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Evaluating the impact of fossil fuel vehicles exit on the oil demand in China¹

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Abstract Vehicle ownership is one of the most important factors affecting fuel demand. Based on the forecast of China's vehicle ownership, this paper estimates China's fuel demand in 2035 and explores the impact of new energy vehicles under the scenarios of slow, medium, and rapid substitution. The main contribution of this paper is making a more detailed estimation on the main parameters such as the saturation level and growth rate of the vehicle ownership by taking into account the heterogeneity of provinces when using the Gompertz model to forecast the future vehicle ownership. On that basis, the fuel demand of each province in 2035 is calculated. The results show that: ①The vehicle ownership rate of each province conforms to the S-shape trend with the growth of real GDP per capita. At present, most provinces are at a stage of accelerating growth. However, the time for the vehicle ownership rate of each province to reach the inflection point is quite different. ②Without considering the replacement of new energy vehicles, China's auto fuel demand is expected to be 746.69 million tonnes (Mt) in 2035. Guangdong, Henan, and Shandong are the top three provinces in fuel demand due to the economic and demographic factors, with the expected fuel demand of 76.76, 64.91 and 63.95Mt respectively. ③Considering the replacement of new energy vehicles, China's fuel demand in 2035 will be 653, 615 and 578 Mt respectively under the scenarios of slow, medium and fast substitution. Even under the scenario of slow substitution, the reduction in fuel demand will be 94 Mt, accounting for 26.3% of China's net oil imports in 2016. Therefore, the withdrawal of fuel vehicles will greatly reduce the oil demand and the dependence on foreign oil of China. Faced with the dual pressure of environmental crisis and energy crisis, the forecast results of this study provide practical reference for policy makers to rationally design the future fuel vehicle exit plan and solve related environmental issues.

Key words vehicle ownership; Gompertz model; fuel demand

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1 Introduction

China has become the world's second-largest oil consumer after the United States. In 2016, China's oil consumption was 579 Mt, accounting for 13.1% of the world's total oil consumption (BP, 2017). In the same year, the net oil import of China was 358 Mt, and its foreign oil dependency rose to 61.8% (National Bureau of Statistics of China, 2017). The continued rising foreign oil dependency has seriously threatened China's energy security (Shen and Xue, 2011). The oil demand for road transportation is currently the largest oil consumer in China. In 2015, the proportion of oil consumption in the road transportation sector accounted for 48.4% of the total (National Bureau of Statistics of China, 2016). In the past three decades, with the sustained and rapid development of China's economy, vehicle ownership keeps rising, while the proportion of new energy vehicles (NEVs) is still small, which has not only increased China's oil demand, but also exacerbated related environmental problems especially air pollution and climate change. To combat global climate change and improve air quality, Norway, Netherlands, India, Germany, the United Kingdom, France and other countries have proposed and later decided to ban vehicles powered by fossil fuels, and encourage the replacement of fuel vehicles with new energy vehicles. After that, in September 2017, the vice minister of the Ministry of Industry and Information Technology (MIIT) of China said that MIIT has started relevant research and will make such a timeline with relevant departments, at an auto industry event in Tianjin (Munroe and Chen, 2017). The timeline is expected to be officially launched in 2035.

The development of NEVs is becoming a strategic choice for many countries to deal with the climate change and energy security as well as to gain advantage in international competition. Thanks to the technological advances, government subsidies, and restrictions on purchases in some cities, sales of NEVs in China continue to rise rapidly, and the substitution effect of fossil fuel vehicles by NEVs cannot be ignored any more. Therefore, it is of practical significance to quantitatively evaluate the development trend of NEVs and their impact on China's oil demand. Against the background of the increasing vehicle ownership, the rising oil dependency, and the accelerating replacement of fuel vehicles with NEVs, this paper estimates China's fuel demand in 2035 based on the prediction of the future vehicle ownership in China, and the impact of NEVs substitution on oil demand under three scenarios of slow, medium and fast substitution. The results may provide practical reference for policy makers to rationally design the future fuel vehicle exit plan and solve related environmental issues.

The structure of the paper is arranged as follows: Section 2 reviews researches on the forecast of vehicle ownership and fuel demand. Section 3 introduces the empirical model, parameter estimation and the data acquisition process of the paper. Section 4 presents the results and discussions. Section 5 conducts a robustness test of different replacement speeds. And Section 6 covers conclusions and policy implications.

2 Related literature

Energy demand analysis and forecast have always been important research topics. The energy

demand forecasting model can be divided into the top-down model, the bottom-up model, and the hybrid model. Zhao et al. (2015) gave a detailed overview of the advantages and defects of the three models, as well as their application in practice in various countries. The bottom-up model is generally based on the engineering technology. It can better describe the technologies and costs used in energy production and energy consumption. It is also useful when analyzing and predicting various scenarios of future technical changes. Thus it is more frequently used in forecasting the transportation energy demand. For example, Johansson and Schipper (1997) developed a method to estimate the long-run vehicle energy demand in the United States based on the estimate results of US vehicle ownership, average fuel economy, and average mileage. After analyzing the composition of Japanese automobile market, Palencia et al. (2017) measured the fuel demand of Japanese light vehicles in the long run.

In recent years, researches on China's automobile fuel demand are gradually enriched, among which the most common methods are those combining vehicle ownership forecast with different technological progress scenarios. Using the data of China's road transport sector between 1997 and 2002, He et al. (2005) developed a bottom-up model to predict the fuel consumption and CO₂ emissions in 2030 under three scenarios regarding motor vehicle fuel economy improvements. Zhang et al. (2010) forecast fuel demand of China in 2030 under three energy consumption decrease scenarios by establishing a LEAP model. The scenarios are: (1) 'business as usual'; (2) 'advanced fuel economy'; and (3) 'alternative energy replacement'. Wang et al. (2017) made a scenario analysis of energy consumption and reductions in CO₂ emissions in China's transport sector in 2050 by using the TMOTEC model which is based on discrete choice method and general transport cost simulation. Wu et al. (2014) used the Gompertz model to forecast China's future vehicle ownership and then measured the fuel demand of China's road transport sector in 2050.

