Article:

Mao, W. orcid.org/0009-0009-8423-4077, Shepherd, S. orcid.org/0000-0002-4420-3382, Harrison, G. orcid.org/0000-0002-4324-772X et al. (1 more author) (2024) Autonomous vehicle market development in Beijing: A system dynamics approach. Transportation Research Part A: Policy and Practice, 179. 103889. ISSN 0965-8564

https://doi.org/10.1016/j.tra.2023.103889

Autonomous vehicle market development in Beijing: A system dynamics approach

Wei Mao[1], Simon Shepherd[2], Gillian Harrison[2], Meng Xu[1*]

[1]School of Systems Science, Beijing Jiaotong University, Beijing 100044, China
[2]Institute for Transport Studies, University of Leeds, Leeds, LS2 9JT, United Kingdom

Abstract

A system dynamics (SD) model for the autonomous vehicles (AVs) market development in Beijing is proposed. The model approaches the vehicle scale evolution with the marketization development of private AVs and shared AVs. Some potential factors such as trust, AV purchase willingness, AV using willingness and shared AV service accessibility, are analyzed. Based on the passenger vehicle situation in Beijing, scenarios from 2014 to 2050 are developed. The base scenario involves the marketization of private AVs and the operation of shared AV fleets, and based on the levels of driving automation, which are divided into six types. The causal feedback relationship and system flow diagram are illustrated. Results show that with the introduction of AVs in Beijing, the number of private vehicles is significantly decreased, which is dependent on the use of shared AVs. To compare with the private vehicle ownership in 2020, the total number of private vehicles has decreased and the number of the private vehicles is over 2.2 million vehicles in 2050. After 2030, the shared vehicle fleet will be dominated by the high-level shared AV and the number of high-level shared AVs is about 2 million. Further, to consider the impact of ride-sharing, the model compares the different attitudes for customers to share their rides and use the shared AV alternative ratio to approach this. The result shows that the extreme ratio will reduce the number of shared AVs, and the fleet size of shared vehicle is about 400,000 vehicles in 2050. For the low ratio scenario, the fleet size of shared vehicle will increase a lot to over 3,186,000 vehicles, which will lead to a large number of cars on the road and thus increase congestion. The introduction of AVs is expected to reduce the number of private vehicles; However, the uncertainty of residents' attitudes towards car sharing will affect the introduction of AVs. At present, the existing policies prefers to limit the number of vehicles by controlling car registration in Beijing. In the future, with the application of AVs, this could be adjusted by encouraging ride sharing, to achieve sustainable urban transport development in Beijing.

Keywords:
Autonomous vehicles; System dynamics; Shared autonomous vehicles; Market share

* Corresponding author
E-mail address: mengxu@bjtu.edu.cn (M. Xu)

1. Introduction

Autonomous vehicles (AVs) are poised to be one of the most disruptive technologies in the current automotive sector. They are expected to make travel safer and more comfortable. High-level AVs are promising to be driven and operated without human control, and can provide services to children, elderly, disabled and anyone who wants to travel by car (Fagnant and Kockelman, 2015; Meyer et al., 2017). Some car manufacturers, e.g., Tesla, GM, Ford, BMW, and companies, e.g., Uber, Google, Baidu, are working on building and testing driverless systems, and pushing these potential operators to commercialize AVs, e.g., the emerging commercial autonomous shared mobility service, ride-hailing (Yao et al., 2020). Some operators are starting to provide test services for AVs. In the next decade, taxi/ride-hailing service is expected to be autonomous (Golbabaei et al., 2021; Haboucha et al., 2017; Tian et al., 2022; Vosooghi et al., 2019). A shared mobility service based on AVs would be able to complement public transport (Fraedrich et al., 2019), like the current taxi and ride-hailing service, or could be the dominant mobility service. By combining AVs with public transport (PT), it is assumed that urban mobility services can be operated with a fleet of "AV+PT" (Xu et al., 2022). For example, the fleet could connect the rail station and provide an efficient shared mobility service in low-density suburban areas (Wen et al., 2018). From the perspective of "real world" mobility service development, regulations and governance of AVs are being refined to accommodate the testing of AVs on the road, which are crucial in preparation for the commercialization of AVs. Considering AVs are expected to lead the next phase of mobility and transport services, their sustainable development plays a key role.

Due to the kind of services that AVs provide, the development of AVs is full of possibilities. Some studies point out that the introduction of AVs will attract more users to drive, increase vehicle miles traveled, affect the operation and development of public transit (Hassan et al., 2019; Mendes et al., 2017), and cause urban sprawl (May et al., 2020). In these studies, the number of AVs influence the development of urban transport. To consider the system dynamics modelling, this paper simulates the development of AVs in Beijing, and assumes that the starting year for the commercialization of AVs is 2024. By considering the driving automation level and ownership, these passenger vehicles are divided into 6 categories. A system dynamics model for the AV market development in Beijing is constructed. This model explores the impact factors on the car market after the introduction of AV, such as technology diffusion time, purchase price, travel cost, and service convenience. Related to the development of driving automation technology, this paper considers the application of private AVs and shared AVs, and simulates the impact of subsidizing AVs. According to the current development and existing regulations of AVs in Beijing, parameters for the AV market development are set firstly in the basic scenario. The number of AVs in Beijing from 2024 to 2050 are simulated, and the changes in the private vehicle market and shared vehicle market are compared. The extended scenarios are set to investigate the impacts of the development of driving automation technology and the application of high-level AVs.

The structure of this paper is organized as follows: Section 2 presents the literature review with respect to AV market development and system dynamic modelling. Section 3 describes the AVs application scenarios and develop an AV market development system dynamics model. Section 4 simulates the AVs market development in Beijing and illustrates the results in multi-scenarios. Section 5 concludes this study.

2. Literature review

In this section, the development of AVs in China, the AV market development and the application of system dynamics modeling in transport studies are discussed.

2.1. The policy for China's AV development

Since 2014, China has been developing driving automation technologies and improving smart city infrastructure, carrying out AV testing, and pushing the commercialization of AVs. Road test licenses have been provided for AVs in 2018, and several leading cities have refined the details of AV road tests in 2019. The city of Wuhan in Hubei province of China has issued the first commercial license plate for AV. Baidu's Robotaxi team has begun trial operations on test roads in Changsha. The opening of road testing and issuing of commercial licenses bring a series of operation and management challenges of AVs (Xue et al., 2020).

Noting that disruptive technologies, mobility service concept innovation, and new mobility infrastructure will challenge existing institutions and regulations (Docherty et al., 2018), some specific measures and regulations have been issued on AV development and applications during the progress of AVs in China. In 2020, the National Development and Reform Commission (NDRC) has proposed the "Intelligent Vehicle Innovation Development Strategy". It was focused on the problem of data security in Intelligent Connected Vehicles (ICVs). ICVs focuses on the use of the Internet to achieve human-vehicle interaction, which is a basis in the realization of autonomous driving. The Ministry of Housing and Urban-Rural Development (MOHURD), together with the Ministry of Industry and Information Technology (MIIT) issued the "Coordinated Development of Smart City Infrastructure and Intelligent Connected Vehicles" to promote the coordinated development of AVs and smart cities. In 2021, the General Office of the State Council issued the plan for the commercialization of AVs in the "New Energy Vehicle Industry Development Plan (2021-2035)". Breakthroughs in key technologies for new energy vehicles will be made in 2025. The safety grade of the car will be improved, and the market competitiveness will be enhanced. It is expected to achieve scale applications within 15 years after road testing of high-level AVs. Specifically, the China Internet Conference (2021) mentioned that the construction of the vehicle networking standard system has been basically completed, and the issued "Management Specification for Road Testing and Demonstration Application of Intelligent Connected Vehicles (Trial)" adds demonstration applications in vehicles with people and loads. It unites multiple authorities to standardize and unify AV testing programs and standards for their application, management, and accident handling. All these regulations and measures provide the basis for the coming commercialization of AVs.

During the market development process of AVs, it is very important to understand the commercial application of AVs, including its impact on the automobile market and urban transport. The research of Conlon and Lin (2019) shows that AV will be expanded on the basis of new electric vehicles (NEVs) in China, and this may change the carbon emission in the urban network. The introduction of low-cost and convenient AVs may lead to a flood of cars, thus hindering the development of public transport (Boesch et al., 2016; Steck et al., 2018). The flood of AVs will not only fail to alleviate traffic congestion but also increase the travel distance of residents and lead to urban sprawl (May et al., 2020). These are not conducive to the sustainable development of urban transport. This forms the motivation of this study in the market development of AVs.

As one of the first demonstration cities, Beijing actively promotes the construction of road testing and an AV application area. Beijing was included in the first batch of demonstration cities for the coordinated development of smart city infrastructure and AVs in May 2021. In December 2018, the "Beijing Intelligent Connected Vehicle Innovation and Development Action Plan (2019-2022)" pointed out that Beijing should be developed into a leading city for the innovation and development of the ICVs industry under the global competitiveness background. In 2021, Beijing set up the first AV test area in China, and issued the "Beijing Intelligent Connected Vehicle Policy Pilot Zone Overall Implementation Plan" to support verified ICVs to take the lead in carrying out trial operation and commercial operation services in the specific area. Specifically, the Beijing Winter Olympics in 2022 achieved an unmanned vehicle torch relay.

At present, the AV test area in Beijing has basically achieved smart infrastructure coverage. The construction of the area has entered the next stage, 3.0. In this stage, the area will expand the coverage of signals to achieve a larger scale of smart road infrastructure and realize high-speed application scenario and business model exploration. This will encourage citizens to trial AV services on the roads. In April 2022, the "Implementation Rules for the Administration of Unmanned Road Testing and Demonstration Applications for Vehicles in the Beijing Intelligent Connected Vehicle Policy Pilot Zone" was issued. It approved Baidu to carry out the manned application of AVs. The trial operation of Baidu's Apollo robotaxi fleet is based on shared, new energy, and autonomous driving travel services. To attract enterprises and institutions in the field of AVs, the municipal of Beijing provides financial support for technological innovation and service exploration of enterprises related to autonomous driving. Considering the incentives in Beijing for AVs applications, AVs will develop rapidly in the city and this may have an impact on urban transport. This paper will discuss the impact of AVs by simulating the sales and use of AV in Beijing.

2.2. AV Market development

Issues on AV market development have already received much attention in existing studies. Bansal and Kockelman (2017) forecast a penetration of Level 4 AV to be 24.8-87.2% in 2045 under different scenario settings with respect to technology price and Americans' willingness to pay. By dividing driving automation technology into six levels, the impact of technology maturity, price, factors on passengers are investigated. The long-term innovation diffusion of AVs is explored in Nieuwenhuijsen et al. (2018). With the system dynamic modelling approach, they estimate the market share for level 4 AVs to be at least 15% in 2030 or 20% in 2050, and the market share will achieve 100% after 2070. Following the market penetration research model in Nieuwenhuijsen et al. (2018), Kaltenhauser et al. (2020) classify driving automation, differs the AV ownership with respect to private and shared, and predicts the market penetration rate of self-driving cars in Germany. This study indicates that the market penetration is expected to start in 2020 and increase quickly so that a 31.5% of market share is reached in 2040. With the introduction of autonomous taxis (ATs), it reduces the vehicle fleet. The vehicles miles travelled will increase and thus, autonomous driving will have a significant effect on congestion. Recently, Litman (2022) assumes that at least 50% of new vehicles will be autonomous before 2045 in the market, and the Level 4 AV fleet will be 30% in 2050 by considering the AVs potential costs and benefits.

Some common factors to investigate the impacts of AVs on travel services include user willingness (Acheampong and Cugurullo, 2019), motivation (Haboucha et al., 2017), travel cost (Bansal and Kockelman, 2017) and travel time (Yap et al., 2016). Moreover, Lavasani et al. (2016) consider the risk-taking, and cultural and lifestyle preferences of the AV market development in the US. The Generalized Bass diffusion modeling approach provides a quantitative analysis of AV market penetration. The prediction shows that the market may reach about 8 million in ten years after AVs become available in 2025, and saturation may occur in 35 years assuming a 75% market scale. Agriesti et al. (2020) assumes three different scenarios and applies optimistic, conservative, and negative scenarios of AV applications and simulate a neighborhood with 100,000 people. They predict that AVs have the potential to impact on government and the municipalities, i.e., traffic congestion and tax revenues may increase, current public transit options become more competitive, parking needs may decrease and roadway infrastructure may need to be adapted.

These researchers consider the inevitability of the commercial development of AVs. However, attitudes towards AVs are different from city to city. One survey shows that cost affects Americans' willingness to pay for an AV (Bansal and Kockelman, 2017). The study of Jing et al. (2019) notices that people's attitude toward AVs in China is more inclined to the technical safety. Therefore, it is necessary to establish the market development of the AVs by simulating residents' choice behavior. This paper hopes to provide a feasible framework for simulating the development of the AV market by building an SD-based AV market development model.

2.3. System dynamic modelling

System dynamics provides a systematic and holistic approach based on the science of complexity, which is designed for handling complex interrelationships among various factors and quantitatively simulate the future development of these systems (Abbas and Bell, 1994). To dealing with a problem with a SD modelling approach, it usually involves the following five steps: 1) System boundary determination in order to clarify the purpose of simulation, find out the key problems, and determine the boundary of the system; 2) Qualitatively analysis and the causal loop diagram determination to identify the elements in the system, define the polarity of arrows and each loop; 3) Quantitative analysis and the stock flow diagram determination to find horizontal variables, auxiliary variables, constants, etc.; 4) System dynamics equations construction to build the SD model, including settings of equations, units, initial values, duration, start and end times, etc.; 5) Model test to build the model in the software, check the model and units, judge whether it conforms to the reality, and then build scenarios.

