Hindawi
Complexity
Volume 2021, Article ID 3435953, 12 pages
https://doi.org/10.1155/2021/3435953

Research Article

China's Auto Industry Upgrade Process Based on Aging Chain and Coflow Model

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Received 2 July 2020; Revised 28 October 2020; Accepted 24 December 2020; Published 7 January 2021

Academic Editor: Yi Su

To protect energy resources and alleviate environmental pollution, many countries attach great importance to the transformation of traditional industries into clean energy industries. In this paper, fuel vehicles (FVs), hybrid vehicles (HVs), and electric vehicles (EVs) are included in the research. Then, based on the aging chain and coflow theory of SDs, we construct a dynamic matching model of the auto industry upgrade process and its energy consumption attributes. The simulation results of China's auto industry show that (1) the upgrading of the auto industry is an evolutionary process from high energy consumption and high pollution to low energy consumption and no pollution and the transition from FVs and HVs to EVs will undergo two adjustments; (2) simply reducing energy supply does not have the expected impact on vehicle size and vehicle energy consumption intensity and only by adjusting the energy supply and upgrade ratios together, energy utilization efficiency can be improved; (3) market screening time has an impact on auto industry upgrade speed by affecting vehicle market share and dwell time; (4) China's auto industry upgrade process should adhere to "problem-oriented" and strengthen consumer guidance, technology innovation, and infrastructure construction. The conclusions can provide references for industrial policy adjustment and industrial structure optimization.

1. Introduction

Transportation, especially autos, consumes large amounts of fossil fuels and has a significant impact on air pollution, greenhouse gas emission, and global warming [1, 2]. China Industry Information Network (CIIN) shows that auto production increased from 2.07 million to 24.5 million during 2000–2015, with an average annual growth rate of 17.92% [3]. Meanwhile, the statistics of the China Association of Automobile Manufacturers (CAAM) show that the sales of autos in 2018 reached 28.08 million [4]. The rapid growth of auto production and sales drives the overall development of the industry, but it also causes a continuous increase in traffic energy consumption and air pollution. This result is mainly related to the fact that the auto industry structure is still dominated by fuel vehicles (FVs) [5]. In order to protect energy resources and the environment, the Chinese government chooses new energy vehicles (including hybrid vehicles (HVs) and electric vehicles (EVs)) as a new strategy to achieve the green development of the auto industry [6]. In addition, the government also adopts differentiated measures for high-pollution and low-pollution vehicles. For example, a CO_2 emission tax is imposed on highly polluting fuel vehicles, while new energy vehicles are provided with incentives and subsidies [7]. With the promotion of new energy vehicles, their advantages compared to traditional fuel vehicles are increasingly apparent, and this strategy makes renewable energy resources (such as electricity and solar energy) become a new way to solve traffic problems [8].

From the perspective of industry development, the auto industry is a technology-oriented industry. Under the background of a new round of technological revolution, the development of auto products with less polluting technologies has undoubtedly become the primary goal of automakers [9, 10]. Automakers are devoted to developing eco-friendly vehicles to help reduce environmental hazards, including common HVs, plug-in HVs, fuel cell vehicles, and EVs [11]. Some or all of these vehicles are driven by renewable energy, with low pollutants and low carbon footprint. They are natural supplementary resources and can be transformed into secondary energy [12]. At present, the types of vehicles classified by energy-driven systems in the Chinese market mainly include FVs (gasoline vehicles and diesel vehicles), HVs (common HVs and plug-in HVs), and EVs [13]. It shows that technological advancement makes auto products more diversified and personalized. Therefore, the optimization of auto structure is also more urgent.

As the issue of environmental pollution has become a hot topic of great concern in many countries, industries, and fields [14, 15], scholars have successively studied the energy consumption and environmental impact of different vehicles. Wang et al. [16] analyzed environmental pollution problems caused by fuel combustion. Considering the high energy consumption and high pollution of FVs, Tang et al. [17] pointed out that the government has successively implemented a series of measures to limit the growth of FVs. These measures provide opportunities for the development of HVs and indicate that reducing emissions and improving fuel economy should be the direction of the auto industry. Research by Dextreit et al. [18] demonstrated that the energy consumption of HVs is in the range of 20–30% lower than FVs. Yu et al. [19] also believed that HVs have better power and economy than FVs, which is mainly because battery energy optimizes power efficiency. Later, Clairand et al. [1] pointed out that EVs are more eco-friendly and efficient than HVs. The development of EVs was considered to be a particularly promising strategy to promote the sustainable development of the auto industry [20, 21]. A comparative literature by Liu et al. [22] showed that energy consumption of EVs is lower than that of FVs and HVs, and under the same driving distance, HVs and EVs saved 4.4% and 19.7%, respectively, compared with FVs, that is, the promotions of HVs and EVs are more conducive to reducing the emissions of SO_2, NO_x, CO, and other pollutants. Besides, Werber et al. [23] also found that EVs can become a substitute for FVs by comparing the life cycle costs, and this replacement is highly efficient and low cost. Therefore, the upgrading of the auto industry (from FVs and HVs to EVs) has become an inevitable choice to enhance industrial international competitiveness.

The structural transformation process of the auto industry involves many factors, and each factor interacts with each other to form a complex and nonlinear evolution process. Most existing literature used modeling methods to focus on the optimization design of vehicle performance and technical innovation. For example, research studies on HVs and EVs focused on the optimal location of charging infrastructures [24, 25], optimal route scheduling and navigation strategy [26, 27], and vehicle scheduling problem [28]. Besides, some scholars also studied the auto industry using the system dynamics (SDs) method. For example, Li et al. [29] analyzed the influence factors of technological innovation capability of the auto industry and their interrelationships, which provided a new reference for technological innovation decision-making. Miao and Liu [30] studied EV's industrialization process and analyzed the impact of government policies on the auto industry chain in the short term and long term. Cheng and Mu [31] used the SD game model to discuss the new energy vehicle's subsidy mechanism, impact, and strategy, which can provide a reference for industry policy adjustment and enterprise production decisions.

