

## Article

# Assessment of the Development of Time-Sharing Electric Vehicles in Shanghai and Subsidy Implications: A System Dynamics Approach

Biyi Zhou, Hao Hu \* and Lei Dai

School of Naval, Architecture, Ocean and Civil Engineering, Shanghai Jiao Tong University, NO. 800 Dongchuan Road, Minhang District, Shanghai 200240, China; Spectre@sjtu.edu.cn (B.Z.); dailei1989@sjtu.edu.cn (L.D.)

\* Correspondence: hhu@sjtu.edu.cn

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**Abstract:** CO<sub>2</sub> emissions reduction has long been discussed, since the problem is one of the most urgent issues we human beings are faced with in the 21st century. Time-sharing electric vehicles (TSEVs), combining the benefits of cleaner energy and more sufficient utilization, are considered a sustainable future transportation tool, with increasing support from governments around the world. Although numerous studies have been carried out in this domain, few have studied the development process, considering the inverse interrelations, including the policy implementation effects and user choice, in a dynamic way. This research fills the previous academic gap and presents a system dynamics (SD) model incorporating scenario analysis to simulate the effect of introducing time-sharing electric vehicles in changing the user quantities in transportation tools, including public and private sectors, under different levels of government subsidies, thus providing policy implications and ex-ante assessment for the subsidies. The results suggest that it is not the greater the subsidy, the better the effect. Considering that one of the purposes of introducing TSEVs is to reduce private vehicles, there is a threshold for user transfer. It is actually under low subsidy that private internal combustion engine vehicle (ICV) users are most attracted to the TSEVs compared to the medium and high ones. The gap between the simulation results and common sense reminds us that ex-ante assessment and overall planning in the process of industry development are necessary.

**Keywords:** time-sharing electric vehicles (TSEVs); subsidy implications; ex-ante assessment; system dynamics; scenario analysis

## 1. Introduction

Nowadays, environmental issues, such as global warming, are continuously drawing people's attention. According to estimates by the United Nations Environment Programme (UNEP), if the temperature increase is to be limited to 1.8 °C by the end of this century, then the total cumulative emissions should not exceed 900 GtCO<sub>2</sub> from 2018 until the time net zero CO<sub>2</sub> emissions are reached (or until 2100 if net-zero is not reached before) [1]. However, the CO<sub>2</sub> emissions of 2018 were reported to have risen 1.7% to a historic high of 33.1 GtCO<sub>2</sub>, according to the International Energy Agency (IEA) [2]. The number has been continuously increasing since the 1970s and there is no sign that this trend will stop. In this way, carbon dioxide emissions will soon exceed the maximum CO<sub>2</sub> emissions value by 2045 (if there is no increase, then 900 (Gt)/33.1 (Gt/Year) = 27 (Year)). However, UNEP has claimed that in the absence of further climate action since 2005, that is, under a no-policy baseline scenario, the total global Greenhouse Gas (GHG) emissions in 2030 would be 65 GtCO<sub>2</sub> e [1]. The situation we face is quite urgent, since there is no possibility that we could reach the goal unless we take action immediately to further reduce emissions.

Road transport is a strong contributor to CO<sub>2</sub> emissions, and the increasing vehicle ownership number may be the key driver. Among all the industries involved in CO<sub>2</sub> emissions, the transportation sector accounted for one quarter of total emissions in 2016, at around 8 GtCO<sub>2</sub>, 71% higher than what was seen in 1990 [2]. Additionally, road transport made up a significant share (74%) of the emissions from transportation section, with the highest absolute increase, in contrast to air and water transport. The continuous growth in vehicle ownership may largely account for the sharp increase in CO<sub>2</sub> emissions from road transport [3]. The statistics from the National Bureau of Statistics of China showed that private car ownership has increased by seven times from 2005 to 2018 [4].

Governments have taken action to relieve the CO<sub>2</sub> emission problem in the past few years, such as announcing a series of measures to promote electric vehicles (EVs), but have accomplished little. This mainly manifested in two aspects. First, the process is relatively slow. For the United States, fewer than 200,000 electric cars were sold in 2017, barely 1% of the 17.25 million total automobile sales under the government subsidies of up to \$7500 when buying an EV [5]. And for China, there are only 2.11 million pure EVs, accounting for 0.88% of total private vehicle ownership domestically by the end of 2018, with the subsidy being RMB 66,000 on the purchase of an EV with a range of 150 miles or greater. Second, the subsidy on purchasing an EV may prompt EV sales and the increase of private vehicle ownership to some extent. Even if an electric vehicle does not produce any pollutants, its mere presence on the road causes other cars to slow down and to pump out more exhaust [6].

To accelerate the process of reducing CO<sub>2</sub> emission in road transport areas, some governments have turned to giving priority to time-sharing electric vehicles (TSEVs), a kind of general public transport which combines the sharing mode with the concept of cleaner energy. As an innovative business model, time-sharing leasing reduces the cost to use by 80% compared with traditional cars, and increases the utilization rate of electric vehicles by two to three times [7]. Actually, in June 2018, the Indian government decided to withdraw from private electric cars and give cash subsidies to those used shared—mobility operators such as Ola and Uber—for the reason that their vehicles will run much more than private cars [8]. In China, the Department of Transport and the Department of Housing Construction jointly issued the “Guidance on Promoting the Healthy Development of Minibus Rental”, endorsing the time-sharing car rental industry at national policy level for the first time in August 2017. Relevant subsidy policies have also been released to promote the implement of the time-sharing car rental industry by provincial and municipal governments, such as Shanghai, Beijing, and other regions, since then [9]. For Shanghai, the local government is offering a cash subsidy on the purchase and operation of time-sharing electric vehicles to the operators, such as the Shanghai Automotive Industry Corporation (SAIC), around RMB 40,000 per vehicle for purchase, and 50%, 30% of the operating fee for operation according to the year [10].

The time-sharing car rental industry is currently developing quickly in China, thanks to the policy guidance and governments’ support to the industry. In 2017, the trading scale of the Internet car time-sharing leasing market has reached 1.792 billion yuan, and more than 90% of time-sharing rental cars on the market are new energy vehicles. The whole market was estimated to be growing at a rate of more than 50% according to a report from PwC Strategy in 2018 [11].

However, is it right that the time-sharing car rental industry should grow so rapidly and substantially? Will it achieve the original target of accelerating the process of reducing CO<sub>2</sub> emissions? Will it bring some unintended effects, causing the final effect to deviate from expectations? Should we make some predictions or simulations to better help the industry develop? The answer is definitely yes. As we can remember, disbalance in supply and demand has just occurred on sharing bikes, resulting in waste of social resources, not long ago, just because of a lack of pre-planning and regulating. Thus, the phenomenon today should be paid attention and the healthy development of the time-sharing car rental industry requires ex-ante assessment and planning beforehand.

Based on the situation and considering that the main purpose of introducing TSEVs is to reduce private vehicles as much as possible, rather than attracting public transportation users, this research builds up a dynamic model which interprets long-term possible user changes in the

transportation system under certain policy subsidies on time-sharing electric vehicles and carries out a case study in Shanghai. According to the simulation results, we can not only have a prediction of the future market, but also reversely evaluate the applicability and rationality of the policy subsidy by comparing the simulation results with the ideal target, thus helping the sustainable development of the city transportation.