The urban transport system represents a typical giant complex system, which includes the interrelation among people, mode choices, and transport infrastructure. To understand the transport system, SD modelling method has been used in urban transport studies (Shepherd, 2014), with some studies applying SD models to simulate the evolution process of new mobility services. For example, Sun and Wang (2018) establish a SD model to analyze the competition and substitution between fuel vehicles and new energy vehicles with the approach of the competitive Lotka-Volterra model. The model investigates the evolution of the NEV market and shows the influence of new mobility services in China. Gómez Vilchez and Jochem (2019) review the SD models on simulating vehicle fleet composition, specially, they focus on SD models to simulate the evolution of the battery price in 'automotive industry-oriented' scenario and 'public policy-oriented' scenario, where the electric vehicle market development SD model mostly consider the use of batteries, charging facilities and their prices.

Different from NEV, an SD model of AV pays more attention to the difference of automated drivers in the process of driving. Most of them have considered the impact of AVs on travel choices and travel service, which are based on technological development. Puylaert et al. (2018) use an SD model to explore the impacts of the early forms of AV (i.e., on Level 1, 2 and 3) in the Netherlands. The model can be used to evaluate different scenarios in a short time, and to assess the impact of AVs on mode choice. At present, AV technology has been developed beyond Level 4, this short-term SD model is clearly not enough for the evaluation. The SD models in Kaltenhauser et al. (2020) and Nieuwenhuijsen et al. (2018) have focused on the implementation of driving automation technology on dealing with the market share of AVs, as introduced in Section 2.1. Relative approaches also include the modelling uptake sensitivities of AVs (Harrison et al., 2021; Puylaert et al., 2018) and AV travel impacts (May et al., 2020; Yu and Chen, 2021). May et al. (2020) update the MARS (Metropolitan Activity Relocation Simulator) model and use it to analyze the potential impact of Level 4 & 5 AVs. The MARS model is an SD model integrating transport and land use (Pfaffenbichler et al., 2010). The study of May et al. (2020) focuses on automation of the car fleet based on market share inputs for Level 4 & 5 AVs, and tests ten scenarios in Leeds, UK. The SD model in Yu and Chen (2021) discuss the impact of AV installation and AV usage and propose the importance of traffic law enforcement in forecasting AV usage by analyzing the potential policy implications. These studies raise a concern that the single promotion of private AVs could create a flood of cars, which could eliminate the advantages of public transport and exacerbate traffic congestion and urban sprawl.

The existing SD models for AV consider the impact of the introduction of AVs and establish the model by discussing the attitudes towards AV travel. However, many issues of AV development are not addressed and studies for AV travel impact depend on the development of AV market. This paper attempts to construct an SD model to simulate the market development of AVs. The scenario construction is based on the current situation of Beijing. By considering the driving automation levels and AV service modes, this SD model will analyze the purchase and use needs of residents, and simulate the long-term quantitative development of AVs in the city.

3. AV market development in Beijing

Based on the SD modelling method, this section presents AV market development scenarios, and establishes the AV market development SD model. The model covers AV market development in Beijing from the year of 2014 to 2050.

3.1. Autonomous vehicle development

According to the International Society of Automotive Engineers (SAE) classification standards for AVs and the Automotive Driving Automation Classification of China (GB/T 40429-2021), the development of AVs is divided into six levels. Among them, vehicles for Level 0 have no system driving controls, Level 1-2 AVs require a driver at all times, although the system can be responsible for emergency and auxiliary actions, i.e., steering, breaking and acceleration, Level 3 AVs can perform driving tasks under the supervision of drivers, and Level 4-5 AVs can complete driving tasks themselves.

Based on the six levels, vehicles in this study are divided into two service types (private, shared) referring to Kaltenhauser et al. (2020) and three automation types, i.e., no automation (V_1 and V_2), conditional automation (V_3 and V_4), and high automation (V_5 and V_6). AVs without automation includes those of Level 2 driving automation system and below, which still require a driver at all times. AVs with conditional automation refers to vehicles equipped with a Level 3 driving automation system. AVs with high automation refers to vehicles equipped with a Level 4 or Level 5 driving automation system. Moreover, according to the vehicle ownership, the vehicles are divided into two categories: private vehicles and shared vehicles. Among them, in the stage of no automation and conditional automation, there are drivers in vehicles. While in the stage of high automation, there is no driver in the AVs. These classifications of AVs are illustrated in Figure 1.

According to the planned date and regulations in the "Technology Roadmap for Intelligent Connected Vehicle 2.0" (Ministry of Industry and Information Technology of China, 2021), the year of 2024 is chosen as the starting year for conditional automation of AVs, and 2030 is chosen as the starting time for high automation of AVs.

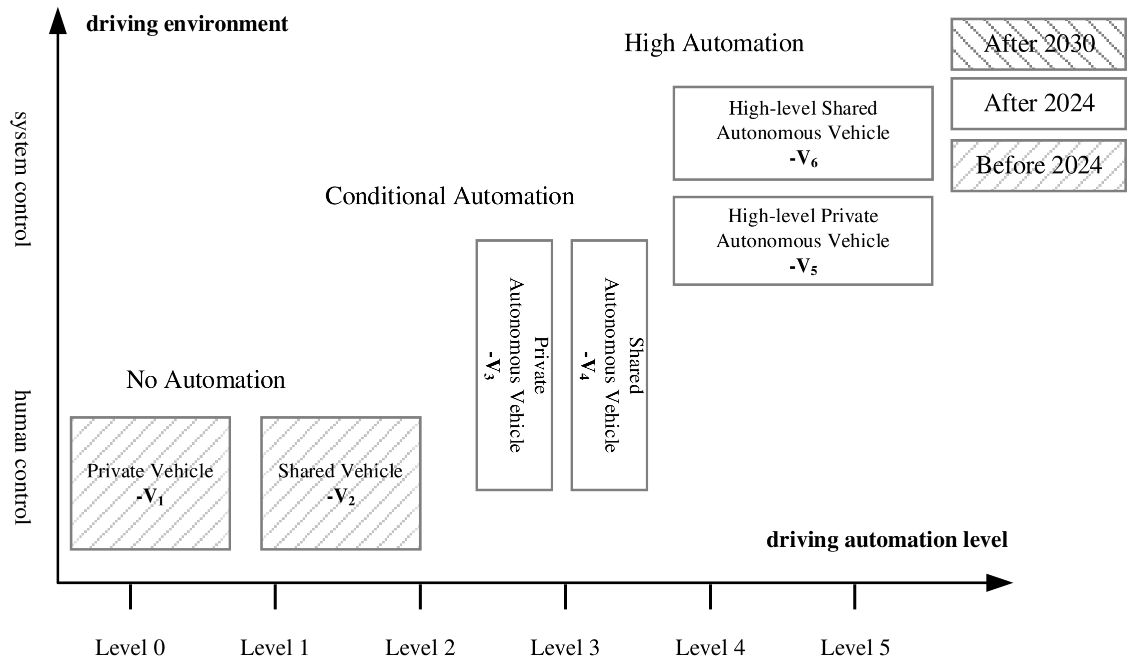


Figure 1. AVs market development and classification

3.2. Modelling process

3.2.1. Causal relationships

Under the framework of SD modelling, causal relationships between system factors are established in a causal loop diagram (CLD). A CLD provides an approach to understanding the complex causal relationships among various variables in the given scenario (Shepherd, 2014). Generally, nodes in the CLD represent variables, which are connected by arrows, which are positive causal links or negative causal links, as shown in Table 1. The symbol "+" represents a positive causal link. It indicates that the arrow points to a variable that increases as the source variable increases (or decreases as the source variable decreases). The symbol "-" represents a negative causal link. It shows the opposite relationship between variables (an increase in the source variable leads to a decrease in the second variable, and vice versa). A causal loop represents a complete closed causal relationship, starting and ending at the same variable, with no variable featured more than once. A Reinforcing feedback loop can enhance the deviation of the variable in the loop (e.g., an increase in a variable will be perpetuated within the loop) and a balancing feedback loop can stabilize the variables in the loop.

Table 1. Symbols in a typical causal loop diagram (CLD)

Symbol	Mean
	Positive causal link: A and B change in the same direction
	Negative causal links: A and B change in the opposite direction
	Reinforcing feedback loop
	Balancing feedback loop

Figure 2 illustrates the flow between the number of cars at different levels of driving automation. There is a balance between the growth of the number of vehicles and the number of scrappage cars.

For example, Loop B1: Conventional vehicle → (+) Car scrap → (-) Conventional vehicle, which represents the increased number of car scrappage will reduce the number of conventional vehicle, also, as the number of conventional vehicles reduce, the number of scrapped cars reduces. Considering the life time, this process has a delay (Hao et al., 2011). It therefore forms three balancing loops, as shown in B1, B2, B3, B5, and B6 in the CLDs (Figure 2 and Figure 3).

Loop B4 in the Figure 2 shows the competition between these two AV technologies (Daziano et al., 2017),

Loop B4: Conventional AV → (+) AV technology → (+) High AV use willingness → (-) Conventional AV. i.e. the development of AV technology will influence the trust and high-AV use willingness respectively, and the number of conditional AV and high-level AV will increase. It forms three reinforcing loops in Figure 2,

Loop R1: AV technology → (+) Trust → (+) Conditional AV → (+) AV technology.

Loop R2: AV technology → (+) Trust → (+) High-level vehicle → (+) AV technology.

Loop R3: AV technology → (+) High-AV use willingness → (+) High-level vehicle → (+) AV technology.

Following the studies, we consider that users will not use AV unless they trust the technology. With the AV technology development, Residents' acceptance of AV will increase (Yu and Chen, 2021) by considering the current incentive policy in AV. Meanwhile, Xie and Liu (2022) pointed out that with the development of driving automation technology and mass production of vehicles, conditional AVs will be squeezed out of the market by high AVs. In this paper, the trust is used to express the acceptance of AV and it will be affected by the development of driving automation technology. Increased trust will reduce the number of conventional vehicles (Serio Agriestib, 2020). Based on the lifetime of the vehicle, users will choose AVs to replace their used vehicles. For example,

Loop R4: AV technology → (+) Trust → (-) Conventional vehicle → (+) Car scrap → (-) Conditional AV → (+) AV technology.

Loop R5: AV technology → (+) Trust → (-) Conventional vehicle → (+) Car scrap → (-) High-level AV → (+) AV technology.

These two loops in Figure 2 shows the substitution relationship between conditional/high-level AVs and conventional vehicles.

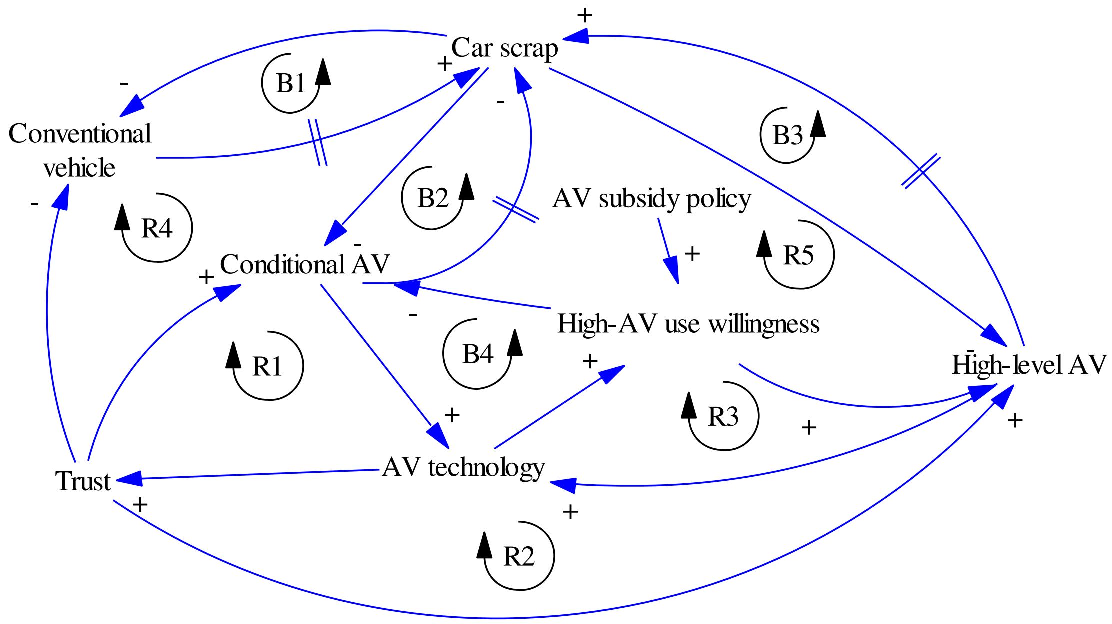


Figure 2. Causal-loop diagram describing the driving automation technology development

In this study, the AV market development model is divided into two modules, i.e. the private vehicle module and the shared vehicle module, to distinguish service types of vehicles in the market, as shown in Figure 3.

The private vehicle module simulates the growth of conventional vehicles and autonomous vehicles. This sub-module uses vehicle ownership to measure the purchase, user change and scrapping of AVs in different levels (Acheampong and Cugurullo, 2019; Hudson et al., 2019; Lavieri and Bhat, 2019). B5 and B6 are similar with the B1, B2 and B3 in Figure 2.

The purchase willingness of the residents will determine whether they will buy a private vehicle. High-level shared AV operation will provide private vehicle users with a new option. However, there is a limit to the number of high-level shared AVs. It cannot meet the needs of all residents in a short time (Kaplan et al., 2019). This forces some residents to use both shared and private vehicles. The model thus sets a parameter to measure the service accessibility of the shared vehicle. Considering the diffusion law of autonomous driving technology and the market penetration of new technologies (Kaltenhauser et al., 2020; Kaplan et al., 2019), this study sets a diffusion time to measure the number of AVs from introduction to saturation. It assumes that technology diffusion in Beijing will take 15 years. For diffusion time in Beijing, it considers the positive effects of policy and the fact that most drivers are between the ages of 18 and 70 (Lee and Kockelman, 2022). After 15 years, the number of shared AVs could respond to the needs of all the residents of a city.

As the shared AV service accessibility increases, it implies that more customers need to be serviced by shared AVs and more shared AVs need to be reach the AV service accessibility before,

Loop B7: Shares AV service accessibility → (+) Users of shared AV → (-) Shares AV service accessibility.