However, in terms of existing literature, the research perspective and content still lack integrity and systematicness. On the one hand, scholars mostly focus on a single vehicle or a comparative study of two types of vehicles. There is no systematic analysis of the auto industry structure (from FVs and HVs to EVs) from the perspective of industrial continuous evolution. On the other hand, there is no literature focus on the good matching between the SDs method and auto industry structure transformation process, and this method is used to construct the model and predict auto industry's overall development trend. In terms of practical development, the development of China's auto industry still exists some problems: First, auto manufacturing, use, scrapping, and disposal processes consume nonrenewable energy and emit large pollutants [32]. The consumption of gasoline and diesel accounts for about 55% of total petrol and diesel consumption [33]. The shortage of resources and environmental degradation caused by excessive energy consumption inevitably affect the long-term development of the auto industry. Second, at present, FVs occupy a large market share in Chinese auto market, while the market shares of HVs and EVs are small. The unreasonable market structure is also the bottleneck for the auto industry development. Third, the auto industry upgrade process is guided by national policies and industrial goals and scholars also conduct research studies around this content. However, theoretical research still lags behind industrial development, which further verifies the gap between literature and practice. Therefore, it is of great theoretical and practical significance to study the auto industry upgrade process from a systematic perspective.

SDs is good at analyzing long-term evolution characteristics and is suitable for exploring the dynamic feedback mechanism of nonlinear and time delay [34]. An aging chain in SDs refers to the flow rate of any object (enters or exits the stock and flow system) related to the object's age. The aging chain is suitable for modeling and analyzing changes of any stock age structure, which has a wide range of applications. Coflow is a record of stock attributes in the stock and flow system, which can be any feature of stock [35]. The auto industry upgrade process includes multiple subsystems. The interaction between various subsystems and internal factors of the subsystem makes the system present characteristics such as delay and feedback, which are very suitable for research using the SDs method. Besides, the tracking surveys of auto enterprises find that the listing rate, upgrade rate, and elimination rate of different vehicles are closely related to vehicle aging. The limitation of energy supply makes vehicle energy consumption become an important characteristic affecting vehicle aging speed. Therefore, the auto industry upgrade process and its energy consumption attributes are well matched with the aging chain and coflow model of SDs.

The transformation and upgrading of the auto industry have become an inevitable trend. Based on the double gap in the literature and practice, firstly, from the two perspectives of environment and energy constraints, the scope of this paper includes FVs, HVs, and EVs. Then, using the aging chain and coflow theory of SDs, a matching model of the auto industry upgrade process and its energy consumption attributes is constructed. The model presents the evolution process of the auto industry from high emissions to low emissions and then to zero emissions from a dynamic perspective. Secondly, the listing rate is a record of the activity status of the "flow" in the auto industry upgrade process subsystem, which reflects the time change of the "flow." It is not only related to the technological innovation speed of enterprises but also closely related to the market demand. Specifically, this paper believes that the listing rate represents the "input" of various types of vehicles and is an important indicator reflecting the upgrading speed of the auto industry and the rationality of industrial structure. Therefore, to further investigate the relationship between the internal structure of the auto industry upgrade process and its dynamic behavior, this paper uses listing rate as a test function to verify the rationality of the model. Meanwhile, this paper also analyzes the influence of energy supply upgrade ratios and market screening time on the sustainable development of the auto industry through the design of different scenarios and finds the main factors that affect the upgrading speed of the auto industry. In addition, this paper further discusses the matching between the theoretical model and industrial situation. The conclusions can provide new insight and suggestions for the optimization and adjustment of industrial structure.

The remainder of this paper is organized as follows. Section 2 identifies model boundaries and constructs the causal loop diagram and stock and flow diagram of the auto industry upgrade process. Section 3 makes a detailed analysis and discussion of simulation results. Section 4 gives the conclusions and policy recommendations.

2. Methods and Model Construction

2.1. System Dynamics. Complex system science mainly focuses on the complexity phenomenon and the evolution of research objects, and all elements within the system are closely related [36]. SDs was first proposed by Professor Forrester in the 1950s, which is used to analyze complex nonlinear problems. It can explain the complex relationships between multiple elements from a macroperspective and predict the dynamic feedback of historical dimensions [35, 37]. The modeling steps of SDs mainly include clarifying problems and determining the system boundaries, proposing initial hypotheses and constructing the causal loop diagram, building the stock and flow diagram by equation design, and carrying out simulation tests [38]. In addition, SDs can optimize models and simulate reality by adjusting model boundaries, structures, parameters, and setting scenario. The aging chain in SDs refers to the flow rate of any object (individual) entering or exiting the stock and flow system (whole) related to its age, that is, the rate at which individuals leave the system is determined by their age. This characteristic determines that the aging chain theory can be applied to various fields. Coflow is a record of stock (level variable) attributes in a stock and flow system, which can be any characteristic associated with the level variable [35, 38]. Richmond [39] and Sterman [34] pointed out that when the quantity and quality of level variables have an impact on the system, the aging chain and coflow should be used together to describe the complex feedback relationship within the system.

The auto industry upgrade process is a nonlinear, complex, and dynamic system. It is difficult to reveal the upgrading rule of the auto industry by conventional analysis methods, and it is also difficult to describe the complex relationship between subsystems. Therefore, this paper uses the SDs method to study this complex system. From the government's restrictive policies (banning FVs) and supporting policies (HVs and EVs), the update of auto products has input (product R&D, listing, and upgrading) and output (product upgrading and eliminating) in each stage. This process is closely related to product life (age), showing obvious aging chain characteristics. Therefore, this paper adopts the aging chain theory to construct the auto industry upgrade model. In addition, considering the elimination of auto products is also the result of energy and environmental problems, and vehicle energy consumption records the energy demand of different vehicles, which is also an important criterion for measuring whether the industrial structure is reasonable. Therefore, based on the aging chain model, this paper further constructs the coflow model of energy consumption that matches the aging chain model. The main steps of model construction include the following:

(1) Causal loop diagram: based on the aging chain and coflow theory of SDs and combined with the empirical investigation of the auto industry, this paper identifies the three stages of the auto industry upgrade process and constructs a causal loop diagram by clarifying the relationships between variables.

(2) Stock and flow diagram: based on the causal loop diagram, the variables are divided into level variables, rate variables, and auxiliary variables, and the relationships between variables are nonlinearly processed. Then, the stock and flow diagram is constructed by equation design.

(3) Model testing and adjustment: the consistency of the model is tested with the real world. Test functions are used to check the graphical trend of output results to further adjust the model structure.

(4) Model simulation: the Vensim PLE software is used to conduct dynamic simulation analysis on the target variable by adjusting relevant parameters.

(5) Suggestions: according to the simulation results, this paper puts forward some recommendations.