As China's vehicle ownership is still in a period of rapid growth and is not saturated, future vehicle ownership, which is regarded as the basis of predicting fuel demand by many researchers, is the most important factor affecting China's fuel demand. International experience shows that vehicle ownership rate of a country increases slowly at the lowest income levels, followed by an increasing rate of growth as income rises, and then slow down as saturation is approached. That is, the relationship between vehicle ownership rate and GDP per capita can be represented by some sort of S-shape curve (Cherif et al., 2017; Dargay and Gately, 1997; Qi, 2010; Wu et al., 2014). In terms of the model fitness of the S-shape curve for fuel demand forecasting, the Gompertz model is proved to be more suitable for the prediction because of its excellent applicability and general characteristics of the growth curve, compared with other S-shape models.

Most of the existing research focuses on fuel demand forecasting at the national level, while few studies at the regional level (e.g. Peng et al., 2018). Due to the vast territory of China and the large differences in provincial economic development, current vehicle ownership and its future trends between provinces are also quite different. Existing research using the S-shape growth model to predict future vehicle ownership in China, but such model does not fully consider provincial heterogeneity. It sets the saturation level and the growth rate of different provinces to the same parameters, and assumes that all the provinces follow the same growth trend, which has a large gap with the reality, thus not only affecting the accuracy of the prediction, but also providing less reasonable information and basis for local policy formulation. This paper takes into account provincial differences in population density, urbanization rate, and economic development, and

makes a more reasonable calculation of the saturation level and variation parameters of the vehicle ownership rate in the forecasting model. Based on that, we forecast China's fuel demand in 2035 under different scenarios from the provincial level, thus making a more detailed assessment of the substitution effect of NEVs on China's oil demand.

3 Methodology

The research purpose of this paper is to evaluate the impact of fossil fuel vehicles exit on China's oil demand. We first predicted the fuel demand of China's 31 provinces in 2035 in two steps (Figure 1): (1) we established the Gompertz model based on the S-shape curve relationship between vehicle ownership rate and GDP per capita to forecast the vehicle ownership rate of each province, and then we took into account the population growth to predict the vehicle ownership in all provinces in 2035. In particular, we took account of the provincial heterogeneity in economic development, population density, and urbanization rate when determining the saturation level of vehicle ownership in each province. (2) Based on the forecast results of the vehicle ownership of each province, combining with the annual average vehicle miles traveled and fuel consumption rate of different types of vehicles, we measured China's fuel demand of each province in 2035 and the substitution effect of NEVs with three different substitution speeds on China's oil demand.

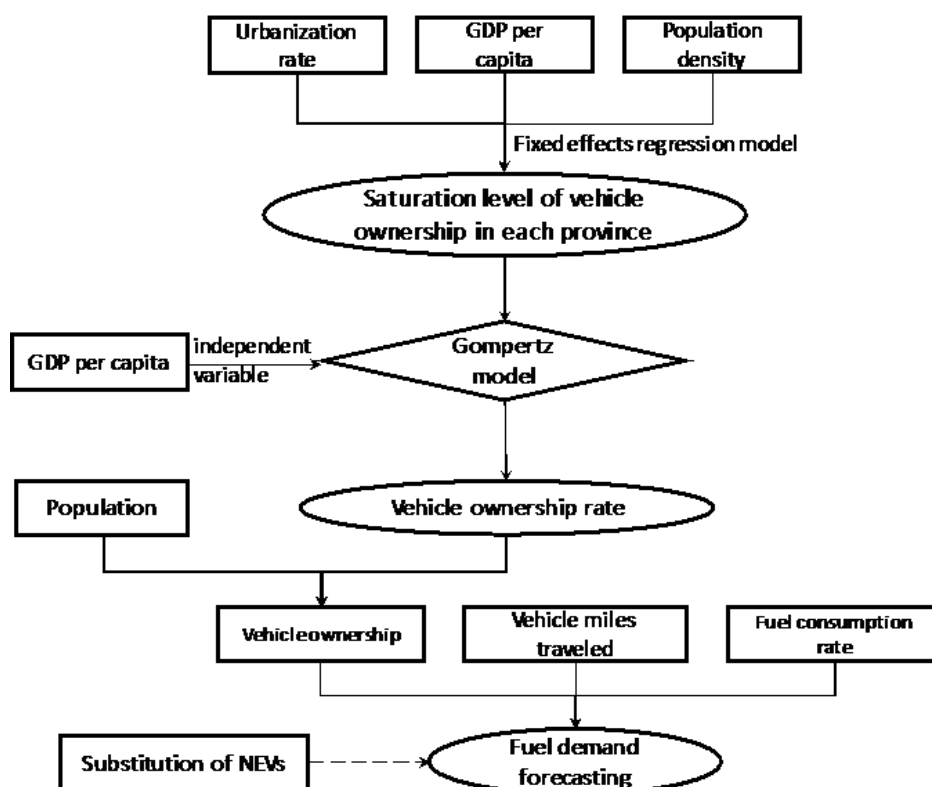


Figure 1 Fuel demand forecasting framework

3.1 Vehicle ownership projection

Previous studies show that there exists an obvious positive correlation between vehicle ownership rate and GDP per capita. However, the correlation of the growth rate of vehicle ownership rate with GDP per capita growth is not a constant but follows an S-shape upward trend. The internal logic is

as follows: When the income level is very low, the increase in income for the residents will be preferentially spent on daily necessities. As resident income rises, together with the social transportation infrastructure improved, the demand for automobiles will rise rapidly because residents have extra money besides the expenditure in food and clothing. Then the growth of vehicle ownership rate will slow down and gradually approach to saturation when resident income reaches a certain level and most residents have their traffic needs met. Finally, at an extremely high income level, residents will not seek to own more cars, but replace the old cars with new ones when necessary. Figure 2 shows the changes in vehicle ownership rate with GDP per capita in different provinces of China. It does not take far to seek that the trend of each province basically conforms to our assumption of the S-shape curve. In most provinces, the vehicle ownerships are still in a period of accelerated growth and have not met the inflexion points where the growth begins to slow. .