Loop B8: Shared vehicle → (+) Shared vehicle user change → (+) User of shared AVs → (-) Shares AV service accessibility → (-) Private vehicle → (+) Car scrap → (-) Shared vehicle.

Loop B9: Shared vehicle → (+) Shared AV service accessibility → (-) Private vehicle → (+) Car scrap → (-) Shared vehicle.

Loop B8 and B9 are similar, both of them describe the balance between the private vehicle and shared vehicle by using “Shares AV service accessibility” and “Shared vehicle user change”. Considering the shared AV will serve more than one person per day, the factor “Shared vehicle user change” measures the number of users that a shared AV can serve per unit time.

With the increase of the number of shared vehicles, there will be enough shared vehicles to meet the demand. It will attract more users of V_6. This causes users who choose shared vehicles to give up their private cars. This will be one of the reasons for the decrease in the number of private vehicles and the increase in the number of shared vehicles. More users will convert to AV users inside the shared vehicles and this will increase the number of shared AV users, forming the R6 in the Figure 3,

Loop R6: Shared vehicle → (+) Shared vehicle user change → (+) User of shared AVs → (+) Give up own car → (-) Private vehicle → (+) Car scrap → (-) Shared vehicle.

The shared vehicle module simulates the operations of taxis, ride-hailing, and shared AVs in Beijing. Considering the growth of shared vehicle, this study assumes that shared vehicles are operated by enterprises. The scale of shared vehicles will be affected by their operation costs. The authorities can impact on the number of shared vehicles (Contreras and Paz, 2018; Docherty et al., 2018; Wang et al., 2018). However, with the operation of V_6, the driver is no longer needed. Therefore, the operation company will have a preference to choose high level shared AVs. There will also be a share of users of conventional shared vehicle moving to shared AV users. More users will become V_6 users. This will increase the demand for high level shared vehicles. Loop R7 describes this situation in the Figure 3,

Loop R7: Shared vehicle → (+) Shared AV service accessibility → (+) User of shared AVs → (+) Shared vehicle.

Loop R8 is similar to R7. With the number of shared vehicles increases, the shared AV service accessibility will increase and thus be more attractive to shared AVs users. However, with the number of shared AVs users, the shared AV service accessibility may decrease.

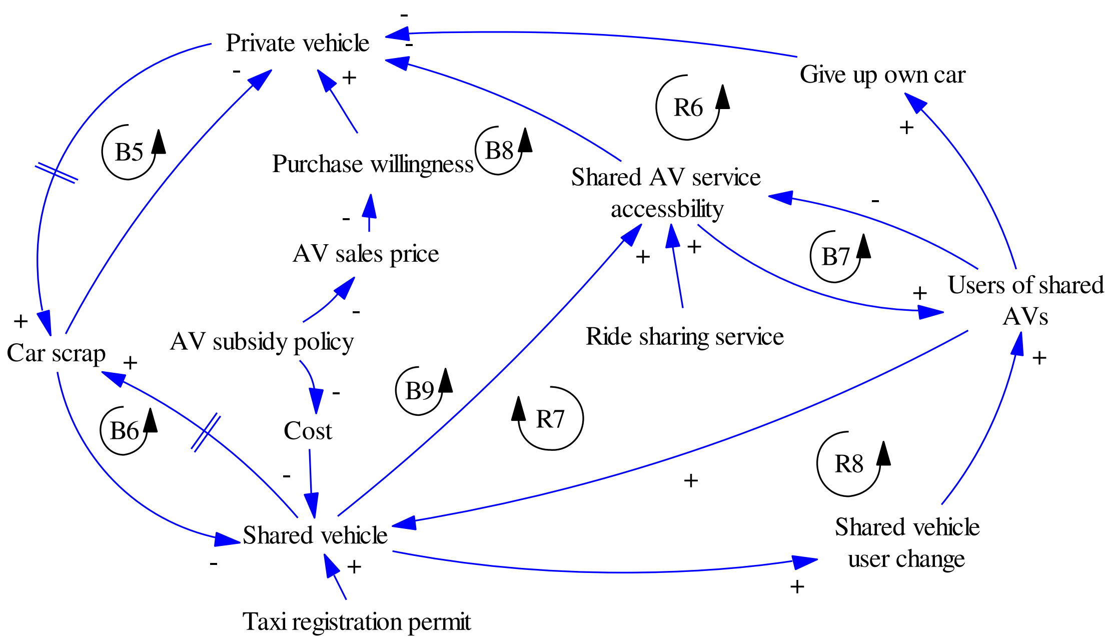


Figure 3. A CLD for the market development of AVs in Beijing

Considering the uncertainty of the AV introduction, the model uses the subside policy to describe the motivation of the AV use. The subsidy policy will change the sales price of AV, and it would affect the purchase willingness of private AV and operation cost of shared AV.

3.2.2. System stock flow diagram in Beijing

The proposed CLDs represent the AV market development in Beijing, which is based on the development of driving automation technology and mobility services. According to the CLDs shown in the Figure 2 and Figure 3, the corresponding stock and flow diagram (SFD) is illustrated in the **Appendix A**, which demonstrates the interactions among given variables, and the details will be given in the Section 3.2.2.1 and the Section 3.2.2.2. Table 2 summarizes the symbols used in the model, and corresponding equations in the SFD are listed in the **Appendix B**.

Table 2. Variables description

Symbol	Unit	Description
TD	Year	CONSTANT variable: constant The number of duration years covering from conditional automation to high automation.
TM	Year	CONSTANT variable: The diffusion years required for market development of shared AVs from emergence to maturity.
TP	Year	CONSTANT variable: Years for private scrapped vehicles.
TS	Year	CONSTANT variable: Years for shared scrapped vehicles.
N_i^t	Vehicle	STOCK variable: Number of the vehicles of type $i, i = 1,2,3,4,5,6$ in the year of t.
NPV^t	Vehicle	STOCK variable: Number of the private vehicles in the year of t.
r	Person	CONSTANT variable: Number of users serviced by one shared AV.

$NU6^t$	Person	STOCK variable: Number of V_6 users in the year of t.
P^t	Person	AUXILIARY variable: The adult population older than 20 years old.
fu^t	Dmnl*	AUXILIARY variable: Factor of high-level AV using willingness in the year of t.
ft^t	Dmnl	AUXILIARY variable: User trust factor for AV technology in the year of t.
fp_i^t	Dmnl	AUXILIARY variable: Factor of AV purchase willingness for the type of vehicle $i, i = 3{,}5$ in the year of t.
gr_i	1/year	AUXILIARY variable: The base growth rate for the vehicle of type $i, i = 1{,}2{,}3{,}4{,}5$.
$u6^t$	Persons/year	RATE variable: Number of potential V_6 users in the year of t.
NV_i^t	Vehicle/year	RATE variable: The number of new registered vehicles of type $i, i = 1{,}2{,}3{,}4{,}5{,}6$ in the year of t.
PV^t	Vehicle/year	RATE variable: The number of new registered private vehicle in the year of t.
R_i^t	Vehicle/year	RATE variable: The number of scrapped vehicles of type $i, i = 1{,}2{,}3{,}4{,}5{,}6$ in the yearof t.
RPV^t	Vehicle/year	RATE variable: The number of reduce of scrapped private vehicle in the year of t.
sr_i	1/year	CONSTANT variable: Scrap rate of the type of vehicle $i, i = 1{,}2{,}3{,}4{,}5{,}6$.
uw	1//year	RATE variable: The increase rate of high-level AV using willingness.
pw	1/year	RATE variable: The increase rate of AV purchase willingness.
sa^t	Vehicle/person	AUXILIARY variable: The service accessibility of shared AV in the year of t.
sp_1^t	Dmnl	CONSTANT variable: Subsidy policy for partial AV in the year of t.
sp_2^t	Dmnl	CONSTANT variable: Subsidy policy for high-level AV in the year of t.
ω^t	Dmnl	AUXILIARY variable: The probability that users choose car to travel in the year of t

* Dmnl means Dimensionless

3.2.2.1. Private vehicle module

The private vehicle module accounts for the private AV development in Beijing, which includes the private vehicles without automation V_1, the private vehicles with conditional automation V_3, and the private vehicles with high-level automation V_5. The module considers the purchase willingness of residents, and the impact of encouraging private owners for giving up their cars and using the shared vehicles (Menon et al., 2018).

$$NPV^t = \begin{cases} NPV^t, & t = 2014 \\ NPV^{t-1} + PV^t - RPV^t, & t \in [2015{,}2050] \end{cases} \tag{1}$$

The number of private vehicles, NPV^t in Eq.(1), is used to estimate the number of private vehicles still in use in the year of t, the number of new registered private vehicles in the year of t, PV^t, describes the sales of private vehicles as inflow, the number of reduced of private vehicles in the year of t, RPV^t, describes the number of vehicles reduced due to scrapping as outflow. The stock of private vehicles is affected by the change of sales and scrap. The year t sets from 2014 to 2050, and the initial value of N_i^{2014} is defined in the Section 4.1.

$$PV^t = NV_1^t + NV_3^t + NV_5^t \tag{2}$$

$$RPV^t = R_1^t + R_3^t + R_5^t \tag{3}$$

The number of new registered private vehicles, PV^t in Eq.(2), summarizes the number of new registered private vehicles of type i in the year t, NV_i^t, $i = 1,3,5$. And the number of reduced of private vehicles, RPV^t in Eq.(3), summarizes the number of reduced private vehicles of type i in the year t, R_i^t, $i = 1,3,5$.

$$R_i^t = N_i^t * sr_i \ , i = 1,2,3,4,5,6 \tag{4}$$

The number of scrapped vehicles of type i, R_i^t in Eq.(4), are determined to calculate the number of reduced of vehicles to a certain proportion, sr, The scrappage rate of the vehicles type i, sr_i takes the reciprocal of years for private scrapped vehicles, the number of the vehicles of type i in the year of t, N_i^t saves the total number of vehicles of type i, i =1,2,3,4,5,6, and its values changes with iteration.

$$NV_i^t = NPV^t * gr_i \ , i = 1,3,5 \tag{5}$$

The number of new registered private vehicles of type i, NV_i^t in Eq.(5), uses the number of private vehicles in the year of t, NPV^t and the annual growth rate of the vehicles type i, gr_i to define the sales of V_i, $i = 1,3,5$,in the year of t.

$$N_i^t = \begin{cases} N_i^t, & t = 2014 \\ N_i^{t-1} + NV_i^t - R_i^t, & t \in [2015,2050] \end{cases}, \ i = 1,2,3,4,5,6 \tag{6}$$

The number of the vehicles of type i, N_i^t in Eq.(6), depends on the number of new registered private vehicles of type i, NV_i^t and the number of reduced private vehicles of type i, R_i^t, $i = 1,2,3,4,5,6$.

$$gr_1 = (\alpha + sr_1) * (1 - ft^t) * \left(1 - \sum_{i=3,5} fp_i^t\right) * (1 - sa^t * fu^t) \tag{7}$$

$$gr_3 = (\alpha + sr_3) * ft^t * fp_3^t * (1 - fu^t) * (1 - sa^t) \tag{8}$$

$$gr_5 = (\alpha + sr_5) * fp_5^t * fu^t * (1 - sa^t) \tag{9}$$

The growth rate of each type of private vehicle, $gr_i, i = 1,3,5$, in Eq.(7), Eq.(8), and Eq.(9), are the rate to simulate the loss of existing users and the conversion of potential users. In the process of iteration, the change of trust, purchase willingness and use willingness will impact gr_i. The parameter sr_i represents the scrappage rate of the vehicles type $i, i = 1,3,5$, the parameter ft^t represents user trust factor for AV technology in the year of t, the parameter fp_i^t is factor of AV purchase willingness for the type of vehicle $i, i = 3,5$, the parameter sa^t means the service accessibility of shared AV in the year of t, and the parameter fu^t represents high-level AV using willingness in the year of t.

$$sr_1 = sr_3 = sr_5 = \frac{1}{TP} \tag{10}$$

The scrappage rate of the vehicles type $i, i = 1,3,5$, sr_i, in Eq.(10), takes the reciprocal of years for private scrapped vehicles, TP.

$$fp_3^t = sp_1^t \times \begin{cases} ft^t \times (1 - sa^t), & t \in [2014,2029] \\ MAX(0, ft^t - fp_5^t), & t \in [2030,2050] \end{cases} \tag{11}$$

$$fp_5^t = \begin{cases} fp_5^t, & t \in [2014,2024] \\ fp_5^{t-1} + pw^t * sp_2^t, & t \in [2025,2050] \end{cases} \tag{12}$$

The model sets the parameters fp_3^t in Eq.(11), and fp_5^t in Eq.(12), to represent AV purchase willingness for the V_3 and V_5. The willingness will increase with the growth of user trust, however, not all users will buy AVs. The increase rate of AV purchase willingness, pw^t is the percentage to define the potential high-AV users to buy a high-AV in the year of t. The parameter pw^t considers the city development in the SD model.

The implementation of subsidy policy for partial AV, sp_1^t, and the implementation of a subsidy policy for high-level AV, sp_2^t, shows the implementation of the AV policy in numerical terms. For example, the value of sp_1^t and sp_2^t is set be "0" or "1" to consider uncertainly of the AV subside in the city. The value "1" represents the city will provide the subsidy and the value "0" means there is no subsidy.

$$fu^t = \begin{cases} fu^t, & t \in [2014,2024] \\ fu^{t-1} + uw^t \times sp_2^t, & t \in [2025,2050] \end{cases} \tag{13}$$

The influence from the subsidy policy for high-level AV, fu^t in Eq.(13), approaches the influence from the subsidy policy for high-level AV. The parameter uw represents the increase rate of AV purchase willingness.

$$sa^t = \begin{cases} \frac{N_4^t * r}{P^t * \omega^t}, & t \in [2014,2029] \\ \frac{1}{2} * \left\{ \left[cos \frac{(t-2024-TD+1)*\pi}{TM} \right] + 1 \right\}, & t \in [2030,2045] \\ \frac{(N_4^t + N_6^t) * r}{P^t * \omega^t}, & t \in [2046,2050] \end{cases} \tag{14}$$

Before 2030, the shared AVs have not formed a fleet, and the number of AVs is small and the service accessibility is low, which could be close to 0. After 2030, the utility of private vehicles is close to the shared vehicles under high driving automation technology, meaning a high service accessibility. The model assumes that the diffusion rate of V_6 presents a curve trend and uses $cos(\cdot)$ function to simulate the introduction of high-level shared AV during the rapid growth of the AVs (Kaltenhauser et al., 2020, Kaplan et al., 2019). The service accessibility of shared AV in the year of t, sa^t, is defined in Eq.(14), and its curve from 2015 to 2050 is shown in Figure 4. It shows that the value of sa^t is close to "0" before 2024 or limited to "1" after 2045. The model use $cos(\cdot)$ function to simulate the change in the demand for shared AV travel from 2024 to 2045, while assuming that shared AV operators continue to increase their investment in response to the demand. And this process will be implemented through SD approach. The notations TD and TM respectively represent the introduction delay between different levels of AVs and the diffusion year required for AV technology from emergence to maturity. The parameter r is set to calculate the number of users serviced by one shared AV, the notation P^t defines the adult population older than 20 years old, and the parameter ω^t defines the probability that users choose private vehicle in the year of t.

