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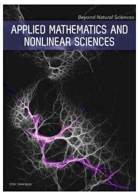

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Prediction of Chinese Automobile Growing Trend Considering Vehicle Adaptability based on Cui–Lawson Model

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Abstract

The rapid growth of fossil fuels and the aggravation of emission pollution can be improved by the green and diversified energy structure of road transport vehicles. In this article, Cui–Lawson model is first introduced to analyse the change trend of pure electric vehicle, hybrid electric vehicle, gas–fuel vehicle, fuel cell vehicle, biofuel vehicle and traditional vehicle in the next 50 years. Considering the climate, environment and economic development of each region, the future ownership of the above six models was studied by region. Moreover, the climate and topography affect the developing trend strongly. The ownership of traditional automobile is more than other kinds of vehicles until 35 and 40 years in Xibei and Dongbei regions for the cold temperature.

Keywords: road transport, power source, population competition model, life cycle
AMS 2010 codes: E4343

1 Introduction

With the increasing energy constraint and environmental problem of China, the sustainable development of socio-economic has been substantially affected. The vehicle fuel accounts for almost one-half of new oil consumption, which is the major factor determining the increase in oil demand [1]. China's dependence on foreign oil imports rose to 65.4% in 2016, which is far beyond 50% of the security cordon [2]. Therefore, promoting a green and diversified development of the energy structure of road transport vehicles is an important issue facing the relevant administrative departments.

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At present, new energy vehicles are mainly divided into hybrid electric vehicles, pure electric vehicles, fuel cell vehicles, gas–fuel vehicles and biofuel vehicles. Many researchers have studied the prediction of car ownership and the development trend of new energy vehicles. Dargar and Gately adopted time series method to predict car ownership [3]. Hung studied the effect of the tax subsidy policy on switching to LPG in Hong Kong [4]. Yuan explained the most suitable power source vehicle for development at the present stage by constructing a five-dimensional evaluation index of the comprehensive development capability of automobiles and using the rough set theory to establish an evaluation model of the comprehensive development capability of new energy vehicles [5]. Steinhilber et al. assessed stakeholders' views on regulation, infrastructure investment and consumer incentives by studying the major barriers to the promotion of electric vehicles in the UK and Germany [6]. Nordlund et al. studied the acceptance of target policy measures by the normative theory of personal values and beliefs of consumers of vehicles with various power sources. They believed that policymakers need to make policies that are considered fair and effective to make them more acceptable to citizens [7]. Morton et al. used spatial autocorrelation technology to study the ownership of electric vehicles in Britain, proving that ownership is closely related to education level, employment status, income level, population density, housing type, family size and vehicle availability [8]. Ma et al. studied the gaps and deficiencies in the development of new energy vehicles in China and summarised by benchmarking the technological frontiers of international pure electric vehicles, plug-in hybrid electric vehicles, fuel cell vehicles, power battery and driving system [9]. Guo et al. cited biological population Lotka–Volterra model to simulate electric vehicles, conventional cars and natural gas vehicles in the next 40 years to maintain the amount of curve [10]. However, in the existing prediction methods, the adaptability of different power source vehicles and regional characteristics was not to be fully considered in the process of prediction. China has vast territory, and complex geographical and climatic conditions. Moreover, the adaptability of different kinds of power supply vehicles varies in different regions. In this article, we use Cui–Lawson model that is generalised the Lotka–Volterra interspecific competition theory to describe the adaptability of different power supply vehicles by the nutrition parameters of environmental resource conditions.

The contribution of this article can be summarised as follows:

1. A multiple species competition model to describe the growing trend prediction problem.
2. The Cui–Lawson model that can reflect the different factors as the adaptability, thus we can predict the growing trend in one by one region.

2 Adaptability analysis of vehicles with different power sources

In China, the development of electric vehicles is relatively mature. The sales of pure electric vehicles accounted for 84.2% of new energy vehicle. The basic data of pure electric vehicles mainly come from publicly published in the catalogues of recommended models for promotion and application of new energy vehicles (the first to third batch in 2017). The performance parameters of other power sources vehicles are referred to other research results. The indicators of vehicles with different power sources are summarised in Table 1.

