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How Does the Collaborative Economy Advance Better Product Lifetimes? A Case Study of Free-Floating Bike Sharing

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Abstract: The collaborative economy is considered to have great potential in promoting the circular economy. However, there is little empirical research in this field. Taking the Beijing free-floating bike sharing (FFBS) program as an example, this study develops a system dynamics (SD) model based on the product lifetime extension business model (PLEBM) framework, and the business practices of FFBS. Combined with the dynamic evolution process of the FFBS market, the impact of FFBS on bicycle lifetime and the utilization efficiency of the urban bicycle system is explored. The results show that FFBS can reduce the required supply scale of the entire bicycle system by about 21%, and increase the average daily usage of bicycles by about 27%. In addition, FFBS also can increase the average lifecycle trip volume per bike in the entire urban bicycle system from approximately 900 to 1060, an increase of 16%. In particular, this study estimates that the optimal supply scale of the FFBS market in Beijing is about 800,000. It is worth noting that although enhancing the PLE strategy can increase the contribution of FFBS to PLE, it may also deteriorate the profitability of the FFBS platform. The authorities and FFBS operators should work together to continuously improve the profitability of the platform and strengthen its innovation capabilities to promote the healthy and sustainable development of FFBS.

Keywords: circular economy; collaborative economy; production lifetime extension business model; free-floating bike sharing; system dynamics

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1. Introduction

With the increasing attention being paid to resource and environmental sustainability, the circular economy has become a popular topic in the academic, business, and policy fields in recent years. In contrast to the traditional "resource extraction-production-consumption-disposal" linear economic model, the circular economy is an economic model of closed-loop material and production flow, which emphasizes that products should be used efficiently and recycled at the end of their life [1–3]. The concept of the circular economy can be characterized as "an economy that is restorative and regenerative by design, and aims to maintain products, components and materials at their highest utility and value at all times" [2] (p. 46). The three key value drivers of the circular economy are increasing resource efficiency, extending the lifespan of the products, and closing the loop (i.e., enhancing multiple product lifecycles of reuse, remanufacturing, and recycling) [2,4–6].

In recent years, the rapid development and application of advanced technologies have greatly accelerated the promotion of the circular economy. Advanced material science and manufacturing technology (e.g., Industry 4.0 and additive manufacturing) can help to lengthen product lifespans and enhance the reusability and durability of products [7–10]. The Internet of Things and Big Data can help to monitor and track product activity, provide preventive and predictive maintenance, optimize product usage, upgrade the product, enhance remanufacture and renovation, and improve other end-of-life activities [6,11–13]. Moreover, with the rapid development of information technology and computer science, emerging economic models and digital platforms are becoming an important driving force for the circular economy. Among them, the most notable is the collaborative economy, which has brought revolutionary changes to people's lifestyle and consumption patterns [14–16]. The collaborative economy is also referred to as the "sharing economy" or "collaborative consumption", and is commonly connected to the temporary and collaborative use of products and services [17]. It emphasizes the access-based consumption of products and services, rather than the traditional ownership-oriented consumption mode [17,18]. There are two general types of business practices in the collaborative economy. One is the Consumer to Consumer (C2C) mode (also known as peer-to-peer sharing), based on the idle resources of individuals in society [17]. Digital platforms integrate these scattered idle resources, and allow individual participants to provide products or services at lower prices. This type of digital platform serves as a connector between users at both ends of supply and demand; examples include Uber, Airbnb, and TaskRabbit. The other is the Business to Consumer (B2C) sharing mode, based on product service systems, where digital platforms are the major providers of products or services. Examples include most car-sharing and bike-sharing platforms (e.g., Car2Go, Zipcar, and Mobike) [18,19].

The business practices of the collaborative economy not only conform to the goals and principles of the circular economy but also provide a new development space for the circular economy. First, it can improve product utilization and extend the service life of products through shared use among multiple users. For example, home and parking lot sharing can improve the utilization rate of rooms and space, and unwanted clothes and books can be shared to extend their service life rather than being thrown away [20–24]. In addition, with cheap and easy access to products owned by other individuals or organizations, consumers could gradually become less dependent on private ownership [17], thereby reducing the total number of goods needed by society overall [20,21]. A prominent case is car sharing programs. Some studies have found that a shared car can replace about 2–7 privately owned cars, and can also reduce car ownership within a city to varying degrees [25–27]. Moreover, the collaborative economy makes consumption activities increasingly integrated into the production process and even the entire product lifetime, contributing to the formation of a continuum from sustainable consumption to sustainable production [20,28]. Business practices are involved in various stages of the product lifecycle, such as product design, manufacture, maintenance, and remanufacture, which can advance better product lifetimes [19,29–32]. Therefore, the collaborative economy has significant potential in promoting the sustainable use of resources.

However, there is a lack of empirical research on the contribution and potential of collaborative economy business practices in promoting the transition to a circular economy. The existing research has mainly focused on the conceptual level and qualitative analysis, which makes it difficult to intuitively recognize and understand this transition. Moreover, studies on the impact of the collaborative economy on the sustainable use of resources is often at the level of individual consumption and the shared product itself, and lacks a comprehensive assessment from the perspective of the entire consumption and supply system. In particular, to the author's knowledge, there is no research exploring how the collaborative economy business model leads to better product lifetimes from a closed-loop perspective (i.e., from the product design and manufacturing stage to the disposal stage). Therefore, in order to respond to these limitations of the existing literature, this paper takes the Beijing free-floating bike sharing (FFBS) program as an example to conduct an empirical study. Combined with the product lifetime extension business model (PLEBM) and the business practices of FFBS platforms, it attempts to comprehensively and systematically explore the contribution and potential of FFBS in advancing better product lifetimes and promoting the transition of the entire urban bicycle system towards sustainability.

2. Materials and Methods

The product lifetime extension business model (PLEBM) is based on the concept of the circular economy, and covers a variety of business processes that can affect the three key value drivers of the circular economy (i.e., increasing resource efficiency, extending the lifespan, and closing the loop) [33–35]. These processes can generally be divided into five key activities: improved product design, access, maintenance, redistribution, and recovery [33–35]. The definition and description of these activities are as follows.

- Improved product design: “improvement of the product and production processes, as well as an improved design for repair” [35] (p. 3);
- Access: “use-oriented service scape, including leasing, renting, mutualizing, and pooling, to temporarily transfer a product from an individual who does not want or need it to another individual who wants or needs it” [35] (p. 3);
- Maintenance: “product-oriented service scape, including maintenance, advice, training, and consultancy contracts” [35] (p. 3);
- Redistribution: “product transfer activities from one individual to another through various activities, such as donation, swapping and second-hand purchase” [35] (p. 3);
- Recovery: “restoring a given product to an initial state of functioning through product repair or remanufacturing, refurbishing, repackaging, or reconditioning” [35] (p. 3).

This framework excludes end-of-life treatment, such as destruction for reutilization, disassembly, and recycling of materials [33,36]. PLEBM is an effective theoretical framework and development tool to study the impact of business practices on advancing better product lifetimes from a managerial viewpoint [33–35].

System dynamics (SD) is a methodology and mathematical modeling technique to frame, understand, and discuss complex issues and problems [37]. The model is built upon qualitative and quantitative analyses based on the microstructure inside the system, and it analyzes the internal relationships between the structural function and dynamic behavior of the system through simulation technology [38]. Its most prominent feature is the ability to deal with nonlinear, high order, multiple feedback loops, and complex time-varying system problems [39,40]. Even if the index is difficult to quantify or the data are insufficient, it can still be used to calculate and analyze problems through a certain structural analysis based on limited data sets and causal relationships [37–41]. In view of these advantages, it has been widely applied in various socio-economic areas [39–43].

Considering that the key activities in the PLEBM framework are not isolated from each other in business practice, and the development of the FFBS market and its impact on sustainability are both complex dynamic processes, this paper employs the PLEBM framework and the system dynamics method to analyze how FFBS advances product lifetime and explores the contribution and potential of FFBS in promoting the transition of the entire urban bicycle system towards sustainability.