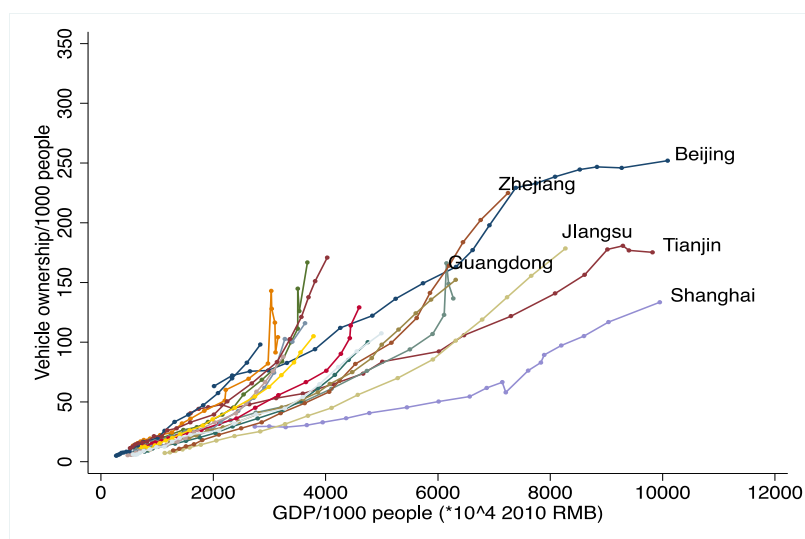


Figure 2 Vehicle ownership per 1000 people versus GDP per 1000 people in China for 1997-2016
Note: GDP data of each province is deflated by the CPI, with 2010 as the base year. All the data here comes from China Statistical Yearbook (1998-2017).

The S-shape curves for demand forecasting can be fit using different models such as the Bass model, the Logistic model and the Gompertz model. All the three models indicate that as the independent variable increases, the growth rate of the dependent variable first increases, then slows down, and finally approaches to a saturation level. The Bass model is usually used to describe the diffusion trend of a technological innovation. The Logistic model is applied to describe the life cycle of a consumer product, with a curve symmetrical about the inflexion point and the time as the independent variable. The Gompertz model has similar features to the Logistic model, with excellent applicability and general characteristics of the growth curve. But its corresponding S-shape curve is asymmetrical about the inflexion point, and the independent variable may not be time. Compared with the Bass model and the Logistic model, the Gompertz model is more suitable for the prediction of vehicle ownership rate, which is also verified by the existing researches. Based on the historical data of vehicle ownership in the United Kingdom, Muraleedharakurup et al. (2010) confirmed that the Gompertz model is better than the Logistic model and the Bass model in terms of forecasting future hybrid vehicle adaptation. Similarly, Huo and Wang (2007) performed regression analysis using data of vehicle sales and stocks in China. The results also showed that the Gompertz model fits best among the three models.

We draw on and expand the Gompertz model established by Dargay and Gately (1999) to forecast the vehicle ownership of the 31 provinces of China in 2035. We assume that the relationship between the vehicle ownership rate and GDP per capita can be expressed as the following:

$$Y_{it} = M_{it}e^{-a_i e^{-b_i PGDP_{it}}} \quad (1)$$

where i and t denote province and time respectively; Y_{it} is the vehicle ownership rate (measured in vehicles per 1000 people) of province i at time t ; $PGDP_{it}$ is the real GDP per capita (measured in GDP per 1000 people) of province i at time t ; M_{it} is the saturation level of vehicle ownership rate (measured in vehicles per 1000 people) of province i at time t ; a_i and b_i are two parameters to be estimated that determine the shape, or curvature of the function.² This model takes into account the provincial differences both in the saturation level of vehicle ownership and in the time required to reach the saturation level in China.

Equation (1) can be mathematically transformed as:

$$\ln(\ln M_i - \ln Y_{it}) = \ln a_i - b_i PGDP_{it} \quad (2)$$

In order to predict the vehicle ownership rate of each province in 2035, we use the data of 31 provinces in the past 20 years to establish the regression model to estimate the parameters a_i and b_i . The model is as follows:

$$y_{it} = \alpha_i + \beta_i PGDP_{it} + \varepsilon_{it} \quad (3)$$

where $y_{it} = \ln(\ln M_i - \ln Y_{it})$, $\alpha_i = \ln a_i$, $\beta_i = -b_i$, $i = 1, 2, \dots, 31$, $t = 1, 2, \dots, 20$. The random error term ε_{it} satisfies the assumption of independence, zero conditional mean, and homoscedasticity. As it can be seen from Figure 2, most provinces in China have not yet reached the level of vehicle saturation, so it is necessary to set M_{it} , the saturation level of vehicle ownership rate in each province. Regarding the setting of M_{it} , there is no unified and standard method for that by now. Gu et al. (2010) divided China's 31 provinces into three groups by their urbanization rate in 2007 and assigned different saturation levels to different groups in their prediction of China's vehicle ownership. Based on the saturation level of US vehicle ownership rate, Dargay et al. (2007) used the data on urbanization rates and population densities to adjust the saturation levels of different countries when predicting the vehicle ownership in 45 countries around the world. According to the domestic and foreign research results, GDP per capita, urbanization rate, and population density are important factors affecting the growth of vehicle ownership rate in a region (Auffhammer and Wolfram, 2014; Zhang and Zhao, 2016). Considering the heterogeneity of different provinces in China, we estimate the saturation levels of vehicle ownership rate in different provinces separately. For province i , the saturation level of its vehicle ownership rate at year t can be expressed as:

$$M_{it} = \delta_0 + \delta_1 PGDP_{it} + \delta_2 Urban_{it} + \delta_3 Density_{it} + e_{it} \quad (4)$$

In Equation (4), $PGDP_{it}$ represents the real GDP per 1000 people; $Urban_{it}$ indicates the urbanization rate; $Density_{it}$ is the population density. Besides, δ_0 , δ_1 , δ_2 and δ_3 are

² Let the second derivative of Equation (1) be equal to 0, and we can get the per capita GDP and the exact year of each province at the inflexion point.

parameters of the model; e_{it} is the error term. As *PGDP*, *Urban*, and *Density* change over time, the maximum potential value of vehicle ownership rate in each province also changes with time. The descriptions of model parameters are shown in Table 1.

Table 1 Descriptions of model parameters

Parameter	Description	Method	Calculation
M_{it}	saturation level of vehicle ownership rate	Linear prediction	1) Estimate the parameters of Equation (4) using the historical data of EU15; 2) Calculate M_{it} with the predicted GDP per capita, urbanization rate, and population density of each province in 2035.
a_i, b_i	parameters determining the shape, or curvature of the S-shape curve	Regression Analysis	Perform regression analysis between the vehicle ownership rate and the real GDP per capita using provincial data over the years.
$\delta_0, \delta_1, \delta_2, \delta_3$	parameters determining M_{it}	Regression Analysis	Perform regression analysis between the vehicle ownership rate and the real GDP per capita, urbanization rate, and population density using historical data of EU15 over the years.

