019; Statistics Canada 2010; Habibi et al., 2016; Henao and Marshall, 2019; Luo et al. 2019; Martin and Shaheen, 2016; Sprei et al., 2019; Union of Concerned Scientists, 2020). The specific details are shown below.

(1) LCI analysis of bikes

With regards to the manufacturing stage of a bike, the Ecoinvent dataset "Bicycle {RoW} production" is used, which refers to a 17 kg urban-used bicycle including additional items (e.g., carriers, lights), and the frame material is aluminum (Wernet et al., 2016). Regarding the maintenance stage, the Ecoinvent dataset "Maintenance, bicycle {RoW}" is used. This dataset includes maintaining a bicycle throughout its life cycle (lifespan is ten years, and VKT is 15,000 kilometers). The maintenance work includes manufacturing, electricity and water consumption, and waste disposal (Wernet et al., 2016). Regarding the end of life stage, The Ecoinvent dataset "Used bicycle {RoW}| treatment of |" is used, which reflects the disposal of a bike of 17 kg, and the aluminum and steel parts are set to be fully recycled.

The average weight of shared bikes is about 20 kg (Luo et al., 2019). The inventory data of the bike production are scaled with bike mass. Simultaneously, the energy and materials consumed during the maintenance phase are proportional to the total mileage traveled, as shown in Supplementary material B. Furthermore, the data about the operation status of SBBS system in Beijing and Toronto are shown in Supplementary material C, and the material consumption for making the required stations and docks are shown in Supplementary material D. According to (Beijing Transport Institute, 2017, 2019; Luo et al., 2019; Bonilla-Alicea et al., 2020), the lifespan of required stations and docks is set to 10 years. Moreover, the environmental impact of stations and docks will be equally distributed across each bike trip. In terms of rebalancing, we used the "Transport, light commercial truck, gasoline-powered (of project USLCI)" process to account for the life cycle impacts of the rebalancing process (680g CO_2-eq /km) (Luo et al., 2019; Bonilla - Alicea et al., 2020).

(2) LCI analysis of cars

The Ecoinvent dataset "Passenger car, petrol/natural gas {GLO}| production |" and

"Passenger car maintenance {RoW}" are used for both the manufacturing and the maintenance stage, respectively. It is assumed that the mass of a passenger car is 1,240 kg and that it can travel a total of 150,000 km within a lifespan of ten years (Wernet et al., 2016). As for the end-of-life stage, the Ecoinvent datasets "Manual dismantling of a used passenger car with internal combustion engine {GLO}," "treatment of Used internal combustion engine, from passenger car {GLO}," and "treatment of Used glider, passenger car {GLO}|" are used (Wernet et al., 2016). The inventory data of battery electric vehicles (BEVs) is shown in Supplementary material E.

This study also assumes that private cars and cars participating in mutualized mobility have the same fuel efficiency (8 liters of gasoline or 18 kWh of electricity per 100 kilometers traveled). The WTW GHG emission intensity for gas is about 2.90 kg CO_2-eq/L (Wernet et al., 2016). The WTW GHG emission intensity for electricity in Beijing and Toronto is 0.920 kg CO_2-eq /kWh and 79.6 g CO_2-eq /kWh, respectively (China Electric Power Development Promotion Association, 2015; Canada Energy Regulator, 2016) (see Supplementary material F).

To examine the GHG emission factors of different transportation modes, we need to know the operating characteristics of each mode to calculate its VKT and PKT first (see formulas in Section 2.1.1 Eq. (9) ~ Eq. (10)). According to Dave (2010), Wernet et al. (2016), Luo et al. (2019), and Bonilla-Alicea et al. (2020), the lifespan and VKT of POB in this study are assumed to be ten years and 15,000 kilometers. As for private cars, the average lifespan of a private car is about 11 years in Canada, and the average annual vehicle-kilometers traveled is approximately 14,520 km (Statistics Canada, 2010). In China, the average lifespan of a private car is about ten years, and the average annual vehicle-kilometers traveled is about 14,755 km (China Industry Information, 2016; Xiao Xiong You Hao, 2017). To facilitate comparative analysis, this article assumes that the life of a private car is ten years and the life cycle mileage is also 150,000 km.

There is no data available on the lifespan of the vehicles that take part in mutualized mobility to the authors' knowledge. Several studies have suggested that shared vehicles wear and tear and replace faster than privately owned vehicles (Chen and Kockelman, 2016; Meijkamp, 1998). Also, to attract customers and enhance market competitiveness, mutualized mobility operators tend to update their vehicles faster (Cision, 2017; Shaw, 2018). Therefore, this study assumes that the lifespan of those vehicles in the fleet of mutualized mobility operators is about 7 to 10 years. In addition to lifespan, there are also some uncertainty variables for mutualized mobility such as the rebalance distance for serving 1 km bike trip for SBBS, β (i.e., percentage of the mileage used for rebalancing) for SBCS and FFCS, deadheading rate (i.e., α) for ride-hailing, and the γ (i.e., the percentage of mileage used for carpooling in the lifetime of a private car) and δ (i.e., percentage of extra driving distance during carpooling) for carpooling. The value ranges of all these uncertain variables are set based on the current research results on mutualized mobility and the statistical reports of the realistic operations of the mutualized mobility operators (Beijing Transport Institute, 2017; Bonilla-Alicea et al., 2020; City of Toronto, 2019; City of Toronto Transportation Services, 2019; Ding et al. 2019; Statistics Canada 2010; Henao and Marshall, 2019; Luo et al. 2019; Martin and Shaheen, 2016; Union of Concerned Scientists, 2020). The real data about the operating characteristics of mutualized mobility in Beijing and Toronto and the corresponding data sources are summarized in Supplementary material G. The corresponding VKT and PKT results for mutualized mobility are shown in Supplementary material H, Supplementary material I, and Supplementary material J.

2.2.3. Life cycle impact assessment (LCIA)

The ReCiPe 2016 hierarchist impact assessment method was used to calculate the score of environmental impact indicators. ReCiPe 2016 is a widely used method in life cycle impact assessment (LCIA), which converts the long list of life cycle inventory results into a limited number of indicator scores (Huijbregts et al., 2017). The score of indicators can directly represent the relative severity on an environmental impact category (Huijbregts et al., 2017). The ReCiPe 2016 hierarchist impact assessment method provides 18 midpoint indicators covering a full range of environmental impacts. In this study, we select the impact category of "Global warming" to explore the environmental impact of mutualized mobility. To better explore the environmental implications of mutualized mobility, we first used gasoline vehicles as the research object to analyze the GHG emissions factors of each mutualized mobility. Due to the uncertainties in the study's data, choices, and models, we performed an uncertainty analysis by employing a Monte Carlo simulation. The simulation was run 10,000 times. A comprehensive list of uncertain model parameters can be found in Supplementary material K. Based on the simulation results. We calculated the mean, standard deviation (SD), and coefficient of variation (CV), 95% confidence interval (CI, i.e., the lower bound is the 2.5th percentiles and upper bound is 97.5th percentiles) for the GHG emissions factors of each mutualized mobility transportation mode. Subsequently, a sensitivity analysis was conducted to understand and identify the key factors affecting each type of mutualized mobility's environmental performance. Additionally, we also assessed the environmental impact of mutualized mobility when the vehicle type used for sharing is BEVs.

2.3. Estimation model for GHG emissions from the transportation system

Combining the GHG emission factors of the transportation modes and the actual traffic data of urban residents, we can further evaluate the effect of mutualized mobility on GHG emissions of the urban transportation system in Beijing and Toronto by using a "bottom-up" approach. The "bottom-up" approach estimates emissions from fewer aggregate travel attributes, including trip volume, mode choice, and average travel distance per trip (IPCC, 2006). This approach requires relatively more detailed data and allows further analyses of the results, such as evaluating emission reduction strategies. Therefore, it is widely used to estimate the emissions generated by urban residents' daily traffic (Bhave et al., 2014; Rui-Qiang et al., 2019). The specific estimation model is shown in Eq. (11).

$$E_{total} = \sum N_j \times D_j \times e_j \tag{11}$$

where E_{total} refers to the total GHG emissions from the urban residents' daily transportation. j refers to the transportation mode, N_j refers to the total trip volume of urban residents using transportation mode j, D_j refers to the average distance traveled per trip by transportation mode j, e_j refers to the GHG emission factor of the transportation mode j. This study selects the year 2011 and the year of 2016 as the comparison time nodes. To control for the impact of urban population growth, the unit for comparison is the annual GHG emissions per capita. The transportation data N_j and D_j of Toronto and Beijing in 2011 and 2016 are shown in Supplementary material L and Supplementary material M. As to the e_j, the GHG emissions factors of mutualized mobility are obtained by the LCA method in Section 2.1. The GHG emissions factors for other transportation modes involved in this study (e.g., bus and subway) are shown in Supplementary material N.

Considering the uncertainty of emission factors for mutualized mobility, this study set up four comparative analysis scenarios. We set the average value, the upper bound of the 95% Confidence Interval, and the lower bound of the 95% Confidence Interval of emission factors when the vehicle type used for mutualized mobility is gasoline vehicle as to the baseline scenario, the worst scenario, and the best scenario, respectively. Also, we set the average value when the vehicle type used for mutualized mobility is BEVs as the "BEV" scenario. To facilitate comparative analyses, we combine POB and SBBS into one group named "Bike." We then combine private cars, car sharing, carpooling, ride-hailing, and taxi into another group called "Car." We finally combine subway, bus, and streetcar into another group named "Public transit."

3. Results

3.1 Life cycle GHG emission factors for mutualized mobility

3.1.1 Life cycle GHG emission factors for bike trips

The life cycle GHG emission factors for POB and SBBS in Beijing and Toronto, and the breakdown of the corresponding value by life cycle stages are shown in Fig.3. The summary statistics of the uncertainty analysis results are shown in Table 1.