This study selects the Beijing FFBS program as the empirical research object. The material and data used in this paper were collected from the statistical reports of the realistic operations of the FFBS platforms, relevant industry reports, and the published literature [44–60]. The SD model was constructed based on the operating data of the Beijing FFBS market, and the entire bicycle system within the city from 2016 to 2019. The specific analysis process and framework in this study are as follows. First, combining FFBS business practices and the PLEBM framework, a target SD model was constructed, and the main assumptions, parameters, and equations of the SD model explained. Secondly, based on the simulation results of the SD model, the contribution and potential of FFBS in advancing product lifetimes and promoting the transition of the entire urban bicycle system towards sustainability were evaluated using quantitative indicators. Finally, the impact of different PLE strategies and government control levels is further discussed.

3. System Modeling

3.1. Model Description

The SD model developed in this research not only includes the scale evolution of the supply and demand ends of the FFBS market but also includes the operation and management of the FFBS platform. The five key PLE activities in the PLEBM framework are the core components of the operation and management of the FFBS platform. These activities can help advance better product lifetimes, such as by improving resource utilization and extending the lifespan, and also can affect the development of the platform itself, such as the market scale and profitability. These business practices are summarized as follows.

(1) Improved product design

By improving the material performance and the structural design of the bicycle, the quality and durability of the bicycle can be improved, so as to directly extend the service life of an FFBS bike [53,55]. A longer service life can slow the update speed of bicycles in the FFBS market, and reduce the corresponding purchase costs of the platform [55]. In addition, the standardized design and manufacture of the bicycle and spare parts facilitate the maintenance and recovery of the bicycles [55,61]. The improvement of the quality and durability of the bicycles can also reduce the damage rate of FFBS bikes, and thus reduce the maintenance costs (e.g., costs of labor, materials, and spare parts). Moreover, the optimization design can improve the comfort and safety performance of the shared bikes, which can attract more users to participate in FFBS, thereby increasing the revenue of the platform [49]. It is worth noting that optimizing the design of the bicycles and improving the performance of materials used in bike manufacturing requires the platform to increase its research and development costs, which may reduce the profitability of the platform.

(2) Access

The FFBS platform can constantly optimize the distribution and rebalancing strategy by using Big Data, the Internet of Things, and other technical means, so as to improve the availability of FFBS [19,49,51]. This could attract more people to adopt shared bikes and improve the utilization of these shared bikes. In addition, due to the low price and convenience of FFBS, large-scale supply could prompt some people to give up owning a private bicycle [46,47,51,54]. Since the average utilization rate of shared bicycles is significantly higher than that of private owned bicycles, under the premise of meeting the same bicycle travel demand of urban residents, the promotion of FFBS could not only reduce the overall supply scale of bicycles required by the entire city but also improve the utilization of the whole bicycle system throughout the city. For the platform, an increase in the FFBS user scale and transaction volume could improve the revenue performance [43].

(3) Maintenance

As a product service system, FFBS transforms the previously decentralized individual maintenance activities into centralized maintenance by a professional team, which makes the bicycle maintenance activities more efficient [55,61,62]. Efficient maintenance can improve the availability of the shared bike and user experience, thereby contributing to the promotion of FFBS [49,63]. For the FFBS platform, the standardized design and manufacturing of the bicycles and spare parts could make the shared bicycles easier to maintain, while improving the quality and durability of the bicycles could reduce the damage rate [55,62]. All these factors could enable the maintenance activities of FFBS to become not only more efficient but also more cost-effective.

(4) Recovery

Collection and disposal of used bicycles has always been a problem in the bicycle industry, especial in China. Since there is no effective management mechanism or specialized organizations, a large number of used bicycles are scattered in every corner of the city. The FFBS platform, which adopts a product lifecycle management system, can collect and dispose of the used shared bicycles (i.e., once a bike reaches the end of normal service life) in a timely and efficient manner [48,53,64]. This not only improves the service quality of the platform but can also help improve the utilization of bicycles through the recovery of valuable used bicycles. The scale, standardization, and specialization of FFBS gives it an advantage in recovery processes, such as remanufacturing, refurbishing, and reconditioning [55,64]. This can not only reduce the platform cost for recovery but also provide better quality assurance for the remanufactured and refurbished bikes, thereby facilitating redistribution.

(5) Redistribution

Remanufactured or refurbished shared bikes have advantages in quality and price for second-hand market sales, which can increase the revenue of the platform. Some high quality remanufactured or refurbished bikes could also be delivered back into the FFBS market, so as to decrease the bicycle procurement expenses of the platform [62,64]. Moreover, the FFBS platform could also donate remanufactured or refurbished bicycles to poor regions or non-profit organizations [64]. These measures can extend the lifetime of bicycles and improve their utilization.

Combined with the business practice of FFBS in Beijing and the real-world data of relevant sectors, the corresponding SD model of this study was constructed based on the PLEBM framework, as shown in Figure 1. Here, considering the availability of data and the research purpose, this study merges multiple platforms of the Beijing FFBS market into one platform; that is, we consider the FFBS market as a whole object for this study. The parameter values in the model are the average of the FFBS market.

3.2. Mathematical Equations

All the parameters and equations of the SD models are shown in Appendices A and B. The main assumptions, parameters, and equations of the SD model were defined and described as below.

3.2.1. Scale Evolution of the Supply and Demand Ends of the FFBS Market

The scale of FFBS users in this article refers to the number of daily active users. The growth rate of the user scale (*UGR*) is mainly determined by the Price Factor (*PF*), Availability (*AVA*), Comfort Index (*CI*), and Safety Index (*SI*), and is also limited by the potential growth space (i.e., growth limit of the user scale (*GLUS*)) [63,65–68]. The details are shown in Equation (1).

$$UGR = PF^{\gamma 1} \times AVA^{\gamma 2} \times CI^{\gamma 3} \times SI^{\gamma 4} \times GLUS \tag{1}$$

where $\gamma 1$, $\gamma 2$, $\gamma 3$, $\gamma 4$, and $\gamma 5$ are the weighting factor of each influencing factor. All these influencing factors are converted into real numbers between 0 and 1. Availability is proportional to the scale of FFBS bikes in the market. The growth limit of the user scale (*GLUS*) is defined according to the Logistic Growth Equation, as shown in Equation (2).

$$GLUS(t) = \frac{PMUS - SAU(t)}{PMUS} \tag{2}$$

where *PMUS* refers to the potential maximum user scale of the FFBS market. $SAU(t)$ refers to the scales of FFBS users at time *t*.

The number of new added users (*NAU*) and $SAU(t)$ can be calculated by Equation (3) and Equation (4).

$$NAU = SAU \times UGR \tag{3}$$

$$SAU(t) = \sum_{t=1}^{T} (NAU) + SAU(t_0) \tag{4}$$

Among them, $SAU(t_0)$ is the initial value of the *SAU*.