Some conclusions can be seen from Table 1. First, there is little difference in the dynamic performance of vehicles with different power sources, which can meet the normal travel demand. Second, the difference in consumption rate is not significant in the economic index. But the driving range varies relatively, and the convenience of fuel replenishment has a great correlation with the improvement of related infrastructure in the region. Third, in terms of environmental adaptability, atmospheric temperature has the greatest impact on the performance of the vehicles. Pure electric vehicle is the most affected by low temperature. The driving range decreases rapidly with the decrease in temperature.

Therefore, this article considers the energy supply infrastructure and temperature of various power vehicles as the most important factors influencing their adaptability.

Table 1 The indicators of vehicles with different power sources

		Pure electric vehicles	Hybrid electric vehicles [11]	Gas–fuel vehicle (e.g. CNG)	Fuel cell vehicle [11]	Biofuel vehicle (e.g. methanol)
Dynamic property	Maximum speed (km/h)	143 [12]	185	140 [13]	153	165 [13]
	Acceleration time (0–100 km/h) (s)	10.2 [12]	6.6 (0–50 km/h)	22.1 [13]	12.5	15.7 [13]
	Maximum gradability (%)	37 [12]	23.8	–	20	30 [14]
Economy	Consumption rate (fuel/100 km)	16.42 kWh [15]	–	26.9 m^3	1.164 kg (hydrogen fuel)	15.5 L (methyl alcohol)
	Driving range (km)	200 [16]	–	600	323	–
Environmental adaptation	Temperature (°C)	-20 0 27	–	-31	-30 to -10 [17]	
	Capacity retention ratio	20%–40% 60%–70% 1	–	No influence on starting performance	Cold boot	7.35 s (-10°C)
	Atmospheric pressure			Low pressure		

3 Methods

Most research in recent years have been focused on car ownership field using predicting methods such as time series method, elastic coefficient method, regression analysis method, grey model method, neural network method and combination prediction method. Unfortunately, these methods do not always take the regional and environmental adaptability of vehicle applications into account. The purpose of this study is to describe and examine the competitive process of six kinds of vehicles: pure electric vehicles, hybrid electric vehicles, gas–fuel vehicles, fuel cell vehicles, biofuel vehicles and traditional vehicles, by population competition analysis. First, when all kinds of cars compete with other cars, they will also produce corresponding influence coefficient, which is in line with the ring competition relationship. Second, the nutrient parameters related to environmental resource conditions and population affinity to resources are closely related to regional attributes. The following section describes the specific construction process of the Cui–Lawson model.

3.1 Cui–Lawson Model

Since the famous Lotka–Volterra competition model [18] has simplified the intermediate competitive process [19], a Cui–Lawson model, shown in Equation (1), was proposed to describe the relationship between non-linear population growth and resource limitation which can be applied to more complex population behaviour analysis:

$$\frac{dX}{dt} = \mu_c^* X \frac{1 - X/X_m^*}{1 - X/X'_m} \tag{1}$$

where X is the population density at time t; X_m^* is the environmental capacity; μ_c^* is the maximum specific rate of population growth under certain environmental conditions and X'_m is a nutrient parameter related to environmental resource conditions and the population's affinity to resources.

There is a production–consumption–scrap life cycle in the automobile market, and there are inputs and outputs of vehicles. So, we consider that the competitive environment is a typical open system. Moreover, vehicles with different power sources have different energy demand. Therefore, we constructed a six-population competition model under open system condition with different nutritional requirements to reflect the adaptability of vehicle types with different power sources to certain environmental characteristics. The density growth rate of vehicle type i can be shown in the following equation:

$$\frac{dX_i}{dt} = \mu_{ci}^{*} X_i \frac{1-(X_i + \sum_{j=1, j\neq i}^{6} a_{ij} X_j)/X_{mi}^{*}}{1-(X_1 + \sum_{j\neq i, j=1}^{6} a_{ij} X_j)/X'_{mi}} \tag{2}$$