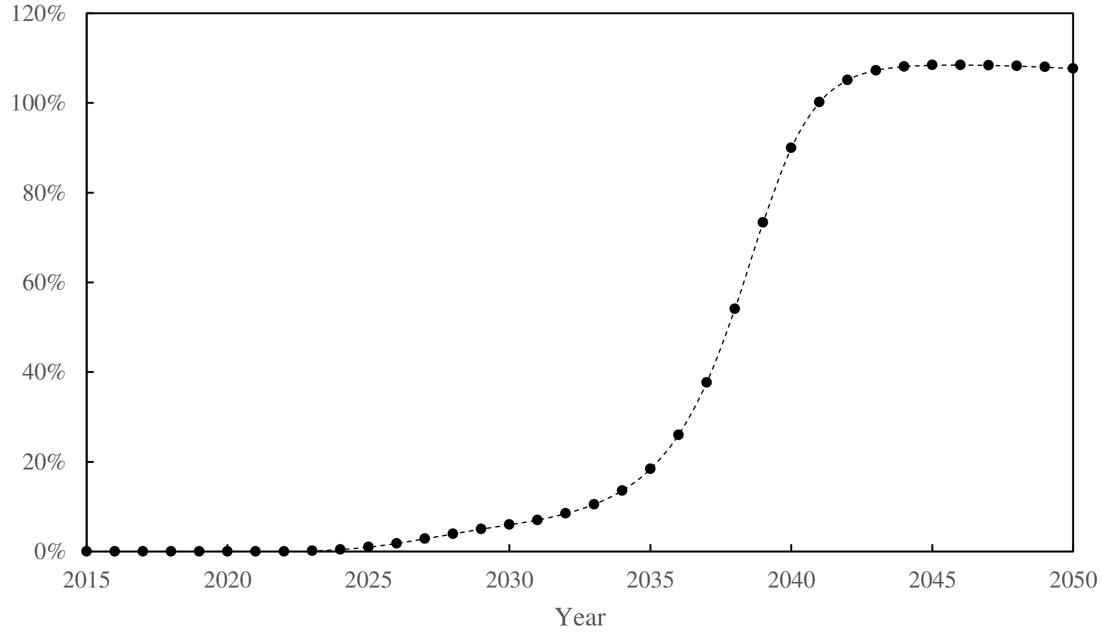


Figure 4. The service accessibility of shared AV in the year of t. The ordinate represents the ratio between the shared AV in operation and the demand for shared AV in the city.

3.2.2.2. Shared vehicle module

The shared vehicle module simulates the shared AV development in Beijing, which includes the shared vehicle without automation V_2, the shared vehicle with conditional automation V_4, and the shared vehicle with high-level automation, V_6. To consider the incentives and measures in the process of AV marketization, the shared mobility service by V_2 will be replaced by the advanced shared AVs, i.e., V_4, V_6, which will also influence the annual registration number for the vehicles of V_2.

The following equations introduce the number of new registrations of shared vehicles of type $i, i = 2,4,6$, NV_i^t, respectively.

$$NV_2^t = N_2^t * gr_2 \quad (15)$$

$$gr_2 = (\beta + sr_2) * (1 - ft^t) * \left(1 - \sum_{i=3,5} fp_i^t\right) * (1 - fu^t * sa^t) \quad (16)$$

The number of new registrations of V_2, NV_2^t in Eq.(15), will decline with the introduction of AVs. Considering the growth in number of V_2, the model sets an initial share of shared vehicles, β. The growth rate of V_2, gr_2 in Eq.(16), is set referring to the growth rate of private vehicle, gr_i, $i = 1,3,5$.

$$NV_4^t = MAX(0, N_2^{t-1} - N_2^t) + N_4^t * (\beta + sr_4) * ft^t * \left(1 - \sum_{i=3,5} fp_i^t\right) - N_4^t * fu^t \quad (17)$$

$$sr_2 = sr_4 = \frac{1}{TS} \tag{18}$$

Similarly, the model calculates the number of new registrations of V_4, NV_4^t in Eq.(17), with the initial share of shared vehicles, β. The model assumes that the scrapped V_2 will be replaced by V_4 at the beginning of AV application. In the period of high AV promotion, some V_4 will upgrade to V_6, and takes the reciprocal of years for shared scrapped vehicles sr_i in Eq.(18), and it is the inflow of N_4^t. The *MAX ()* function is used to ensure the quantity is positive.

$$NV_6^t = N_4^t * fu^t + \frac{u6^t}{r} + R_6^t \tag{19}$$

The number of new registrations of V_6, NV_6^t in Eq.(19), considers the following situation that the lower-level AVs, V_4, will be upgraded to higher-level AVs, V_6, and the value of NV_6^t also connects to changes in demand from car-sharing users. The number of potential V_6 users, $u6^t$, is used to save the number of new high-AV users in the year of t, the parameter, r records the number of users serviced by one shared AV, and the ratio of $u6^t$ to r gives the number of shared high-AVs that the city need.

$$NU6^t = \begin{cases} 0, & t \in [2014,2029] \\ NU6^{t-1} + u6^t, & t \in [2030,2050] \end{cases} \tag{20}$$

The number of V_6 users in the year of t, $NU6^t$ in Eq.(20),will continue to increase with the introduction of high-level AVs. There is no outflow from the stock of V_6 users.

$$u6^t = ft^t * fu^t * MAX(-0.05, 1 - fp_5^t) * sa^t * (P^t * \omega^t - NU6^t) \tag{21}$$

The number of potential V_6 users in the year of t, $u6^t$ in Eq.(21), increase from the trust in AV technology and the lower cost in AV travelling. The product of the population older than 20 years old, P and the probability that users choose car to travel in the year of t, ω^t calculate the potential car users. The model combines parameters, i.e., user trust factor for AV technology ft^t, high-level AV using willingness fu^t,V_5 purchase willingness fp_5^t and shared vehicle service accessibility sa^t.

4. Case study

According to the proposed SD model in the Section 3, this section provides further details on implementing the AV market development in Beijing.

4.1. Data sources

As introduced, the process begins in the year 2014. To consider the development of AVs in Beijing, the starting year of the introduction of AVs is set as 2024, and the high-level AVs will appear in 2030.

The settings of parameters in the SD model are summarized in Table 3. It's noted that the shared vehicle model doesn't categorize taxi and ride-hailing. However, taxi serves passengers while operating, and the ride-hailing serves passengers through an app that allows passengers to search for a car and determine the pickup spot. The current taxis service in Beijing is basically compatible with online ride-hailing travel functions. Therefore, the shared vehicle model integrates taxis and ride-hailing. In Beijing, the number of taxis has been stable at 67,546 since 2017, which depends on the regulation of the government. To prevent traffic congestion caused by ride-hailing, the introduction of ride-hailing vehicles is relatively strict, and taxis in Beijing are promoting to be compatible with ride-hailing. These have been considered while developing the shared vehicle model.

The parameter TD defines the number of duration years covering from conditional automation to high automation and its' value is set as six years. Considering the scrapping standards in Beijing, the years of vehicles scrapped TP and TS are set. As a new technology, it takes time for AV to emerge and be accepted, and this process can be described by the technology diffusion function (Kaplan et al., 2019). The parameter TM sets the diffusion years required for market development of shared AVs from emergence to maturity.

The number of private vehicles at the initial year NPV^{2014}, and the number of shared vehicles of type i, $N_i^{2014}, i = 1,2,3,4,5,6$ are set, which are based on the Beijing Statistical Yearbook 2014 from the Beijing Municipal Bureau Statistics. Since there are no AVs in 2014, the initial value of i, $N_i^{2014}, i = 3,4,5,6$ and the number of V_6 users $NU6^{2014}$ are 0. Meanwhile, the value of NPV^{2014} is the same as the value of N_1^{2014}, and this situation will continue until the appearance of V_3. The initial share of private vehicles and shared vehicles are calculated by the number of vehicles. For example, the initial share of private vehicles, α, is calculated based on the number of private vehicles from 2014 to 2020 in the statistics report. It determines the average growth rate of private vehicle before the introduction of AV. With the introduction of AV, the initial share will be used as a reference, and the growth rate of each type of private vehicle is more influenced by parameters i.e., trust, purchase willingness. Through the ride-hailing registration data and related Policies in Beijing from 2014 to 2020, it shows that the number of V_2 barely increased compared with private vehicles. Based on this, the initial rate of shared vehicles, β, is set.

The parameter r describes the number of users that can be serviced by one shared AV for one day. If all the cars in a city are replaced with shared AVs, the number of vehicles can be reduced to 10 times while ensuring the travel demand of residents (Spieser et al., 2014), however, Levin et al. (2017) considering the commuting peak and shared AV distribution, found that one shared AV could replace at most 3.6 personal vehicles, and it differs from the scenario in Fagnant and Kockelman (2015), which required far more SAVs than 1 per 9.3 travelers. Based on these data, the range of r is between 4 and 10. The model assumes that shared vehicles may provide the service of short-term rental and ride-sharing. The high-level AV will control by the system and there is no driver in the vehicle. The customers can share rides with others, and the value of r sets 6 as shown in the Table 3.

The parameters pw and uw are used to describe the annual increase in AV purchase willingness and annual increase in high-level AV using willingness, respectively. The model assumes that users may not have the willingness to purchase V_5 until the introduction of high-level AVs, sets the value of pw as 4% and thus the value of fp_5^{2050} will be 80% in 2050. The set for the value of uw is similar and the value of uw is set as 4% to make sure the value of fu^{2050} will be 80% in 2050.

The parameter ft^t defines the user trust for AV technology in the year of t. The user trust for AV technology will increase before the introduction of AV. The model assumes the maximum value of the parameter ft^t, the maximum value may less than 100% and the value of ft^t is shown in the following Figure 5.

Table 3. Parameters settings

Name	Value	Explanation/Source	Unit
TD	6	Introduction year difference between AVs and high-level AVs	year
TM	15	Kaplan et al. (2019); Kaltenhauser et al. (2020)	year
TP	15	Compulsory scrapping standards for private vehicles in Beijing	year
TS	6	Compulsory scrapping standards for service vehicles in Beijing	year
NPV^{2014}, N_1^{2014}	4,372,000	Beijing Statistical Yearbook 2014	vehicle
N_2^{2014}	67,546	Beijing Statistical Yearbook 2014	vehicle
N_i^{2014}, $i = 3,4,5,6$	0	The initial value set by the model	vehicle
$NU6^{2014}$	0	The initial value set by the model	person
α	3.5	Beijing Statistical Yearbook 2014-2020	%
β	0.5	Beijing Statistical Yearbook Ride-hailing registration data and related Policies	%
r	6	The value ranges from 4 to 10 (Fagnant and Kockelman, 2014; Levin et al., 2017; Spieser et al., 2014).	person/vehicle
pw,uw	4	The average increase rate set by the model	%

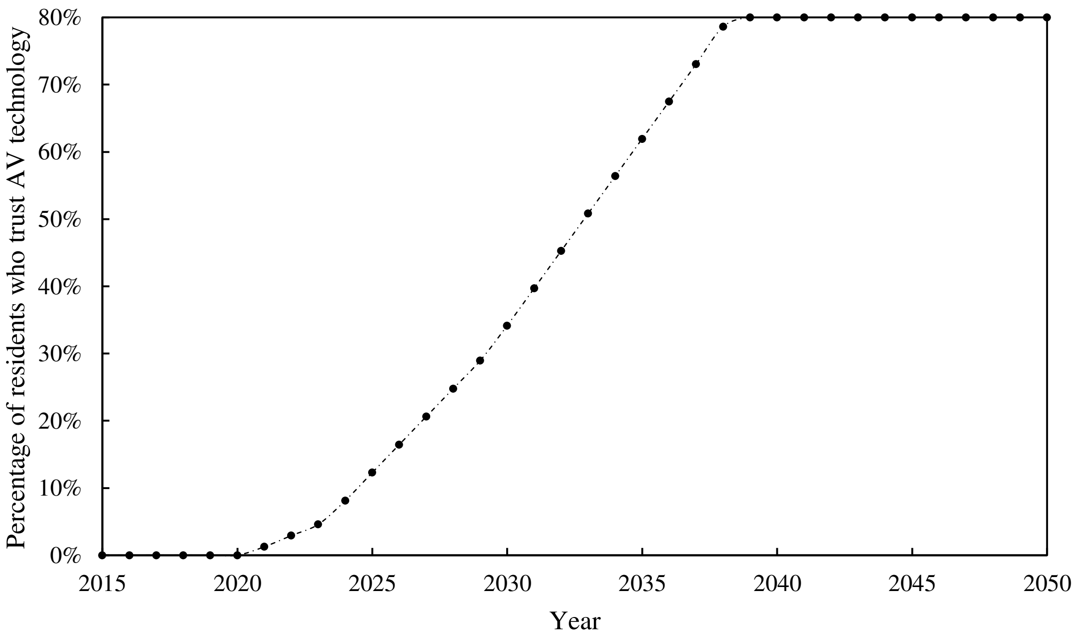


Figure 5. The value of user trust in AV technology

Table 4 shows the number of private vehicles in Beijing from 2014 to 2020. The model estimates the probability that users may choose car to travel, ω^t, by assuming that each private vehicle serves one resident, and comparing the number of private vehicles with the population over 20 years old i.e. the adult population. This paper assumes that private vehicle owners will be the first to switch to shared AVs due to purchase and travel costs after the introduction of high-level AVs. There will be some users of public transit, walking and other travel modes, choose to share AVs over time(May et al., 2020). The model assumes that the parameter ω^t will reach 60% in 2050.