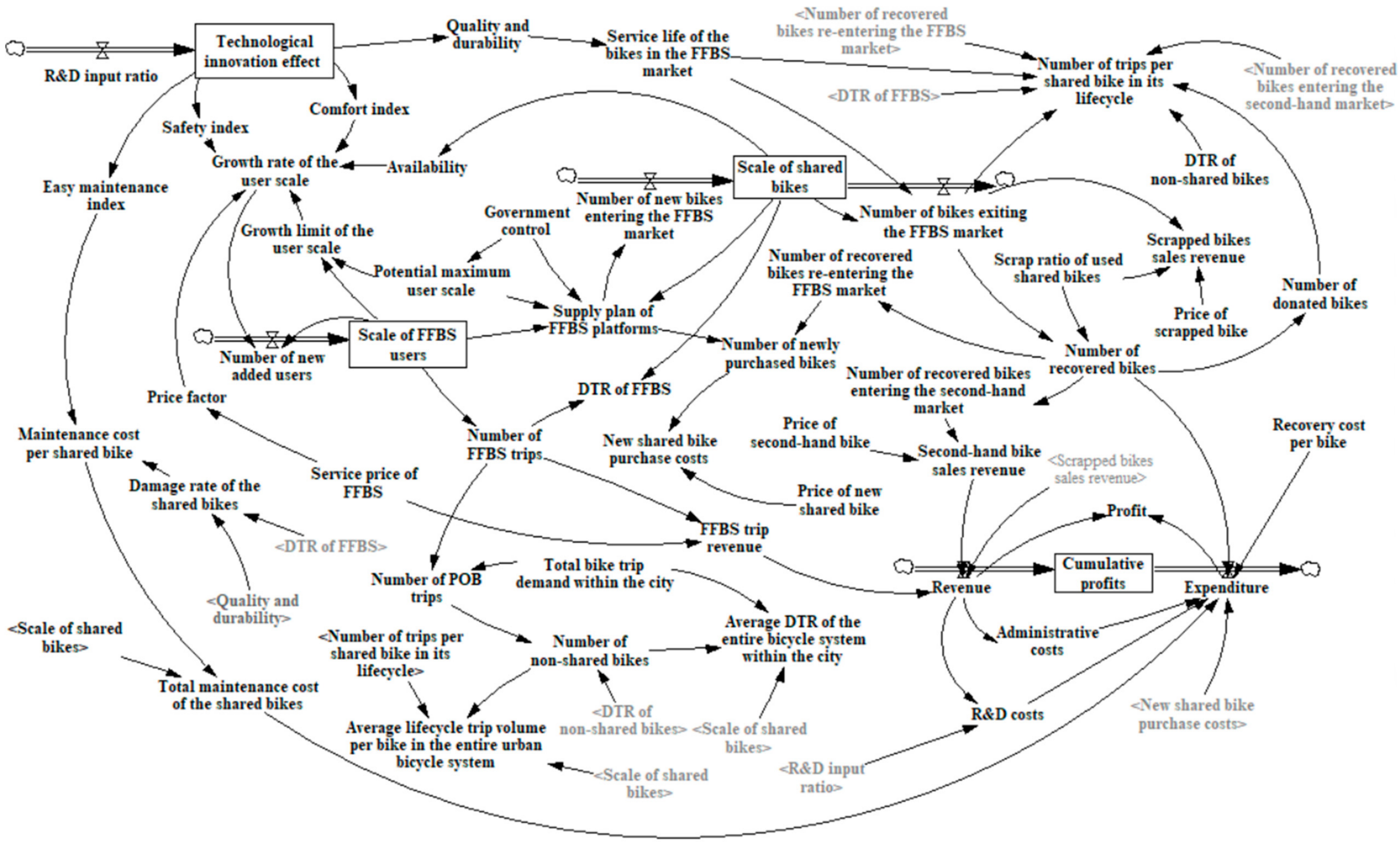

Figure 1. The stock and flow diagram of the system dynamics (SD) model.

The scale of shared bikes (*SBS*) refers to the number of bikes available on the FFBS market, and can be calculated by Equation (5).

$$SBS(t) = \sum_{t=1}^{T} (NNBEM(t) - NBEM(t)) + SBS(t_0) \tag{5}$$

where $SBS(t_0)$ is the initial value of the scale of shared bikes. $NNBEM(t)$ refers to the number of new bikes entering the FFBS market at time *t*, which is determined by the supply plan of the FFBS platform. $NBEM(t)$ refers to the number of used shared bikes exiting the FFBS market. Of the used shared bikes are those bicycles that have reached the specified service life, and can be calculated by Equation (6).

$$NBEM = \frac{SBS}{SL} \tag{6}$$

These used shared bikes can be divided into two parts: one part is the valuable bikes that can be recovered for reuse (i.e., remanufacture and refurnishing), and the other part is scrapped bikes which are usually sold to recycling companies for end-of-life processing (e.g., bicycle dismantling, material disposal, and recycling). The number of recovered bikes (*NRB*) is calculated by Equation (7).

$$NRB = NBEM \times (1 - SRB) \tag{7}$$

where *SRB* refers to the scrap ratio of used shared bikes (i.e., the retired shared bikes exiting the FFBS market). The bikes recovered by the FFBS platform can be used to re-enter the FFBS market, or for second-hand market sales and donations.

3.2.2. Profit of FFBS Platforms

This SD model only focuses on the FFBS service, and does not consider the cost and revenue of advertising, capital investment, and other new business. The revenue of the FFBS platform (*REV*) can be calculated by Equation (8):

$$REV = FFBSTR + SBSR + SHSR \tag{8}$$

$FFBSTR$ refers to the FFBS trip revenue, $SBSR$ refers to the scrapped bikes sales revenue of the platform, and $SHSR$ refers to the second-hand bike sales revenue of the platform.

The expenditure of the FFBS platform (*EXP*) can be calculated by Equation (9).

$$EXP = TMC + RDC + BPC + AC + RCPB \times NRB \tag{9}$$

where TMC refers to the total maintenance cost of the shared bikes. RDC refers to the research and development (R&D) costs of the platform, including technological innovation in materials and design. BPC refers to the new shared bike purchase cost. AC refers to administrative cost of the platform. In addition, it also includes the cost for recovering used shared bikes, which is determined by the recovery cost per bike (*RCPB*) and the number of recovered bikes (*NRB*).

Maintenance costs include the maintenance and rebalancing expenses of the shared bikes during their service life. The maintenance cost per shared bike (*MCPB*) can be calculated by Equation (10).

$$MCPB = b \times (1 - EMI)^{\gamma 5} \times DRB^{\gamma 6} \tag{10}$$

where b refers to the baseline value of the maintenance cost. EMI and DRB refer to the easy maintenance index and the damage rate of the shared bikes, respectively, which are determined by the platform's R&D investment. $\gamma 5$ and $\gamma 6$ are the weighting factors of EMI and DRB.

The profit of the FFBS platform (*PRO*) can be calculated by Equation (11)

$$PRO = REV - EXP \tag{11}$$

where REV refers to the total revenue of the platform, and EXP refers to the total expenditures of the platform.

3.2.3. Evaluation Indicators

This study used three indicators to evaluate the contribution and potential of FFBS in advancing better product lifetimes and promoting the transition of the entire urban bicycle system towards sustainability: the number of trips per shared bike in its lifecycle (*NTPBLC*), the average lifecycle trip volume per bike in the entire urban bicycle system (*LCUBS*), and the average daily turnover rate (DTR) of the entire bicycle system within the city (*ADTRBS*). DTR refers to the average number of trips per bike per day.

Considering that some retired shared bikes can be recovered and reused to re-enter the FFBS market, donation, and the second-hand market, the average number of trips per shared bike in its lifecycle (*NTPBLC*) can be calculated by Equation (12).

$$NTPBLC = \frac{DTRBS \times NBEM \times SL + DTRNSB \times (NBESHM + NDB) \times SL + DTRBS \times NBRM \times SL}{NBEM} \tag{12}$$

where $DTRBS$ refers to the DTR of FFBS. SL refers to the service life of the bikes in the FFBS market. $NBEM$ refers to the number of bikes exiting the FFBS market. $DTRNSB$ refers to the DTR of non-shared bikes. $NBRM$ refers to the number of recovered bikes re-entering the FFBS market. $NBESHM$ refers to the number of recovered bikes entering the second-hand market. NDB refers to the number of donated bikes.

The $ADTRBS$ can be calculated by Equation (13).

$$ADTRBS = \frac{TBTD}{SBS + NPOB} \tag{13}$$

where *TBTD* refers to the total bike trip demand within the city. *SBS* refers to the scale of the shared bikes. *NPOB* refers to the number of non-shared bikes within the city, which is defined as privately owned bikes (POBs) in this study. Considering that a large-scale FFBS can encourage some people to give up owning private bicycles [46,47,51,52], the required number of privately owned bikes (*NPOB*) can be calculated by Equation (14) under the premise of meeting the same bicycle travel demand of urban residents.

$$NPOB = \frac{TBTD - NBST}{DTRNSB} \tag{14}$$

where *NBST* refers to the number of FFBS trips, and *DTRNSB* refers to the DTR of privately owned bikes.

The average lifecycle trip volume per bike in the entire urban bicycle system (*LCUBS*) is defined in Equation (15).

$$LCUBS = \frac{NTPBLC \times SBS + NPOB \times LNSB \times DTRNSB}{SBS + NPOB} \tag{15}$$

where *NTPBLC* refers to the average number of trips per shared bike in its lifecycle. $LNSB$ refers to the lifespan of a non-shared bike. $NPOB$ refers to the number of non-shared bikes. $DTRNSB$ refers to the DTR of a non-shared bike.