2.2. Model Boundary and Basic Hypotheses. This paper uses level variables to determine system boundaries. The dynamic upgrading process of the auto industry mainly includes three major stages: FVs, HVs, and EVs. Considering that this paper aims to study the matching model between different vehicles and their corresponding energy requirements, the model's boundary involves FVs, HVs, EVs, and their energy consumption. This paper is an abstract model of the auto industry upgrade process. The following hypotheses are proposed for subsequent research:

H1: auto industry upgrade is a continuous and dynamic process. Vehicles that cannot withstand market inspection at each stage will be eliminated or withdrawn from the market.

H2: the energy supply is limited, and the industry upgrade process needs to match energy supply.

H3: the energy consumption of different vehicles is significantly different.

H4: the vehicle listing rate, market share, and energy consumption at different stages affect the whole structure of the auto industry.

H5: the impacts of the financial crisis and other unforeseen factors on the model are not considered.

2.3. Causal Loop Diagram. The causal loop diagram is a feedback analysis diagram that describes the structure of the system and the relationship between variables in the form of a causal relationship chain. It is composed of two types of elements: variables and connections, among which variables are the boundaries and influence factors of the system and the connections are represented by directional arrows and ± polarity, reflecting the relationship between variables and the direction of change. In this section, the relationships between vehicles and their energy consumption in each stage are sorted out, and a causal loop diagram is constructed. The causal loop diagram in this paper only considers the system formed by the interrelationship between variables and does not consider the influence of other possible factors on the whole system. The causal loop diagram is shown in Figure 1. Taking the dynamic changes of FVs as an example, FV upgrade rate and FV elimination rate will reduce the number of FVs. Therefore, in the stage of FVs, the closed loops based on the causal association between variables are all negative feedback loops. The main circuits of Figure 1 include the following:

(1) Total vehicle ⟶ vehicle market screening rate ⟶ vehicle listing rate ⟶ total vehicle

(2) Total vehicle ⟶ vehicle market screening rate ⟶ vehicle elimination rate ⟶ total vehicle

(3) FV ⟶ FV market screening rate ⟶ FV upgrade rate ⟶ FV

(4) FV ⟶ FV market screening rate ⟶ FV elimination rate ⟶ FV

(5) HV ⟶ HV market screening rate ⟶ HV upgrade rate ⟶ HV

(6) HV ⟶ HV market screening rate ⟶ HV elimination rate ⟶ HV

(7) FV energy consumption ⟶ FV energy consumption intensity ⟶ HV energy demand increase rate ⟶ FV energy consumption

(8) HV energy consumption ⟶ HV energy consumption intensity ⟶ EV energy demand increase rate ⟶ HV energy consumption

(9) EV energy consumption ⟶ EV energy consumption intensity ⟶ EV energy demand reduction rate ⟶ EV energy consumption

2.4. Stock and Flow Diagram. According to the causal loop diagram, this paper constructs a stock and flow diagram that matches the auto industry upgrade process with the energy consumption demand. Figure 2 is composed of the auto industry upgrade process subsystem (the aging chain model) and the energy consumption subsystem (the coflow model), and the vehicle average energy consumption intensity is an intermediary bridge connecting two subsystems. The auto industry upgrade process subsystem includes FV subsystem, HV subsystem, and EV subsystem. The energy consumption subsystem includes FV energy consumption subsystem, HV energy consumption subsystem, and EV energy consumption subsystem. The model includes 6 level variables, 12 rate variables, and 14 auxiliary variables. Among them, the level variables are determined by inflow rate and outflow rate, which are cumulative values (integral equation) and can describe the system state. The rate variables reflect the characteristics of the level variable changing with time, which are differential equations. The auxiliary variables are intermediate variables that convey information between level variables and rate variables. The equation design between variables is shown in the following section.

2.5. Equation Design and Data Collection. Figure 2 shows that the variables in the subsystem interact with each other, and the subsystems are interrelated. This paper takes the FV subsystem as an example to explain the key variables and main equations as follows:

(1) FV = INTEG (FV listing rate − FV upgrade rate − FV elimination rate, initial value). The FV is affected by the FV listing rate, FV upgrade rate, and FV elimination rate. Among them, the FV listing rate indicates R&D speed, and the faster the FV listing rate, the more the number of FVs. The FV upgrade rate indicates the rate at which the FVs are converted to HVs. The higher the FV upgrade rate, the lower the number of FVs. The FV elimination rate refers to the rate at which the FV fails to market or exits (the life is exhausted). The higher the FV elimination rate, the lower the number of FVs. The initial value is derived from the real statistics of vehicles.

(2) FV market screening rate = FV/FV screening time. The FV market screening rate is determined by FV and FV screening time. The FV market screening rate is proportional to FV and inversely proportional to FV screening time.

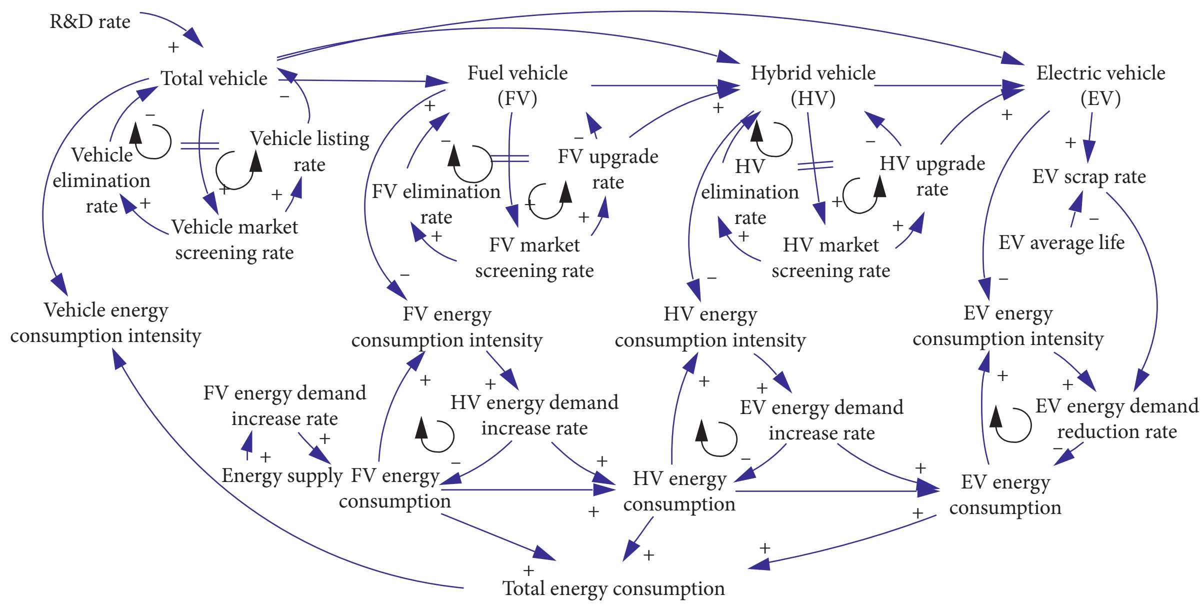

Figure 1: Causal loop diagram.