In the previous research, EV adoption (e.g., [12]) and car-sharing development (e.g., [13]) have been studied by scholars widely, however rarely has research been carried out on the development of time-sharing EVs. Considering the synergy, the problem of time-sharing electric vehicles could not simply be regarded as the combination of electric vehicles and sharing mode.

This research focuses on the issue of TSEV and has made the following contributions. First, this study explicates the complex process of user changes within the transportation system after TSEV is introduced under a certain policy subsidy. Second, we build up a system dynamics (SD) model to effectively interpret the evolution of TSEV adoption and development under a certain policy subsidy. Third, we combine the method of scenario analysis with the SD model to predict the development trends and processes under different levels of policy subsidies, thus evaluating the policy effects to find out the appropriate subsidy range.

The remainder of this paper is organized as follows. Section 2 is the literature review. Section 3 introduces the system dynamics model of time-sharing electric vehicles adoption, considering the constantly changing user choice. Section 4 presents the simulation and results. Finally, conclusions and future research are discussed in Section 5.

## 2. Related Work

### 2.1. Research on Time-Sharing Electric Vehicles

Electric vehicles and mobility sharing have attracted research attention from scholars across the academic spectrum, such as transportation (e.g., [14]), management (e.g., [15]), energy and environmental studies (e.g., [16]). From the energy and environment side, electric vehicles have been commonly proven to be greener compared to the conventional internal combustion engine vehicles (e.g., [17]). From the operation side, car sharing has been reported to contribute to lower consumption of physical and economic resources, and reduction of energy and environmental impacts [16].

Naturally, electric vehicle sharing is viewed as a promising future trend and numerous studies have been conducted on the topic, as shown in Table 1.

**Table 1.** Review of previous studies.

| Theme                   | Summary   |
|-------------------------|---|
| Case Study and Opinions | Beijing: The government should provide policy support to encourage the development of the industry and the guidance should be strengthened from the level of urban planning [18].                             |
|                         | Shanghai: The population characteristics of people choosing to use sharing EVs are male, aged between 18 and 30, and usually taking the subway and bus as the daily transportation modes [19].                |
|                         | San Francisco Bay Area: An EV carsharing program could potentially complement travel patterns and price sensitivity [20].   |
|                         | Germany: Carsharing with EVs is particularly attractive for younger people who (i) live as a couple but without cars or (ii) are starting a family and use carsharing as a supplement to their own cars [21]. |

Table 1. Cont.

| Theme                         | Summary  |
|-------------------------------|--|
| Preference of Consumers       | Rental price, vehicle availability, type of vehicle are the main attributes of choice. All else being equal, users most prefer Hybrid vehicles [22].   |
|                               | Users pay more attention to convenience and the economy of sharing EVs [19].   |
| System Design or Optimization | Service attributes, including travel time, travel cost, registration fees, and capital cost, were significant in acceptance of car sharing systems [23].   |
|                               | Green Move: an electric vehicle sharing system with the characteristics of multi-ownership [24].   |
|                               | Optimal management of the EV sharing system is configured using genetic algorithms, indicating that the optimal number of EVs is about half the total number of parking stalls [25].   |
|                               | A closed queueing network model of the EV sharing system was formulated to derive the asymptotic behavior of vehicle availability at an arbitrary rental station with respect to fleet size, and meanwhile a profit-maximizing optimization problem was also determined for optimal fleet size [26]. |

To briefly conclude, previous studies in this domain have predominantly focused on case studies, the preferences of consumers, system design, or optimization. Hardly any research has been conducted on the topic of the prediction of impacts on the market brought about by EV sharing. A demand modeling study on car-sharing was complemented by applying an expert elicitation and aggregation technique that relies on transport experts' opinion, and the penetration rates in 2030 were given by countries [27]. A game-theoretic model was set to investigate how the introduction of car sharing has an impact on the market. The results indicate that car sharing does not always reduce vehicle quantity. Specifically, only when the producing cost and transportation need are below some thresholds and the market size is greater than a threshold, can car sharing decrease the total number of vehicles [14]. However, the problem of electric vehicle sharing is neither equal to the pure car-sharing problem, nor to the simple combination of the electric vehicle and the car-sharing because of the synergy, since electric vehicles differ from ICVs in the energy cost, government support, etc., to a large extent. Thus, it is quite necessary and meaningful to study the impacts to the market with the research object being sharing EVs, and the prediction and assessment of the development process as well.

## 2.2. System Dynamics Modeling

There have been very few studies carried out on the development scale problems of TSEV to date, especially considering the government subsidies. However, academic studies on the likely uptake of alternative fuel vehicles (AFVs) have been conducted since the 1980s. These studies consider generic AFVs through factors ranging from attributes such as accessibility and performance, to technologies such as the detailed energy types. Although studies vary in their approach to forecasting, most have used a static discrete choice or system dynamics method, combined with the theory of product diffusion.

Discrete choice models use stated preference surveys or revealed preference data to assess consumer behaviors and attitudes towards AFVs. Then, the outputs of this are used to predict the likely uptake of AFVs following the product diffusion theory. David has made remarkable work in this domain by combining this method with multinomial and mixed logit models to account for the large range of choices that exist in the vehicle market place [28]. Additionally, a large number of works have also been conducted to examine individual preferences for AFVs [29–31].

System dynamics modeling is a well-established method which can accept the complexity, nonlinearity, and feedback loop structures that are inherent in social and physical systems. Many scholars have used the system dynamics model to study the dynamic process of researching problems.

An integrated and comprehensive framework which makes it possible to account for all three dimensions of sustainability (economic, environmental, social) was provided with the SD method to give ex-ante estimates of environmental health impacts of EVs uptake according to different scenarios, and then propose recommendations for the definition of Sustainable Urban Mobility Plans of a smart city [32]. The system dynamics method was adopted and incorporated with fuzzy logic to simulate the adoption process of electric vehicles (EVs) as a substitute for internal combustion engine vehicles (ICVs) and to examine the emergence of EVs as a mobile intelligent terminal of social commerce [12]. The method was also used to explain the inverse interrelations between the main parameters of a dry port and evaluate the sustainability of the system [33].

In this paper, the system dynamics method is adopted to capture the process of TSEV development under different scenarios, for which the introduction of TSEVs into the existing market will influence other parts within the transportation system, and the influences are not unidirectional, but mutual. This means we have to think systematically and regard the problems as a whole, instead of looking at isolated events and their causes. For the method of static discrete choice combined with product diffusion theory, although scholars may be able to successfully obtain data of users' behaviors and attitudes which perfectly match the reality, through its good design, and then use the product diffusion theory to predict the scale, they follow the logic of studying some phenomena first and then step further using the formal results. Finally, some policy implications may be provided according to the study. There are flaws of this method if applied to this research, as they cannot take the effect of policy implementation into consideration for its one-way process. Additionally, the mutual influence among the inner parts are hard to interpret and consider. Thus, as mentioned above, TSEV development is a dynamic and complex process with interactive feedback and causal loops rather than static, and the SD model is adopted to simulate the process in this research.

### 3. System Dynamics Model of TSEV Adoption

#### 3.1. Basic Assumptions

First, we made it clear that the purpose of introducing time-sharing electric vehicles was set to be attracting more people from private internal combustion engine vehicles (ICVs), rather than public sectors, to the TSEVs, thus to release as much as possible the advantage of sharing mode and cleaner energy.