[INSERT FIGURE 3 ABOUT HERE]

[INSERT TABLE 1 ABOUT HERE]

As shown in Fig. 3, the average GHG emission factor of SBBS in Toronto was about 64.00 CO_2-eq/pkm (SD= 2.94, CV= 4.60). The 95% confidence interval was found to lie between 58.30 and 69.85 g CO_2-eq/pkm, a range that spans about 18% of the average value. As to the GHG emission factor of SBBS in Beijing, the average value, standard deviation, coefficient of variation, and 95% confidence interval were 63.19kg CO2eq/pkm, 2.98 CO2eq/pkm, 4.72%, and 57.35~68.99 g CO2eq/pkm respectively, which were similar to those of SBBS in Toronto. Overall, the average GHG emission factor of SBBS was about 63.6 g CO_2-eq/pkm, which was six times that of POB (10.5 g CO_2-eq/pkm). The bike rebalancing process and the required docks and stations were the primary sources of GHG emissions for the SBBS system, accounting for about 43% and 35% of GHG emissions. More specifically, compared to public transit, SBBS didn't provide essential advantages in GHG emissions (see Supplementary material N). In Beijing, the GHG emission factor of SBBS was higher than that of the subway (39.50 g CO_2-eq/pkm) or the bus (30.65 g CO_2-eq/pkm). Although the GHG emission factor of Toronto's SBBS was lower than that of buses (97.80 g CO_2-eq/pkm), it was much higher than that of the subway (31.16 g CO_2-eq/pkm) and streetcars (11.33 gCO_2-eq/pkm). In addition to the impact of bike rebalancing and supporting infrastructure, another main reason for the high GHG emission factor of the SBBS system was that the utilization of shared bikes in these two cites was not high (see Supplementary material H). The annual VKT of SBBS in Beijing and Toronto was about 1,357.1 kilometers and 1,623.7 kilometers, respectively, similar to POB (1,500.0 kilometers). Considering that a shared bike's service life is likely to be shorter than that of POB, it may have a lower VKT during the whole lifespan. Taking the SBBS system in Beijing as an example, if a shared bike's service life is two years less than that of POB (i.e., ten years), the total VKT of a shared bike during the lifespan is 28% less than that of POB.

Fig. 4 presents the results of the sensitivity analysis about the lifespan of the shared bike and the rebalance distance required for serving 1 km of a bike trip.

[INSERT FIGURE 4 ABOUT HERE]

It can be seen that increasing the shared bike's service life and reducing the required rebalance distance can make SBBS more environmentally friendly. However, compared to the lifespan of the bike, the uncertainty of the rebalancing process has a greater impact on the results, since for a 1 km bike trip, GHG emissions caused by the rebalancing process range from 18.7 to 35.7 gCO_2-eq. This variation range is much more extensive than the range caused by lifespan changes. As the lifespan increases, increasing the lifespan to reducing the emission factor will gradually decrease.

3.1.2 Life cycle GHG emission factors for car trips

The life cycle GHG emission factors for car trips in Beijing and Toronto with the breakdown of the corresponding value by life cycle stages are shown in Fig.5. The summary statistics of the uncertainty analysis results are shown in Table 2 and Fig.6.

[INSERT FIGURE 5 ABOUT HERE]

[INSERT TABLE 2 ABOUT HERE]

[INSERT FIGURE 6 ABOUT HERE]

As shown in Fig. 5, ride-hailing and taxis emission factors are similar, being the highest among all car travel modes. The average GHG emission factor of ride-hailing was 34.4%

(95% CI: 25.3% ~ 43.0%) higher than that of private cars (252.7CO_2-eq/pkm) in Toronto, while the emission factor of ride-hailing in Beijing was on average 20.6% (95% CI: 14.6 % ~ 27.3%) higher than that of private cars (232.6CO_2-eq/pkm). SBCS and carpooling in Toronto were the most environmentally friendly car travel modes since, on average, their emission factors were approximately 29.3% (95% CI: 26.1% ~ 32.1%) and 16.1% (95% CI: 11.5% ~ 20.3%) lower than that of private cars, respectively. It's worth noting that FFCS in Toronto didn't show an important advantage in terms of GHG emission reduction because the 95% CI of GHG emission factor ranged from 249.6 to 283.2 CO_2-eq/pkm, with an average value of 265.3 CO_2-eq/pkm(SD= 8.54, CV=3.22), which was about 5.0 % higher than that of private cars. According to the CV and 95% confidence intervals presented in Table 3, it also can be found that the emission factors of ride-hailing and FFCS had a higher uncertainty than that of Carpooling and SBCS. Fig. 6 presents the uncertainty of the difference between the emission factors of mutualized car trips and private car trips based on 10,000 times simulations. The results showed that in 100% of cases, ride-hailing's emission factor was higher than that of a private car, while the emission factors of SBCS and Carpooling had a lower emission factor than the private car. As to the comparison between FFCS and private car trips, FFCS had a higher emission factor in about 94% of the cases, meaning that it is almost certain that FFCS was less environmentally friendly than a private car trip.

Also, GHG emissions of automobiles were mainly concentrated in the use phase, accounting for about 80% of the total emissions. However, there were still some differences between various modes of car travel. In Toronto, the proportion of GHG emissions during the use phase of SBCS and FFCS were about 74.3% and 54.4%, respectively, which was lower than that of a private car (82.0%), ride-hailing (83.2%), and taxi (83.9%). The GHG emissions of a vehicle in the use phase are closely related to the VKT during its service life. The vehicle utilization of SBCS and FFCS in Toronto was relatively low (see Supplementary material I and Supplementary material J), especially FFCS. The annual VKT was about 4036.7km, which was only 27% of private cars (15000.0 km).

Fig. 7 presents the results of the sensitivity analysis of the uncertain factors of mutualized car trips.

[INSERT FIGURE 7 ABOUT HERE]

As for SBCS and FFCS, compared to β (i.e., percentage of the mileage used for rebalancing), the uncertainty of lifespan has a greater impact on the results. This is notably the case for FFCS, in which case, increasing the utilization of vehicles can reduce its GHG emission factor. Besides, when the lifespan of the vehicle changes from 7 years to 10 years, the GHG emission factor can be reduced by about 18% (51 g CO_2-eq).

For ride-hailing, deadheading is the most critical factor affecting the emission factor. The high deadheading rate is also the main reason for the high GHG emission factor of ride-hailing. The average deadheading rate of ride-hailing was about 39%, contributing approximately 32% of the total life cycle GHG emissions. In particular, with the increase of the deadheading rate, the emission factor shows a superlinear growth. Reducing deadheading can curb the environmental impact of ride-hailing. If the deadheading rate is reduced from 45% to 33%, the value of the GHG emission factor can be reduced by about 15% (54 g CO_2-eq).

In terms of carpooling, compared to δ, γ has a greater impact on the results.

Increasing the percentage of mileage used for carpooling in the life cycle of a private car significantly improves the GHG emission reduction potential of carpooling when the γ increases from 10% to 30%, the GHG emission factor of carpooling can be reduced by about 15% (34 g CO_2-eq).

To further explore the emission reduction potential of mutualized mobility, we compared and analyzed emission factors under two gasoline vehicles and BEV scenarios. The comparison is based on the average value, as shown in Fig. 8.

[INSERT FIGURE 8 ABOUT HERE]

As can be seen in Fig. 8, adopting BEVs can significantly increase the GHG emission reduction potential of mutualized mobility, since compared to gasoline vehicles, BEVs can reduce the emission intensity of carpooling, FFCS, SBCS, and ride-hailing in Toronto by about 75% (159 g CO_2-eq), 37% (97g CO_2-eq), 62% (110 g CO_2-eq), and 70% (235 g CO_2-eq), respectively. This will make all mutualized car travel more environmentally-friendly than a private gasoline car trip. The emission factor of carpooling, FFCS, SBCS, and ride-hailing will be about 79% (200 g CO_2-eq), 34% (85 g CO_2-eq), 73% (184 g CO_2-eq), and 60% (152 g CO_2-eq) lower than that of a private gasoline car, respectively. Compared to Toronto, although the emission reduction effect of adopting BEVs in Beijing is much smaller, it can also reduce the GHG emission intensity of ride-hailing trips by about 19% (53 g CO_2-eq). In comparison, the GHG emission factor will be about 3% (7 g CO_2-eq) lower than that of private gasoline cars.

3.2. GHG emissions impact of mutualized mobility to the urban transportation system

Based on Beijing and Toronto's actual transportation data in 2011 and 2016, we compared and analyzed the changes in urban residents' daily traffic structure and the annual GHG emissions per capita. Following the scenario set in section 2.3, the detailed changes in the mode share, and the corresponding annual GHG emissions per capita are summarized in Table 3.

[INSERT TABLE 3 ABOUT HERE]

Although mutualized mobility has increased in Beijing and Toronto, both cities differ significantly in GHG emissions. As for Beijing, in 2016, per capita GHG emissions increased compared to 2011; although this increase is mainly due to public transit, emissions from car trips and bike trips have also increased. The proportion of car trips had increased by 0.37%. That increase has propelled the corresponding amount of emissions by 5.98 kg CO_2-eq under the baseline scenario and 6.59 kg CO_2-eq under the worst-case scenario. Even in the best-case scenario, the increase in the proportion of car trips can only reduce 0.18kg CO_2-eq, but adopting BEVs for ride-hailing can reduce the emissions of car trips by 7.90 kg CO_2-eq. It can be seen that the large-scale development of ride-hailing in Beijing may increase people's demand for car trips, which may have a negative impact on the environment. It is also worth noting that the promotion of SBBS in Beijing did not increase the total amount of bicycle trips but increased the total emissions of bicycle trips.