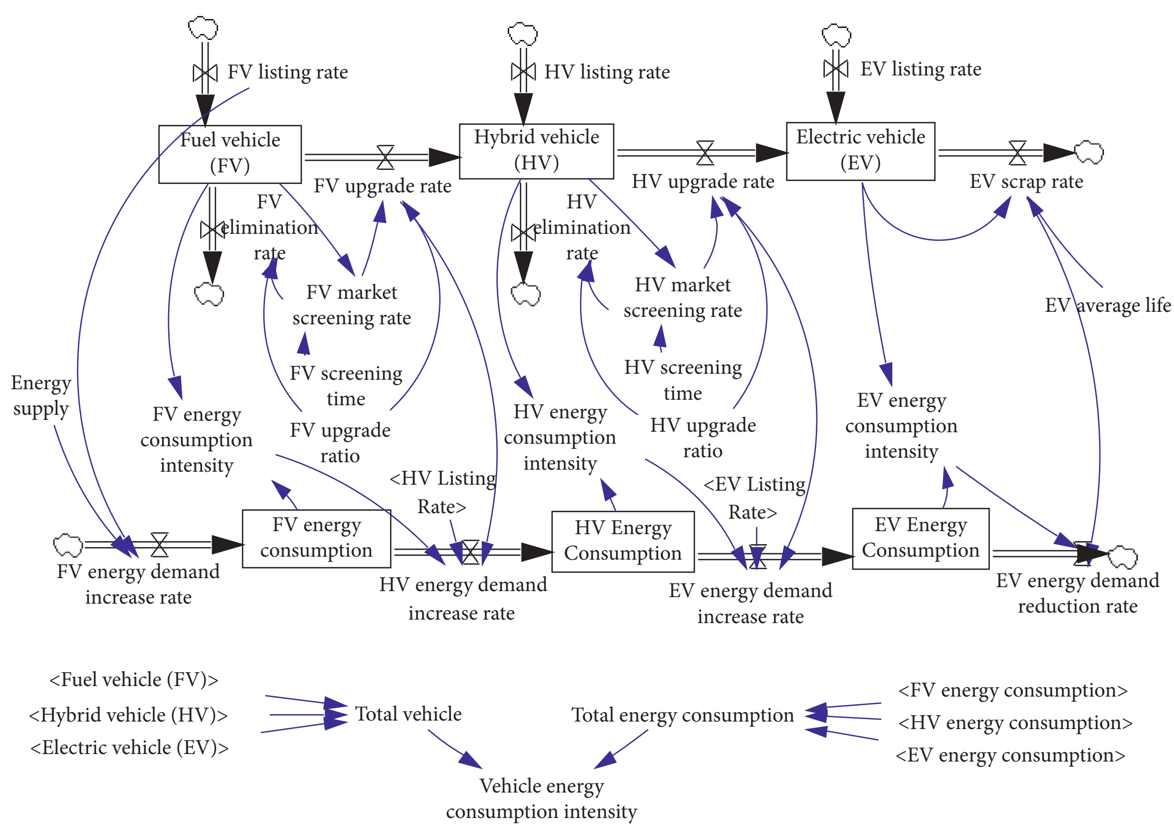

Figure 2: Stock and flow diagram.

(3) FV upgrade rate = FV market screening rate ∗ FV upgrade ratio. The FV upgrade rate is related to FV market screening rate and FV upgrade ratio. Among them, the FV upgrade ratio is set to a constant according to expert experience data.

(4) FV elimination rate = FV market screening rate ∗ (1 − FV upgrade ratio).

(5) FV energy consumption intensity = FV energy consumption/FV. The FV energy consumption intensity is determined by FV energy consumption and FV.

(6) FV energy consumption = INTEG FV energy (demand increase rate − HV energy demand increase rate, energy supply ∗ FV). The FV energy

consumption is affected by FV energy demand increase rate and HV energy demand increase rate. The initial value is the energy supply multiplied by FV, which is calculated using the auto statistics data.

(7) FV energy demand increase rate = energy supply ∗ FV listing rate.

(8) HV energy demand increase rate = (FV upgrade - rate + HV listing rate ∗ FV energy consumption intensity.

(9) Total vehicle = FV + HV + EV.

(10) Total energy consumption = FV energy consumption + HV energy consumption + EV energy consumption.

(11) Vehicle energy consumption intensity = total energy consumption/total vehicle.

The initial values of vehicles are mainly derived from the statistics of China's basic passenger vehicle (sedan car), which is released by China Industry Information Network (CIIN), China Auto Information Net (CAIN), and China Association of Auto Manufacturers (CAAM). The initial data include 1,163 (ten thousand vehicles) fuel vehicles, 13 (ten thousand vehicles) hybrid vehicles, and 24 (ten thousand vehicles) electric vehicles. The initial value of energy supply is determined by the conversion formula of gasoline into standard coal and vehicle's average mileage life, which is about 45 (ten thousand tons/ten thousand vehicles). The initial energy consumptions of different vehicles are equal to the corresponding energy supply multiplied by the number of vehicles. In addition, the parameters are mainly determined by the empirical data of authoritative experts and the empirical investigation of auto enterprises. The initial values of auxiliary variables are as follows: FV market screening time is 7 years and HV market screening time is 8 years. The setting of market screening time comprehensively considers the influence of factors such as consumer preference, market demand, and average vehicle price on different vehicles. The FV upgrade ratio is 0.5, and the HV upgrade ratio is 0.6. The setting of the upgrade ratio takes into account the impact of factors such as R&D intensity, technological progress, and supporting infrastructure construction. The EV average life is 12.5 years, which is an average estimate of empirical data. The proposed control parameters: initial time = 2016, final time = 2050, and time step = 1.