Before modeling, we raised five assumptions about the potential users of TSEVs:

1. We divided the whole crowd into three categories from a macroscopic perspective: public transportation users, potential private vehicle buyers (who are using public transportation right now and plan to purchase private vehicles in the short-term), and private car users (including ICVs and PEVs);
2. The influencing factors of users' choice were simplified to be convenience (indicating availability of the mobility) and cost, since convenience and affordability are core features of car-sharing, and of particular interest to consumers [34];
3. TSEV could attract people from three groups, which Huang and Yang summarized as the possible target markets of the new public transport pattern of vehicle sharing, that is, people who have no private cars or have a high cost of ownership [35]: (1) potential private vehicle buyers; (2) private ICV users who are paying high amounts for the operations; (3) public transportation users with a pursuit of travel comforts. Here, it should be mentioned that the people owning or planning to buy a plug-in electric vehicle (PEV, including plug-in hybrid electric vehicle, battery electric vehicle, and fuel cell electric vehicle) were not considered because of the definite advantages of PEVs over TSEVs in their low operation cost brought by the electricity, and their convenience as private cars;
4. These three potential user groups naturally have different tolerances for the convenience and cost of time-sharing electric vehicles;



5. The government subsidizes the users directly or indirectly (through the operation subsidy to the operators, and then from the operators to the users by discounts) to some degree. The degree of the subsidy would impact the cost of use, thus influencing the decision of users from each group to choose time-sharing electric vehicles or not;
6. Changes in the number of users can affect the real-time availability of the vehicles, namely convenience, which in turn will also affect the user choice according to the acceptance of convenience of each group.

In addition to the users, the other key assumptions were as follows: the annual increase in small private passenger vehicles will not be influenced by either the new-tech PEVs or the innovative time-sharing mode; the annual growth will maintain constant and unchanged, using the average value from 2010 to 2017.

### 3.2. System Dynamics Modeling

Based on the principles and assumptions in Section 3.1, the relationships among the flows and auxiliaries were bridged using the system dynamics method. The model and the descriptions were as follows (Figure 1).

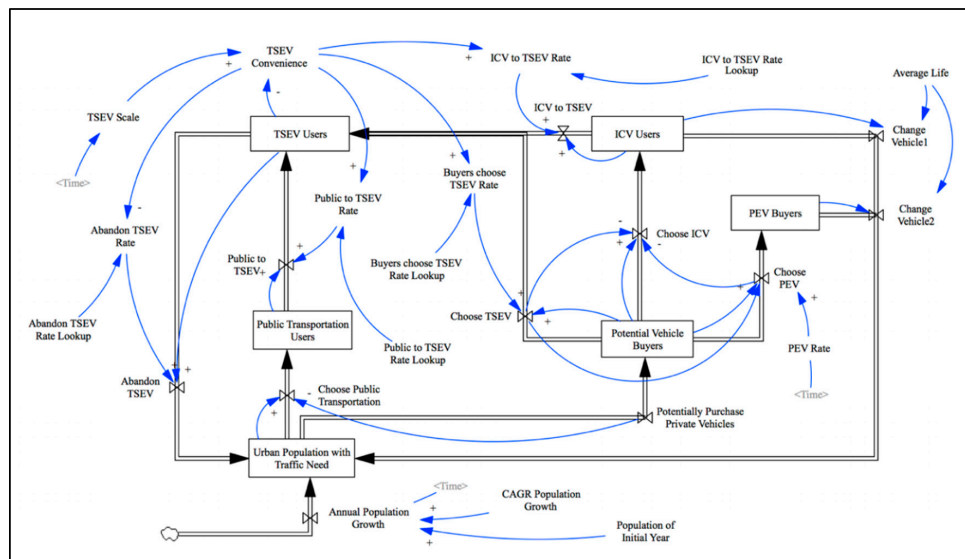


Figure 1. Formal model with stocks and flows.

The box of “Urban Population with Traffic Need” refers to the urban population with traffic needs of the city we studied at present. The flows that go to this box are “Annual Population Growth”, “Abandon TSEV”, “Change Vehicle1”, and “Change Vehicle2”. “Annual Population Growth” refers to the annual increase in the permanent residents of the city, since almost everyone has a need to go out. “Abandon TSEV” refers to those who had chosen TSEV, however perhaps due to cost or convenience concerns, decided to abandon TSEV. “Change Vehicle1” and “Change Vehicle2” refer to those who need to change their private ICVs and PEVs because of vehicle scrapping. Thus, they need to choose again the type of transportation. The flows from “Urban Population with Traffic Need” are “Choose Public Transportation” and “Potentially Purchase Private Vehicles”. The former one clearly refers to the people who choose the general public transportation section. Then, the latter one refers to those who have a plan to purchase a private vehicle, rather than public section. The temporal accumulation of “Urban Population with Traffic Need”,  $UPTN(t)$ , was calculated using Equation (1), where  $UPTN(0)$  is 0:

$$UPTN(t) = \int_0^t \text{Annual Population Growth}(t)dt + \text{Abandon TSEV}(t)dt - \text{Potentially Purchase Private Vehicles}(t)dt - \text{Choose Public Transportation}(t)dt + UPTN(0). \quad (1)$$

The box of “Potential Vehicle Buyers” refers to those who are planning, and have quite a high possibility of purchasing a private ICV. The flow that goes to this box is “Potentially Purchase Private Vehicles”, which represents the strong willingness and need to use a car instead of the general public transportation, such as subways and buses. The flows from “Potential Vehicle Buyers” are “Choose TSEV”, “Choose ICV”, and “Choose PEV”, indicating that when people are planning to purchase a private car, they may ultimately choose the TSEV rather than buying a car, and even if they choose to buy a car, they may choose either an ICV or a PEV. The temporal accumulation of “Potential Vehicle Buyers”,  $PVB(t)$ , was calculated using Equation (2), where  $PVB(0)$  is 0:

$$PVB(t) = \int_0^t \text{Potentially Purchase Private Vehicles}(t)dt - \text{Choose TSEV}(t)dt - \text{Choose ICV}(t)dt - \text{Choose PEV}(t)dt + PVB(0). \quad (2)$$

The box “PEV Buyers” is the number of PEV users, and it is the accumulation of the flow “Choose PEV”, deducting the number of “Change Vehicle2”, which could be calculated using Equation (3), as  $PEV(t)$ . The  $PEV(0)$  is the number of PEV users of the initial study year, that is, 31,454 by the end of 2017, according to data from the Shanghai New Energy Automobile Office [36].

$$PEV(t) = \int_0^t \text{Choose PEV}(t)dt - \text{Change Vehicle2} + EV(0). \quad (3)$$