Table 4. Parameters settings ('*' means estimated value)

Year	Number of private vehicles (Unit: million vehicles)	Value of ω^t
2014	4.372	23.94%
2015	4.403	23.78%
2016	4.528	24.34%
2017	4.672	25.04%
2018	4.790	25.86%
2019	4.974	26.78%
2020	5.079	27.56%
2050*	-	60.00%

Considering the private vehicles without automation V_1 has entered the market. The number of the private vehicles without automation N_1^t, where the year t is set from 2015 to 2020, is given in the Table 4. The SD model can be validated according to the N_1^t. As shown in the Figure 6, the maximum gap between the real data and the estimated data from the SD model is 6.1%. The Figure 6 shows the immediate discrepancy of 2.8% the following year i.e. 2015, and the gap continues to grow over the years. There are no other private vehicles by 2020 here i.e. we only have N_1 by 2020 and no other types. The growth rate and the scrappage rate which gives rise to this gap in model and data for private vehicles. Moreover, we have no data to validate the AV uptake and so whilst the maximum gap is 6.1% by 2020, it is the future which this paper is really interested in showing and in particular the evolution of the different shares of vehicles. We have implemented what we think is a reasonable baseline for this and justified choices in parameters which control this baseline. The shifting downwards the first few years of N_1 would not affect the results in terms of shares of AVs. We also look at low, medium and high scenarios of the share ratios in the following Section 4.2.2 which affects the V_6 fleet but less so the V_1 discards or shedding.

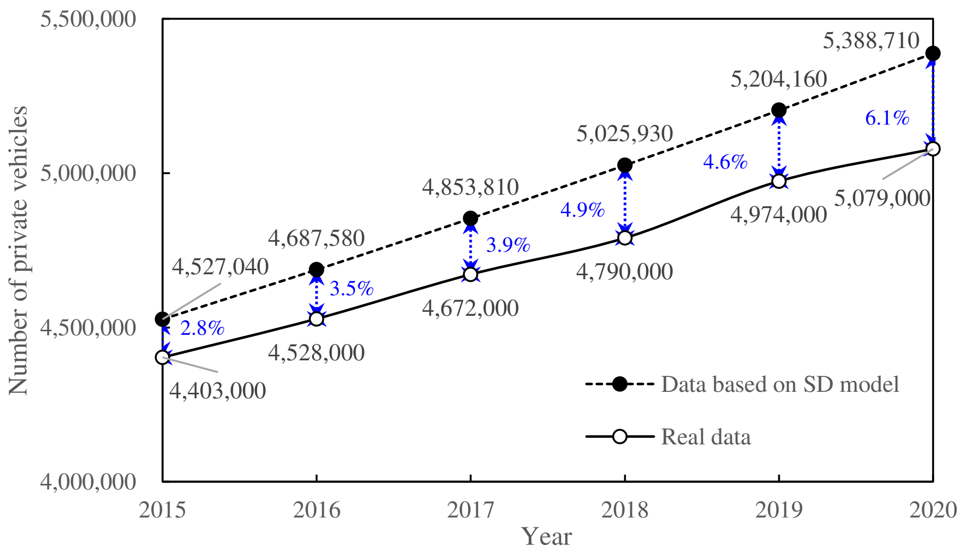


Figure 6. The SD model validation with respect to the number of the private vehicles without automation N_1^t

Table 5 provides the data about the adult population (older than 20 years) P^t according to Beijing Statistical Yearbook from 2014 to 2021, and it set the maximum value of P^t according to Beijing Urban Master Plan.

Table 5. The adult population from 2014 to 2021 (Unit: 10,000 persons)

Year	Total population	The adult population	The percentage of the population older than 20 years old
2014	2151.60	1854.68	86.20%
2015	2170.50	1879.65	86.60%
2016	2172.90	1888.25	86.90%
2017	2170.70	1892.85	87.20%
2018	2154.20	1878.46	87.20%
2019	2153.60	1882.25	87.40%
2020	2189.00	1867.22	85.30%
2021	2188.60	1869.06	85.40%
max	2300.00	1955.00	85.00%

4.2. Scenarios simulation

4.2.1. AVs market development in Beijing

Based on the SD approach given in Section 4, Figure 7 illustrates the AV market development in Beijing from 2024 to 2050, which is represented by the number of vehicles of the six levels i.e., from V_1 to V_6. In Figure 7, the numbers of V_2 and V_4 are low. This is based on their initial share, β is set as 0.5% considering current taxi management policy in Beijing.

The result shows, after the introduction of AVs in the year of 2024, the public shows their preference for the AVs. The number of private vehicles V_1 will peak in 2028 and then decrease. Comparing the maximum number of V_1, the number of V_1 has reduced by about 4.32 million vehicles. However, the total number of V_3 and V_5 does not replace the reduction of V_1. And the population in the city is increasing, which means that some residents will reduce their use of private vehicles. In 2038, the number of V_3 have peaked at over 438,000 vehicles, and then it will fall with the introduction of the high-level AVs. In 2042, the number of V_5 have peaked at over 60,000 vehicles.

Considering the development of shared AVs, the number of shared vehicles V_2 decreases gradually after 2024. The use of V_4 is much similar to human controlling shared vehicle, V_2, the growth of V_4 is little. After the introduction of V_6, the number of vehicles has decreased. The total number of V_6 will exceed V_3 after 2040. Between the years of 2035 and 2040, the number of V_6 has increased, and the number of V_1 decreased significantly during this period.

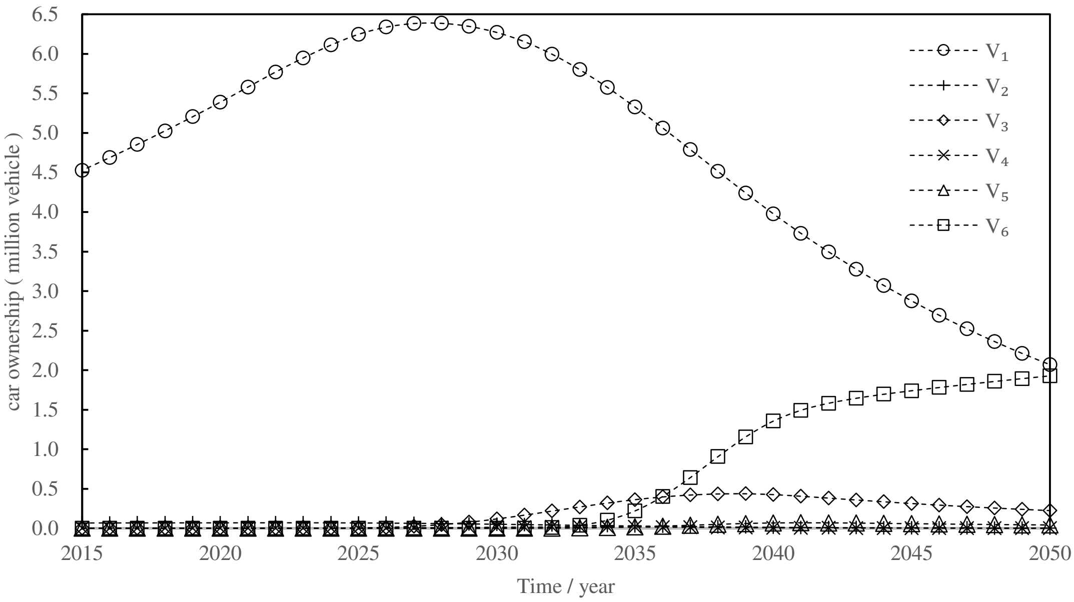


Figure 7. Number of vehicles at the six levels (V_1 -V_6) from 2025 to 2050 in Beijing

The number of V_6 is limited considering the population in the Beijing Urban Master Plan. Figure 8 explains the reason for the reduction in growth of the number of V_6. As demand approaches supply, the growth in V_6 is slows. However, the supply of shared AV is affected by the alternative ratio, r, which is used to describe the number of users serviced by one shared AV. The effects of this variable are discussed in detail in the next section 4.2.2.

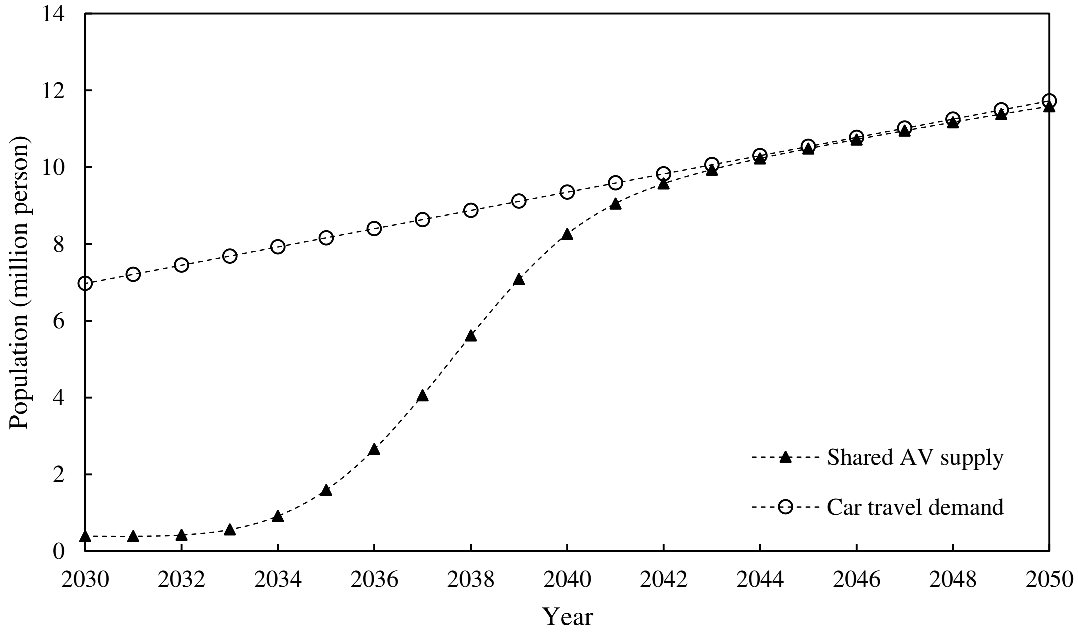


Figure 8. Car travel demand versus shared AV supply. 'Shared AV supply' represents the number of users that shared AV can service on time. 'Car travel demand' represents the population who might choose to travel by car.

As shown in the following Figure 9, the number of AV is expected to exceed the number of human vehicles (HV) in 2050. The total number of autonomous and human vehicles will be around 4.27 million in 2050. With the increase of the shared AV service accessibility, some of the private vehicle owners change to use shared AVs, like V_6, the registration of the private vehicle will reduce, and thus lead to this result.

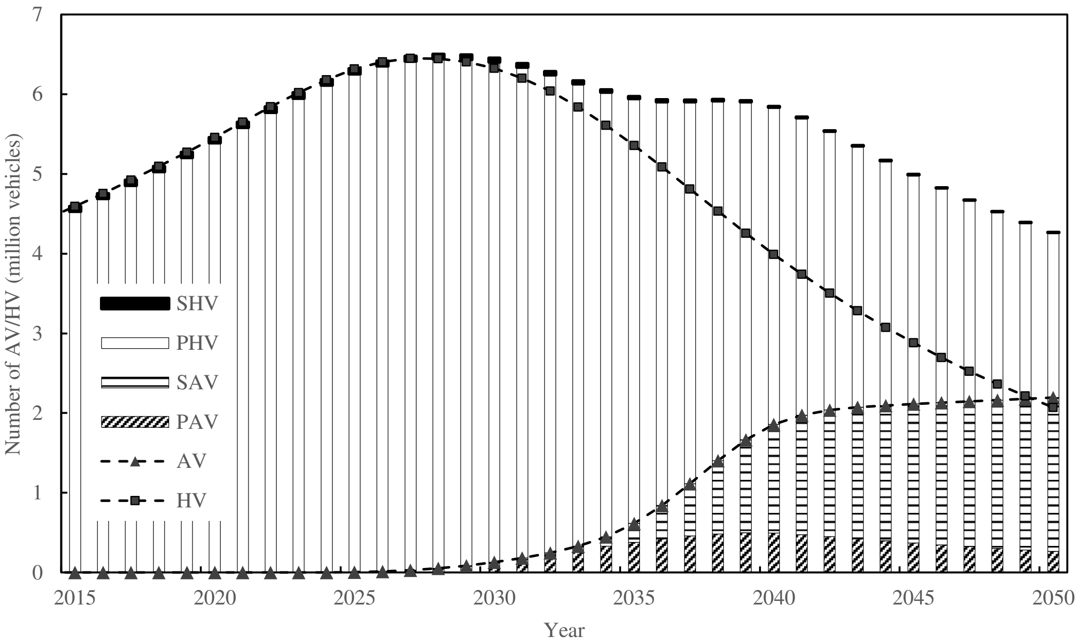


Figure 9. Autonomous vehicle versus human vehicle. 'AV' and 'HV' represent autonomous vehicle and human vehicle respectively. 'SHV' means the shared human vehicle, and it contains the V_2. 'PHV' means the private human vehicle, and it contains V_1. 'SAV' means the shared AV and it includes the V_4 and V_6. 'PAV' means the private AV and it includes the V_3 and V_5.