where X_i is the density of vehicle type i, i = 1, 2, ..., 6; μ_{ci}^{*} is the maximum specific rate of population growth under certain environmental conditions of vehicle type i, $\mu_{ci}^{*} = \mu_{ci} - D_i$, D_i is population mortality rate. $X'_{mi} = k_i/a_i + X_{mi}$ is the nutrient parameter of vehicle type i, X_{mi} is the environmental capacity of vehicle type i. X_{mi}^{*} is the maximum density of vehicle type i, $X_{mi}^{*} = \frac{1-D_i/\mu_{ci}}{1-(D_i/\mu_{ci})(X_{mi}/X'_{mi})} X_{mi}$. Obviously, X_{mi}^{*} will be less than X_{mi} in general. a_{ij} is the competition coefficient of population j to population i, and it represents how much population j per unit quantity is equivalent to population i. The positive or negative value of a_{ij} represents the influence nature of population j on population i, and the absolute value represents the influence intensity.

In this article, six populations, namely traditional vehicle, pure electric vehicle, hybrid electric vehicle, gas–fuel vehicle, fuel cell vehicle and biofuel vehicle, will be targeted predict trend by population competition analysis. In the process of competing, vehicles of various energy source types will be produced and then scrapped. Therefore, the competitive system of various energy source vehicles is defined as an open system. At the same time, different types of vehicles use different energy sources, for example, the nutritional requirements of competing species in the system are not the same. Based on the earlier analysis, the interspecific competition equations (3)–(8) were constructed under open system condition with different nutritional requirements for competing species.

$$\frac{dX_1}{dt} = \mu_{c1}^{*} X_1 \frac{1-(X_1 + \sum_{j=2}^{6} a_{1j} X_j)/X_{m1}^{*}}{1-(X_1 + \sum_{j=2}^{6} a_{1j} X_j)/X'_{m1}} \tag{3}$$

$$\frac{dX_2}{dt} = \mu_{c2}^{*} X_2 \frac{1-(X_2 + \sum_{j=1, j\neq 2}^{6} a_{2j} X_j)/X_{m2}^{*}}{1-(X_1 + \sum_{j=1, j\neq 2}^{6} a_{2j} X_j)/X'_{m2}} \tag{4}$$

$$\frac{dX_3}{dt} = \mu_{c3}^{*} X_3 \frac{1-(X_3 + \sum_{j=1, j\neq 3}^{6} a_{3j} X_j)/X_{m3}^{*}}{1-(X_1 + \sum_{j=1, j\neq 3}^{6} a_{3j} X_j)/X'_{m3}} \tag{5}$$

$$\frac{dX_4}{dt} = \mu_{c4}^{*} X_4 \frac{1-(X_4 + \sum_{j=1, j\neq 4}^{6} a_{4j} X_j)/X_{m4}^{*}}{1-(X_4 + \sum_{j=1, j\neq 4}^{6} a_{4j} X_j)/X'_{m4}} \tag{6}$$

$$\frac{dX_5}{dt} = \mu^*_{c5} X_5 \frac{1-(X_5+\sum\limits_{j=1,j\neq 5}^{6} a_{5j}X_j)/X^*_{m5}}{1-(X_5+\sum\limits_{j=1,j\neq 5}^{6} a_{5j}X_j)/X'_{m5}} \tag{7}$$

$$\frac{dX_6}{dt} = \mu^*_{c6} X_6 \frac{1-(X_6+\sum\limits_{j=1}^{5} a_{6j}X_j)/X^*_{m6}}{1-(X_6+\sum\limits_{j=1}^{5} a_{6j}X_j)/X'_{m6}} \tag{8}$$

Equations (3)–(8) constitute the prediction model for the development trend of environmental adaptability of six energy source kinds of vehicles under open condition. In the following section, we will explain the parameter selection of simulation prediction in detail.

3.2 Simulation

According to the geographical location, economic development and climatic conditions, China can be divided into six regions, namely north China, northeast China, east China, south China, southwest China and northwest China. The socio-economic status and geographical characteristics of the six major regions in China are shown in Table 2.