It can be demonstrated from Equation (4) that parameters $(\delta_0, \delta_1, \delta_2, \delta_3)$ in the above model must be obtained first to obtain the vehicle saturation level of each province in 2035. China's vehicle ownership rate has not yet reached the saturation level, and it is impossible to use China's historical data to estimate these parameters. This paper uses the historical data of EU15 to measure the parameters in the model. This is mainly for two reasons: Firstly, countries or regions to be chosen must have already reached or approached to the saturation level of vehicle ownership rate in order to meet the requirements in Equation (4). Around the world, countries and regions with a high vehicle ownership rate include countries in North America and some other developed countries in Europe. As it can be seen from Figure 3, the vehicle ownership rate in EU15 is relatively stable between 2005 and 2015. Secondly, to more accurately estimate the saturation level of China's vehicle ownership rate, it is necessary to select countries and regions with similar population distribution and geographical structure to China to minimize the error. The population density of the United States and Canada in North America is far less than China, while EU15 are more similar to China in terms of population distribution and regional structure³. Therefore, we finally choose the historical data of EU15 to measure the parameters in Equation (4). After determining the parameters in Equation (4), the predicted real GDP per capita (2010 RMB), urbanization rate, and population density of each province in 2035 need to be estimated to obtain the saturation level of vehicle ownership rate. This paper assumes that the total population and GDP per capita of each province increase at the average annual growth rate between 2013 and 2016. The urban population grows linearly at the average number between 2013 and 2016. The land area of each province remains constant until 2035.

After determining the saturation level of vehicle ownership rate of each province, we can estimate

³ In 2016, China, the United States, Canada, and EU15 had a population density of 143.1 peo./km², 35.3 peo./km², 4 peo./km², and 125.6 peo./km² respectively.

the parameters a_i and b_i in the Gompertz model by the regression model using the historical data of the vehicle ownership rate and real GDP per capita (2010 RMB) of the 31 provinces from 1997 to 2016. After that, we can get the forecast results of vehicle ownership rate of each province in 2035. On the basis of the forecast vehicle ownership rate, this paper assumes that the total population of each province increases at the average growth rate between 2013 and 2016, and obtains the forecast results of vehicle ownership in each province in 2035.

In the vehicle ownership forecasting model, the data involved includes real GDP per capita, vehicle ownership rate, and the saturation level of vehicle ownership rate for each province. Among them, real GDP per capita of each province over the years comes from *China Statistical Yearbook* from 1996 to 2017, deflated by the CPI, with 2010 as the base year. Vehicle ownership rate is the ratio of vehicle ownership to total population, taken from *China Automotive Market Yearbook* and *China Statistical Yearbook* over the years respectively.

In the setting of the saturation level of vehicle ownership rate, the data involved includes vehicle ownership, the real GDP per capita (2010 RMB), the urbanization rate and the population density in EU15 and in the 31 provinces of China. Among them, the data of vehicle ownership in EU15 comes from the International Organization of Motor Vehicle Manufacturers (OICA). The real GDP per capita (2010 RMB), urbanization rate and population density are obtained from the World Bank database. The historical data of vehicle ownership, real GDP per capita (2010 RMB), urbanization rate and population density of 31 provinces over the years are taken from the provincial statistical yearbooks.

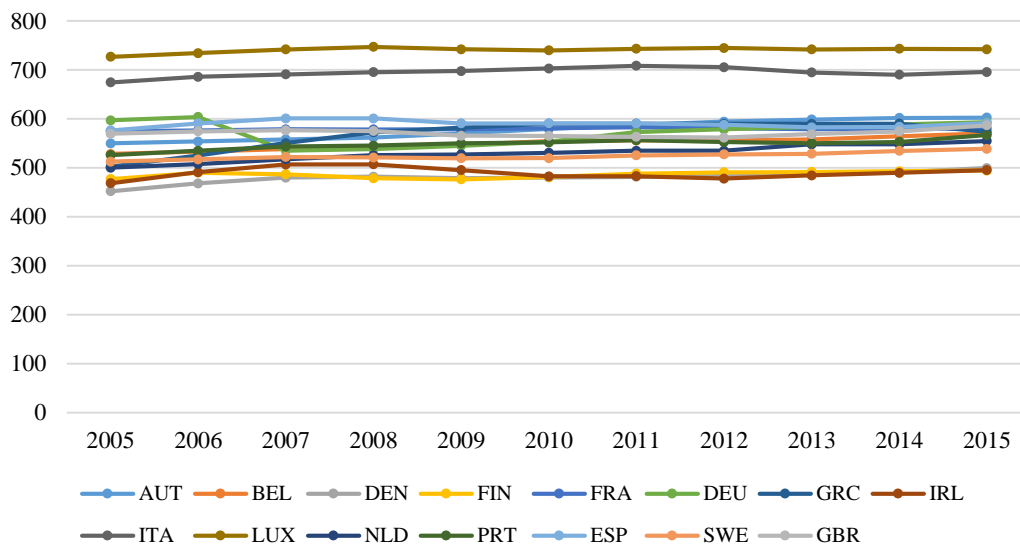


Figure 3 Annual Vehicle Ownership per 1000 people of EU15

Source: OICA

3.2 Fuel demand projection

Fuel demand is determined by vehicle population, average miles traveled, and fuel consumption rates (Huo et al., 2007). Since the average mileage and fuel economy of different types of vehicles vary greatly, we further categorize them into eight types. Fuel demand of each type can be expressed as follows:

$$FC_{it} = \sum_j (Y_{ijt} \times VMT_{ijt} \times FR_{ijt} \times FD) \quad (5)$$

where FC_{it} is the fuel consumption of province i in the year t ; Y_{ijt} denotes the vehicle type j ownership of province i in the year t , and $Y_{it} = \sum_j Y_{ijt}$, in million; VMT_{ijt} is the annual miles traveled by vehicle type j of province i in the year t , in kilometers; FR_{ijt} is the fuel consumption rate of vehicle type j of province i in the year t , in L/100km; FD indicates the density of the fossil fuel, and the unit is kg/L.