3. Model Simulation and Analysis

3.1. Model Testing Analysis. This paper uses Vensim PLE for model simulation. On the basis of model construction and equation design, the validity and reliability of the model are tested. The results show that the model passed the "system boundary rationality test," "unit test," "extreme situation test," and "abnormal behavior test." It shows that the model is well constructed and can be used for further analysis.

SDs believes that setting specific variables as test functions can judge a model's ability to predict reality. This study focuses on the impact of FV listing rate, HV listing rate, and EV listing rate on vehicle size and auto industry structure. The test equations are determined by the empirical investigation of the auto industry and related statistics, including FV listing rate = 0 (FVs are gradually decreasing, no longer R&D and listing), HV listing rate = 8 + STEP (16, 2025) − STEP (10, 2035), and EV listing rate = 17.5 + STEP (35, 2025) + STEP (35, 2035). STEP (height, time) is a step function. The results are shown in Figure 3.

Figures 3(a) and 3(b) present the FV listing rate, HV listing rate, EV listing rate, and the changes of three types of vehicles, respectively. According to the statistics data of CAIN, FVs far exceed the sum of HVs and EVs at present. However, under the guidance of the national new energy vehicle policy, the FVs in basic passenger vehicles have shown a continuous downward trend since 2016, indicating that traditional vehicles are gradually withdrawing from the market. Meanwhile, according to the "A study on China's timetable for phasing-out traditional ICE-vehicles" initiated by the Innovation Center for Energy and Transportation (iCET), when the sales of FVs are banned around 2035, FV's market share will continue to decline until it is completely withdrawn from the market [40]. Therefore, this paper sets the FV listing rate to 0, which is in line with the auto industry development situation and future trend. The exit of FVs mainly includes two parts: one is natural scrapping and the other is the conversion from oil to electricity. The "oil to electricity" is the upgrading process of auto products from FVs to HVs. With the upgrade of FVs, HVs will show an increasing trend. However, as HVs still consume nonrenewable energy resources and emit pollutants, it will also show a downward trend in the future until it exits the market. This paper sets the HV listing rate based on the development of China's auto industry. The changing trend of FVs is consistent with simulation results (Figure 3(b)). The decline in HVs is accompanied by a second upgrade of the auto industry, that is, from HVs to EVs. As the main type of new energy vehicles in China, EVs will continue to expand market share and far exceed FVs and HVs due to their advantages in energy-saving and environmental protection. The model test results are consistent with the real and theoretical evolution process of the auto industry, and further simulation analysis can be continued.

3.2. Energy Supply Analysis. In order to analyze the impact of the energy supply on the auto industry upgrade process, this paper adjusts rate variables as constants. With reference to the energy supply of 45 (ten thousand tons/ten thousand vehicles), the energy supply is adjusted to 22.5 (ten thousand tons/ten thousand vehicles), and the FV upgrade ratio and HV upgrade ratio are adjusted accordingly. We use a comparative analysis method to study the effects of different energy supplies on vehicles and energy consumption intensity. The adjustment of each parameter value is determined by expert opinions and investigation results of the auto industry. The scenario designs are shown in Table 1.

Figure 4 shows that when FV listing rate, HV listing rate, and EV listing rate remain unchanged, the trends of the three types of vehicles are consistent with the actual situation (Figures 4(a)–4(c)). The simulation results support

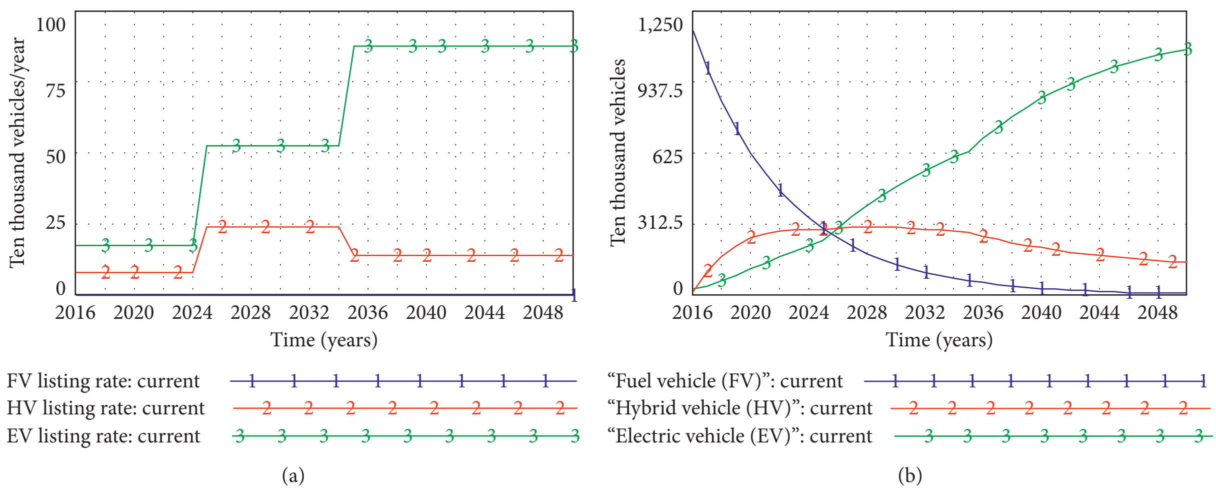

Figure 3: Test function and the number of different types of vehicles. (a) Listing rate; (b) number of FVs, HVs, and EVs.

Table 1: Design of energy supply and vehicle upgrade ratio under three scenarios.

Scenario	Variables		
	Energy supply (ten thousand tons/ten thousand vehicles)	FV upgrade ratio	HV upgrade ratio
Original scenario	45	0.5	0.6
Scenario 1	22.5	0.5	0.6
Scenario 2	22.5	0.7	0.8

Figure 3(b), indicating that the model has good stability. At present, the energy dilemma urgently requires an innovation development path for high energy-consuming industries. In order to analyze the impact of the energy supply on the structural adjustment of the auto industry, this paper designs scenario 1 (energy supply is reduced to half). By comparing the trends of different vehicles under the original scenario and scenario 1, we find that the two curves are consistent, i.e., only reducing the energy supply does not result in an expected change in FVs, HVs, and EVs. On this basis, this paper continues to design scenario 2 (adjusting energy supply and vehicle upgrade ratio). Comparing the trends of vehicles, we find that HVs and EVs show a significant increasing trend, further verifying that the model of excessive consumption of energy resources in exchange for the auto industry long-term development is not correct. Only by adjusting the upgrade ratios, the speed of auto industry upgrade can be accelerated.