The box “TSEV Users” is the number of time-sharing electric vehicle users. It comes from the flows of “Choose TSEV”, “ICV to TSEV”, and “Public to TSEV”. “Choose TSEV” has been explained before as people who have the initial plan to buy a private vehicle but ultimately choose TSEVs in comprehensive consideration of cost and convenience. The flow of “ICV to TSEV” refers to the behavior of people owning a private ICV but turning to use TSEVs under the situation that the government subsidy is so attractive that the TSEVs have an obvious price advantage over private ICVs when traveling. As for “Public to TSEV”, this refers to those who are using public transportation but have the potential tendency of pursuing travel comfort with some cost, and once the government subsidy could make it happen that the usage cost of TSEVs reaches the acceptance line of these people, they will transfer to the TSEV section. The flow that comes from “TSEV Users” is “Abandon TSEV”. Since people have chosen TSEV, then the cost is no longer an influencing factor, because the usage price and government subsidy are supposed to be constant in the continuous years. The only factor that does affect TSEV users’ choice is the convenience. With TSEV user numbers still increasing, it means that there will be more people sharing the limited cars, thus leading to a decrease of TSEV convenience. When the value drops down to the bottom line of people’s endurance, they will abandon the TSEV and choose again for the transportation tool. Thus, the temporal accumulation of “TSEV Users”,  $TSEV(t)$ , was calculated using Equation (4), where  $TSEV(0)$  is the number of TSEV users of the initial calculating year. Here, we adopted 736,842 to be the user number of 2017 in Shanghai, according to the user number of EVCARD (time-sharing electric vehicles operated by SAIC) being 730,000, and the market share being 95% in Shanghai. Additionally, the active users only accounted for 15–30% of the membership, which was concluded by a report from Roland Berger over survey. Thus, we set  $TSEV(0)$  to be 165,789, taking an average value of 22.5% to be the active percentage [37,38]:

$$TSEV(t) = \int_0^t \text{Choose TSEV}(t)dt + \text{ICV to TSEV}(t)dt + \text{Public to TSEV}(t)dt - \text{Abandon TSEV}(t)dt + TSEV(0). \quad (4)$$

The box “ICV Users” is the number of small private ICV users. It is an accumulated stock that includes the flows of “Choose ICV”, “ICV to TSEV”, and “Change Vehicle1”. The first one refers to those who were willing to purchase a private vehicle and ultimately chose an ICV. The second one refers to those who had an ICV, but out of operating cost concern, changed to TSEV. The “Change Vehicle1” refers to those who need to change their vehicles because of scrapping. “ICV Users”,  $IU(t)$

was calculated using Equation (5), where  $IU(0)$  is the number of small private ICV owners of the initial calculating year, that is,  $1.9299 \times 10^6$  by the end of 2017, according to the data from the Shanghai Statistics Bureau. Here, it should be mentioned that the number of PEV buyers, 31,454, was excluded.

$$IU(t) = \int_0^t \text{Choose ICV}(t)dt - \text{ICV to TSEV}(t)dt - \text{Change Vehicle1} + IU(0). \quad (5)$$

The stock of “Public Transport Users” represents the number of public transport users. It includes the flows of “Choose Public Transportation” and “Public to TSEV”. “Choose Public Transportation” refers to the natural increase which comes from the population growth. “Public to TSEV” represents the number of users who changed from public to TSEVs out of convenience concern. “Public Transport Users”,  $PTU(t)$ , was calculated using Equation (6), where  $PTU(0)$  is the number of public transport users of the initial calculating year. Since the number of permanent residents in Shanghai was 24,183,300 by 2017, according to the Shanghai Statistics Bureau, we removed the number of TSEV users and private vehicle users also by 2017 to get  $PTU(0)$ , that is, 21,485,058:

$$PTU(t) = \int_0^t \text{Choose Public Transportation}(t)dt - \text{Public to TSEV}(t)dt + PTU(0). \quad (6)$$

In addition to the equations and descriptions of the model structure, the detailed variable settings are shown as follows in Tables 2–4. The initial year of the simulation was set to be 2017.

**Table 2.** Flows, equations, dimensions, and explanations.

| Flow                                  | Equation   | Unit <sup>1</sup> | Explanation  |
|---------------------------------------|--|-------------------|--|
| Annual Population Growth              | =Population of Initial Year $\times$ $((1 + \text{CAGR}^1 \text{ Population Growth})^{\text{Time}} - (1 + \text{CAGR} \text{ Population Growth})^{\text{Time}})$ | Per/Year          | The number of permanent residents increase of the city annually.   |
| Potentially Purchase Private Vehicles | =123,567   | Per/Year          | The number of potential private vehicle buyers every year in Shanghai.<br>For the figures involved, we adopted the average growth from 2010 to 2017 as the number of new private vehicle increase of the city annually [39].<br>* Data type: Integer |
| Choose Public Transportation          | =Urban Population with Traffic Need – Potentially Purchase Private Vehicles  | Per/Year          | The annual increase in public transport section.   |
| Choose PEV <sup>1</sup>               | =(Potential Vehicle Buyers – Choose TSEV) $\times$ PEV Rate  | Per/Year          | The annual increase in PEV users.  |
| Choose TSEV <sup>2</sup>              | =(Potential Vehicle Buyers – Choose PEV) $\times$ Buyer to TSEV Rate   | Per/Year          | The number of people who initially chose TSEV rather than general public section or a private vehicle.   |
| Choose ICV <sup>1</sup>               | =Potential Vehicle Buyers – Choose TSEV – Choose PEV   | Per/Year          | The annual increase in small private ICVs.   |
| ICV to TSEV                           | =ICV Users $\times$ ICV to TSEV Rate   | Per/Year          | The number of people changing from ICVs to TSEVs.  |
| Public to TSEV                        | =Public Transportation Users $\times$ Public to TSEV Rate  | Per/Year          | The number of people changing from general public transport section to TSEVs.  |
| Abandon TSEV                          | =TSEV Users $\times$ Abandon TSEV Rate   | Per/Year          | The number of TSEV users who abandon TSEV and to choose again the transport tool.  |
| Change Vehicle1                       | =ICV Users/Average Life  | Per/Year          | The number of people who change their ICVs per year.   |
| Change Vehicle2                       | =PEV Users/Average Life  | Per/Year          | The number of people who change their PEVs per year.   |

Unit: Per (Person), Dmnl (Dimensionless). <sup>1</sup> CAGR: Comprehensive annual growth rate; <sup>2</sup> PEV: Plug-in electric vehicle; <sup>3</sup> TSEV: Time-sharing electric vehicle; <sup>4</sup> ICV: Internal combustion engine vehicle.