Table 2 The socio-economic status and geographical characteristics of the six major regions

Regions	Vehicle ownership (10,000)	Resident population (10,000)	Vehicle ownership by 100 person	GDP (100 million yuan)	Per capita GDP (10,000)	Geographical features
North China	3,587	17,522	20	119,247	6.8	Plain and mountainous region
Northeast China	1,696	10,836	16	56,752	5.2	Plain and forest
East China	7,806	41,172	19	345,738	8.4	Hill, basin and plain
South China	5,835	39,627	15	246,311	6.2	Mountain and basin
Southwest China	2,725	20,217	13	95,207	4.7	Plateaus and basins
Northwest China	1,583	10,279	16	51,454	5.0	Plateaus, basins and mountain

Note: The data in the table are collected from China Statistics Yearbook 2019.

As shown in Table 2, in terms of vehicle ownership, the total number of civil motor vehicles in east China is the highest. The terrain of east China is dominated by hills, basins and plains. East China generates 38% of GDP with 9% of the land area. The second region is south China, with a total of 58.35 million civilian motor vehicles, in which population and GDP account for 28.4% and 26.9%, respectively. In order of vehicle ownership, north China, southwest China, northeast China and northwest China are followed. In terms of the number of motor vehicles per 100 people, north China is the highest with 20, followed by eastern China with 19, northeast and northwest China with 16 and south and southwest China with 15 and 13 motor vehicles, respectively.

According to the traffic administration bureau of the ministry of public security published data from 2015 to 2019, pure electric vehicles account for about 80% of new energy vehicles, and currently all motor vehicles account for a maximum of 1.3%. We assume that the proportions of various types of vehicles in different regions are the same to better analyse the adaptability of vehicles with different power sources to regional environmental conditions. Population density and economic development level are important factors influencing the growth rate of motor vehicles, while geographical characteristics and climatic conditions highly influence the choice of vehicle types. According to the development trend of motor vehicle ownership, regional economic development and climatic and geographical conditions in recent years, relevant parameters of each region were set.

Consider north China as an example: this region has a high level of economic development and the highest per capita motor vehicle ownership. The terrain is dominated by plains. There is no extreme cold in the climate. The adaptability of all kinds of power vehicles is good. Thus, the parameters that will be used are given in Table 3.

Table 3 Simulation parameters in north China

	Population 1	Population 2	Population 3	Population 4	Population 5	Population 6
X_{mi}	5,000	6,500	10,000	5,000	8,000	8,000
r_i	8%	55%	27%	32%	28%	12%
X_i	3,515	57.4	10.8	1.2	1.2	1.2
D_i	0.9%	1.4%	1.4%	1.4%	1.4%	1.4%