In addition, vehicle energy consumption intensity represents the energy utilization efficiency of per unit vehicle, which is also a key indicator reflecting whether the auto industry structure is reasonable. Figure 4(d) shows that the vehicle energy consumption intensity curve of the original scenario coincides with scenario 1, but the energy consumption intensity is significantly reduced in scenario 2. It shows that the reduction of the energy supply does not improve vehicle's energy utilization efficiency. If we continue to maintain the auto industry structure dominated by FVs, it will not be able to fundamentally alleviate energy crisis and environmental pollution. Therefore, the improvement of energy efficiency still depends on the innovation of vehicle upgrading technology. For auto enterprises, the key to breaking through the limitations of the current development model is to improve vehicle R&D and upgrade ratio through innovative energy-saving and emission-reduction technologies.

3.3. Industry Upgrade Cycle Analysis. The industry upgrade cycle is an important criterion for measuring the healthy development of the auto industry. When FV listing rate, HV listing rate, EV listing rate, and energy supply are constant, the FV screening time and HV screening time may become the key factors affecting auto industry upgrade speed. This paper adjusts rate variables and energy supply as constants to study the impact of screening time on the auto industry upgrade process. The time parameters are determined based on real industry conditions and expert opinions. The scenario designs are shown in Table 2.

In this model, the market screening time affects vehicle upgrade rate and elimination rate, which is an important factor affecting vehicle market share, and the market share is crucial to the industrial evolution cycle. This paper designs scenario 1 and scenario 2 (adjusting FV market screening time and HV market screening time, respectively) and compares those scenarios with the original scenario to analyze the impact of screening time on the auto industry upgrade process. Figure 5(a) shows that shortening FV screening time will accelerate FV upgrade rate and elimination rate, i.e., accelerate FV's exit speed (scenario 1), which is consistent with government FV policy orientation. Figure 5(b) shows that shortening FV screening time will

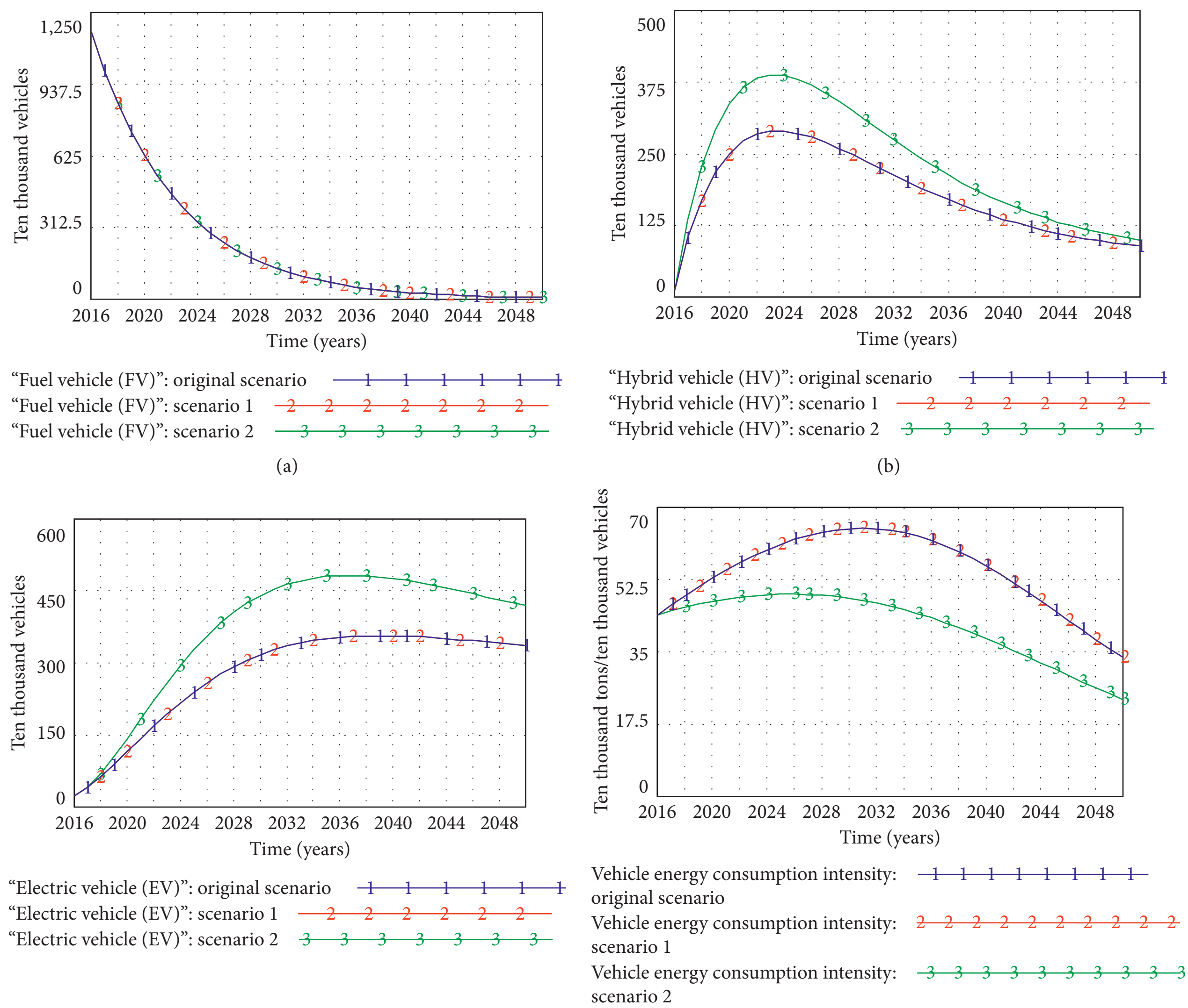

Figure 4: The changing trend of vehicles and vehicle energy consumption intensity under three scenarios. (a) FV. (b) HV. (c) EV. (d) Vehicle energy consumption intensity.

Table 2: Time changes in the auto industry upgrade process under three scenarios.