**Table 3.** Auxiliaries, equations, dimensions, and explanations.

| Auxiliary           | Equation   | Unit <sup>2</sup> | Explanation   |
|---------------------|--|-------------------|---|
| TSEV Scale          | $= \text{IF THEN ELSE} (\text{Time} \leq 8, 6000 \times 1.45^{\wedge} \text{Time}, 117,245 + 4000 \times (\text{Time} - 8))$ | Veh/Year          | <p>TSEV Scale is the number of TSEVs, and it changes every year because of the increase.</p> <p>For the figures involved:</p> <ol style="list-style-type: none"> <li>“6000”: The initial TSEV scale in Shanghai by 2017. Supporting evidence: It was reported by news that there were around 5700 TSEV vehicles in Shanghai by 2017 according to EVCARD, accounting for 95% of the market share [37];</li> <li>“1.45”: The increase rate of TSEV from 2017 to 2025. Supporting evidence: i. Shaheen reported that the CAGR of the number of shared vehicles reached 44% in 2012–2014 (rapid growth period) in North America [40]; ii. According to the estimate from the report of Roland Berger on the topic of time-sharing vehicles, the annual CAGR will be maintained at 45% until 2025, an estimate in accordance with the guidance of Shanghai Economic and Information Commission (SEIC) that 20,000 TSEV vehicles should be in operation by 2020. Thus, we adopted the increase rate of 45% from 2017 to 2025;</li> <li>“117,245”: The TSEV scale by 2025. Supporting evidence: It was calculated by the equation “<math>6000 \times 1.45^{(2025 - 2017)}</math>”;</li> <li>“4000”: The increase number of TSEVs from 2025 to the last calculating year. Supporting evidence: For the years after 2025, SEIC claimed that no less than 4000 qualifications would be issued to the TSEVs annually to support the industry.</li> </ol> |
| TSEV Convenience    | $= \text{TSEV Users} / \text{TSEV Scale}$  | Per/Veh           | The convenience of TSEV, measured by the ratio of TSEV users and TSEV scale.  |
| PEV Rate            | $\text{IF THEN ELSE} (\text{Time} \leq 23, 0.016 \times 1.1968^{\wedge} \text{Time}, 1)$                                     | Dmnl              | <p>The rate of potential vehicle buyers who will choose PEVs.</p> <p>For the figures involved:</p> <ol style="list-style-type: none"> <li>“0.016”: The PEV rate of 2017. The figure was obtained from field research;</li> <li>“1.1968”: The CAGR of the PEV rate from now to 2040. Supporting evidence: The Chinese Government is drafting the documents to ban the sales of ICVs. According to the published regional document, the deadline is 2030 for Hainan Province and 2040 for Taiwan. Here, we made an assumption that China will overall prohibit ICV sales by 2040, which means that after 2040, the PEV adoption rate will be 100%. Before that, we took the CAGR of 19.68% to estimate the growth, calculated by the equation “<math>\text{power}((1 - 0.016), 1/(2040 - 2017))</math>”;</li> <li>“23”: The period during which the CAGR will stay as 1.1968. Supporting evidence: It was calculated by the equation “<math>2040 - 2017</math>”.</li> </ol>   |
| ICV to TSEV Rate    | ICV to TSEV Rate Lookup (TSEV Convenience)   | Dmnl              | Here, we give a simulation example of the user choice by piecewise distribution. The equation column represents that there is a function here for each auxiliary, in which the rates will change according to the TSEV convenience. The detailed setting will be explained in Section 4.  |
| Public to TSEV Rate | Public to TSEV Rate Lookup (TSEV Convenience)  | Dmnl              |   |
| Buyer to TSEV Rate  | Buyers choose TSEV Rate Lookup (TSEV Convenience)  | Dmnl              |   |
| Abandon TSEV Rate   | Abandon TSEV Rate Lookup (TSEV Convenience)  | Dmnl              |   |

Unit: Per (Person), Veh (Vehicle), Dmnl (Dimensionless)

**Table 4.** Constants, descriptions, dimensions, and explanations.

| Constant                   | Description           | Unit <sup>3</sup> | Explanation  |
|----------------------------|-----------------------|-------------------|--|
| Population of Initial Year | $2.41833 \times 10^7$ | Per               | The number of permanent residents by the end of 2017 in Shanghai was $2.41833 \times 10^7$ according to the 2018 Shanghai Statistical Yearbook.<br>< <a href="http://www.stats-sh.gov.cn/tjnj/nj18.htm?d1=2018tjnj/C0201.htm">http://www.stats-sh.gov.cn/tjnj/nj18.htm?d1=2018tjnj/C0201.htm</a> > |
| CAGR Population Growth     | 0.007026              | Dmnl              | We acquired the compound annual growth rate with the historical records of permanent residents from 2010 to 2017.  |
| Average Life               | 10                    | Year              | The average life of a vehicle was consulted with the marketing panel [12].   |

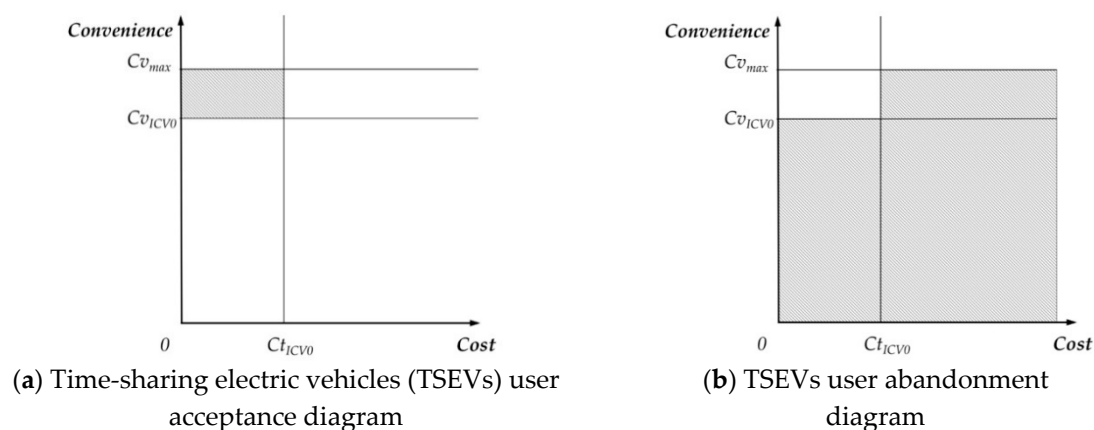
Unit: Unit: Per (Person), Veh (Vehicle), Dmnl (Dimensionless).

We made a simulation with the case of Shanghai as model validation. Thus, the data caliber was Shanghai City.

#### 4. Simulation and Results

##### 4.1. Hypothesis on Parameter Settings

Ning Wang claimed that 42.6% of people who have no private vehicles are willing to use TSEVs rather than the options “Neutral” and “Not Choose”. For people who have one private car, the percentage of willingness is 44.7% [19]. Thus, here, we adopted the percentages to be the acceptance limit for the certain groups. The mutative acceptance rates were further affected by convenience and cost. For the users from certain groups, when the price is lower than the highest acceptable price, and the convenience level is higher than minimum expectation, the user will choose TSEVs, as Figure 2a shows. When the cost exceeds the limit or the convenience level is lower than the bottom line, the user will abandon TSEVs, as Figure 2b shows.