The National Bureau of Statistics divides vehicles into passenger vehicles and trucks. The passenger vehicles are further divided into large passenger vehicles (LPVs), medium passenger vehicles (MPVs), small passenger vehicles (SPVs), and mini cars (MCs). Trucks are further divided into heavy-duty trucks (HDTs), medium-duty trucks (MDTs), light-duty trucks (LDTs), and mini trucks (MTs). Based on the type of fuel consumed by vehicles, each type is subdivided into petrol ones and diesel ones. Since the population of diesel vehicles in MTs and MBs, and gasoline vehicles in LPVs and HDTs is extremely small, it is feasible in our calculation to assume that all mini vehicles consume gasoline and all heavy vehicles consume diesel.

The number of each vehicle type in each province is determined both by the total vehicle population in the province and by the proportion of the vehicle type. In the past three years, the proportion of each type of automobiles in China has changed little (National Bureau of Statistics of China, 2017). Therefore, we assume that the proportion of each vehicle type in each province remains constant from 2015 to 2035. Y is predicted by the Gompertz model; VMT and FR come from *Annual Report on Automobile Energy-saving in China (2015)*. The statistics show that the average annual mileage of each type of vehicles changed little in recent years (CATARC, 2015; Huo et al., 2012). Hence we assume that VMT for each vehicle type is constant until 2035. FR reduces by the average speed between 2004 and 2014. FD is based on National VI Standard (the fifth phase of the national gasoline and diesel national standard). Involved parameters above are summarized in Table 2.

Table 2 Model parameters: vehicle types, mileage and fuel economy

	Passenger vehicles				Trucks			
	LPVs	MPVs	SPVs	MCs	HDTs	MDTs	LDTs	MTs
Fuel type⁴	diesel	diesel	petrol	petrol	diesel	diesel	diesel	petrol
Proportion⁵	0.01	0.01	0.83	0.02	0.03	0.01	0.08	0.00
VMT (km)	54 000	52 000	19 000	26 000	55 000	35 000	28 000	19 500
FR (L/100km)	15.13	11.09	4.39	4.39	24.06	11.80	5.33	3.69

⁴ The fuel of automobiles is divided into gasoline and diesel. Currently, most of SPVs, MCs, and MTs in China consume gasoline, while LPVs and HDTs are mainly powered by diesel. Other types of vehicles are mixed with gasoline powered and diesel powered. Since diesel enjoys obvious advantage in cost, fuel efficiency, and cleanliness, dieselization of trucks and large and medium passenger vehicles is increasingly obvious. Therefore, we assume that SPVs, MCs, and MTs continue consuming gasoline in 2035, while other vehicles are fueled by diesel.

⁵ Vehicles other than passenger vehicles and trucks account for less than 1%, so this paper ignores other vehicles when forecasting the total fuel demand.

4 Results and analysis

4.1 Vehicle ownership

Using the panel data of EU15, we establish a fixed effect model to estimate the parameters in Equation (4). The regression results are displayed in Table 3. The t-value is in the parentheses. R^2 is 0.846, and the model has a good fitting degree. The regression results show that GDP per capita and population density have significantly positive correlation with the vehicle ownership rate. That is, the more developed the economy and the denser the population, the higher the saturation level of the vehicle ownership rate. The coefficient of urbanization rate δ_2 is significantly negative, which means that the higher the level of urbanization, the lower the saturation level of the vehicle ownership rate. That is probably because regions with higher urbanization level are usually equipped with more developed public transportation and more improved traffic infrastructure.

Table 3 Regression results of Equation (4)

Coefficient	Result
δ_1	0.003***(6.92)
δ_2	-1.863**(-3.21)
δ_3	0.115**(2.85)
δ_0	584.672*** (14.19)
R^2	0.846
N	165

Note: t values are shown in the parentheses; *** $p < 0.01$, ** $p < 0.05$

After determining the parameters of Equation (4), we can estimate the saturation level of vehicle ownership rate M_{it} in each province. The estimation results are shown in the sixth column of Table 4. On that basis, parameters in the Gompertz model (3) is estimated from the data of provincial vehicle ownership rate and the real GDP per capita (2010 RMB) between 1997 and 2016. Then we forecast the vehicle ownership rate of each province in 2035 based on the estimate results above. The regression results and forecast results are shown in Table 4 and Figure 4. Taking the population growth in to consideration, the projection results of vehicle ownership in each province in 2035 are shown in Figure 5. In particular, for the three municipalities Beijing, Shanghai, and Tianjin, the saturation level of the vehicle ownership rate is more affected by the government's control policies. The automobile purchase restriction policies of the three cities have greatly limited the growth of vehicle ownership. It could be demonstrated in Figure 2 that the vehicle ownership rate of the three cities has already entered a stage of decelerating growth in recent years. Therefore, our study assumes that the annual increase of automobiles is equal to the number of new license plates.⁶ According to the current purchase restriction policy, the total number of new license plates in Shanghai and Tianjin is maintained at around 100,000 per year, and the number of car license plates in Beijing has dropped from 150,000 to 100,000 per year since 2018. In our forecast, it is assumed

⁶ In fact, the purchase restriction policy is only for passenger cars. But for the three economically developed cities, more than 90% of the increase in vehicle ownership can be accounted for the increase of passenger cars. Therefore, the annual increase of automobiles can be approximately seen as the number of new license plates.

that the number of new license plates will remain at this level in the three municipalities in the future.

According to the results of regression and prediction, we can find that: ① the two parameters a and b in the Gompertz model are positive. Combined with Equations (2), (3), (4), it can be concluded that with the growth of GDP per capita, its positive marginal effect on vehicle ownership rate will increase first and then decrease. That is, as GDP per capita rises, the willingness of residents to increase the proportion of their income for automobile purchase will increase firstly and then gradually decrease but it still be positive. Besides, the larger b is, the smaller GDP per capita corresponding to the saturation level is. ② Overall, the growth rate of China's vehicle ownership rate will arrive at the inflection point in 2023, which means that the growth of China's vehicle ownership rate with GDP per capita will slow down after 2023. In addition, except a few provinces such as Xinjiang, most provinces in China will meet their inflexion points between 2020 and 2029. In other words, vehicle ownership rate in most provinces is growing at a slower pace in 2035. ③ The average vehicle ownership rate of China in 2035 is 436 vehicles per thousand people, which is nearly three times the number of 118 vehicles per thousand people in 2015, with an average annual growth rate of 6.7%. At the same time, the provincial difference in vehicle ownership rate will continue to increase in the future. In 2035, Jiangsu, Chongqing, and Zhejiang have the highest vehicle ownership rates, with 654, 621, and 612 vehicles per thousand people, respectively. Rapid growth is inseparable from the economic development and urban construction in these regions. While in Beijing and Shanghai, where the economy is also very developed, their vehicle ownership rates have gradually approached to saturation and grown with a narrow range due to the policy control. Heilongjiang, Xinjiang, and Shanxi, the three provinces with the lowest vehicle ownership rate, have only 131, 142, and 159 vehicles per thousand people in 2035. The low growth in these regions is mainly affected by their geographical location and stagnant economic growth. ④ Taking the total population into account, the total number of vehicle ownership in China will reach 667 million in 2035, which is about three times higher than the number of 163 million in 2015, with an average annual growth of 7.3%. Driven by population or economy, Guangdong, Shandong, and Jiangsu will become the three provinces with the highest vehicle ownership in China. Their vehicle ownership will reach 78.26, 59.23, and 48.84 million, respectively. While the least three provinces, Qinghai and Tibet, Ningxia have only 2.46, 2.68, and 3.49 million vehicles. At the same time, it can be easily found from Figure 5 that Guangdong, Shandong and Jiangsu, which have great potential for development, are the main driving forces for China's automobile growth in the future. Part of that is because of the restriction policy over the extremely densely populated areas especially Beijing and Shanghai.