4.2.2. Impact of Shared AVs service

The SD model introduces the concept of alternative ratio's between shared vehicles and private vehicles, which is used to describe the number of users that a shared AV can serve to meet the travel demand in the city and provide the shared mobility service, like short-term car rental, ride-sharing, etc. However, the alternative ratio is constant in the base scenario. The model assumes that ride-sharing exists in cities after the application of high AVs, and it does not consider users' perception of ride-sharing. This section expands scenarios based on alternative ratio's of shared vehicles. The scenarios are set as following:

(1) Low ratio scenario, users are more likely to use the shared AVs alone, rather than share the journey with other users. Considering the users' attitude, the alternative ratio is set as 3.6 persons/vehicle.

(2) Extreme ratio scenario, users enjoy sharing the journey with others. The alternative ratio between shared AVs and private AVs fluctuates greatly. In the studies of Fagnant and Kockelman (2014) and Levin et al. (2017), the alternative ratio's are over 10 persons/vehicle. Therefore, this scenario considers the extreme scenario and sets the value of alternative ratio as 31.4 persons/vehicle.

In addition, the ratio is set as 6 persons/vehicle in the base scenario. The following Figure 10 shows the number of V_6 in different scenarios. In the extreme ratio scenario, the fleet size of shared AVs decreases significantly. In the low ratio scenario, residents tend to use shared AVs alone, compared with the base scenario, the size of the shared AVs fleet increases. In these three scenarios, the change of the ratio has effect on the number of shared vehicles. When the scale of the shared car fleet is too large, it may cause the traffic congestion in the city.

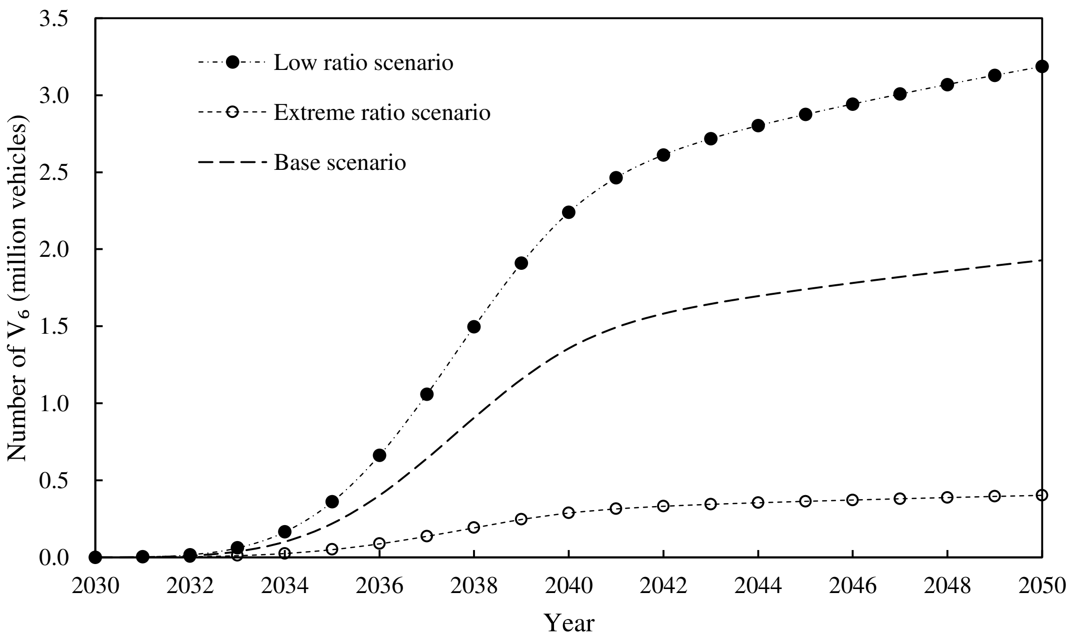


Figure 10. Changes of the number of V_6 in different scenarios

The difference is that the number of total private vehicles has barely changed, as shown in Figure 11. However, comparing different scenarios, the number of private AVs varies, as shown in Figure 12 and Figure 13.

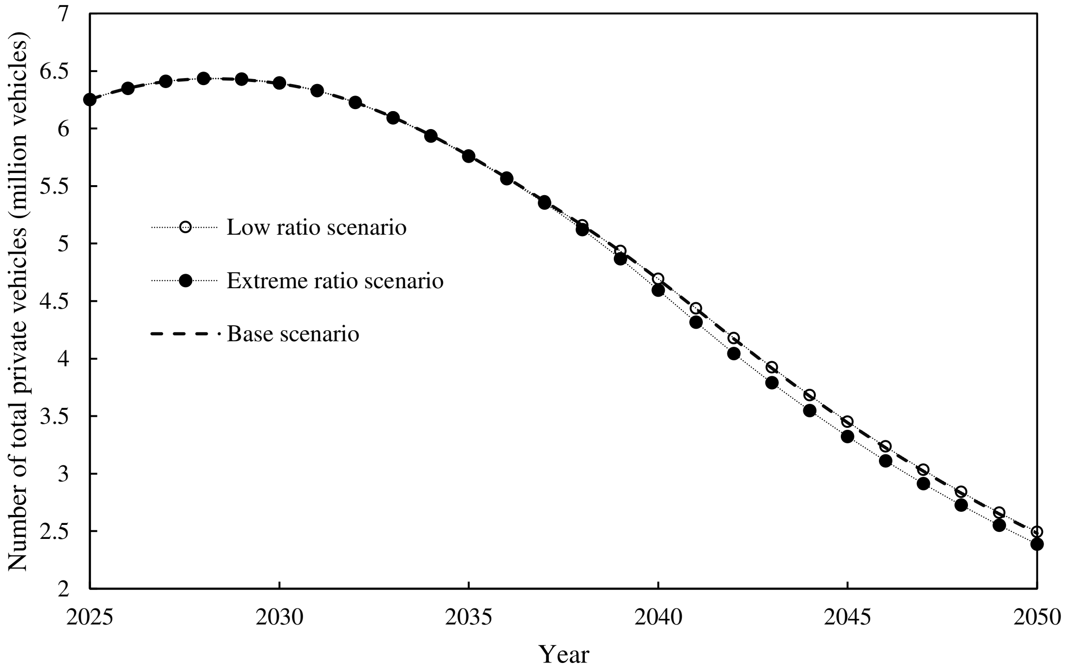


Figure 11. Changes of the number of private vehicles in different scenarios

The Figure 12 and Figure 13 shows the number of V_3 and the number of V_5 in the different scenarios. It shows that the higher ratio will reduce the number of private AVs, especially for V_5. The higher ratio indicates that users will attractive by ride-sharing, and it implies that more residents will choose to share AV for travel, thus reducing the sales of private AV, and the number of different types of private AVs will decline.

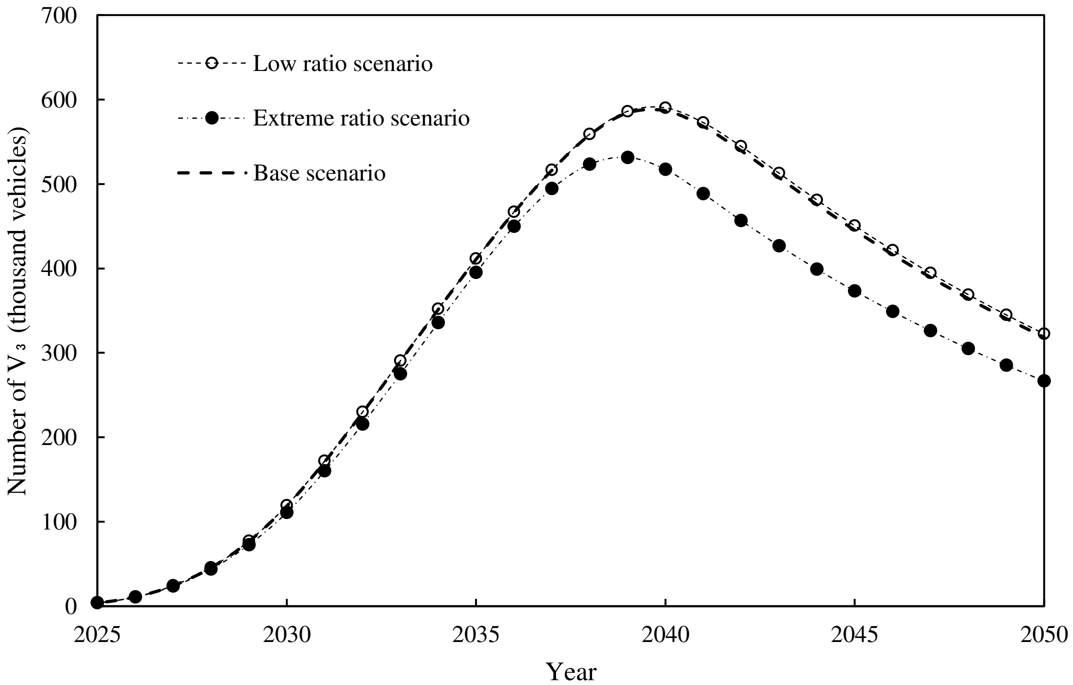


Figure 12. Changes of the number of V_3 in different scenarios

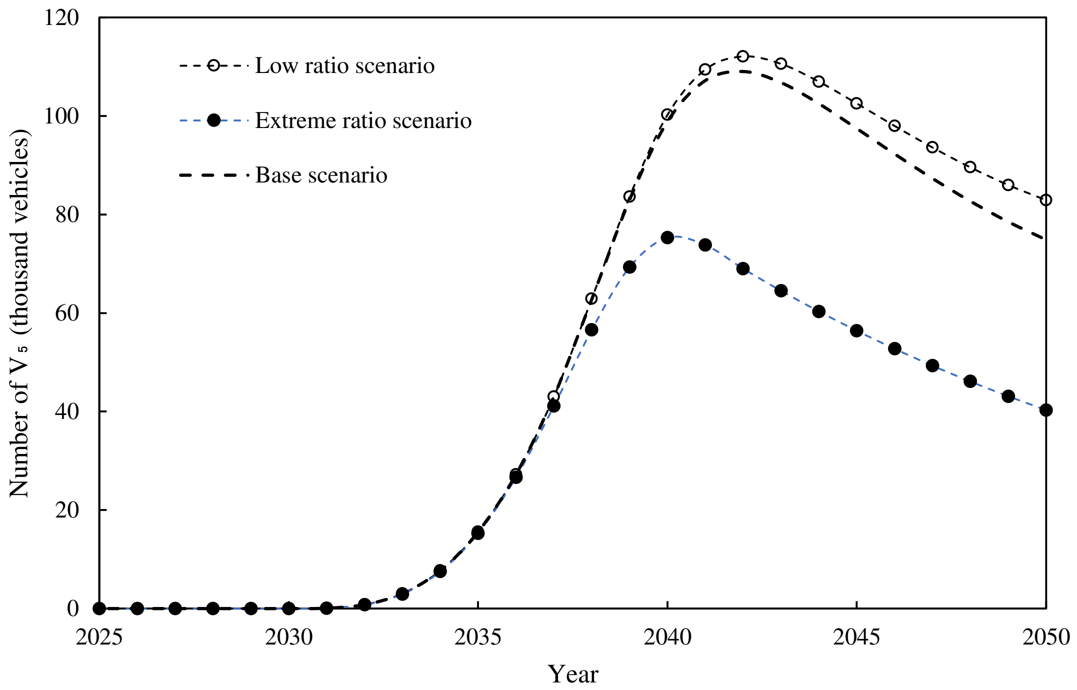


Figure 13. Number of V_5 changes in different scenarios

The Figure 14 compares the car travel demand and the population that shared AVs can service. In the extreme scenario, the costumers are positive to the car-sharing, and fewer vehicles can service more customers. At the year of 2041, the shared AV fleets is equilibration. After the iteration of the model, the number of shared vehicles is about 342,000 vehicles. Comparing to the base scenario, the number of shared vehicles is about 1,747,500 vehicles in 2045 and the supply of shared AV will over the demand. According to the result, the government can control the number of shared vehicles by the policy of the taxi registration and could reduce the number of shared vehicles by incentivizing users to share rides.

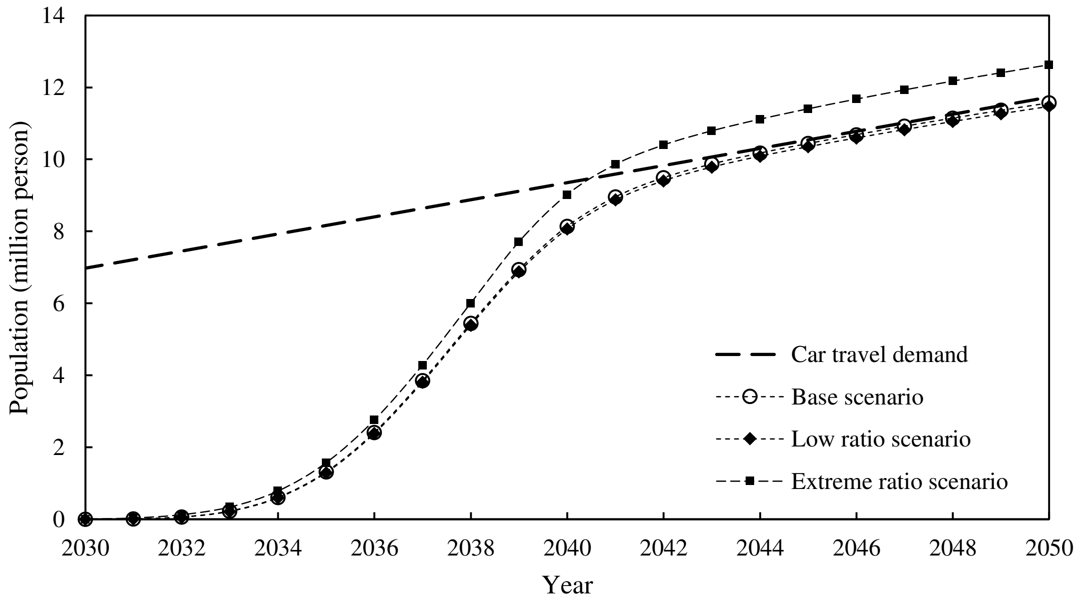


Figure 14. Car travel demand versus shared AV supply under different ratio.