Scenarios	Variables	
	FV screening time	HV screening time
Original scenario	7	8
Scenario 1	5	8
Scenario 2	7	6

increase first and then reduce HV market share (scenario 1), but shortening HV screening time will reduce the overall HV market share (scenario 2), mainly because shortening market screening time can increase HV upgrade rate, that is, considering factors such as vehicle performance and environmental protection, consumers may scrap FVs and purchase HVs. However, with the popularity of EVs, many consumers will replace old cars (selling HVs and purchasing EVs), which will further reduce HVs market share. Figure 5(c) shows that shortening FV screening time and HV screening time will also increase EVs market share (scenario 1 and scenario 2). This trend is in line with the long-term development of the auto industry. The popularity of EVs is an important symbol of the optimization of auto industry structure. Therefore, this paper believes that the auto industry upgrade cycle is affected by market screening time.

Total energy consumption is a key index for measuring the green development of the auto industry. The traditional auto industry is a high-energy consumption and high-pollution industry. At present, under the guidance of national energy-saving and emission-reduction policy, the auto industry is undergoing a new round of technological reform. This paper analyzes the impact of time parameters on total energy consumption by adjusting vehicle market screening time, which is used as a measure of the success of auto industry upgrade. Figure 5(d) shows that shortening FV market screening time and HV market screening time

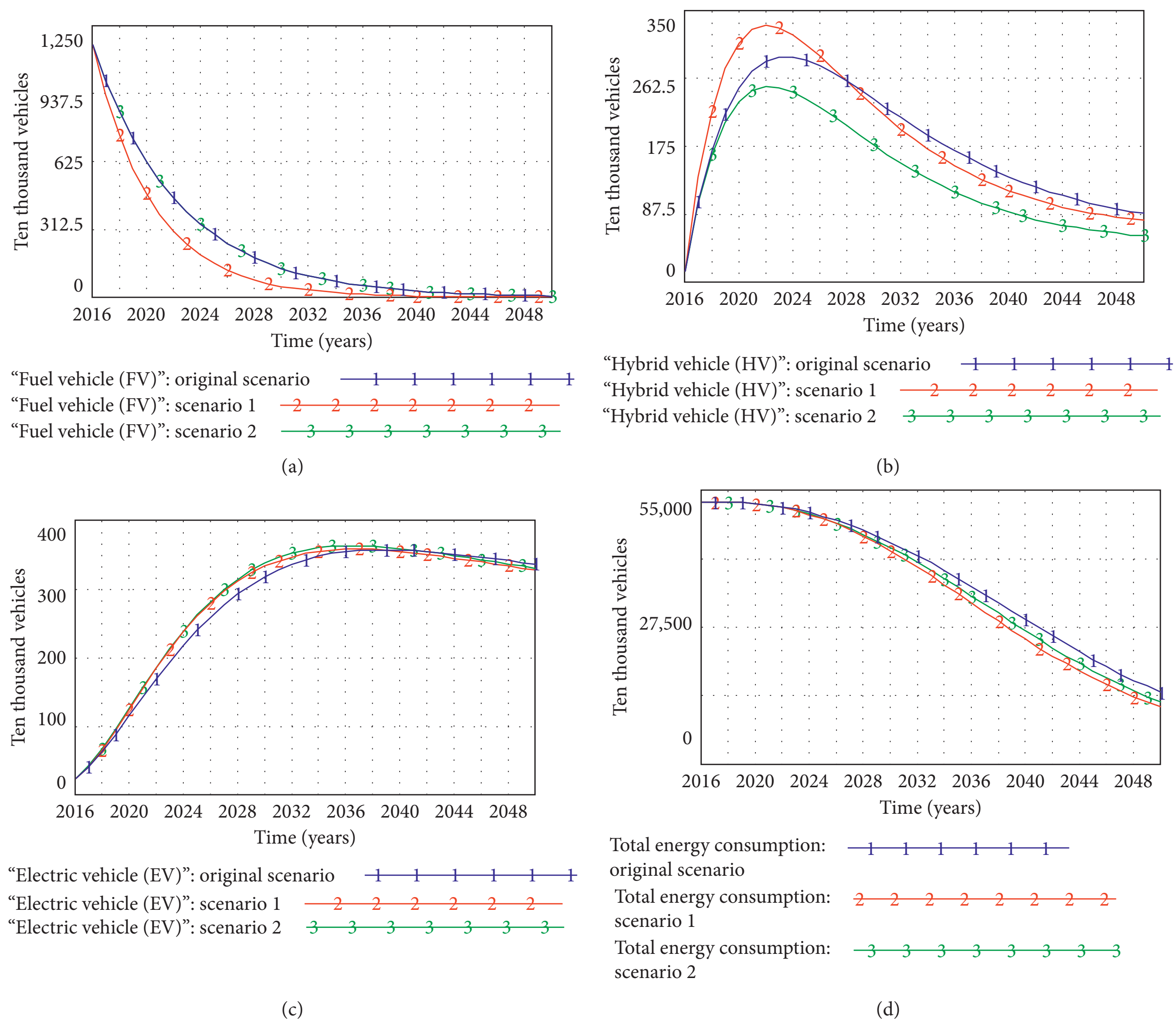

Figure 5: The changing trend of vehicles and total energy consumption under three scenarios. (a) FV. (b) HV. (c) EV. (d) Total energy consumption.

reduces total energy consumption (scenario 1 and scenario 2), and the rate of decline is faster than the original scenario. It indicates that market screening time will affect vehicle's market dwell time (from listing to exiting). The market dwell time is an important factor affecting auto industry life cycle. Therefore, in order to protect nonrenewable energy resources and promote the green development of the auto industry, we must pay attention to the impact of time parameters on industrial structure.

3.4. Supplementary Analysis. Section 3.1 tests the structure and validity of the model. Besides, in this section, we also select the data of basic passenger vehicles of 2016–2018 to compare the simulated values and historical values. The results show that errors are within a reasonable range, and error values (absolute value) are 0.25%, 5.52%, and 8.11%, respectively. Besides, the direction of vehicle change is also consistent with real data. For example, by the end of the simulation period (2050), there are only about 6.15 (ten thousand) fuel vehicles in the auto market, which is in line with the government's goal of achieving the complete withdrawal of FVs by 2050 [40]. Meanwhile, at the end of the simulation period, there approximately 1,083 (ten thousand) electric vehicles, consistent with the trend of new energy vehicles becoming the mainstream of the auto market. These results further verify the credibility of the model.