4. Results and Discussion

4.1. Model Validation

The validity test was carried out in accordance with the rules and procedures proposed by Barlas [69]. Since this study is forward-looking, and the FFBS market is still in a transition period towards sustainability after explosive growth, there are not adequate quantitative data to conduct comprehensive behavior pattern tests. In this case, a system dynamics study usually only focuses on a direct structure test and structure-oriented behavior tests (i.e., extreme conditions test and sensitivity analysis) [42,43,70]. For the direct structure test, the structures and interrelationships of elements of the SD model were formulated based on PLEBM, the business practice of FFBS, and the relevant existing literature. Parameters in the SD model all have their meaningful counterparts in the real world. For the extreme conditions test, the SD model shows the expected effect when individual parameters are affected by extreme condition. For example, when setting the R&D input ratio to zero, the maintenance cost per bike and the service life of a shared bike will not be improved. The following sensitivity analysis results show that the SD model exhibits different types of dynamic behavior when the value of different parameters changes, and the changes in the model's dynamic behavior pattern caused by the changes in individual parameter values can correspond to the available knowledge of real-world systems. Therefore, the SD model is suitable for evaluating the potential improvement strategies of the system through scenario simulation.

In addition, another problem for this SD study is the time dimension. The SD model in this study combines the PLEBM framework and the evolution of the FFBS market. Driven by huge market capital, FFBS has grown explosively and reached market saturation in less than a year in Beijing, both in terms of shared bike supply and total FFBS trip volume. The FFBS market evolution in the SD model is constructed based on the operating data of the Beijing FFBS market from 2016 to 2019. However, the impact of FFBS on sustainability (e.g., increasing resource utilization and extending product lifespan) needs to be observed and analyzed over a longer period of time. Therefore, in order to resolve this contradiction and better demonstrate the potential evolution of a benign FFBS business model, this study unifies the time step of the model as 1 year, and treats relevant quarterly operation data as annual data. In order to test whether the SD model has a stable output when setting different time steps, a robust test was conducted. The time step was set to 0.25, 0.5, and 1, respectively. The simulation results of the number of FFBS trips and profit are shown in Figure 2.

It can be seen from Figure 2 that the SD model developed in this study is robust. Therefore, it is appropriate and feasible in this study to slow down the growth of the FFBS market.

According to the results of the validity test, the SD model developed in this study is valid and can be used for further simulation and analysis. This study used the Vensim 8.0 for SD simulation and analysis. The time frame of the SD model is 0–20, and the time step is set to 1 (unit: year). Based on the simulation of the SD model, we first explore the contribution and potential of FFBS in advancing production lifetimes and promoting the transition of the entire urban bicycle system towards sustainability, and then we analyze the impact of different PLE strategies and government control levels.

4.2. *Scale and Efficiency of the Entire Bicycle System within the City*

With the promotion of FFBS, the evolution of scale and utilization of the entire bicycle system within the city is shown in Figure 3.

It can be seen from Figure 3 that FFBS can significantly reduce the scale of the entire bicycle system within the city. As the market scale of FFBS expands, the substitution effect on POB becomes stronger. When the market scale of FFBS reaches the government's control level of about 1 million, the number of POBs is expected to drop from the initial 8.7 million to about 6 million, a decrease of about 30% (2.7 million). The scale of the entire urban bicycle system will also reduce from the initial 8.9 to 7 million, a decrease of 2.9 million (21%). In addition, FFBS also can increase the DTR of the bicycle. Unlike privately owned bicycles, which maintain a relatively stable DTR, shared bicycles are more like public transportation facilities, following the scale law. Due to the scale effect, the DTR of shared bicycles continues to increase with the expansion of the scale of FFBS. When the market scale of FFBS reaches about 1 million, the DTR of the shared bike will be about 1.49 which is three times that of privately owned bicycles. The average DTR of the entire bicycle system can increase from initially 0.51 to 0.64, an increase of about 27%. Under the premise of meeting the same bicycle trip demand for urban residents, the promotion of FFBS can not only increase the utilization rate of the entire urban bicycle system but also significantly reduce the production and supply of bikes.

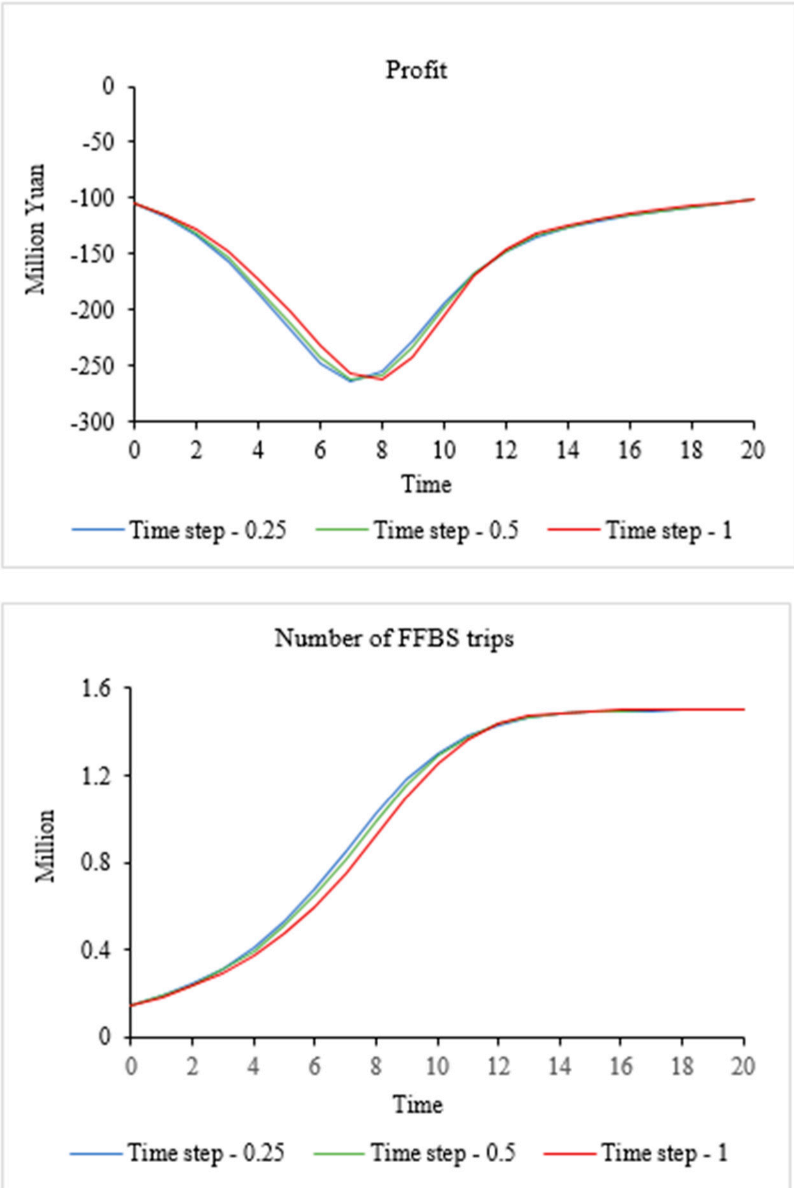

Figure 2. Robust test of the SD model.

4.3. Utilization Rate of Bicycles Throughout the Lifecycle

The utilization rate of a bicycle throughout its lifecycle refers to the number of trips provided by the bicycle during its lifecycle. The FFBS platform adopts two measures for a used bike that has exited the market. The scrapped bike will be directly delivered to recycling companies for dismantling and professional recycling treatments, and some valuable used bikes will be recovered for reuse. The lifecycle utilization rates of bicycles under different scenarios are shown in Figure 4. “No recovery” refers to all the used shared bikes delivered to recycling companies (i.e., in the SD model, the scrap ratio = 1). “Recovered bike” scenarios refer to 90% of the used shared bikes delivered to recycling companies and 10% of the used shared bikes being recovered for donation, second-hand sales, or re-entering of the FFBS market (i.e., in the SD model, scrap ratio = 0.9).