As shown in Table 3, Mutualized mobility appears to have made a positive contribution to Toronto's transportation sustainability. Under the baseline, worst-case, and best-case scenarios and BEV, the per capita emissions in 2016 diminished by 2.80 kg CO2-eq, 1.36 kg CO2-eq, and 4.17 kg CO_2-eq, and 20.83 kg CO_2-eq respectively compared with 2011. The diversified forms of mutualized car trips have played a major role in reducing GHG emissions per capita in Toronto. The proportion of car trips in Toronto had dropped by 1.04%, while the proportion of public transit, bicycle, and walk trips had increased by 0.24%, 0.35%, and 0.45%, respectively. The decline in the proportion of car trips has reduced the corresponding annual GHG emissions per capita by 7.11kg CO_2-eq under the baseline scenario. Even in the worst-case scenario, the decline in the proportion of car trips can still reduce GHG emissions by 5.68 kg CO_2-eq, whereas, in the BEVs scenario, the reduction can reach 25.14 kg CO_2-eq. Notably, the scale of SBBS is also negligible in the case of Toronto, with limited effects on reducing annual GHG emissions per capita.

4. Discussion

Increasing global population, economy, and technological development are likely to increase the need for mobility over the next years, resulting in a similar increase in pressures on transportation systems and the environment. Mutualized mobility is considered a promising way to support transportation sustainability (Shaheen and Chan, 2016; Cohen and Shaheen, 2018). Yet, this is not certain. For example, ride-sharing services are of particular concern since they have often been associated with rebound effects (e.g., Yin et al., 2018), and therefore more GHG emissions. Therefore, to curb environmental impacts, it should be examined how mutualized mobility contributes to decreasing GHG emissions. By applying the LCA framework and the actual transportation data for Toronto and Beijing, this study explores the effect of mutualized mobility on GHG emissions for urban transportation from a life cycle perspective and critical factors affecting the environmental performance of each type of mutualized mobility. This paper contributes meaningfully to extant research on the environmental impact of transportation in several ways.

Firstly, although there are various forms of mutualized mobility in the urban transportation system, most research studies them separately instead of conjointly to show synergies and comparisons (Martin and Shaheen, 2011; Chen and Kockelman, 2016; Nijland and Van Meerkerk, 2017; Qiu and He, 2018), which makes the research on the environmental impact of mutualized mobility lack a systematic and comprehensive perspective. This article explores the environmental impact of the entire "mutualized mobility industry" on the urban transportation system from a systematic perspective, making up for under-theorization in this research area.

Secondly, using an LCA methodology and big data about mutualized mobility operations, the environmental impact of mutualized mobility is examined throughout all stages of the life cycle, providing more in-depth and broader insights. The study assessed and compared the environmental impact of different mutualized mobility modes (i.e., breadth) and explored and identified the key factors affecting the environmental performance of each type of mutualized mobility throughout their lifecycle (i.e., depth). The emissions factor of SBBS is much higher than that of POB, which is attributed to docks and stations and rebalancing activities that occur throughout the life cycle of SBBS bicycles. Also, the low utilization rate of shared bicycles is a major reason for that higher amount of emissions than POB. More importantly and perhaps more counter-intuitively, SBBS may be less environmentally friendly than public transit, suggesting that substituting public transportation modes with SBBS might be more detrimental to reduce the (global) environmental footprint. The emission factor of ride-hailing is higher (20% on average in Beijing and 34% on average in Toronto) than private cars, which is attributable to deadheading. The vehicle utilization rate of FFCS in Toronto is low, with an annual VKT that is even less than 30% that of private cars, so that FFCS does not show obvious advantages in reducing GHG emissions. In contrast, SBCS and carpooling appear to have a stronger potential in reducing emissions compared to other car travel modes since their emission factors are about 29% and 16% lower than that of private cars, respectively.

Thirdly, existing research (e.g., Chen and Kockelman 2016; Martin and Shaheen, 201; Qiu and He, 2018; Zhang and Mi, 2018) assesses environmental impacts of mutualized mobility based on assumptions and scenario predictions rather than real data, so that following conclusions are likely to be less reliable. In contrast, the results in this study are based on real-world big data and thus inform more accurate assessments. More specifically, the "bottom-up" approach used in the study can well include the impact of mutualized mobility on changes in transportation structure and trip volumes. The effect of mutualized mobility on GHG emissions of urban transportation can be assessed more systematically and accurately.

Fourthly, by using real-world data, this study partially verified some conclusions drawn from previous studies that car sharing has a specific GHG emission reduction potential (Martin and Shaheen, 2011; Chen and Kockelman, 2016; Nijland and Van Meerkerk). But we also found that the low utilization of shared vehicles reduces their emission reduction advantages. For example, in Toronto, the average GHG emission factor of FFCS is higher than that of private cars. As for bike-sharing, the assumption that bike-sharing can reduce emissions by replacing car travel with cycling (Zhang and Mi 2018; Qiu and He, 2018) is not supported by the results of this study. The promotion of SBBS in Beijing did not increase the total amount of bicycle trips since the annual VKT of SBBS is similar to POB. Still, the average GHG emission factor is almost six times that of POB, even much higher than public transit. Therefore, from a life cycle perspective, the claimed environmental benefits brought by SBBS are questionable. These results complement Sun and Ertz's (2021) finding that FFBS fares higher on resource conservation capabilities than SBBS, suggesting that SBBS is a relatively sub-optimal strategy for curbing GHG emissions in contrast to other bike-centric systems.

Fifthly, past research already showed the negative impacts of ride-hailing from a sustainability perspective by emphasizing that it leads to more vehicle miles traveled (Henao and Marshall, 2019) and heightened rebound effects (Yin et al., 2018). In contrast to past research, this study shows that the large-scale development of ride-hailing is likely to increase people's demand for a car trip and have a negative impact on the environment from a life cycle perspective. Last but not least, the development of the mutualized mobility industry differs across cities. Notably, the same mutualized mobility mode in different towns may also have other operating characteristics, making the environmental impact of mutualized mobility on the urban transportation system vary across cities and regions. In a city like Toronto, with high car ownership per capita (about 0.8) (Transportation Association of Canada, 2016), strongly decreasing environmental impacts, such as the GHG emission factors, is more likely with carpooling and car-sharing as they involve more genuine forms of vehicle sharing, especially carpooling. The large-scale promotion of such modes of transport may significantly contribute to strategies aimed at mitigating climate change and should therefore be considered a priority by policy-makers seeking to curb the global environmental footprint caused by anthropogenic activities. In a city such as Beijing, with low car ownership per capita (about 0.25) (Beijing Transport Institute 2017), large-scale development of ride-hailing may increase people's demand for car trips, which may have a negative impact on the environment. However, adopting BEVs may be a promising way to reduce the negative impact of ride-hailing effectively. In brief, it should be stressed that cities should fully consider the actual local conditions when promoting mutualized mobility and formulate reasonable and practical strategies to promote the sustainable development of urban transportation.

This study offers empirical evidence for authorities, scholars, managers, and the public to comprehensively understand the environmental implications of mutualized mobility. The results can be used as a reference by the authorities to formulate more adequate and effective mutualized mobility strategies to promote the sustainability of the urban transportation system. According to the uncertainty analysis results, the rebalancing process is the crucial factor affecting the environmental performance of SBBS. The operators should take effective measures such as sustainable station design and careful location selection and continuously optimize the rebalancing strategy to improve the overall operational efficiency of the SBBS system. Also, deadheading is the critical factor affecting the environmental performance of ride-hailing, which accounts for about 30% of the total life cycle emissions, so that the emission intensity of ride-hailing may grow exponentially with the increase of the deadheading rate. Therefore, further attempts to reduce the deadheading rate can decrease the environmental impact of ride-hailing. To improve the current environmental benefits of car sharing, vehicle utilization is a more pressing issue than optimizing rebalancing strategies.

Moreover, private cars should be encouraged to participate in carpooling and increase the proportion of carpooling mileage in the vehicle life cycle. Although this might generate additional distances traveled, it would still provide considerable environmental benefits. Finally, adopting BEVs can increase the GHG emission reduction potential of mutualized mobility, especially in cities with a high proportion of clean electricity.

5. Conclusion

This study employs the LCA framework and actual transportation big data to examine the impact of mutualized mobility on GHG emissions from urban transportation systems. The emission reduction potential of various forms of mutualized mobility is also analyzed and compared.

SBCS and carpooling appear to have a stronger potential in reducing emissions compared to ride-hailing. In Toronto, the GHG emission factors of SBCS and carpooling are on average 29.3% (95% CI: 26.1% ~ 32.1%) and 16.1% (95% CI: 11.5% ~ 20.3%) lower than that of private cars respectively, while the GHG emission factors of ride-hailing is on average 34.4% (95% CI: 25.3% ~ 43.0%) higher than that of private cars. In Beijing, The GHG emission factor of ride-hailing is also 20.6% (95% CI: 14.6 % ~ 27.3%) higher than that of private cars due to deadheading, which appears to be the main issue in ride-hailing, causing it to be less ecological transport mode. Deadheading contributes approximately 30% of the total life cycle GHG emissions for ride-hailing. It is worth noting that lower vehicle utilization rates significantly attenuate the emission reduction advantages of FFCS. The annual VKT of FFCS is less than 30% of private cars, and the accompanying GHG emission factor is about 5.0% (-1.2% ~ 12.1%) higher than that of private cars.

Station-based bike sharing is not as environmentally friendly as expected. The average GHG emission factor of SBBS is almost six times that of POB and even much higher than public transit. The bike rebalancing process and the required docks and stations are the two primary sources of GHG emissions for the SBBS system, accounting for about 78% of the total GHG emissions of SBBS. Moreover, SBBS has no significant advantages in terms of bike utilization. The annual VKT of SBBS is similar to that of POB, which also largely limits the emission reduction potential of SBBS.