With the overall decline of the auto market, the productions of China's basic passenger vehicles have also shown a continuous downward trend since 2016. The statistics provided by the National Bureau of Statistics (NBS) also show that basic passenger vehicle production reached 7.324 million from January to September 2019, a cumulative decline of 15.1% [41]. The conservative productions of auto enterprises are closely related to purchasing power, as consumers are holding a wait-and-see attitude toward buying cars. Facing the sluggish auto market, how to restore market vitality is both a challenge and an opportunity. Therefore, auto enterprises should seize market opportunities, keep up with consumer demand, and eliminate outdated productivity timely. Enterprises should also expand the market share of EVs (representatives of new energy vehicles) and enhance the competitiveness of the auto industry through a new round of technological innovation.

The construction of EVs infrastructure is another bottleneck in the auto industry upgrade process. Driven by policy incentives and consumer demand, the development of EVs has driven the rapid growth of public charging infrastructure. According to the statistics released by China Industrial Economic Information Network, the possession of new energy vehicle charging piles increased from 3.3 (ten thousand) to 77.7 (ten thousand) in 2014–2018, greatly improving the difficulty of charging [41]. However, there are still some problems in EVs infrastructure construction, such as unreasonable layout, low utilization rate, and long charging time. Therefore, in the future, auto enterprises should pay more attention to the improvement of the supporting service system.

In addition, in theory, the auto industry consumes nonrenewable energy (such as gasoline and diesel) and emits large amounts of pollutants during the FV stage. When the auto industry enters the HV stage, energy consumption and pollution emissions are greatly reduced. Later, as the auto industry gradually upgraded to the EV stage, the driving of vehicles mainly relies on the motor system, which maximizes environmental protection, that is, the upgrading of the auto industry is an evolution process from high energy consumption and high pollution to low energy consumption and no pollution. However, the development situation of the auto industry shows that only about 30% of the electricity supply of EVs comes from clean energy in China, i.e., EVs still consume a lot of nonrenewable energy (main coal) and emit pollutants, which is far from the theoretical goal. At present, the Chinese government takes new energy vehicles as a strategic pillar industry and believes that developing new energy vehicles is an inevitable way from a big country to a powerful country in auto industry. Therefore, the development of EVs should continue to breakthrough in technology and accelerate the replacement of FVs and HVs through the development and application of power generation technologies such as wind, solar, and tidal energy.

4. Conclusions and Implications

4.1. Conclusions. Based on the two perspectives of environment and energy constraints, this paper divides the auto industry upgrade process into three stages: FVs, HVs, and EVs. Combined with vehicle energy consumption attributes, this study constructs an aging chain and coflow model. Furthermore, taking China's auto industry as an example, we select the statistics of basic passenger vehicles to simulate and study the impact of test function, energy supply, and time parameters on auto industry structure. The main conclusions include the following:

(1) The upgrade process of China's auto industry structure from FVs and HVs to EVs will undergo two important adjustments. The first upgrade is the natural scrapping of FVs and the conversion of "oil to electricity." The second upgrade is the gradual reduction of HVs (low-energy and low-pollution) and the overall popularity of EVs.

(2) This paper studies the impact of energy supply and upgrade ratios on auto industry structure by using vehicle size and vehicle energy consumption intensity. The scenario test results indicate that a single reduction in energy supply does not change vehicle size and vehicle energy consumption intensity, that is, the development model of excessive consumption of energy resources cannot improve energy utilization efficiency and promote the sustainable development of the auto industry. Only by adjusting energy supply and upgrade ratios together, the speed of industry upgrade can be accelerated and the energy crisis and environmental pollution can be alleviated.

(3) This paper analyzes the impact of market screening time on auto industry life cycle using vehicle size and total energy consumption. For one thing, the market screening time on the auto industry upgrade process is mainly achieved by affecting vehicle's market share. For another, the market screening time will also affect auto industry life cycle by affecting vehicle's market dwell time. Therefore, we must pay attention to the impact of time parameters on industrial structure.

(4) The upgrading of the auto industry also needs to focus on the consumer preferences of the demand side, the technological innovation of the supply side, and the improvement of the infrastructure system. The auto industry upgrade process should be designed and planned from the perspective of the whole industrial chain.

4.2. Implications. In order to accelerate the structural adjustment of China's auto industry, the following suggestions are proposed. First, China's auto industry is still in the stage of "big but not strong," and the international competitive advantage is not obvious. In the new round of industrial transformation, government and enterprises should continue to implement innovation-driven strategy and build the new energy vehicle innovation development system. On the one hand, it is necessary to build a public R&D platform to help enterprises reduce R&D threshold and improve R&D success rate and market share. On the other hand, government should improve the supporting infrastructure and service facilities of EVs, such as cross-regional power grid layout, standardized maintenance, and battery life extension, to improve EVs performance and convenience. Second, the current development model at the expense of energy resources not only fails to solve energy and environmental problems but also is not conducive to the sustainable development of the auto industry. Governments and industry organizations should strengthen market supervision, eliminate high-pollution vehicles in time, and transform the traditional auto industry into a clean energy industry. Meanwhile, government and enterprises should take energy conservation and environmental protection as development goals and increase capital investment in power generation technologies to fundamentally protect nonrenewable energy resources. Third, as a major auto manufacturing and consumption country, the upgrading of China's auto industry should pay more attention to consumer guidance. We can encourage and guide consumers to use low-carbon and pollution-free vehicles by providing consumer subsidies, creating consumption environment, and innovating marketing channels.

4.3. Limitations and Future Research Directions. This study has two limitations. First, this paper constructs a matching model of the auto industry upgrade process and its energy consumption attributes. However, due to the complexity of the factors, this paper only considers the system formed by the interrelationship between FVs, HVs, EVs, and their corresponding energy consumption. Other influencing factors, such as vehicle price and consumer preference, are only considered in the design of auxiliary variables, and the independent impact of each variable on industrial upgrading is not considered. Future research can further extend the impact of other possible influencing factors on the overall auto system. Second, this paper uses the statistical data of China's basic passenger vehicles to simulate and predict the auto industry upgrade process. However, due to the lack of industry panel data, this paper does not simulate the cross section data, which reduces the accurate prediction ability of the model. Future research can further conduct in-depth comparative studies by collecting industry panel data.

Data Availability

The data used in this study are partly from China Industry Information Network (CIIN), China Auto Information Net (CAIN), and China Association of Auto Manufacturers (CAAM), and partly from the empirical investigations of authoritative experts in the auto industry and auto companies.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

This research was funded by the National Natural Science Foundation of China (Grant no. 71974119) and Humanities and Social Sciences Foundation of the Ministry of Education of China (Grant no. 18YJA630137).

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