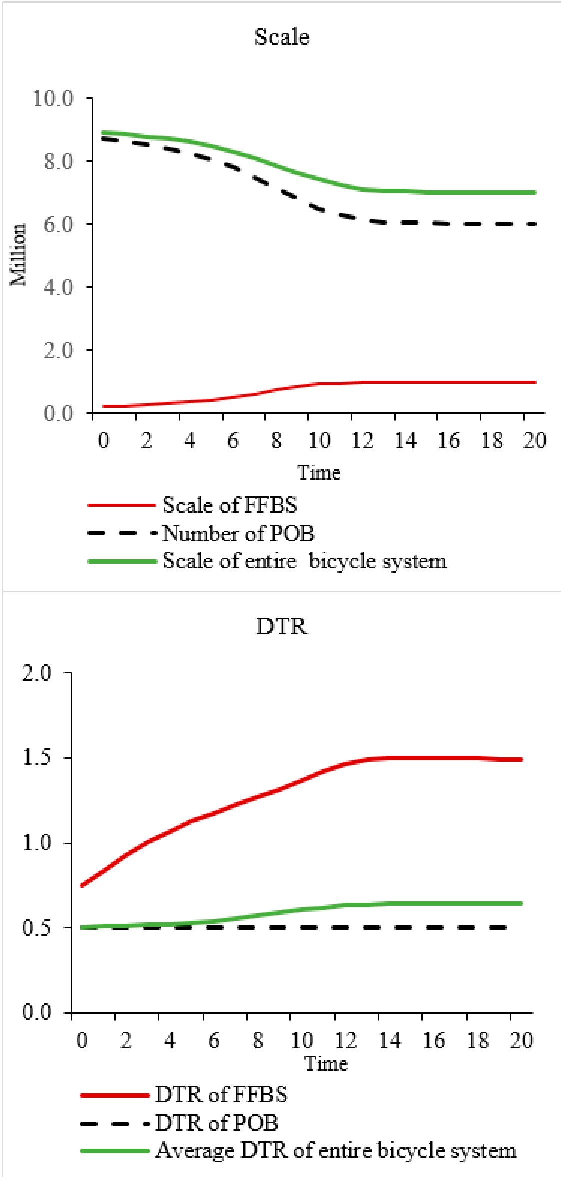

Figure 3. Scale and efficiency of the entire bicycle system within the city.

It can be seen from Figure 4 that a shared bike can provide more trips than a POB during its lifetime. When FFBS reaches the maximum market scale, the lifecycle trip volume per shared bicycle will be about 2000, which is more than twice that of a POB. In addition, FFBS can also increase the average lifecycle trip volume per bike in the entire urban bicycle system from about 900 to 1060, an increase of 16%. Compared with delivering all used shared bicycles directly to recycling companies, recovering some used shared bikes can improve the lifecycle utilization rate of bicycles to a certain extent. If these recovered bicycles can be put back into the FFBS market, the number of trips per shared bike in its lifecycle can increase by 10%, and the average lifecycle trip volume per bike of the entire urban bicycle system can also increase by 2.6%.

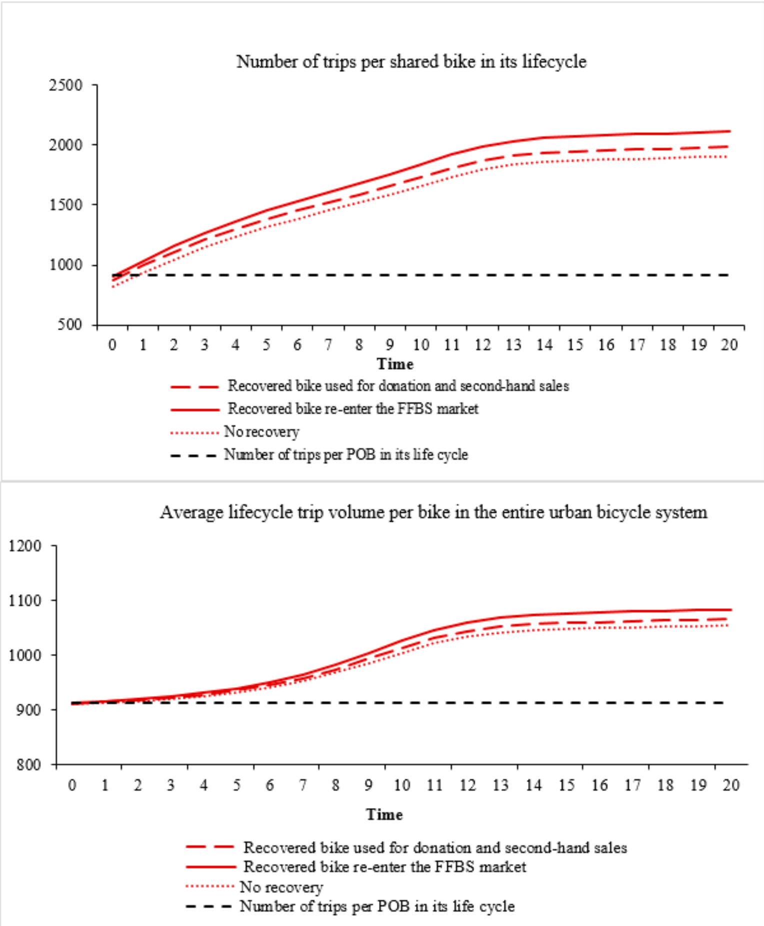

Figure 4. Lifecycle utilization rate of bicycles.

4.4. The Impact of PLE Strategies

In order to further analyze the impact of the PLE strategy of the FFBS platform on the utilization rate of the bicycle system and the profitability of the platform itself, we increased the strength of the PLE strategy; that is, we increased the value of the R&D input ratio to observe the changes in the value of related indicators. The detailed results are shown in Figure 5 (average service life of the shared bike), Figure 6 (number of trips per shared bike in its lifecycle), Figure 7 (average lifecycle trip volume per bike in the entire urban bicycle system), and Figure 8 (profit of the FFBS platform).

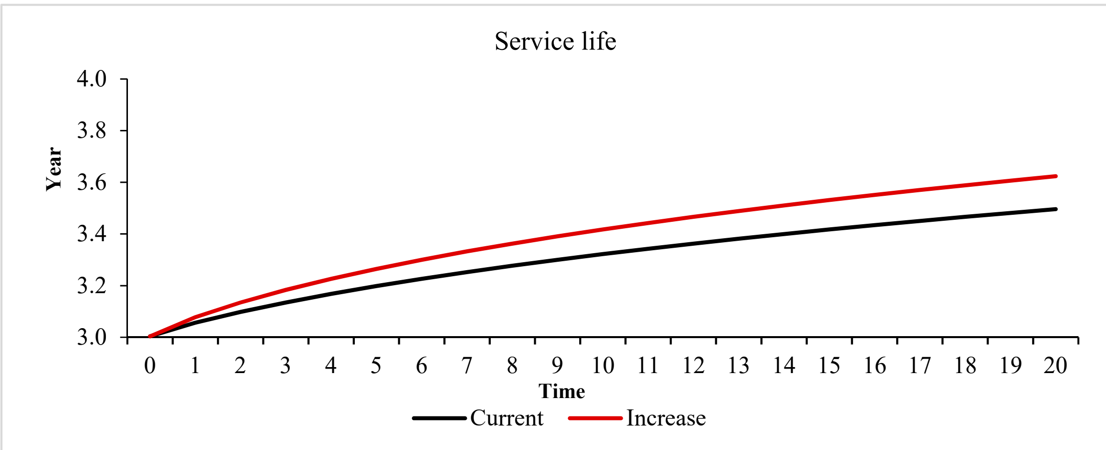

Figure 5. Average service life of a shared bike.

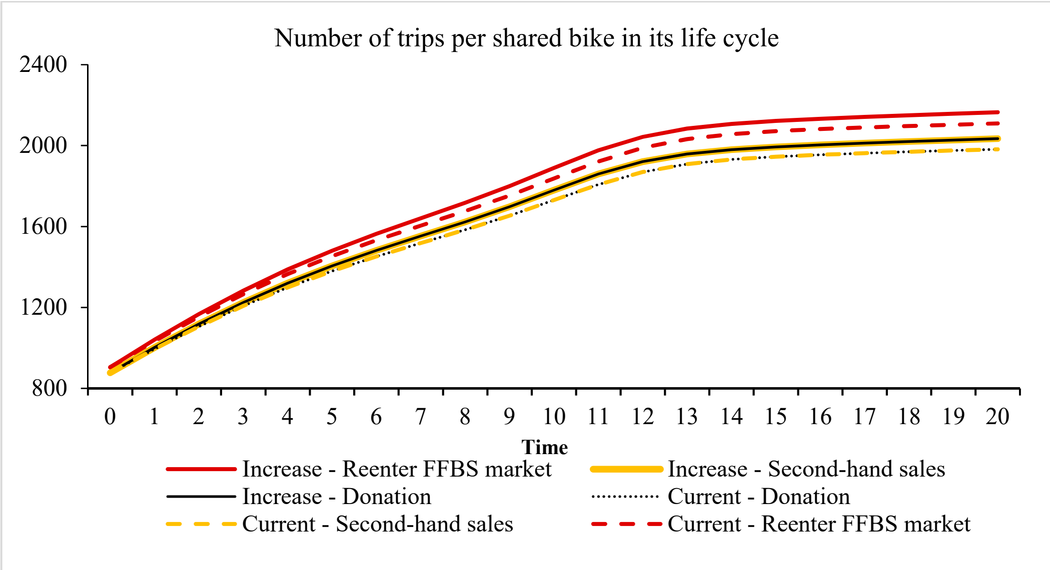

Figure 6. Number of trips per shared bike in its lifecycle.