Table 4 Provincial projections of saturation level and vehicle ownership per 1000 people in 2035

Province	Abbr.	$\beta_i(\times 10^{-4})$	α_i	a_i	$b_i(\times 10^{-4})$	Saturation	Inflexion	2035
Beijing	BJ	-1.15***	1.15***	3.17	1.15	765	2016	288
Tianjin	TJ	-0.88***	1.26***	3.52	0.88	803	2029	204
Hebei	HE	-3.16***	1.63***	5.12	3.16	635	2037	220
Shanxi	SX	-3.13***	1.53***	4.60	3.13	613	2051	159
Inner Mongolia	IM	-1.67***	1.44***	4.22	1.67	586	2038	204
Liaoning	LN	-1.74***	1.47***	4.36	1.74	617	2040	183

Jilin	JL	-2.10***	1.50***	4.50	2.10	600	2029	297
Heilongjiang	HL	-2.69***	1.61***	5.00	2.69	592	2057	131
Shanghai	SH	-0.79***	1.55***	4.71	0.79	1030	2026	209
Jiangsu	JS	-1.65***	1.67***	5.32	1.65	674	2019	654
Zhejiang	ZJ	-2.22***	1.73***	5.61	2.22	652	2017	612
Anhui	AH	-3.00***	1.69***	5.43	3.00	644	2026	459
Fujian	FJ	-1.93***	1.68***	5.37	1.93	627	2021	589
Jiangxi	JX	-2.92***	1.71***	5.55	2.92	619	2025	474
Shandong	SD	-2.18***	1.65***	5.22	2.18	667	2022	519
Henan	HA	-2.96***	1.68***	5.38	2.96	655	2024	512
Hubei	HB	-2.01***	1.60***	4.96	2.01	624	2023	548
Hunan	HN	-2.37***	1.66***	5.26	2.37	626	2026	459
Guangdong	GD	-1.75***	1.54***	4.66	1.75	671	2022	578
Guangxi	GX	-3.04***	1.69***	5.41	3.04	611	2026	427
Hainan	HI	-2.56***	1.57***	4.81	2.56	618	2025	455
Chongqing	CQ	-2.06***	1.61***	5.00	2.06	634	2021	621
Sichuan	SC	-3.31***	1.69***	5.42	3.31	606	2024	352
Guizhou	GZ	-3.67***	1.62***	5.03	3.67	609	2020	503
Tibet	XZ	-3.24***	1.43***	4.20	3.24	585	2021	558
Shaanxi	SN	-2.41***	1.55***	4.73	2.41	607	2026	354
Gansu	GS	-4.15***	1.69***	5.40	4.15	591	2041	173
Qinghai	QH	-2.87***	1.50***	4.46	2.87	585	2025	352
Ningxia	NX	-2.97***	1.52***	4.59	2.97	598	2022	424
Xinjiang	XJ	-2.87***	1.50***	4.50	2.87	586	2069	142
Yunnan	YN	-3.85***	1.54***	4.68	3.85	600	2024	435
China	CHN	-2.49***	1.60***	4.95	2.49	602	2023	436