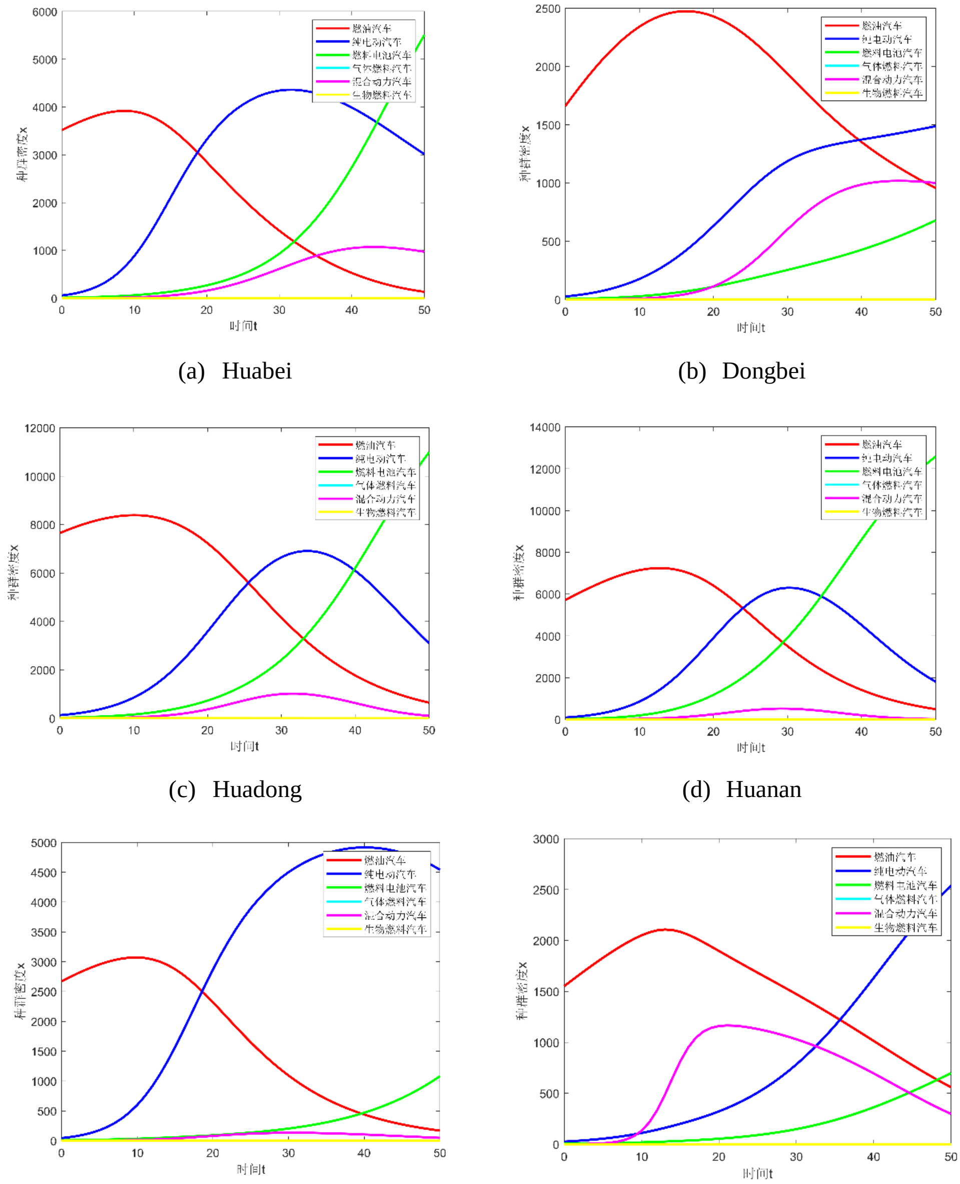
To investigate the performance of population competition, we execute a variety of case studies with different presetting parameters. All the simulations are performed on a personal computer with 1.80 GHz CPU and 4.00 GB memory, and the algorithms are coded in Matlab R2018b. The prediction result of north China can be seen in Figure 1(a). Similarly, simulation parameters are set in the other five regions according to the regional characteristics, and the results are shown in Figure 1(b)–(f).

As shown in Figure 1(a), the traditional vehicle ownership presents a parabolic development trend that will increase steadily in 10 years. It is estimated that the traditional car ownership will reach the peak value around 2030, about 40 million, and then decrease. Among the new energy vehicles, the ownership of pure electric vehicle also presents a parabolic development trend, with a low speed growth in the past 10 years. Then, encouraged by the government's promotion and technological progress, the ownership of pure electric vehicles will grow rapidly in the next 10–30 years. Thirty years later, as technology improved significantly, the ownership of zero-emission fuel cell vehicle will increase rapidly, showing a S-shape, and eventually become a mainstream power source. The development trend of hybrid electric vehicle is similar to the parabolic shape of pure electric vehicles ownership. But earlier, the hybrid vehicle has no advantage in technology maturity and the government subsidies compared with pure electric vehicles. Moreover, in terms of environmental protection, hybrid vehicle cannot be compared with hydrogen fuel cell vehicle. However, the traditional vehicle will drop into a period of decline, when the hybrid vehicle can obtain a relatively loose development and environment. Due to the limitation of living environment and development, the ownership of gas–fuel cell vehicle and biofuel vehicle has been at a low level of development.