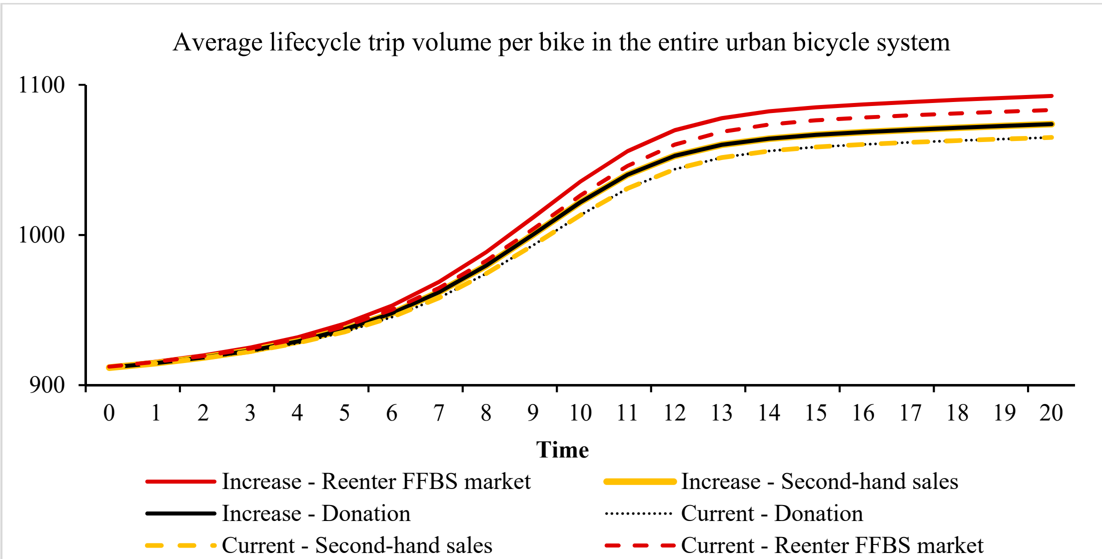

Figure 7. Lifecycle utilization rate of the entire bicycle system within the city.

"Current" refers to the baseline scenario for comparison. "Increase" refers to the scenario of improving the PLE strategy (i.e., keeping all the parameters unchanged except for the R&D input ratio, which is increased by 20%). "Re-enter FFBS market", "second-hand sales", and "donation" refer to the three strategies for the recovered used shared bikes. As shown in Figures 5–7, if the R&D input ratio of the FFBS platform increases, the average service life of the shared bikes will increase. The number of trips per shared bike in its lifecycle and the lifecycle utilization rate of the entire bicycle system will also be improved. However, improving the PLE strategy will worsen the profitability of the FFBS platform (see Figure 8), which affects the platform's motivation to adopt a more aggressive PLE strategy.

FFBS can promote green travel in cities, which is in line with the goal of sustainable development of the urban transportation system. Therefore, in order to better promote the transition of the FFBS industry and entire urban bicycle system to a circular economy, the government should provide appropriate policy support and financial subsidies to stimulate the innovation activates of FFBS. As to the FFBS platform, they should take effective measures to improve profitability. First, the platform should continuously improve its own operational management capabilities and efficiency to reduce the overall operational management expenditure. In addition, the platform should continuously strengthen the cooperation between industries and enterprises to develop new businesses, so as to increase profit opportunities. As a digital platform with scale effects, the FFBS platform has unique advantages in terms of users and data resources, and can penetrate into almost all aspects of the life service ecosystem with travel services as the core, such as shopping, catering, entertainment, and express delivery. Through joint development with related industries and platforms, FFBS can continuously expand its business scope and share commercial cooperation benefits. Last but not least, the platform should strive to find the optimal point of balance between the PLE strategy and the company's profitability, in order to gradually promote the healthy and sustainable growth of FFBS.

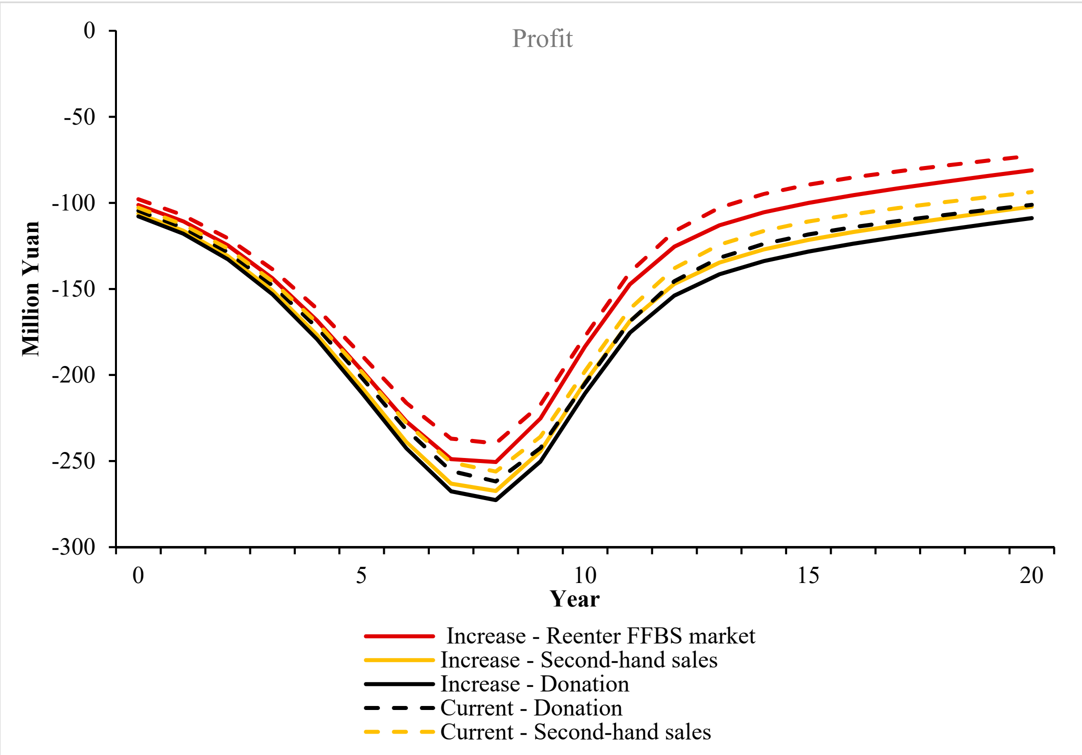

Figure 8. Profit of the free-floating bike sharing (FFBS) platform.

4.5. The Impact of Government Control

In order to seize market share, FFBS platforms have continuously delivered shared bikes into the market. The rapid expansion of the FFBS market has had some negative impacts on urban development, such as compressing public spaces and disorderly parking problems [50,59]. Therefore, the government has adopted a series of measures to limit the scale of the FFBS market [44,45,50]. Considering that government regulation will affect the development of FFBS to a certain extent, and thus further affect the contribution and potential of FFBS in advancing better production lifetimes and promoting the transition of the entire urban bicycle system towards sustainability, we set the value of the variable "government control" (i.e., the maximum FFBS market scale set by the government) in the SD model to a range of 500,000 to 1.5 million to observe the impact of changes in government control levels on the system. The observed variables were the DTR of FFBS, number of trips per shared bike in its lifecycle, average lifecycle trip volume per bike in the entire urban bicycle system, and the cumulative profits of the FFBS platforms. The comparison is based on the final time (i.e., time = 20) value of each simulation. The specific results are shown in Figure 9.