Although mutualized mobility can improve urban transportation sustainability, different development models and directions will produce other effects. Beijing's large-scale development of ride-hailing has increased urban residents' car trips, which has exerted a negative impact on the environment to some extent. By contrast, Toronto has achieved better emission reduction effects with its strong and diverse networks of mutualized cars, but challenges remain especially regarding FFCS and SBBS.

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Figure and Table

Fig. 1.

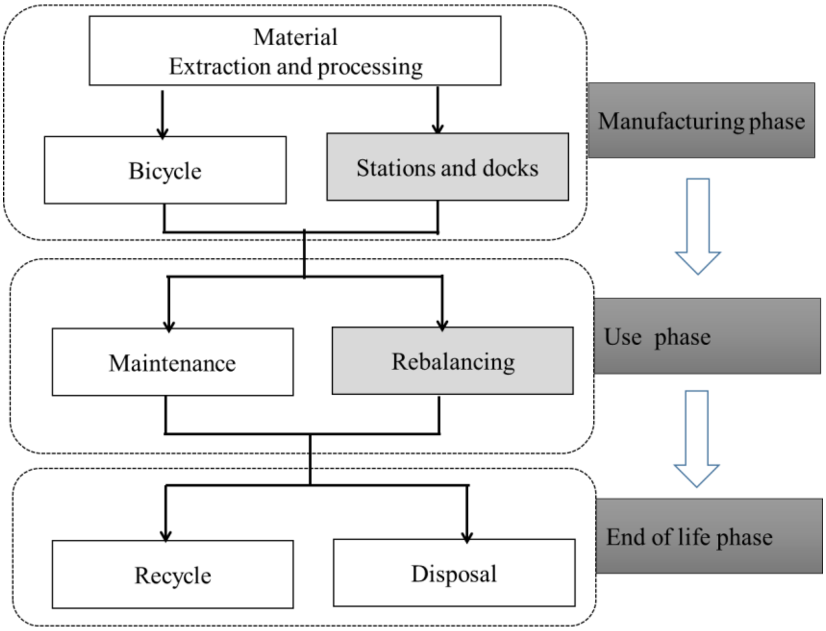


Fig. 1. System boundary of the bike systems

Note: "Rebalancing" and "Station and docks" are only for SBBS

Fig. 2

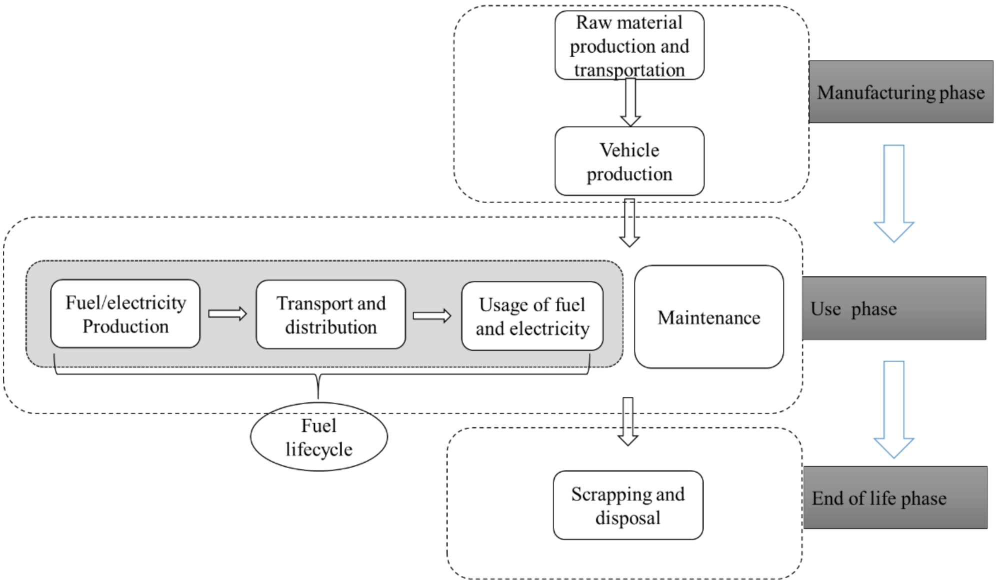


Fig. 2. System boundary of the car systems

Fig. 3

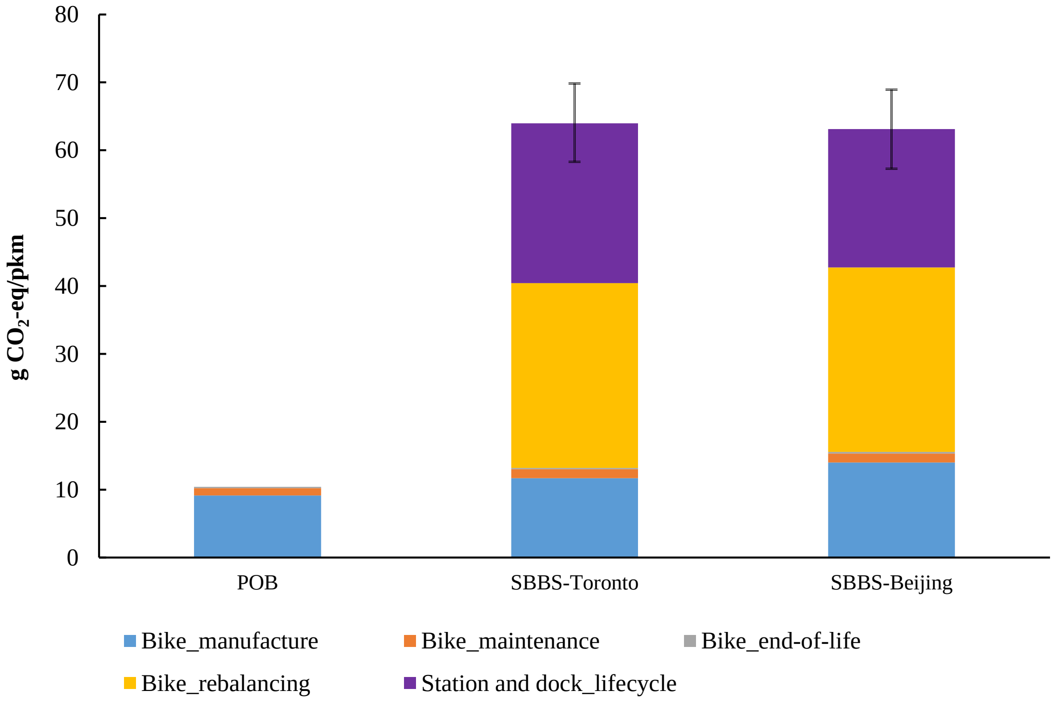


Fig. 3 Life cycle GHG emission factors for POB and SBBS. The colored bars represent the average value of the GHG emission factor with the corresponding breakdown values. The hanging bars indicate 95% confidence intervals.