Note: *** $p < 0.01$

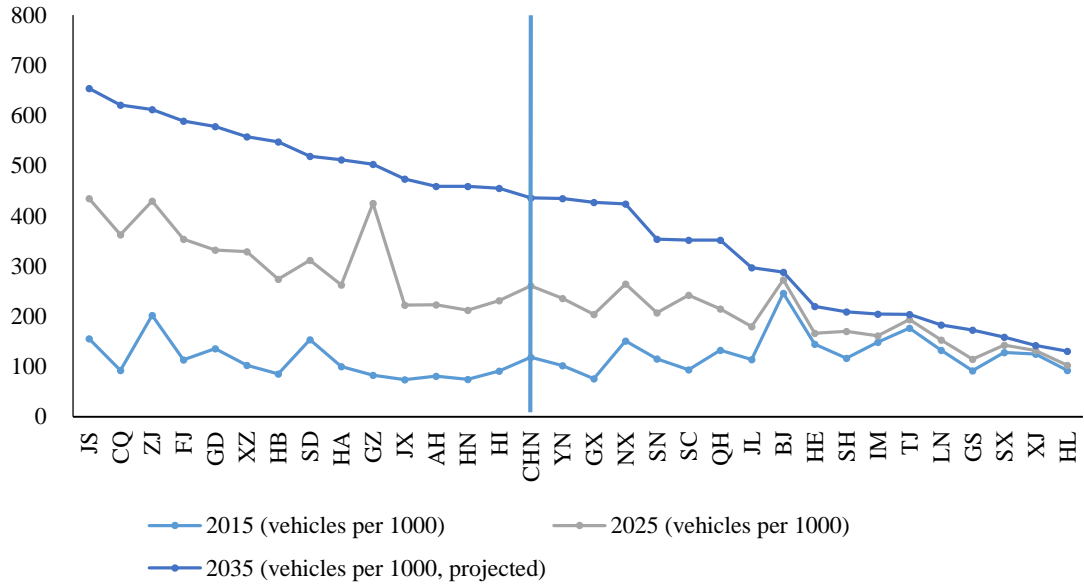


Figure 4 Provincial projections of vehicle ownership per 1000 people in 2035

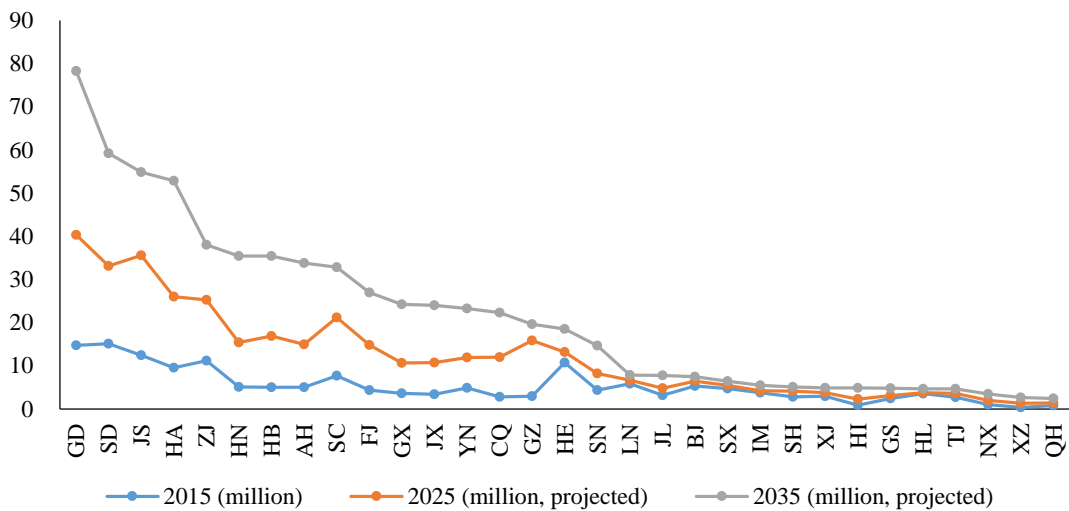


Figure 5 Provincial projections of vehicle ownership in 2035

4.2 Fuel demand

On the basis of the forecast results of vehicle ownership of each province, we take into account factors including the proportion of different vehicle types, annual average mileage, fuel consumption rate, etc., and we get the forecast results of fuel consumption in each province in 2035 (Table 5). It can be seen from the forecast results that: ① the total national automobile fuel demand is estimated to be 746.69 Mt (gasoline and diesel) in 2035, which is two times higher than the number of 230 Mt in 2015, with an average annual growth of 5.7%. ② Guangdong, Henan and Shandong are the three provinces with the highest demand for automobile fuel, which are 76.76, 64.91 and 63.95Mt respectively. Compared with the previous results of vehicle ownership in each province, we can find that the ranking of vehicle ownership among the provinces is not exactly the same as the ranking of fuel demand. This can be explained by the different structure of vehicle stock in each province. Take Henan Province as an example. Henan has a lower vehicle ownership than Jiangsu and Shandong, but it has a larger number of trucks than the other two provinces. The higher

fuel consumption rate of trucks increases the demand for automobile fuel in Henan Province (Figure 6). ③ Examining the percentage of gasoline and diesel demand in different provinces (Figure 7), we can come to the conclusion that more developed regions are usually with higher demand for gasoline, while diesel often accounts for a higher proportion in less developed regions. In economically underdeveloped regions like Tibet, Ningxia, and Xinjiang, where industry has a greater role in driving regional economic development, residents have lower demand for passenger cars because of their lower incomes. Thus there are more trucks usually fueled by diesel in these regions. While in those relatively developed provinces, such as Zhejiang, Beijing, and Guangdong, the regional economy is more driven by the service industry. Therefore, the demand for passenger vehicles especially cars is much higher and the demand for gasoline is greater in these regions.

Table 5 Provincial projections of fuel consumption structure in 2035

Province	Vehicle ownership (million)	Fuel demand (Mt)	Fuel demand structure			
			Diesel	Gasoline	Passenger vehicles	Trucks
Guangdong	78.26	76.76	34.40	42.36	50.05	26.71
Henan	52.83	64.91	36.61	28.30	31.93	32.98
Shandong	59.23	63.95	31.03	32.92	36.29	27.66
Jiangsu	54.85	57.13	25.82	31.30	35.64	21.49
Anhui	33.78	48.07	31.00	17.07	19.98	28.09
Hubei	35.40	40.33	21.79	18.53	22.25	18.07
Hunan	35.42	38.44	19.66	18.78	22.61	15.83
Sichuan	32.79	34.98	17.00	17.98	20.54	14.44
Jiangxi	23.99	32.54	20.43	12.11	13.94	18.60
Zhejiang	38.00	33.20	11.81	21.39	23.47	9.73
Guangxi	24.19	29.02	16.51	12.51	14.53	14.49
Fujian	26.93	28.00	13.91	14.09	16.30	11.71
Chongqing	22.31	26.00	14.21	11.79	13.93	12.07
Yunnan	23.24	24.58	12.60	11.98	13.44	11.13
Hebei	18.48	22.63	12.60	10.02	10.82	11.80
Guizhou	19.66	21.53	11.56	9.97	11.73	9.80
Shaanxi	14.65	16.29	8.31	7.98	9.08	7.21
Liaoning	7.87	9.75	5.63	4.11	5.10	4.65
Jilin	7.79	9.42	5.25	4.17	4.98	4.44
Shanxi	6.39	7.81	4.30	3.51	3.86	3.95
Xinjiang	4.90	6.82	4.45	2.37	2.93	3.89
Beijing	7.44	6.81	2.58	4.23	5.33	1.48
Tibet	2.68	6.45	5.65	0.80	3.61	2.84
Heilongjiang	4.68	6.51	4.14	2.37	2.94	3.57
Inner Mongolia	5.45	6.15	3.21	2.94	3.25	2.90
Shanghai	5.13	5.82	2.99	2.83	3.66	2.15
Gansu	4.83	5.66	3.57	2.08	2.50	3.16

Ningxia	3.49	4.84	3.23	1.62	1.91	2.93
Hainan	4.86	4.93	2.43	2.49	3.18	1.75
Tianjin	4.64	4.49	1.92	2.57	2.98	1.51
Qinghai	2.46	2.87	1.64	1.22	1.46	1.41
China	666.61	746.69	390.28	356.41	414.23	332.45