**Figure 2.** User choice based on convenience and cost.

##### 4.1.1. Cost

For the potential TSEV users from three groups, the daily travel expenditure was different. The cost for ICV owners is the daily operation and maintenance fees, including fuel costs. The cost for potential private vehicle buyers additionally includes the vehicle purchase fee, other than the operation and maintenance fees. The cost for public transportation users is the ticket fee. Thus, the successive group order of cost acceptance from high to low is potential private vehicle buyers, private ICV owners,

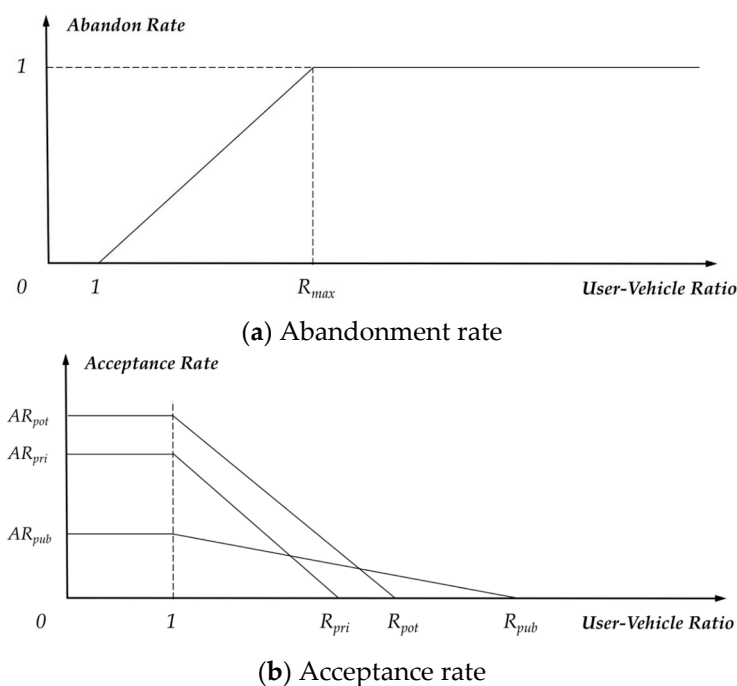
and public transportation users. According to this basis, we built scenarios of government subsidies on user costs, as shown in Table 5.

**Table 5.** Cost acceptance of users in different scenarios of government subsidies.

| Scenario      | Public Transportation Users | Private ICV Owners | Potential Private Vehicle Buyers |
|---------------|-----------------------------|--------------------|----------------------------------|
| S1 (ref): Low | 1%                          | 15%                | 20%                              |
| S2: Medium    | 1.5%                        | 20%                | 26%                              |
| S3: High      | 2%                          | 28%                | 35%                              |

#### 4.1.2. Convenience

The convenience factor will influence the user choice from both acceptance rate and abandonment rate. Tuan reported that a Singaporean company, NTUC Income Car Co-operative Limited, allocated sharing-vehicles based on a ratio of 1:20, which means 4 cars were allocated by the co-operative to serve a total of 80 members [41]. Thus, here, we assumed that the ratio of 1:20 was the service capacity limit. The abandonment rate grows with the ratio of membership–vehicle. Once the ratio reaches the limit, the abandonment rate grows up to 100%. For the acceptance side, since the convenience acceptance of potential users from the three groups differs, the limits are also different, as in Figure 3b.



**Figure 3.** Relationship between abandonment rate and user–vehicle ratio.

Here, we assumed  $R_{pub}$ ,  $R_{pot}$ ,  $R_{pri}$  to be 20, 12, and 5. ( $R_{pub}$ ,  $R_{pot}$  and  $R_{pri}$  refer respectively to User-Vehicle Ratio of public transportation users, potential vehicle buyers, and private vehicle user). Thus the acceptance and abandonment rates were as shown in Table 6, under government subsidies of different levels.

Table 6. Lookups, equations.

| ICV to TSEV Rate Lookup    | Equation  |
|----------------------------|---|
| S1: Low                    | $[(0, 0) - (+\infty, 1)], (0, 0.06705), (1, 0.06705), (5, 0), (1000, 0)$    |
| S2: Medium                 | $[(0, 0) - (+\infty, 1)], (0, 0.0894), (1, 0.0894), (5, 0), (1000, 0)$      |
| S3: High                   | $[(0, 0) - (+\infty, 1)], (0, 0.12516), (1, 0.12516), (5, 0), (1000, 0)$    |
| Public to TSEV Rate Lookup | Equation  |
| S1: Low                    | $[(0, 0) - (+\infty, 0.1)], (0, 0.00426), (1, 0.00426), (20, 0), (1000, 0)$ |
| S2: Medium                 | $[(0, 0) - (+\infty, 0.1)], (0, 0.00639), (1, 0.00639), (20, 0), (1000, 0)$ |
| S3: High                   | $[(0, 0) - (+\infty, 0.1)], (0, 0.00852), (1, 0.00852), (20, 0), (1000, 0)$ |
| Buyer to TSEV Rate Lookup  | Equation  |
| S1: Low                    | $[(0, 0) - (+\infty, 1)], (0, 0.0852), (1, 0.0852), (12, 0), (1000, 0)$     |
| S2: Medium                 | $[(0, 0) - (+\infty, 1)], (0, 0.11076), (1, 0.11076), (12, 0), (1000, 0)$   |
| S3: High                   | $[(0, 0) - (+\infty, 1)], (0, 0.1491), (1, 0.1491), (12, 0), (1000, 0)$     |
| Abandon TSEV Rate Lookup   | Equation  |
| S1: Low                    | $[(0, 0) - (+\infty, 10)], (0, 0), (1, 0), (20, 1), (1000, 1)$              |
| S2: Medium                 | $[(0, 0) - (+\infty, 10)], (0, 0), (1, 0), (20, 1), (1000, 1)$              |
| S3: High                   | $[(0, 0) - (+\infty, 10)], (0, 0), (1, 0), (20, 1), (1000, 1)$              |

## 4.2. Model Validation

### 4.2.1. Direct Structure Tests

The direct structure tests included a structure assessment, parameter assessment, boundary adequacy test, and dimension test.

First, in our model, all the variables and their relationships were natural, or developed on the basis of the previous literature on TSEV adoption, real cases, and data. Therefore, there was basically no possibility that the model we set up could be unreasonable. To further ensure this, we consulted 12 experts in the transportation industry to validate and ensure the rationality of the model, to make it more scientific. It was unanimously approved by the experts. Thus, the model passed the structure assessment, with all the structures and casual loops in the model theoretically and empirically matching the real world. Second, in the parameter assessment, four experts in the area of TSEV and SD modeling were invited to assess and adjust all the constant variables in our model to ensure that these critical variables were reasonable and conceptually matched the real world. Third, all the important model variables were endogenous (which is shown in Tables 2–4), which means that our model passed the boundary adequacy test. Finally, the dimensions of all variables were checked using the “Unit Check” function in VensimPLE, and our model also passed the dimension consistency test.