5. Conclusion

To consider the development of driving automation technology and the introduction of AV commercialization, this paper proposes a system dynamics model for AV market development in Beijing. The SD model consists of a private vehicle module and shared vehicle module. In the proposed causal loop diagram, the service accessibility of shared AVs is based on technology diffusion theory. The model is applied for the AV market development in Beijing from 2024 to 2050.

This proposed model describes the introduction of AVs and the current development progress of driving automation technology in Beijing. The AV purchase willingness represents the purchase rate of residents and the AV using willingness is characterized by the residents' attitudes toward different levels of driving automation technology. In the shared vehicle submodule, shared AV users and shared AV service accessibility are considered, characterizing the transition between the users of private vehicles and the shared high-level automation V_6 users. This paper considers some incentive policies in Beijing, such as opening the operation of shared AVs and providing purchase subsidies for AVs, and their impacts are simulated with the Beijing car market development from 2014 to 2050.

The results show that the number of AVs will increase after their introduction and human controlling vehicles are gradually being replaced. In 2020, there are over 5 million private vehicles in Beijing. With the introduction of the AV, the number of private vehicles will fall to 2.2 million by 2050. This is benefit from the creation of shared AV fleet.

Then, by setting the alternative ratio that one shared vehicle can service the number of users per day, the causal relationship module of shared AV service scenarios are established. The results show that the changes in number of private vehicles is limited. The number of shared vehicles will decrease a lot with the higher value of ratio. This extension shows that users' attitudes towards ride-sharing will influence the shared AV fleet size. During the promotion of AVs, the government could need to encourage people to share rides with others while controlling the growth of private vehicle. The extended scenario shows that residents' attitude towards ride-sharing has a significant impact on the development of shared AV, however, it has little impact on private cars. That's because the market share in private AVs is small. In the future, the impact of shared AVs on urban mobility could be further explored through vehicle mileage and vehicle emissions.

The commercial application of AVs could bring promising developments in sustainable mobility. Policies that encouraging the marketization of AVs and open the operation of shared AV fleets may reduce car ownership in Beijing. During the introduction of AVs, it is necessary to balance the development of private AVs and shared AVs, especially for Beijing, a densely populated city with congestion. It is necessary to avoid the rapid growth of private AVs and ensure a positive role of AVs in solving road congestion. In addition, the AV market development SD model in this paper is worth discussing the AV subsidy schemes. Future studies can discuss the motivations of residents to buy or take AVs under different subsidy schemes, and construct the AV scenarios under different subsidy schemes.

Author Contributions: Conceptualization, Simon Shepherd, Meng Xu and Gillian Harrison; Data curation, Wei Mao and Meng Xu; Formal analysis, Wei Mao, Simon Shepherd, Gillian Harrison and Meng Xu; Funding acquisition, Meng Xu and Simon Shepherd; Investigation, Wei Mao, Gillian Harrison, Simon Shepherd and Meng Xu; Methodology, Wei Mao, Gillian Harrison, Simon Shepherd and Meng Xu; Supervision, Simon Shepherd and Meng Xu; Validation, Wei Mao, Gillian Harrison, Simon Shepherd and Meng Xu; Visualization, Wei Mao and Gillian Harrison; Writing – original draft, Wei Mao and Meng Xu; Writing – review & editing, Wei Mao, Meng Xu, Simon Shepherd and Gillian Harrison.

Acknowledgements: This work was funded through the National Natural Science Foundation of China (Grant No. 72288101), and the U-PASS project, funded through JPI-Urban Europe and ESRC (ES/T000074/1) and NSFC (71961137005)).

Data Availability Statement: Data supporting reported results may be available from the authors on request.

Conflicts of Interest: The authors declare no conflict of interest.

Reference

Abbas, K. A., Bell, M. G. H., 1994. System dynamics applicability to transportation modeling. *Transportation Research Part A: Policy and Practice, 28*(5), 373-400.

Acheampong, R. A., Cugurullo, F., 2019. Capturing the behavioral determinants behind the adoption of autonomous vehicles: Conceptual frameworks and measurement models to predict public transport, sharing and ownership trends of self-driving cars. *Transportation Research Part F: Traffic Psychology and Behavior, 62*, 349-375.

Agriesti, S., Brevi, F., Gandini, P., Marchionni, G., Parmar, R., Ponti, M., Studer, L., 2020. Impact of driverless vehicles on urban environment and future mobility. *Transportation Research Procedia, 49*, 44-59.

Bansal, P., Kockelman, K. M., 2017. Forecasting Americans' long-term adoption of connected and autonomous vehicle technologies. *Transportation Research Part A: Policy and Practice, 95*, 49-63.

Boesch, P. M., Ciari, F., Axhausen, K. W., 2016. Autonomous vehicle fleet sizes required to serve different levels of demand. *Journal of the Transportation Research Record,* 2542, 111-119.

Contreras, S. D., Paz, A., 2018. The effects of ride-hailing companies on the taxicab industry in Las Vegas, Nevada. *Transportation Research Part A: Policy and Practice, 115*, 63-70.

Conlon, J., Lin, J. E., 2019. Greenhouse gas emission impact of autonomous vehicle introduction in an urban network. *Transportation Research Record, 2673(5),* 142-152.

Daziano, R. A., Sarrias, M., Leard, B., 2017. Are consumers willing to pay to let cars drive for them? Analyzing response to autonomous vehicles. *Transportation Research Part C-Emerging Technologies, 78,* 150-164.

Docherty, I., Marsden, G., Anable, J., 2018. The governance of smart mobility. *Transportation Research Part A: Policy and Practice, 115*, 114-125.

Fagnant, D. J., Kockelman, K., 2015. Preparing a nation for autonomous vehicles: opportunities, barriers and policy recommendations. *Transportation Research Part A: Policy and Practice, 77*, 167-181.

Fagnant, D. J., Kockelman, K. M., 2014. The travel and environmental implications of shared autonomous vehicles, using agent-based model scenarios. *Transportation Research Part C: Emerging Technologies, 40*, 1-13.

Fraedrich, E., Heinrichs, D., Bahamonde-Birke, F. J., Cyganski, R., 2019. Autonomous driving, the built environment and policy implications. *Transportation Research Part A: Policy and*

Practice, 122, 162-172.

Golbabaei, F., Yigitcanlar, T., Bunker, J., 2021. The role of shared autonomous vehicle systems in delivering smart urban mobility: A systematic review of the literature. *International Journal of Sustainable Transportation, 15(10),* 731-748.

Gómez Vilchez, J. J., Jochem, P., 2019. Simulating vehicle fleet composition: A review of system dynamics models. *Renewable and Sustainable Energy Reviews, 115(2019),*109367.

Haboucha, C. J., Ishaq, R., Shiftan, Y., 2017. User preferences regarding autonomous vehicles. *Transportation Research Part C: Emerging Technologies, 78*, 37-49.

Hao, H., Wang, H., Ouyang, M., Cheng, F., 2011. Vehicle survival patterns in China. *Science China Technological Sciences, 54(3),* 625-629.

Harrison, G., Shepherd, S. P., Chen, H., 2021. Modelling uptake sensitivities of connected and automated vehicle technologies. *International Journal of System Dynamics Applications, 10(2),* 88-106.

Hassan, H. M., Ferguson, M. R., Razavi, S., Vrkljan, B., 2019. Factors That Influence Older Canadians' Preferences for using Autonomous Vehicle Technology: A Structural Equation Analysis. *Transportation Research Record, 2673(1),* 469-480.

Hudson, J., Orviska, M., Hunady, J., 2019. People's attitudes to autonomous vehicles. *Transportation Research Part A: Policy and Practice, 121*, 164-176.

Jing, P., Huang, H., Ran, B., Zhan, F., Shi, Y., 2019. Exploring the Factors Affecting Mode Choice Intention of Autonomous Vehicle Based on an Extended Theory of Planned Behavior—A Case Study in China. *Sustainability, 11(4)*, 1155-1175.

Kaltenhauser, B., Werdich, K., Dandl, F., Bogenberger, K., 2020. Market development of autonomous driving in Germany. *Transportation Research Part A: Policy and Practice, 132*, 882-910.

Kaplan, S., Gordon, B., El Zarwi, F., Walker, J. L., Zilberman, D., 2019. The future of autonomous vehicles: lessons from the literature on technology adoption. *Applied Economic Perspectives and Policy, 41(4)*, 583-597.

Lavasani, M., Jin, X., Du, Y., 2016. Market penetration model for autonomous vehicles on the basis of earlier technology adoption experience. *Journal of the Transportation Research Board, 2597(1),* 67-74.

Lavieri, P. S., Bhat, C. R., 2019. Modeling individuals' willingness to share trips with strangers in an autonomous vehicle future. *Transportation Research Part A: Policy and Practice, 124*, 242-261.

Lee, J., Kockelman, K. M., 2022. Access Benefits of Shared Autonomous Vehicle Fleets: Focus on Vulnerable Populations. *Transportation Research Record, 2676(11)*, 568-582.

Levin, M. W., Kockelman, K. M., Boyles, S. D., Li, T., 2017. A general framework for modeling shared autonomous vehicles with dynamic network-loading and dynamic ride-sharing application. *Computers, Environment and Urban Systems, 64*, 373-383.

Ling, Z. W., Cherry, C. R., Yang, H. T., 2019. Emerging mini electric cars in China: User experience and policy implications. *Transportation Research Part D: Transport and Environment, 69*, 293-304.

Litman, T., 2022. Autonomous vehicle implementation predictions implications for transport planning. *Victoria Transport Policy Institute*.

May, A. D., Shepherd, S., Pfaffenbichler, P., Emberger, G., 2020. The potential impacts of automated cars on urban transport: An exploratory analysis. *Transport Policy, 98*, 127-138.

Mendes, L. M., Bennassar, M. R., Chow, J. Y. J., 2017. Comparison of Light Rail Streetcar Against Shared Autonomous Vehicle Fleet for Brooklyn-Queens Connector in New York City. *Transportation Research Record, 2650,* 142-151.

Menon, N., Barbour, N., Zhang, Y., Pinjari, A. R., Mannering, F., 2018. Shared autonomous vehicles and their potential impacts on household vehicle ownership: An exploratory empirical assessment. *International Journal of Sustainable Transportation, 13*(2), 111-122.

Meyer, J., Becker, H., Bösch, P. M., Axhausen, K. W., 2017. Autonomous vehicles: The next jump in accessibilities? *Research in Transportation Economics, 62*, 80-91.

Ministry of Industry and Information Technology of China. Technology Roadmap for Autonomous Vehicle 2.0, Ministry of Industry and Information Technology of China:

Beijing , China, 2021.
Nieuwenhuijsen, J., Correia, G. H. d. A., Milakis, D., van Arem, B., van Daalen, E., 2018. Towards a quantitative method to analyze the long-term innovation diffusion of automated vehicles technology using system dynamics. *Transportation Research Part C: Emerging Technologies, 86*, 300-327.
Pfaffenbichler, P., Emberger, G., Shepherd, S., 2010. A system dynamics approach to land use transport interaction modelling: the strategic model MARS and its application. *System Dynamics Review, 26*(3), 262-282.
Puylaert, S., Snelder, M., van Nes, R., van Arem, B., 2018. Mobility impacts of early forms of automated driving – A system dynamic approach. *Transport Policy, 72*, 171-179.
The Beijing Municipal Science & Technology Commission. Implementation Rules for the Administration of Unmanned Road Testing and Demonstration Applications for Vehicles in the Beijing Intelligent Connected Vehicle Policy Pilot Zone. Retrieved 2022-04-28 from http://kw.beijing.gov.cn/art/2022/4/28/art_1136_628686.html
The National Development and Reform Commission. Intelligent Vehicle Innovation Development Strategy. Retrieved 2020-02-24 from https://www.ndrc.gov.cn/xxgk/zcfb/tz/202002/t20200224_1221077_ext.html
The General Office of the State Council. New Energy Vehicle Industry Development Plan (2021-2035). Retrieved 2020-11-02 from http://www.gov.cn/zhengce/content/2020-11/02/content_5556716.html
The Ministry of Industry and Information Technology and the Ministry of Housing and Urban-Rural Development. Coordinated Development of Smart City Infrastructure and Intelligent Connected Vehicles. Retrieved 2021-05-13 from http://www.gov.cn/xinwen/2021-05/13/content_5606151.html
The People's Government of Beijing Municipality. Beijing Intelligent Connected Vehicle Policy Pilot Zone Overall Implementation Plan. Retrieved 2021-04-19 from http://www.beijing.gov.cn/zhengce/zcjd/202105/t20210510_2385462.html
The Beijing Municipal Bureau of Economy and Information Technology. Beijing Intelligent Connected Vehicle Innovation and Development Action Plan (2019-2022). Retrieved 2018-12-28 from http://www.beijing.gov.cn/zhengce/zhengcefagui/201905/t20190522_61732.html
Serio Agriestib , F. B., Paolo Gandinia Marco Pontia, Luca Studera, Giovanna Marchionnia, 2020. Impact of driverless vehicles on urban environment and future mobility. *47th European Transport Conference 2019, ETC 2019, 9-11 October 2019, Dublin, Ireland*.
Shepherd, S. P., 2014. A review of system dynamics models applied in transportation. *Transportmetrica B: Transport Dynamics, 2*(2), 83-105.
Spieser, K., Treleaven, K., Zhang, R., Frazzoli, E., Morton, D., Pavone, M. (2014). Toward a systematic approach to the design and evaluation of automated Mobility-on-Demand systems: A case study in Singapore. *Road Vehicle Automation*, 229-245.
Steck, F., Kolarova, V., Bahamonde-Birke, F., Trommer, S., Lenz, B., 2018. How Autonomous Driving May Affect the Value of Travel Time Savings for Commuting. *Journal of the Transportation Research Record, 2672*(46), 11-20.
Sun, S., Wang, W., 2018. Analysis on the market evolution of new energy vehicle based on population competition model. *Transportation Research Part D: Transport and Environment, 65*, 36-50.
Tian, J. J., Jia, H. F., Wang, G. F., Lin, Y., Wu, R. Y., Lv, A., 2022. A Long-Term Shared Autonomous Vehicle System Design Problem considering Relocation and Pricing. *Journal of Advanced Transportation, 2022,* 1905526.
Vosooghi, R., Puchinger, J., Jankovic, M., Vouillon, A., 2019. Shared autonomous vehicle simulation and service design. *Transportation Research Part C-Emerging Technologies, 107,* 15-33.
Wang, H., Zhang, K., Chen, J., Wang, Z., Li, G., Yang, Y., 2018. System dynamics model of taxi management in metropolises: Economic and environmental implications for Beijing. *Journal of Environmental Management, 213*, 555-565.
Wang, T. F., Li, H., Xiao, B. R., Wei, D., 2021. Policy analysis and Implementation Impact of

government subsidies on shared-bikes operation mode using system dynamics methodology: A case of Mobike in China. *Simulation: Transactions of the Society for Modeling and Simulation International, 97*(9), 589-599.