Fig. 4

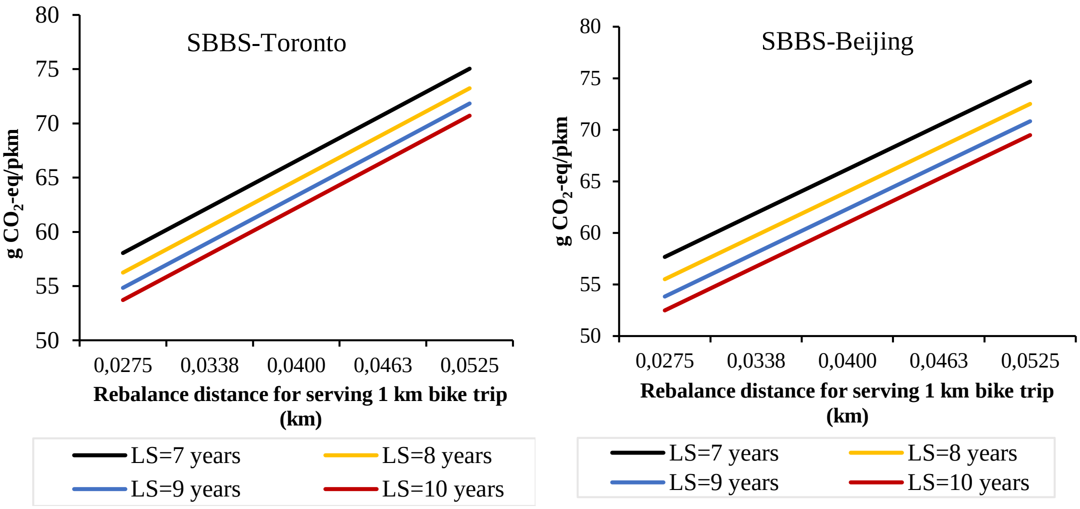


Fig. 4. **Sensitivity analysis for SBBS system**

Fig. 5

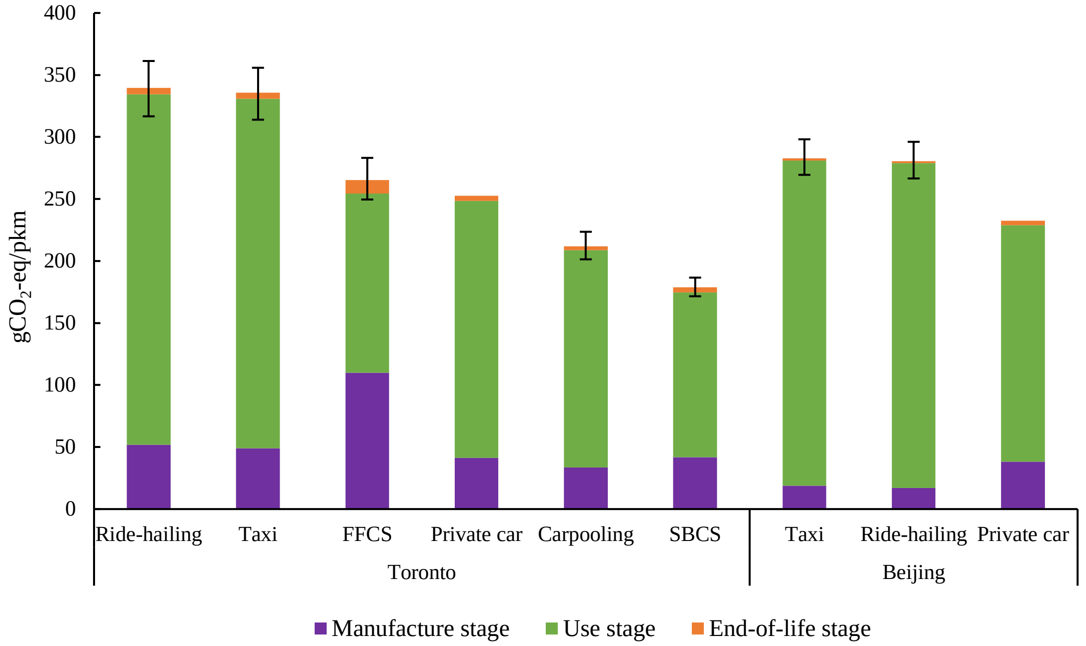


Fig. 5. Life cycle GHG emission factors for different modes of car travel. The colored bars represent the average value of the GHG emission factor with the corresponding breakdown values. The hanging bars indicate 95% confidence intervals.

Fig. 6

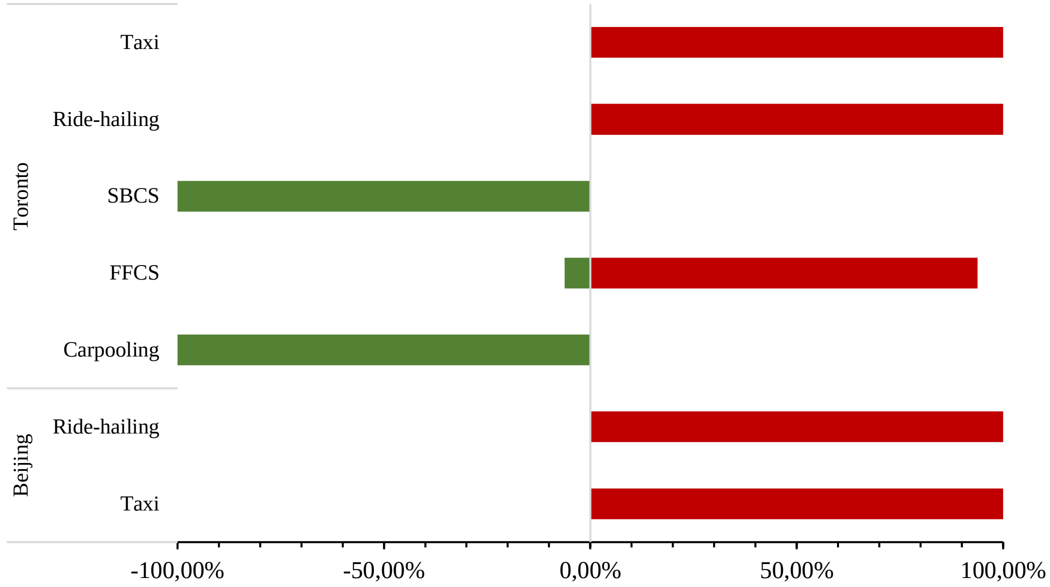


Fig. 6. Uncertainty analysis of the difference between the emission factors of mutualized car trips and private car trips. The statistic was based on 10,000 times simulations. The red bars represent the number of times (percentage) that the emission factor of other car travel modes (e.g., ride-hailing) was higher than that of a private car trip. The green bars represent the number of times (percentage) that other car travel modes (e.g., SBCS or Carpooling) had a lower emission factor than a private car trip.

Fig. 7

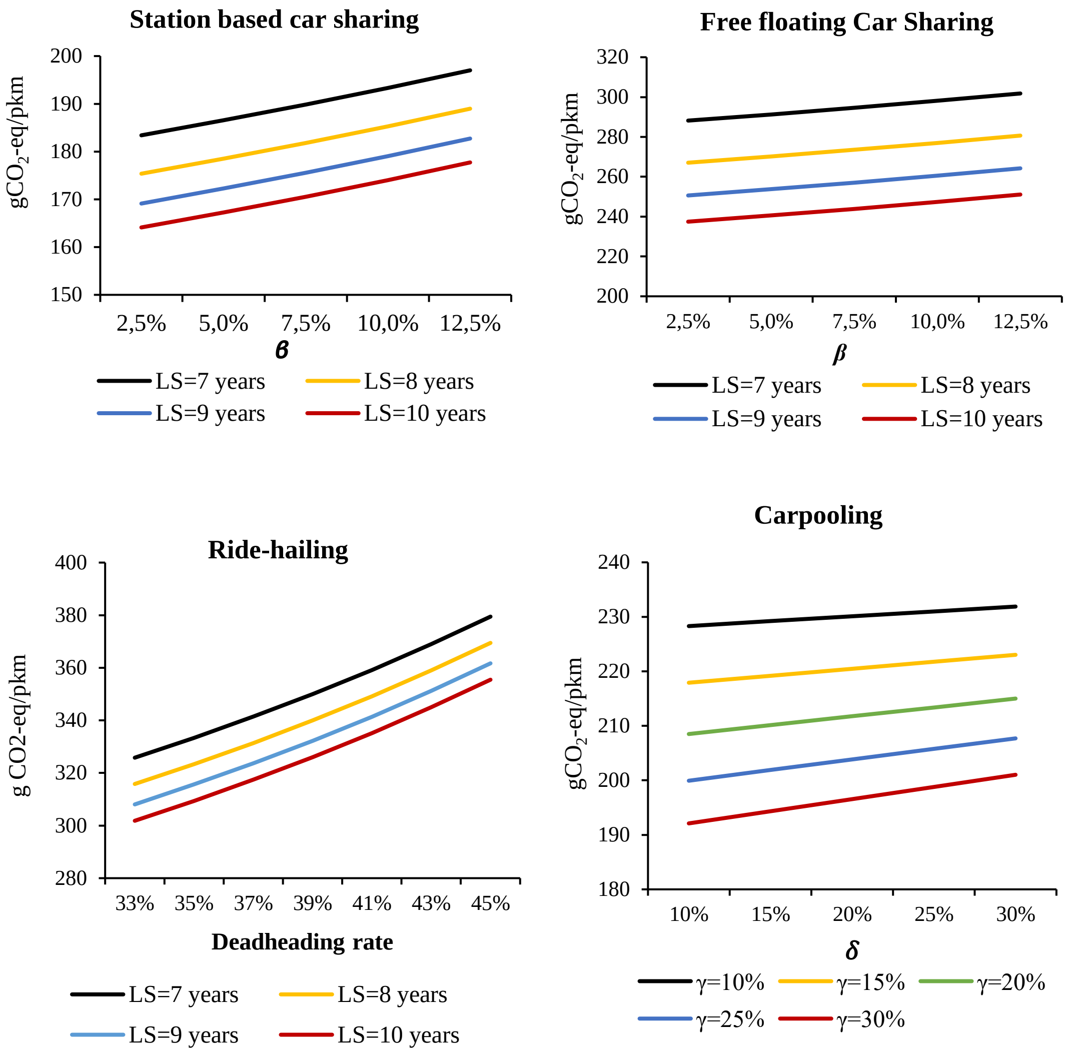


Fig. 7. Sensitivity analysis of mutualized car trips in Toronto

Fig 8.

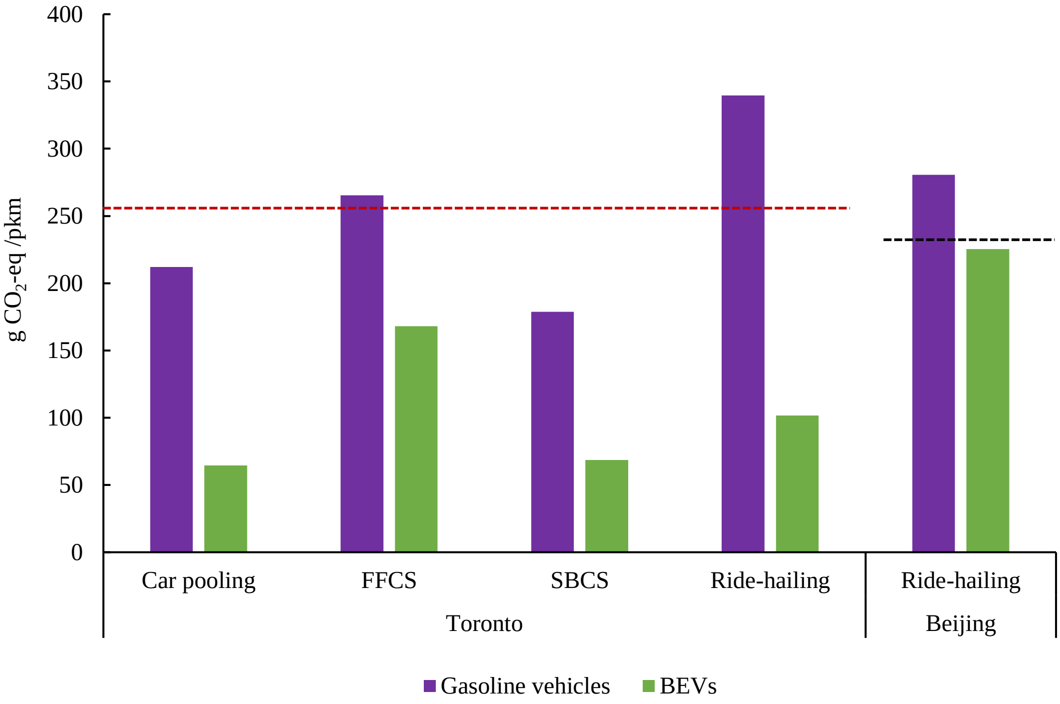


Fig. 8. Comparison of gasoline vehicle scenarios and BEVs scenarios. The red line represents the emission factor of private cars (gasoline) in Toronto, and the black line represents the emission factor of a private vehicle (gasoline) in Beijing.