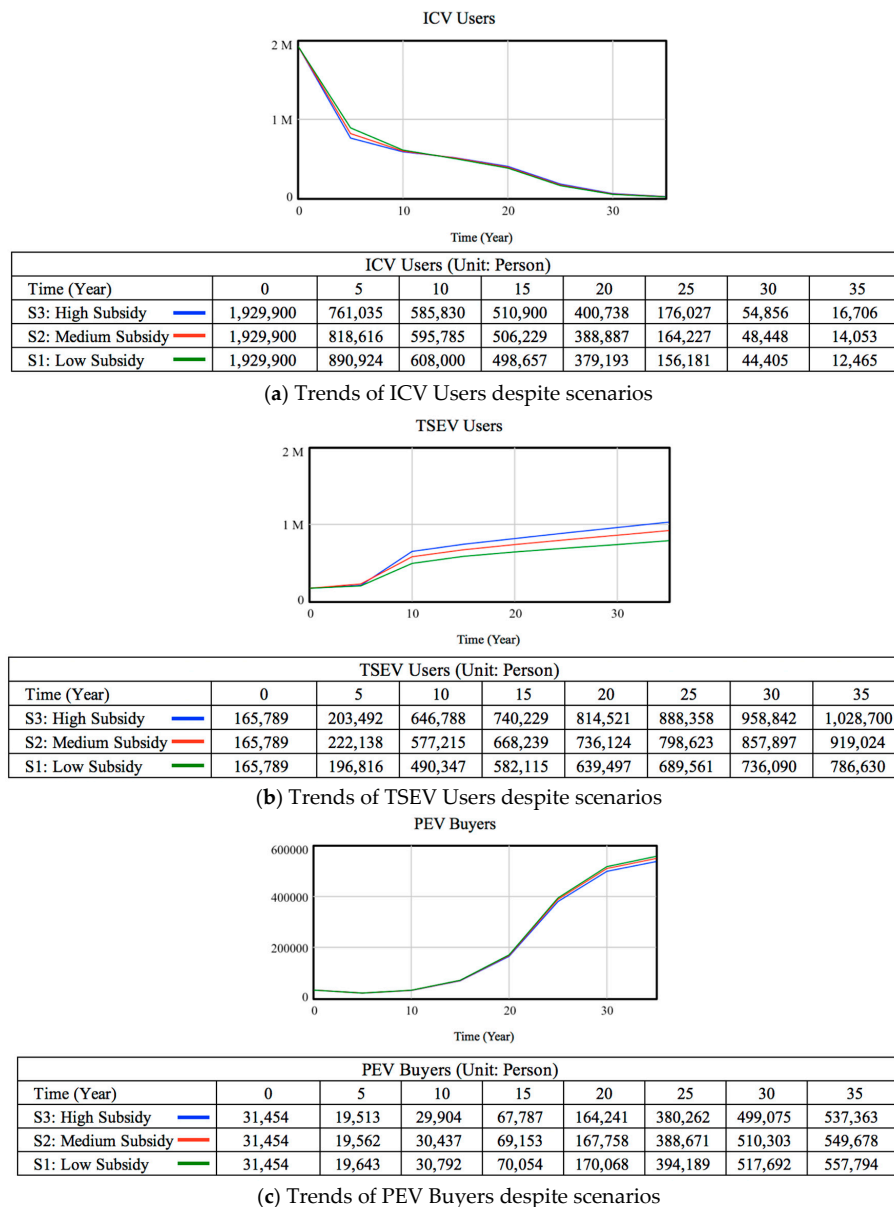
### 4.2.2. Behavior Pattern Test

This test aimed to assess whether the generated behavior pattern of our model was in accord with the pattern in a real situation. We compared the simulation results with the historical data of TSEV users, ICV users, and PEV buyers from 2017 to 2019. The differences between the two patterns of the three samples were all within 15%, and we could conclude that our model passed this test.

## 4.3. Simulation Results

Once the model was verified, the simulation was implemented using the Vensim software (<http://vensim.com/>). The chosen time horizon was 35 years (until 2052) and the initial year was 2017, with a simulation time step equal to one year.

Figure 4 shows that along the simulation time horizon, there were some general trends, despite the scenarios.



**Figure 4.** General trends despite different levels of subsidies.

First, TSEV users will increase slowly in the first five years, and turn to a comparatively sharp increase in the next five years. After 10 years, the number of TSEV users will grow steadily. For the first five years, the TSEV users growing slowly may because of the adoption curve for the new business model and the comparatively imperfect development of infrastructure. In the second stage, that is, the boom years of TSEVs, people may get used to the new business model and the new technology of cleaner energy, and meanwhile, the infrastructure and ancillary services are also mature enough to attract more people. In the long-term, the market will go back into a steady status after self-regulation of supply and demand.

Second, ICV users will decrease sharply in the first five years, and turn to a steady decrease later. Finally, it will drop down to zero because of the policy of banning sales of ICVs. As we can see from the statistics from Shanghai Statistical Bureau, the annual growth in car ownership is dropping these years, maybe because of the terrible peak-hour traffic, the sufficiently convenient urban public transport system, or the license plate limitation policy. The emergence of new energy vehicles and the relevant subsidy on purchases may also attract some people to choose a PEV rather than an ICV, further aggravating the downward trend in the number of ICV users. These reasons may account for



obvious decrease in the first five years. In the second stage, the number of ICV users remains at a comparatively low but steady level. People may get into the transfer in a more normal way after the upsurge fades. With the scrapping of ICVs and the ban on them, the number of users will ultimately drop to zero.

PEV buyers will retain a comparatively slow increase in 20 years because of the adoption curve for the new technology, since the battery's mileage and service life are yet to be improved and verified. In the long-term, there will be an explosive growth after 20 years, maybe also because of the policy of banning sales of ICVs and the maturity of technology and improvement of supporting facilities.

Figure 5 shows that along the simulation time horizon, there are different results under high, medium, and low levels of subsidies.