It can be seen from Figure 9 that the operation status of the FFBS market and the utilization of urban bicycle resources change significantly under different government control levels. As the government-controlled scale of the FFBS market gradually increases from 500,000 to 1.5 million, the DTR of FFBS, number of trips per shared bike in its lifecycle, and the average lifecycle trip volume per bike in the entire urban bicycle system increase first and then decrease. When the maximum market scale of FFBS is controlled at around 800,000, the shared bike has the highest utilization efficiency, and the DTR of FFBS and the number of trips per shared bike in its lifecycle can reach the maximum values of approximately 1.6 and 2045, respectively. As for the utilization efficiency of the entire urban bicycle system, when the market scale of FFBS is controlled between 8 and 1.2 million, it does not fluctuate much, and its maximum value is obtained at a market scale of about 1 million.

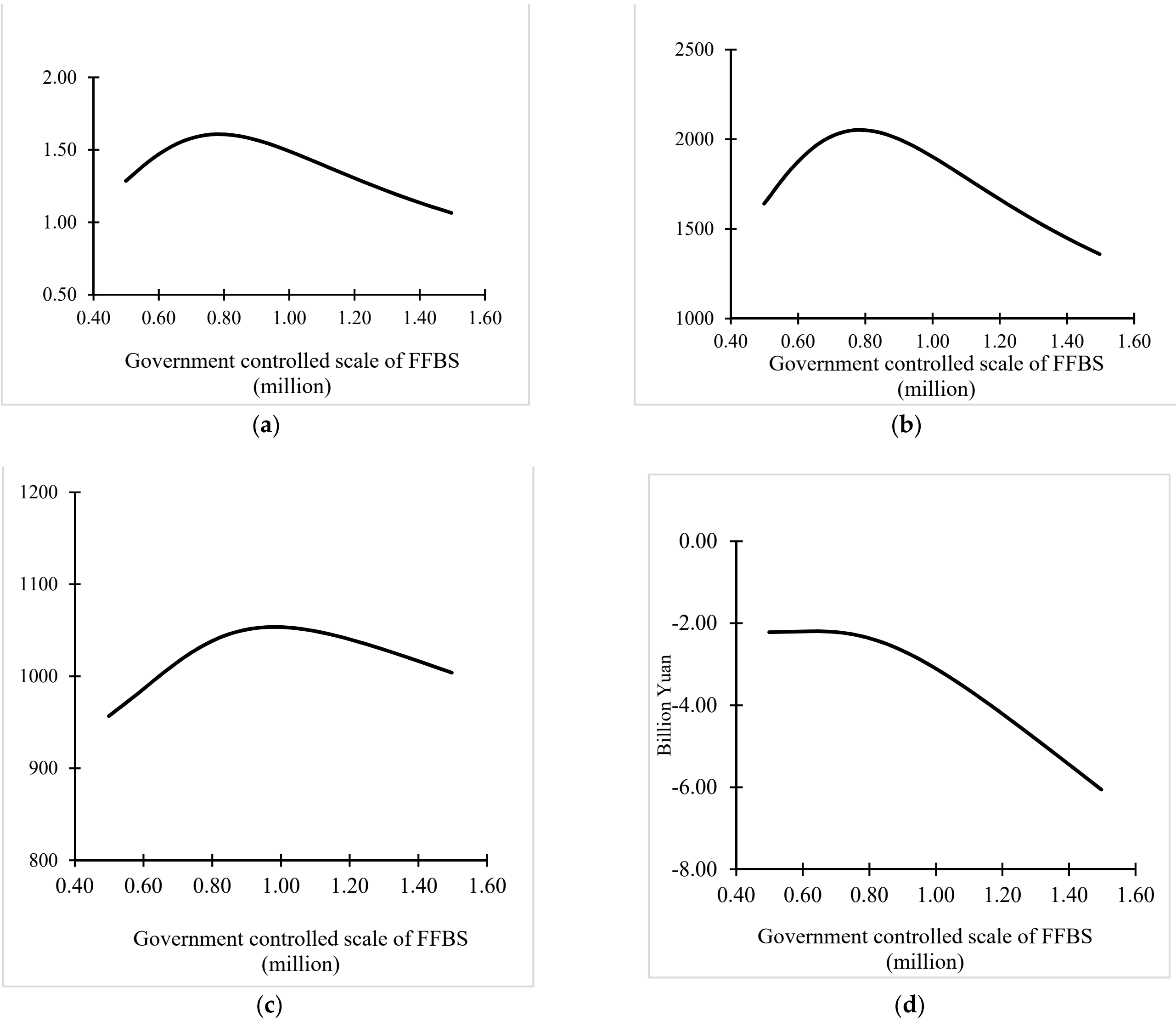

Figure 9. The impact of government control. (**a**) DTR of FFBS, (**b**) Number of trips per shared bike in its life cycle, (**c**) Average lifecycle trip volume per bike in the entire urban bicycle system, (**d**) Cumulative profits of FFBS platforms.

In addition, the market scale of FFBS will also have an impact on the profitability of the FFBS platform. As shown in Figure 9, when the government-controlled scale of FFBS is less than 800,000, the cumulative profit of the FFBS platforms does not change much. If the market scale is greater than 800,000, the profitability of the FFBS platform will deteriorate significantly as the scale increases. Therefore, although FFBS has the potential to promote the transition of the urban transportation system towards sustainability, the blind pursuit of market share will bring unnecessary investment into enterprises, and will worsen corporate profitability and reduce overall resource utilization efficiency. Considering the operating efficiency and profitability of the FFBS platform, as well as the resource utilization rate of the entire bicycle system within the city, the optimal supply scale of FFBS in Beijing is about 800,000.

The emergence of FFSS has provided a potential way to the promote the transition of the urban bicycle system to a circular economy. The promotion of FFBS can not only increase the utilization rate of the entire urban bicycle system but also can significantly reduce the production and supply of the bikes. In addition, FFBS platforms are striving to establish a full lifecycle management system for the shared bike, so that they can better participate in all key activities that contribute to PLE, such as improving design access, maintenance, redistribution, and recovery. For example, Mobike (an FFBS platform in China) has implemented the "full lifecycle management" plan since May 2017 [61]. It is not only responsible for the whole process management of the shared bikes, from design and manufacture to maintenance, but also cooperates with professional organizations to dispose of and recycle the used shared bikes. On Mobile's full lifecycle intelligent management platform, the maintenance history of each component of every bike is recorded, and the service life of each component can be clearly tracked. According to the maintenance records, the design and production of bicycles can be optimized to extend the lifetime of the bicycles, and reduce resource consumption caused by maintenance. Another representative FFBS company, Helloglobal, also formulated a "Bicycle Full Link Operation Management" plan. It established a closed-loop management system of "production-scrapping-recycling" for shared bikes [61]. Helloglobal actively improves the durability design of products and actively recovers and disposes of used bicycles. The current service life of a shared bike in these leading platforms can reach around four years, which is higher than the initial market average value (i.e., 3 years) [62].

Although this study does not include the end-of-life treatment of the shared bikes, such as recycling and destruction for reutilization, FFBS platforms are actively cooperating with bicycle manufacturers and recycling organizations to strive for a 100% recycling rate of the scrapped shared bikes and parts. For example, smart locks and wheel sets from used shared bikes are reused after passing a test. The main frame and other metal materials can be used to make metal ingots or other metal products. The plastic is processed into plastic particles for reuse, such as plastic washbasins, plastic seats, and automotive interiors. For the tires, seat cushions, and other parts that cannot be completely decomposed, a scientific harmless treatment is utilized. As of July 2019, Mobike has refurbished and reused 1.48 million tires and 1.26 million smart locks, and recycled 3152 tons of aluminum and 6897 tons of steel [53]. Helloglobal has also reused more than 500,000 wheels, nearly 70,000 seats, and over 250,000 baskets [48].

In addition, the used parts of the shared bicycle can also be reutilized through technical means, giving them new value. For example, Helloglobal provides new nests for stray animals by deforming and reorganizing the wheels [64]. Mobike recycles and rescreens the scrapped parts, and uses them for recliners, vertical lamps, coffee tables, and candlesticks. Mobike also built a multifunctional rubberized playground with more than 7800 recycled tires [64]. In the future, FFBS enterprises will continue to work on exploring more possibilities for resource conservation and reuse, through cross-border cooperation and technological innovation.