Table 1. Summary statistics for the uncertainty analysis of SBBS

	Mean	Standard deviation	Coefficient of variation	95% Confidence Interval

	g CO_2-eq/pkm	g CO_2-eq/pkm	%	lower bound/ g CO_2-eq/pkm	upper bound/ g CO_2-eq/pkm
SBBS in Beijing	63.19	2.98	4.72	57.35	68.99
SBBS in Toronto	64.00	2.94	4.60	58.30	69.85

Table 2. Summary statistics for the uncertainty analysis of car trips

	Mean	Standard deviation	Coefficient of variation	95% Confidence Interval	
	g CO_2-eq/pkm	g CO_2-eq/pkm	%	lower bound/ g CO_2-eq/pkm	upper bound/ g CO_2-eq/pkm
Ride-hailing in Beijing	280.56	7.73	2.75	266.56	296.11
Taxi in Beijing	282.81	7.54	2.67	269.48	298.15
Carpooling in Toronto	211.97	5.65	2.67	201.36	223.59
FFCS in Toronto	265.26	8.54	3.22	249.60	283.16
Ride-hailing in Toronto	339.52	11.84	3.49	316.67	361.28
SBCS in Toronto	178.73	3.85	2.15	171.59	186.62
Taxi in Toronto	335.61	11.14	3.32	313.95	355.80

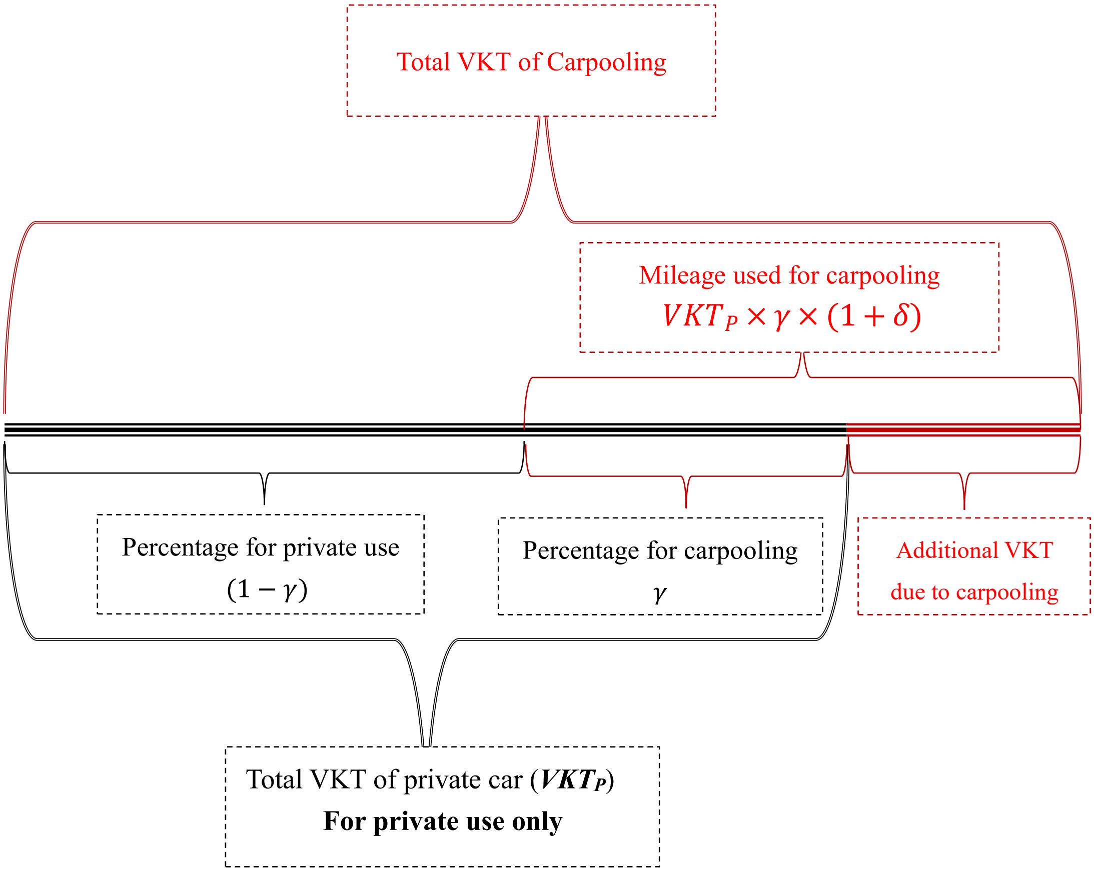
Table 3. Change in mode share and annual GHG emissions per capita in Beijing

		Change in mode share	Change in annual GHG emissions per capita (kg CO_2-eq)			
			Baseline	Worst	Best	BEVs
Beijing	Car	0.37%	5.98	6.59	-0.18	-7.90
	Bike	-0.37%	0.25	0.28	0.21	0.25
	Public transit	0.77%	17.85	17.85	17.85	17.85
	Other	-0.39%	-0.49	-0.49	-0.49	-0.49
	Walk	-0.37%	—	—	—	—
	Total	0.00%	23.60	24.24	17.40	9.72
Toronto	Car	-1.04%	-7.11	-5.68	-8.47	-25.14
	Bike	0.35%	0.18	0.19	0.17	0.18
	Public transit	0.24%	4.13	4.13	4.13	4.13
	Walk	0.45%	—	—	—	—
	Total	0.00%	-2.80	-1.36	-4.17	-20.83

Note: The data in the table is the difference between the value of 2016 and 2011.

Supplementary material

Supplementary material A. Total VKT of Carpooling



Supplementary material B. Main inventory data and processes for a shared bike

Process	Inputs from the Technosphere/Outputs to the Technosphere		unit	value
Manufacturing stage	Inputs from the technosphere	aluminum, wrought alloy	kg	8.885
		chromium steel removed by turning, average, conventional	kg	0.188
		electricity, medium voltage	kWh	8.130
		heat, district or industrial, natural gas	MJ	16.048
		heat, district or industrial, other than natural gas	MJ	0.228
		injection molding	kg	2.313
		polyethylene, high density, granulate	kg	2.313
		polyurethane, flexible foam	kg	0.035
		powder coat, aluminum sheet	m^2	0.413
		road vehicle factory	unit	0.000
		section bar extrusion, aluminum	kg	4.449
		steel, chromium steel 18/8, hot rolled	kg	1.876
		steel, low-alloyed, hot rolled	kg	5.782
		synthetic rubber	kg	0.664
		tap water	kg	0.878
		welding, arc, aluminum	m	0.885
		wire drawing, steel	kg	0.399
	Outputs to technosphere, wastes	municipal solid waste	kg	5.310
		used bicycle	unit	1
		wastewater	m^3	0.001
Use stage	Inputs from the technosphere	road	my	5.81E-05
		aluminum alloy, AlMg3	kg	0.445
		chromium steel removed by turning, average, conventional	kg	0.269
		injection molding	kg	1.155
		polyethylene, high density, granulate	kg	1.155
		polyurethane, flexible foam	kg	0.035
		section bar extrusion, aluminum	kg	0.445
		steel, low-alloyed, hot rolled	kg	0.269
		synthetic rubber	kg	1.994
		tap water	kg	0.088
	Outputs to the	waste plastic, mixture	kg	1.192

	technosphere, wastes	waste rubber, unspecified	kg	0.996
End of life stage	Outputs to technosphere	waste plastic, mixture	kg	2.348
		waste rubber, unspecified	kg	0.332

Note: The data about the use stage in the table is based on the VKT of 15000km. During the specific calculation process, the energy and materials consumed during the maintenance phase are proportional to the actual VKT of each type of vehicle. In addition, the rebalancing process is not included in the table.

Supplementary material C. Operation status of SBBS system in Beijing and Toronto

	Beijing	Toronto
Number of stations	3575	360
Number of bikes	104000	3750
Number of docks	156, 000	6170
Bikes/per station	29.1	10.5
Docks/per station	43.6	17.1
Average trip distance (km)	2.20	3.23
Average DTR	1.69	1.32
Annual VKT (km)	1357.07	1623.67

Note: source from (Beijing Transport Institute, 2019; Bike Share Toronto,2020)

Supplementary material D. Main material consumption for making one station, and one dock

Component	Material / Ecoinvent unit process	Unit	Value
Station	Photovoltaic panel, multi-Si wafer {GLO}| market for | APOS, U	m^2	1.5
	Steel, chromium steel 18/8 {GLO}| market for | APOS, U	kg	45.36
	Aluminium alloy, AlMg3 {GLO}| market for | APOS, U	kg	38.5
	Flat glass, uncoated {GLO}| market for | APOS, U	kg	6.8
	Battery, Li-ion, rechargeable, prismatic {GLO}| market for | APOS, U	kg	81.5
	Electronics, for control units {GLO}| market for | APOS, U	kg	10
Dock	Steel, chromium steel 18/8 {GLO}|	kg	30

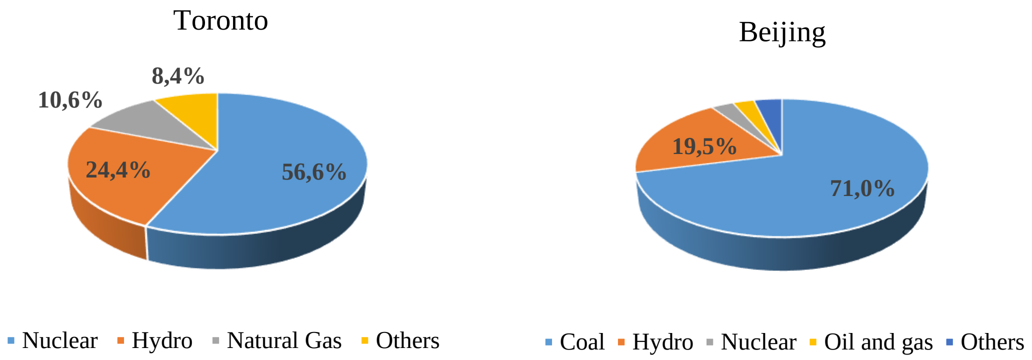
Note: source from (Luo et al., 2019; Bonilla-Alicea et al., 2020).