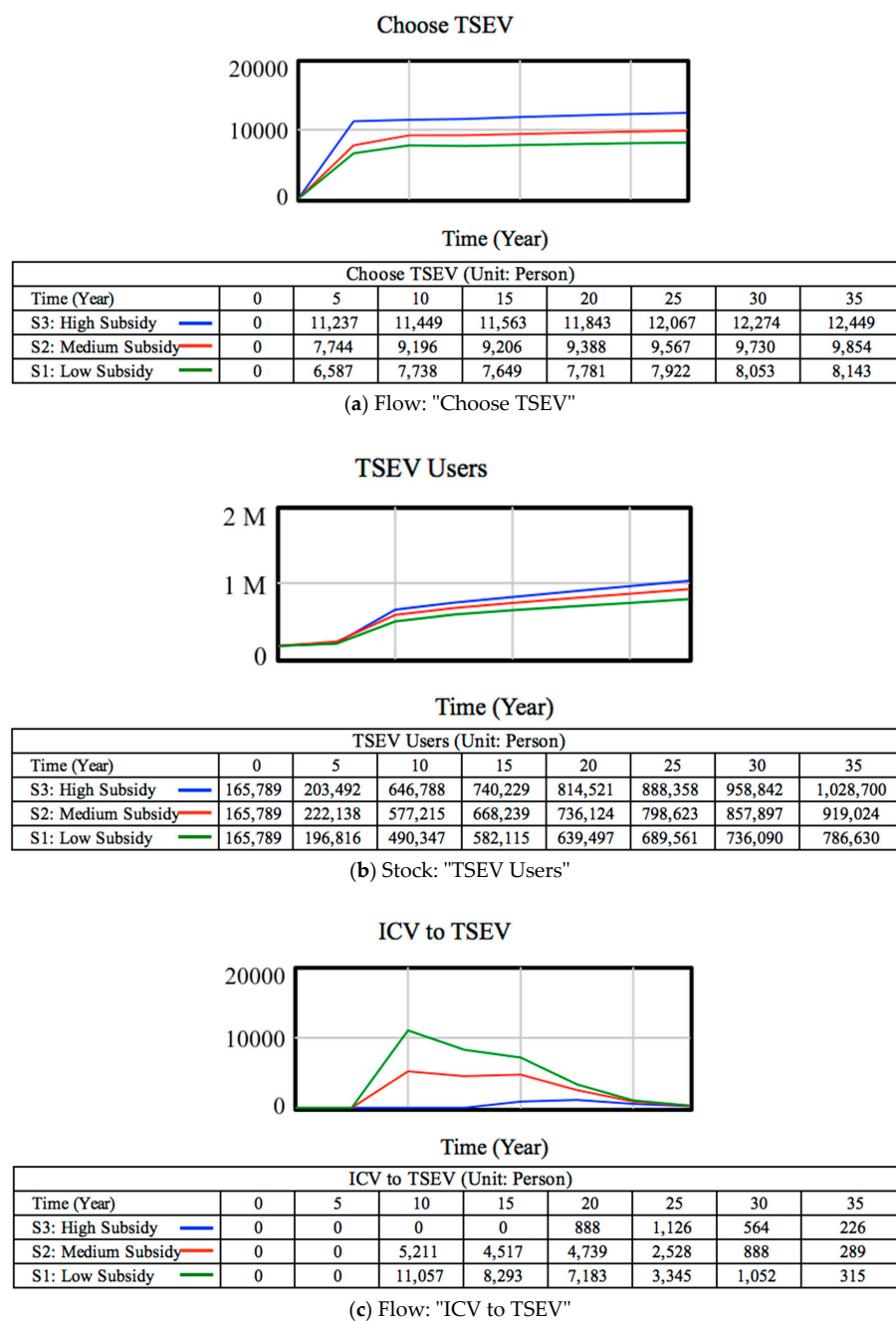
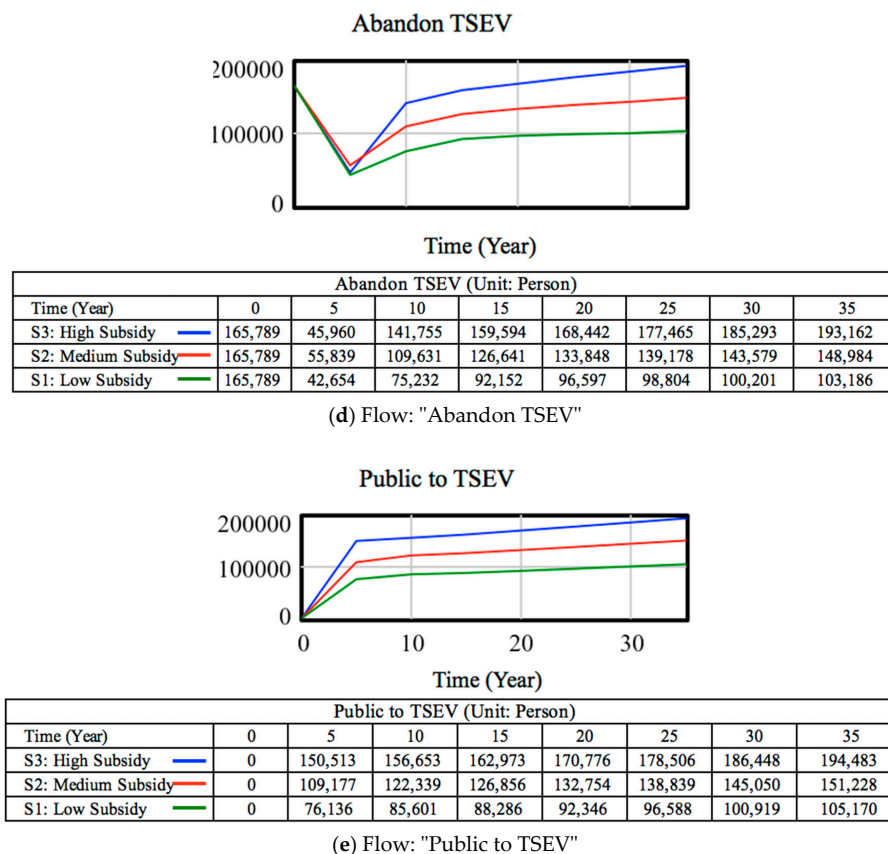


Figure 5. Cont.



**Figure 5.** Simulation results in the scenarios with different levels of subsidies.

From the simulation results shown above, we can make some conclusions about TSEV users under different government subsidies. First, the number of TSEV users is the largest under the high government subsidy model. However, the high subsidy attracts more users from potential private vehicle buyers and public transportation users, instead of private ICVs. Second, it is under the low subsidy scenario that the ICV users are most attracted to TSEVs. Third, since the abandon TSEV rate is only influenced by the convenience factor, we can conclude from the simulation results that the lower appeal from the TSEV to ICV users may be due to inconvenience brought by the big shift from other sectors to TSEVs, except ICV users.

## 5. Conclusions

This study was driven by real cases of Shanghai from the TSEV industries. TSEV adoption and development is a complex dynamic process, in which the government is dedicated to relieving traffic congestion and reducing CO<sub>2</sub> emissions. By taking advantage of cleaner energy and an innovative sharing business model, TSEVs have the potential to become an important member of the public transport system. Considering the fact that driverless technology will be realized in the near future, further helping the development of the sharing business model, it is a certain trend in the future.

In the process of development, the government is to play an important role in guiding the healthy development of the industry. Therefore, it is necessary to make an ex-ante assessment and formulate reasonable policies to help the industry develop in a healthy way and achieve the target effect. The purpose of advocating time-sharing electric vehicles should be to encourage private car users to participate in the sharing mode and use the general public transport tool with clean energy rather than private ones as much as possible, thus slowing down the growth of private cars, alleviating traffic congestion, and reducing CO<sub>2</sub> emission. Therefore, the core target group is private car users of traditional fuel vehicles. Meanwhile, it also functions as a transportation supplement for a small

number of public transport users, but not mainly. To forecast the future development trend and find out a method to determine a proper scale of the subsidy was the research objective.

In this paper, a system dynamic model incorporating scenario analysis was presented to simulate the development process under different levels of user subsidies. From the simulation results and discussion, we can conclude that:

- Despite the subsidy scenarios, the number of ICV users will drop obviously in the short-term of about five years, and go steadily down to zero in the long-term because of the traffic problem, license plate restriction policy, increasingly mature public transportation system, the high subsidy for EVs right now, and the trend of electric vehicles. Conversely, the PEV users will increase slowly in the first five years because of the immature battery technology and the supporting facilities, and the number of PEV users will begin to explode after 10 years;
- The TSEV users will definitely increase under government subsidies, but the scope of the subsidy will influence the percentage of the target group attracted to the TSEV sector. The results suggest that it is under a low subsidy that private internal combustion engine vehicle (ICV) users are attracted to TSEVs the most.

Thus, the simulation and results gave us some subsidy implications that for the specific purpose of attracting private vehicle users to the sharing mode, the government subsidies should be carefully considered and kept at a comparatively low level. It is not the case that the higher the subsidy, the better effect it will achieve; there should be some ex-ante assessment and overall planning in the process of industry development.

For now, the model has been proven to be able to predict the general trend of development and determine the scope of the subsidy. However, it is still just a preliminary model to study the problem of time-sharing electric vehicles, since the model has simplified the user choice based on convenience and cost as a linear problem, and the settings are also assumptions. In future work, focus will be laid on the portrayal of the actual user choice through questionnaires to obtain the joint probability distribution of cost–convenience, and make the study more practical and applicable to the city.

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## Nomenclature

|      |   |
|------|---|
| TSEV | Time-sharing electric vehicle: vehicle  |
| ICV  | Internal combustion engine vehicle, vehicle   |
| PEV  | Plug-in electric vehicle, including plug-in hybrid electric vehicle, battery electric vehicle and fuel cell electric vehicle, vehicle |

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