In sum, FFBS shows great potential in advancing product lifetimes and improving the utilization of the entire bicycle system within the city. FFBS platforms are actively cooperating with bicycle manufacturers and recycling organizations to take advantage of resource integration capabilities, moving FFBS and the traditional bicycle industry into the era of the circular economy. With the joint efforts of the government, platforms, and the public, FFBS will play a significant role in promoting the development of the circular economy.

5. Conclusions

This study aimed to explore the contribution and potential of FFBS in advancing product lifetimes and promoting the transition of the entire urban bicycle system towards sustainability. Taking the Beijing FFBS market as an example, a system dynamics model was developed based on the PLEBM framework and the business practices of FFBS. Combined with the dynamic evolution process of the FFBS market, the impact of FFBS on the scale and efficiency of the urban bicycle system was observed and analyzed. The influence of different platform strategies and government control levels on the development of FFBS and the resource utilization efficiency of urban bicycle systems is also discussed, through SD simulation.

FFBS can significantly lower the required supply scale of the entire bicycle system within the city. When the market scale of FFBS reaches the current government's control level (i.e., 1 million), the scale of the entire city bicycle system can be reduced by about 21% (2.9 million). Since the DTR of a shared bike is about three times that of privately owned bicycles, the DTR of the entire bicycle system can increase from 0.51 to 0.64—an increase of about 27%. In addition, FFBS can also increase the average lifecycle trip volume per bike in the entire urban bicycle system from about 900 to 1060, an increase of 16%. It is worth noting that although enhancing the PLE strategy can increase the contribution of FFBS to PLE, it may also deteriorate the profitability of the FFBS platform. Moreover, although FFBS has the potential to promote the transition of the urban transportation system towards sustainability, the blind pursuit of market share will invite unnecessary investment into enterprises, and will worsen corporate profitability and reduce overall resource utilization efficiency. According to the simulation results of this study, the optimal market size of the Beijing FFBS should be controlled at around 800,000. The authorities and the FFBS platform should work together to continuously improve the profitability of the platform, and strengthen the technological innovation capabilities, to promote the healthy and sustainable development of FFBS.

This study offers a variety of contributions to both theory and practice. First, this study takes the Beijing FFBS program as an example to quantitatively analyze the contribution and potential of collaborative economy business practices in promoting the transition to a circular economy, supplementing the existing literature. The results can be used as guidance and reference for authorities and platform managers to better promote the sustainable and healthy development of the collaborative economy. In addition, the SD model developed in this study can be further adjusted and improved according to the actual operating conditions of enterprises to help managers formulate more effective operating strategies to improve profitability. It can also be used as a development tool for industries or enterprises to evaluate and formulate sustainable development strategies, such as PLE strategies. Moreover, this study is practical and forward-looking; it develops an SD model based on the PLEBM framework and business practices of FFBS, bridging the gap between theory and practice, and providing new methods and ideas for related research fields.

Several limitations are noteworthy in this study. Due to limited data, this paper only provides a simplified representation of the real world. More details, such as cost and revenue structure of the FFBS platform, input and output efficiency of the R&D, and the interaction between the five key activities in the PLEBM framework, need to be gradually supplemented and perfected. The growth of FFBS is a process of dynamic change, and is affected by a variety of internal and external factors, such as price strategy and government regulation. However, this article does not conduct further in-depth discussion and analysis of these factors. In addition, FFBS platforms have developed over a relatively short period of time, and the impact of the platform's PLE strategy needs to be observed and analyzed over a longer period of time. Therefore, this paper provides a simulation and scenario analysis with a longer time frame to explore the impact of the PLE strategy however, the model and results still need to be tracked, verified, and adjusted over a longer period of time.

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Appendix A. Summary of Model Parameters

Administrative cost	AC
Availability	AVA
Average DTR of the entire bicycle system within the city	ADTRBS
Average lifecycle trip volume per bike in the entire urban bicycle system	LCUBS
Comfort index	CI
Cumulative profits	CP
Damage rate of the shared bikes	DRB
DTR of FFBS	DTRBS
DTR of non-shared bikes	DTRNSB
Easy maintenance index	EMI
Expenditure	EXP
FFBS trip revenue	FFBSTR
Government control	GC
Growth limit of the user scale	GLUS
Growth rate of the user scale	UGR
Lifespan of non-shared bikes	LNSB
Maintenance cost per shared bike	MCPB
New shared bike purchase cost	BPC
Number of bikes exiting the FFBS market	NBEM
Number of donated bikes	NDB
Number of FFBS trips	NBST
Number of new added users	NAU
Number of new bikes entering the FFBS market	NNBEM
Number of newly purchased bikes	NPB
Number of non-shared bikes	NPOB
Number of non-shared bikes trips	NPOBT
Number of recovered bikes	NRB
Number of recovered bikes entering the second-hand market	NBESHM
Number of recovered bikes re-entering the FFBS market	NBRM
Number of trips per shared bike in its lifecycle	NTPBLC
Potential maximum user scale	PMUS
Price factor	PF
Price of new shared bike	PNB
Price of scrapped bike	PSB
Price of second-hand bike	PSHB
Profit	PRO
Proportion of recovered bikes entering second-hand market	PESM
Proportion of recovered bikes re-entering FFBS market	PRM
Proportion of recycled bikes used for donations	PRBD
Quality and durability	QD
R&D input ratio	RDIR
Recovery cost per bike	RCPB
Research and development costs	RDC
Revenue	REV
Safety index	SI
Scale of FFBS users	SAU
Scale of shared bikes	SBS
Scrap ratio of used shared bikes	SRB
Scrapped bikes sales revenue	SBSR
Second-hand bike sales revenue	SHSR
Service life of the bikes in the FFBS market	SL

Service price of FFBS	SP
Supply plan of FFBS platforms	SPO
Technological Innovation Effect	IE
Total bike trip demand within the city	TBTD
Total maintenance cost of the shared bikes	TMC

Appendix B. Parameter Equations of the SD Model

AC	REV × 0.4
ADTRBS	TBTD/(SBS + NPOB)
AVA	(SBS/1,200,000)^0.8 × EMI^0.2
BPC	NPB × PNB
CI	0.5 × IE^0.2
CP	INTEG (REV−EXP, 2,000,000,000)
DRB	(1−QD^0.2) × DTRBS^0.2
DTRBS	NBST/SBS
DTRNSB	0.5
EMI	0.1 + 0.5 × IE^0.2
EXP	TMC + RDC + BPC + AC + RCPB × NRB
FFBSTR	NBST × SP × 365
GC	1,200,000
GLUS	(PMUS − SAU)/PMUS
IE	INTEG (RDIR × 0.2, 0.1)
LCUBS	((NTPBLC/365 × SBS + NPOB × LNSB × DTRNSB)/(SBS + NPOB))/(DTRNSB × LNSB)
LNSB	5
MCPB	1000 × (1 − EMI)^0.4 × DRB^0.6
NAU	SAU × UGR
NBEM	SBS/SL
NBESHM	NRB × PESM
NBRM	NRB × PRM
NBST	SAU × 0.75
NDB	NRB × PRBD
NNBEM	SPO
NPB	SPO−NBRM
NPOB	NPOBT/DTRNSB
NPOBT	TBTD−NBST
NRB	NBEM × (1 − SRB)
NTPBLC	(DTRBS × NBEM × SL + DTRNSB × (NBESHM + NDB) × SL + NBRM × SL × DTRBS) × 365/NBEM
PESM	Random (0, 1, 0.4)
PF	1−SP/3
PMUS	2,000,000
PNB	1000
PRBD	Random (0, 1, 0.4)
PRM	Random (0, 1, 0.2)
PRO	REV−EXP
PSB	15
PSHB	500
QD	0.1 + 0.5 × IE^0.3
RCPB	300
RDC	REV × RDIR
RDIR	0.12
REV	SHSR + FFBSTR + SBSR
SAU	INTEG (NAU, 200,000)
SBS	INTEG (NNBEM − NBEM, 200,000)
SBSR	SRB × NBEM × PSB
SHSR	NBESHM × PSHB

SI	0.5 × IE^0.3
SL	3 + 3 × (QD − 0.35)^0.9
SP	1.5
SPO	(SAU/PMUS)^0.3 × ((GC−SBS)/(GC))^0.7 × SBS
SRB	0.9
TBTD	4,500,000
TMC	MCPB × SBS
UGR	AVA^0.4 × CI^0.15 × SI^0.25 × PF^0.2 × GLUS

Note: Data source from [43–47,52,55,57–60].

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