Supplementary material E. Main inventory data and processes for BEVs

	Ecoinvent unit process	Unit	value
Manufacture stage	Passenger car, electric, without battery {GLO}| market for | APOS, U	kg	918.22
	Battery, Li-ion, rechargeable, prismatic {GLO}| market for | APOS, U	kg	262
Usage stage	Maintenance, passenger car, electric, without battery {GLO}| market for | APOS, U	p	1
	Battery, Li-ion, rechargeable, prismatic {GLO}| market for | APOS, U	kg	131
	Electricity, low voltage	kWh	27000
	Road {GLO}| market for | APOS, U	my	73.122
End of life stage	Manual dismantling of used electric passenger car {GLO}| processing | APOS, U	p	1
	Treatment of used glider, passenger car {GLO}| market for | APOS, U	kg	838
	Treatment of used powertrain for electric passenger car, manual dismantling | APOS, U	kg	80.22
	Treatment of used Li-ion battery {GLO}| market for | APOS, U	kg	393

Note: Inventory data and processes are based on the Ecoinvent dataset "Transport, passenger car, electric {GLO}| processing | APOS, U." Default values for the weight of a private car without battery and the importance of a battery are 918.22kg and 262kg, respectively. The average lifetime for the battery of 100,000 km. The data about the use stage in the table is based on the VKT of 150,000km. During the specific calculation process, the data about the use phase will be changed according to the actual VKT of each type of transport mode.

Supplementary material F. Electricity generation mix (percentage) of Toronto and Beijing



Note: 1) source: Canada Energy Regulator (2016), China electric power development promotion association (2015)

2) "Others" in Toronto refers to Wind, Solar, Biomass, etc. "Others" in Beijing refers to Wind, Solar, etc.

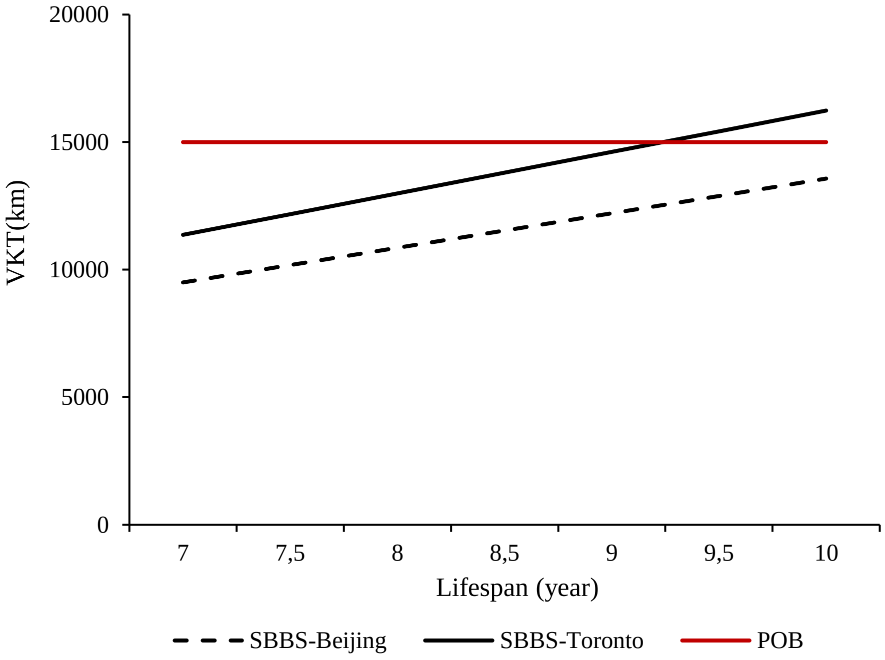
Supplementary material G. Operating characteristics and parameters of mutualized mobility

Mode	Operating characteristics and parameter	Reference
FFCS in Toronto	• DTR_{CS} is 3.2. • d_{CS} is 3.3 km. • O_{CS} is about 2.0 • β ranges from 2.5% to 12.5%. • L_{CS} ranges from 7 to 10 years.	(Habibi et al., 2016; Sprei et al, 2019; Statista, 2019)
SBCS In Toronto,	• DTR_{CS} is 4.6. • d_{CS} is 6.04 km. • O_{CS} is about 2.0 • β ranges from 2.5% to 12.5%. • L_{CS} ranges from 7 to 10 years.	(Habibi et al., 2016; Martin and Shaheen, 2016; Statista, 2019)
Carpooling in Toronto	• γ ranges from 10% to 30%. • δ ranges from 10% to 30%. • O_{Cp} is about 2.5. • O_p is about 1.16. • L_{CS} is ten years • VKT_p is 150000 km.	(Statistics Canada 2011, 2016; Natural Resources Canada, 2011; Transportation Tomorrow Survey, 2014; 2018)
Ride-hailing in Toronto	• DTR_{R_T} is 7.2. • d_{R_T} is 4.4 km. • O_{R_T} is about 1.41. • α ranges from 33% to 45%. • L_{R_T} ranges from 7 to 10 years.	(Union of Concerned Scientists, 2020; Henao, and Marshall, 2019; City of Toronto Transportation Services, 2019)
Taxi in Toronto	• DTR_{R_T} is 9.5. • d_{R_T} is 5.0 km.	(City of Toronto, 2019; Ding et al. 2019; Union of

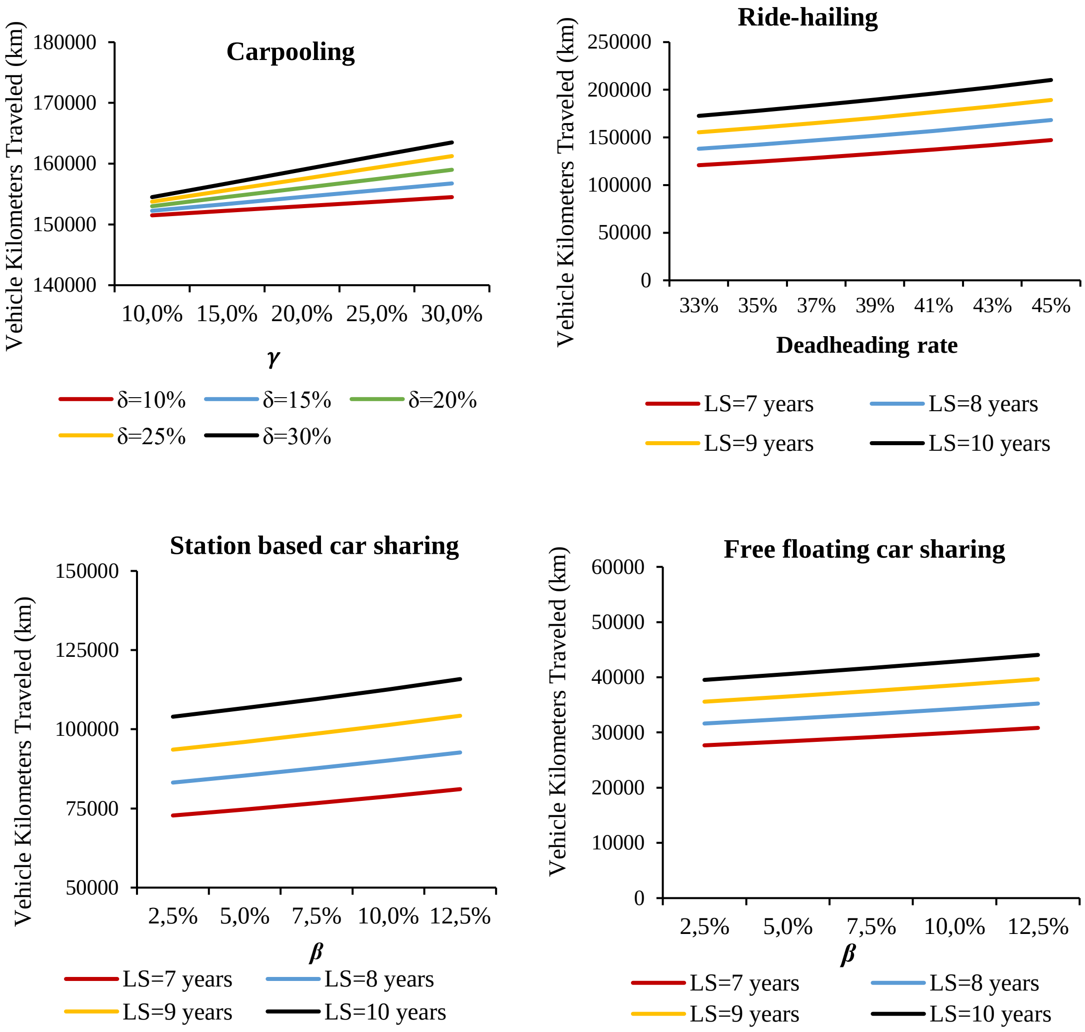
Mode	Operating characteristics and parameter	Reference
	- O_{R_T} is about 1.41 - α ranges from 33% to 45%. - The lifespan is six years.	Concerned Scientists, 2020)
Taxi in Beijing	- DTR_{R_T} is 13.6. - d_{R_T} is 9.1 km. - O_{R_T} is about 1.41. - α ranges from 32% to 40%. - The lifespan is six years.	(Beijing Transport Institute, 2017; Ding et al. 2019)
Ride-hailing in Beijing	- DTR_{R_T} is 12.8. - d_{R_T} is 7.6 km. - O_{R_T} is about 1.41 - α ranges from 32% to 40%. - L_{R_T} ranges from 7 to 10 years.	(China Beijing Transport Institute, 2017; Ding et al., 2019; Wang and Teng, 2020)
SBBS in Toronto	- DTR_{SBBS} is 1.32. - d_{SBBS} is 3.37km - L_{SBBS} ranges from 7 to 10 years. - Rebalance distance for serving 1 km bike trip range from 0.0275 km to 0.0525 km.	(Ding et al. 2018; Luo et al. 2019; Wikipedia. 2020; Bike Share Toronto, 2020; Bonilla-Alicea et al., 2020).
SBBS in Beijing	- DTR_{SBBS} is 1.69. - d_{SBBS} is 2.20 km. - L_{SBBS} ranges from 7 to 10 years. - Rebalance distance for serving 1 km bike trip range from 0.0275 km to 0.0525 km.	(Beijing Transport Institute, 2017; Luo et al., 2019; Ding et al., 2018; Bonilla-Alicea et al., 2020)