As detailed in Figure 1(b), the development trend of traditional vehicle in northwest China also presents a parabolic sharp, with the highest ownership gained after 17 years. But unlike in north China, traditional vehicle will be the most kind for the next 40 years. This indicates that the influence of climate and terrain condition in northeast China on the adaptability of vehicles with various power sources is mainly reflected in the proportion of low temperature weather throughout the year which is much higher than that in north China. At this time, the endurance of pure electric vehicles is greatly affected.

Comparing Figure 1(c) and (d) shows that similar behaviour was observed in both east China and south China, with a major development of pure electric vehicle at first stage and fuel cell vehicle at a later stage, although the vehicle ownership in east China is higher.

As illustrated in Figure 1(e), the development trend is in line with the trend previously shown in east China. However, in the long term, the development trend of fuel cell vehicles in southwest China is better than that of



(a) Huabei (b) Dongbei

(c) Huadong (d) Huanan

(e) Xi'nan (f) Xibei

Fig. 1 Different energy sources vehicle ownership forecast.

hybrid electric vehicles.

As indicated in Figure 1(f), the development trend of northwest China is noticeably different from trends in the other five regions. It is obvious that the hybrid electric vehicle increases rapidly from 2030 to 2040. To the knowledge of the authors, the possible reasons may be as follows. First, high altitude and cold weather have great influence on the power performance of fuel cell vehicle and the endurance of pure electric vehicle, respectively. Thus, the adaptability of these two energy source vehicles that have a good development in other regions in northwest China is much lower than hybrid electric vehicle. Besides, the development stage lags in other regions due to their backward economy.

In general, based on the accumulated industry advantages of policy bias, pure electric vehicles have certain advantages in cost and infrastructure construction and will continue to develop rapidly soon. However, in the later stage, with the promotion of energy transformation and the continuous development of technology, cost and infrastructure, fuel cell vehicles have greater development space. The social and economic differences between regions are the main reason why the competitive market of automobiles is in different stages. In addition, low temperature, high altitude and other special conditions will limit the development space of some vehicles in the region.

4 Conclusion

In this study, the Cui–Lawson model in biological population competition was introduced to simulate the change trend of the ownership of traditional vehicles, pure electric vehicles, hybrid vehicles, gas–fuel vehicles, fuel cell vehicles and biofuel vehicles. Specific conclusions are explained as follows.

The holding volume of traditional automobiles develops in a parabolic trend, and the year when it reaches the highest value is closely related to the social and economic development conditions in this region. The development trend of pure electric vehicle ownership is also parabolic, occupying the mainstream trend soon, while the fuel cell vehicle will become the vehicle with the largest long-term ownership. Similar to pure electric vehicles, the development curve of hybrid electric vehicles is parabolic, and the main models have a better development trend when they are not well adapted to the environment. Due to the limitation of living environment and development, the ownership of gas–fuel vehicles and biofuel vehicles has been at a low level of development.

The climate and terrain conditions in each region have a great influence on the development trend of automobile type competition. Consider, for example, the traditional automobile, whose amount is higher than other kinds of vehicles until 35 and 40 years in Xibei and Dongbei regions, respectively. Since both Xibei and Dongbei are colder than other regions, those regions are not suitable for the development of electric vehicle and fuel cell vehicle.

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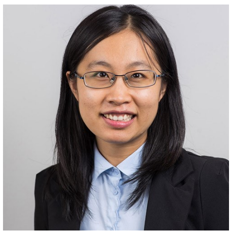

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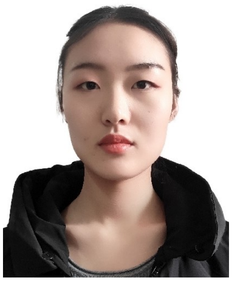

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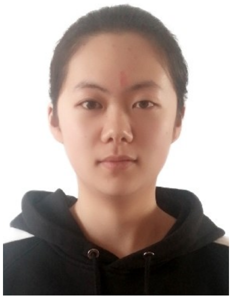

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