Wen, J., Chen, Y. X., Nassir, N., Zhao, J., 2018. Transit-oriented autonomous vehicle operation with integrated demand-supply interaction. *Transportation Research Part C: Emerging Technologies, 97*, 216-234.

Xie, T. T., Liu, Y., 2022. Impact of connected and autonomous vehicle technology on market penetration and route choices. *Transportation Research Part C-Emerging Technologies, 139(2022),* 103646.

Xue, Q. J., Xu, M., Mullen, C., 2020. Governance of emerging autonomous driving development in China. *Journal of the Transportation Research Record, 2674*(6), 281-290.

Xu, M., Liu, T., Zhong, S. P., &Jiang, Y. 2022. Urban smart public transport studies: A review and prospect. *Journal of Transportation Systems Engineering and Information Technology*, *22*(2), 91-108.

Yao, F., Zhu, J., Yu, J., Chen, C., Chen, X., 2020. Hybrid operations of human driving vehicles and automated vehicles with data-driven agent-based simulation. *Transportation Research Part D: Transport and Environment, 86*, 102469.

Yap, M. D., Correia, G., van Arem, B., 2016. Preferences of travellers for using automated vehicles as last mile public transport of multimodal train trips. *Transportation Research Part A: Policy and Practice, 94*, 1-16.

Yu, J., Chen, A., 2021. Differentiating and modeling the installation and the usage of autonomous vehicle technologies: A system dynamics approach for policy impact studies. *Transportation Research Part C: Emerging Technologies, 127(2021),* 103089.

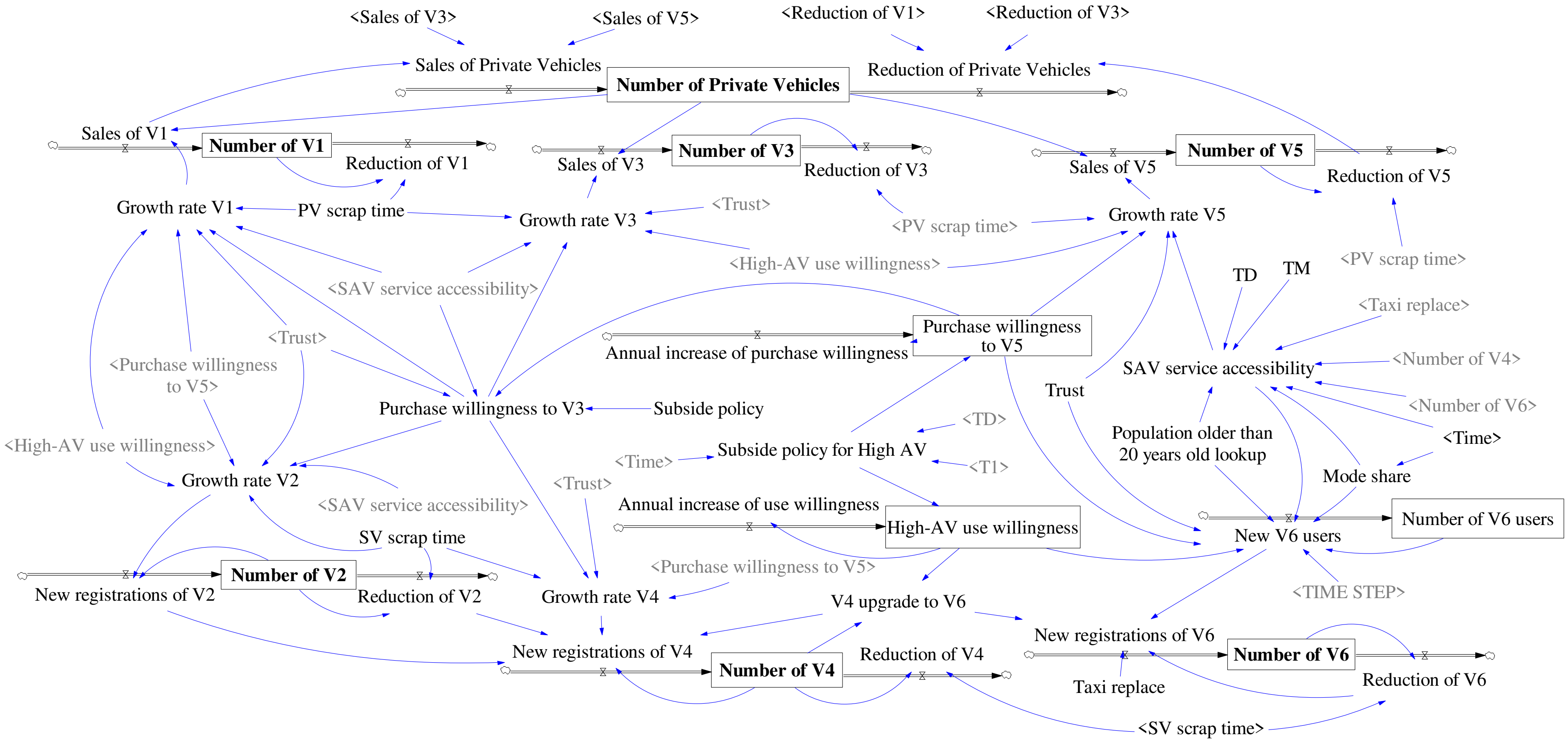
Zhang, Q., Ou, X. M., Yan, X. Y., Zhang, X. L., 2017. Electric vehicle market penetration and impacts on energy consumption and CO2 emission in the future: Beijing case. *Energies, 10*(2), 228-243.

Zhang, X., Bai, X., Zhong, H., 2018. Electric vehicle adoption in license plate-controlled big cities: Evidence from Beijing. *Journal of Cleaner Production, 202*, 191-196.

Zhuge, C. X., Wang, C. Y., 2021. Integrated modelling of autonomous electric vehicle diffusion: From review to conceptual design. *Transportation Research Part D: Transport and Environment, 91(2021)*, 102679.

Zhuge, C. X., Wei, B. R., Shao, C. F., Dong, C. J., Meng, M., Zhang, J., 2020. The potential influence of cost-related factors on the adoption of electric vehicle: An integrated micro-simulation approach. *Journal of Cleaner Production, 250.*

Appendix A. The SFD for the market development in Beijing



Appendix B. Equations used in this study

The model is developed in the Vensim® DSS for Windows Version 9.1.1. Two functions in Vensim, i.e., *MAX()* and *WITH LOOKUP()* are introduced first.

Given two values/alternatives A and B, the function *MAX*(A, B) can compare the value of A and B, and return the maximum of A and B.

Given n-dimension vectors $\boldsymbol{x} = (x_1, x_2, \cdots, x_n)$ and $\boldsymbol{y} = (y_1, y_2, \cdots, y_n)$, the function $L(\boldsymbol{x}, \boldsymbol{y})$ defines a nonlinear relationship between inputs $(\boldsymbol{x}, \boldsymbol{y})$ and output *by passing the input through a series of the pair* $(\boldsymbol{x}, \boldsymbol{y})$ *specified as numbers*. The function *WITH LOOKUP*$(X, (L(x)))$ will find the Y value corresponding to X in $L(\boldsymbol{x}, \boldsymbol{y})$ and return the value of Y. It is given by the following,

$$L(x) = L(\ (x_1, y_1), (x_2, y_2), \ldots, (x_n, y_n)\ )$$

$$Y = WITH\ \ LOOKUP\ \ (X\ \ , L(\boldsymbol{x}, \boldsymbol{y}))$$

The symbol t is used to describe the iteration year in this SD approach, and the symbol V_i describes the different type of vehicle, i.e. no automation private vehicle (V_1), no automation shared vehicle (V_2), conditional automation private vehicle (V_3), conditional automation shared vehicle (V_4), high automation private vehicle (V_5), and high automation shared vehicle (V_6).

The main equations in SD model is shown as following:

Formulation	**Unit**
(01) $N_i^t = \begin{cases} N_i^t, & t = 2014 \\ N_i^{t-1} + NV_i^t - R_{i,}^t & t \in [2015,2050] \end{cases}, i = 1,2,3,4,5,6$	Vehicle
(02) $NPV^t = \begin{cases} NPV^t, & t = 2014 \\ NPV^{t-1} + PV^t - RPV^t, & t \in [2015,2050] \end{cases}$	Vehicle

(03)	$NU6^t = \begin{cases} 0, & t \in [2014,2029] \\ NU6^{t-1} + u6^t, & t \in [2030,2050] \end{cases}$	Person
(04)	$NV_i^t = NPV^t * gr_i \ , i = 1,3,5, t \in [2014,2050]$	Vehicle/year
(05)	$NV_2^t = N_2^t * gr_2, t \in [2014,2050]$	Vehicle/year
(06)	$NV_4^t = MAX(0, N_2^{t-1} - N_2^t) + N_4^t * (\beta + sr_4) * ft^t * \left(1 - \sum_{i=3,5} fp_i^t\right) - N_4^t * fu^t, t \in [2014,2050]$	Vehicle/year
(07)	$NV_6^t = N_4^t * fu^t + \frac{u6^t}{r} + R_6^t \ , t \in [2014,2050]$	Vehicle/year
(08)	$PV^t = NV_1^t + NV_3^t + NV_5^t, \ t \in [2014,2050]$	Vehicle/year
(09)	$R_i^t = N_i^t * sr_i \ , i = 1,2,3,4,5,6, \ t \in [2014,2050]$	Vehicle/year
(10)	$RPV^t = R_1^t + R_3^t + R_5^t, \ t \in [2014,2050]$	Vehicle/year
(11)	$fp_3^t = sp_1^t \times \begin{cases} ft^t \times (1 - sa^t), & t \in [2014,2029] \\ MAX(0, ft^t - fp_5^t), & t \in [2030,2050] \end{cases}$	Dmnl
(12)	$fp_5^t = \begin{cases} fp_5^t, & t \in [2014,2024] \\ fp_5^{t-1} + pw^t * sp_2^t, & t \in [2025,2050] \end{cases}$	Dmnl
(13)	$ft^t = WITH\ \ LOOKUP\ \left(t, \left((2021,0), (2024,0.05), (2030,0.3), (2039,0.8), (2050,0.8)\right)\right), t \in [2014,2050]$	Dmnl

(14)	$fu^t = \begin{cases} fu^t, & t \in [2014,2024] \\ fu^{t-1} + uw^t \times sp_2^t, & t \in [2025,2050] \end{cases}$	Dmnl
(15)	$gr_1 = (\alpha + sr_1) * (1 - ft^t) * \left(1 - \sum_{i=3,5} fp_i^t\right) * (1 - sa^t * fu^t),\ t \in [2014,2050]$	1/year
(16)	$gr_2 = (\beta + sr_2) * (1 - ft^t) * \left(1 - \sum_{i=3,5} fp_i^t\right) * (1 - fu^t * sa^t),\ t \in [2014,2050]$	1/year
(17)	$gr_3 = (\alpha + sr_3) * ft^t * fp_3^t * (1 - fu^t) * (1 - sa^t), t \in [2014,2050]$	1/year
(18)	$gr_5 = (\alpha + sr_5) * fp_5^t * fu^t * (1 - sa^t), t \in [2014,2050]$	1/year
(19)	$pw^t = WITH\ \ LOOKUP\left(t, \left((2014,0),(2024,0),(2030,0.01),(2035,0.03),(2040,0.1),(2045,0.05),(2050,0.03)\right)\ \right), t \in [2014,2050]$	1/year
(20)	$sa^t = \begin{cases} \frac{N_4^t * r}{P^t * \omega^t}, & t \in [2014,2029] \\ \frac{1}{2} * \left\{\left[cos\frac{(t-2024-TD+1)*\pi}{TM}\right] + 1\right\}, & t \in [2030,2045] \\ \frac{(N_4^t + N_6^t) * r}{P^t * \omega^t}, & t \in [2046,2050] \end{cases}$	Vehicle/person
(21)	$sp_1^t = \begin{cases} 0, & t \in [2014,2023] \\ 1, & t \in [2024,2050] \end{cases}$	Dmnl
(22)	$sp_2^t = \begin{cases} 0, & t \in [2014,2030] \\ 1, & t \in [2030,2050] \end{cases}$	Dmnl
(23)	$sr_m = \frac{1}{TP}\ \ , m = 1,3,5$	1/year

(24) $sr_n = \frac{1}{TS}$, $n = 2,4,6$	1/year
(25) $u6^t = ft^t * fu^t * MAX(-0.05,1 - fp_5^t) * sa^t * (P^t * \omega^t - NU6^t), t \in [2014,2050]$	Persons/year
(26) $uw^t = WITH\ \ LOOKUP\Big(t,\big((2014,0),(2020,0),(2024,0.01),(2029,0.03),(2037,0.1),(2045,0.05),(2050,0.01)\big)\Big), t \in [2014,2050]$	1//year
(27) $\omega^t = WITH\ \ LOOKUP\Big(t,\big((2014,0.21),(2016,0.21),(2018,0.23),(2020,0.24),(2050,0.60)\big)\Big), t \in [2014,2050]$	Dmnl