Note: The average occupancy of the private car in Beijing is 1.26 (China Beijing Transport Institute, 2017; Ding et al., 2019).

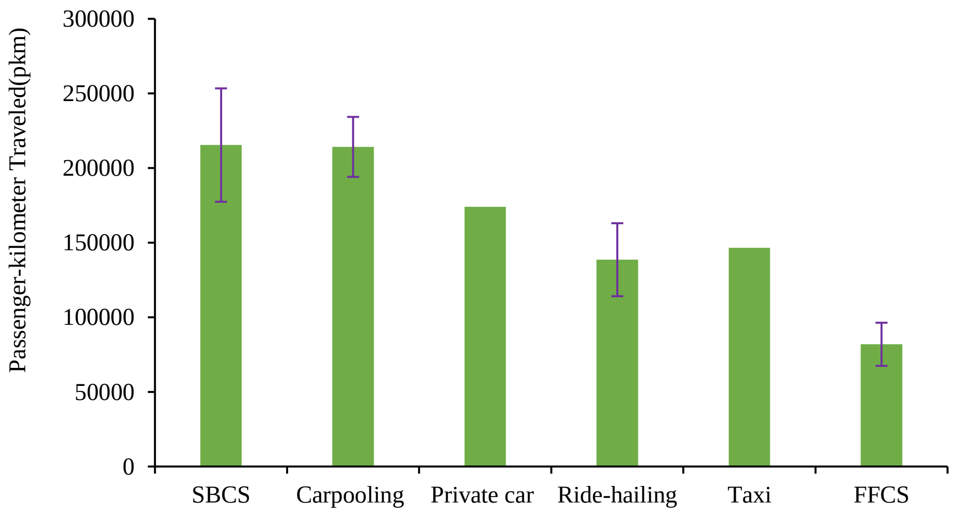
Supplementary material H. VKT of the bike during the lifespan



Supplementary material I. Vehicle-kilometers traveled during the lifespan of shared car (in Toronto)



Supplementary material J. PTK during the lifespan for different car travel modes (in Toronto). The green bar represents the average value, while the hanging bar represents the variation range of PKT under the influence of uncertain factors.



Supplementary material K. Distribution type and parameters of uncertain factors

	Uncertain factor	**Distribution type**	**Distribution parameters**
FFCS in Toronto	β	Normal distribution.	Mean=7.5%; Standard deviation(SD)= 0.01667
	L_{CS}	Normal distribution.	Mean=8.5; SD= 0.5
SBCS In Toronto	β	Normal distribution.	Mean=7.5%; SD= 0.01667
	L_{CS}	Normal distribution.	Mean=8.5; SD= 0.5
Carpooling in Toronto	γ	Normal distribution.	Mean=20%; SD= 0.03
	δ	Normal distribution.	Mean=20%; SD= 0.03
Ride-hailing in Toronto	α	Triangular	Mean =41% Minimum=33% Maximum=45%
	L_{R_T}	Normal distribution.	Mean=8.5 SD= 0.5
Taxi in Toronto	α	Triangular	Mean=41% Minimum=33% Maximum=45%
Taxi in Beijing	α	Triangular	Mean=36% Minimum=32% Maximum=41%
Ride-hailing in Beijing	α	Triangular	Mean=41% Minimum=33% Maximum=45%
	L_{R_T}	Normal distribution.	Mean=8.5 SD= 0.5

SBBS in Toronto	L_{SBBS}	Normal distribution.	Mean=8.5 SD= 0.5
	Rebalance distance for serving 1 km bike trip	Normal distribution.	Mean=0.04 SD= 0.00417
SBBS in Beijing	L_{SBBS}	Normal distribution.	Mean=8.5 SD= 0.5
	Rebalance distance for serving 1 km bike trip	Normal distribution.	Mean=0.04 SD= 0.00417

Note: Source from (Habibi et al., 2016; Sprei et al., 2019; Martin and Shaheen, 2016; Statistics Canada 2010; Union of Concerned Scientists, 2020; Henao and Marshall, 2019; City of Toronto Transportation Services, 2019; City of Toronto, 2019; Beijing Transport Institute, 2017; Ding et al. 2019; Luo et al. 2019; Bonilla-Alicea et al., 2020).

Supplementary material L. Transportation data in Toronto for 2011 and 2016

	Annual trips per capita 2011	Annual trips per capita 2016	Mode share 2011	Mode share 2016	Average travel distance per trip
Subway	83.38	82.21	9.87%	9.55%	7.56
Bus	85.38	92.58	10.11%	10.75%	6.28
Street car	22.52	22.19	2.67%	2.58%	4.02
Taxi	6.00	5.35	0.71%	0.62%	5.00
Ride-hailing	0.00	4.89	0.00%	0.57%	4.50
Car pooling	49.93	58.15	5.91%	6.75%	10.00
FFCS	0.00	0.44	0.00%	0.05%	3.30
SBCS	0.63	1.44	0.07%	0.17%	6.00
Private car	523.85	512.28	62.00%	59.50%	11.00
FOB	11.08	14.06	1.31%	1.63%	4.20
SBBS	0.07	0.31	0.01%	0.04%	3.37
Walk	62.04	67.08	7.34%	7.79%	_

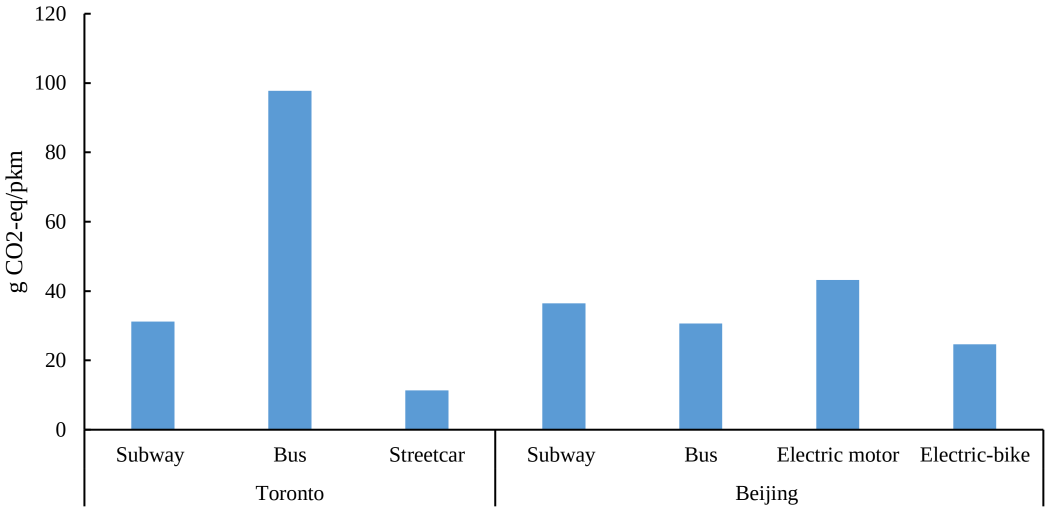
Note: source from Statistics Canada (2011, 2016), Toronto Transit Commission (2011, 2016), City of Toronto Transportation Services (2019), Transportation Tomorrow Survey (2014, 2018)

Supplementary material M. Transportation data in Beijing for 2011 and 2016

	Annual trips per capita 2011	Annual trips per capita 2016	Mode share 2011	Mode share 2016	Average travel distance per trip
Subway	72.91	112.83	10.03%	15.26%	17.83
Bus	145.40	115.05	20.01%	15.56%	11.03
Taxi	35.68	21.39	4.91%	2.89%	9.05
Ride-hailing	0.00	21.90	0.00%	2.96%	7.60
Private car	165.76	164.44	22.81%	22.24%	14.17
FOB	77.45	73.46	10.66%	9.93%	3.00
SBBS	0.00	2.66	0.00%	0.36%	2.20
Electric-bicycle	4.30	3.21	0.59%	0.43%	5.00
Electric-motor	6.45	4.81	0.89%	0.65%	5.00
walk	218.65	219.77	30.09%	29.72%	—

Note: source from Beijing Transport Institute (2012, 2017)

Supplementary material N. GHG emission factors of transportation modes in Beijing and Toronto



Note: Source from (Condon and Dow, 2011; Yan, 2013). All related infrastructure such as bus stations, subway and streetcar stations, rails, roads are included.