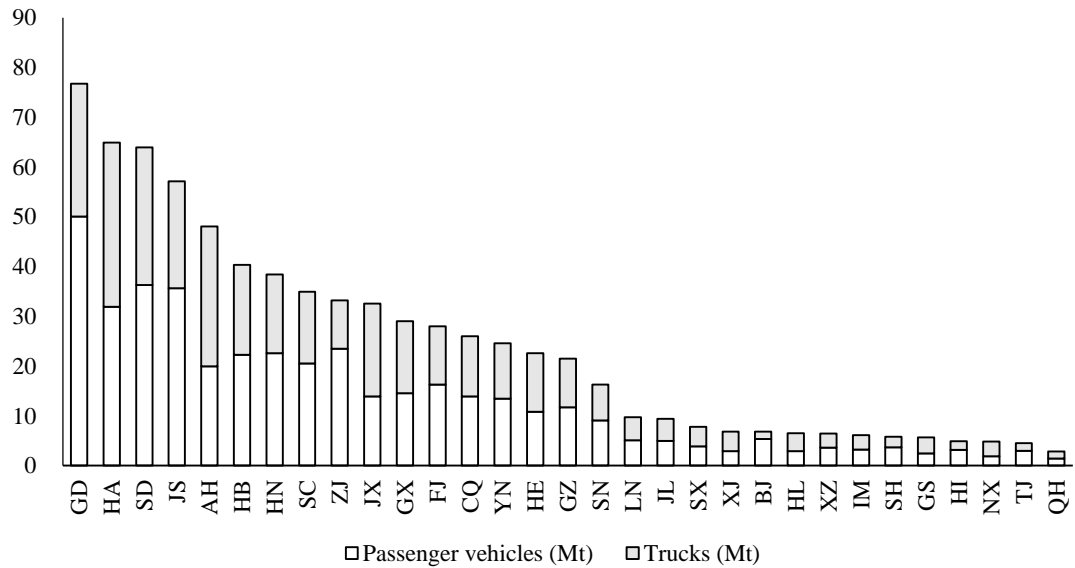


Figure 6 Provincial projections of fuel consumption in 2035

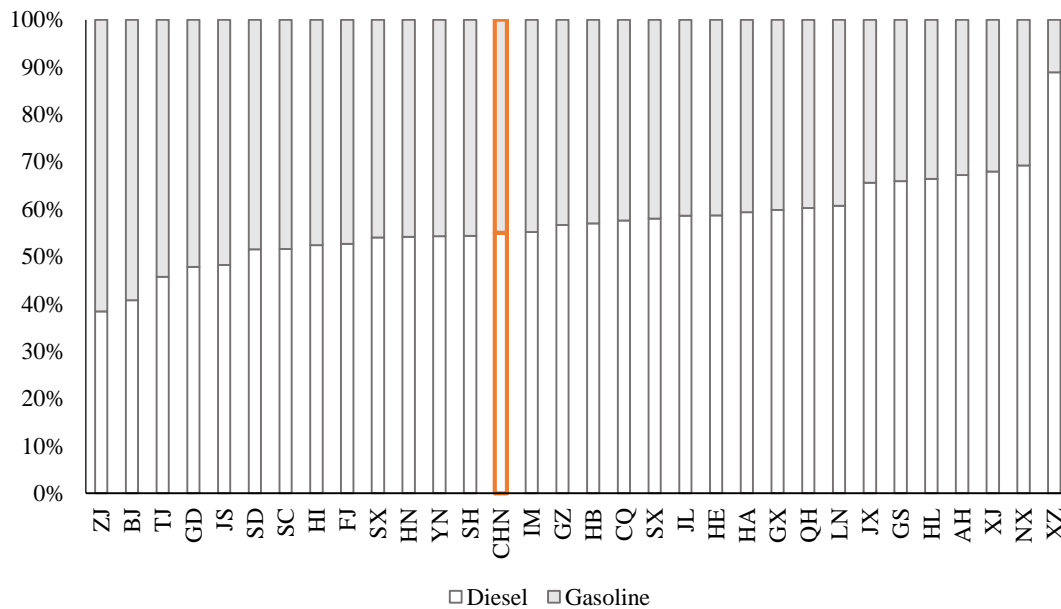


Figure 7 Provincial projections of gasoline and diesel consumption in 2035

4.3 Impact of fossil fuel vehicles exit on the oil demand

After estimating the fuel demand in each province, we start to evaluate the substitution effects of

NEVs in this part. According to the statistics of the Ministry of Public Security, there are 1.53 million NEVs at the end of 2017, accounting for only 0.7% of the total number of vehicles.

However, with the continuous advancement of NEV technology, the percentage of NEVs represented by electric vehicles will continue growing before the exit timeline of fossil fuel vehicles is officially launched in China, thus the total fuel demand will be lower than we predicted before (Zhang et al., 2010).

Regarding the prediction of the percentage of NEVs, domestic and foreign researchers have not reached a consistent conclusion. Bloomberg (2017) and ExxonMobil (2016) predicted the proportion of NEVs worldwide in 2040, and their predictions were similar, with 33% and 35% respectively. As for the proportion of China's NEVs, MIIT (2018) proposed the goal that NEVs should make up 10% of all the automobiles in China by 2020. What's more, according to the International Energy Agency (IEA, 2017), China's NEVs will account for 25% of total vehicles by 2035.

Based on the research above, this paper calculates provincial fuel demand of Chinese vehicles in 2035 considering the substitution of NEVs. The substitution speeds in different provinces may vary because of their different policy restrictions and state of supporting facilities. Taking these provincial differences into account, we made a hierarchical cluster analysis and divide the 31 provinces of China into three groups. In our study, four indicators are selected to reflect provincial differences in the two aspects we mentioned above (Table 6). For the hierarchical cluster analysis, the method of Ward (1963) is selected because it outperforms other hierarchical cluster methods when outliers are absent. Some researches on regional cluster analysis also demonstrate that Ward's method gives the best interpretative solution (Del Campo et al., 2008; Yang et al., 2012). To eliminate the effects of different scales, we standardize the four variables when making the cluster analysis. The dendrogram shows that the 31 provinces can be grouped into three clusters. Table 7 shows the mean values of the indicators in each cluster. It does not take far to seek that clusters 1 and 2 are more densely populated, more urbanized, and more economically developed provinces, which means the local government is more capable of providing supporting facilities of NEVs, thus promoting the growth of NEVs. Compared with cluster 2, cluster 1 are regions with much more dense population, with an average projected population density of 1206.4 people per square kilometers in 2035, which is two more times that of cluster 2. More dense population will surely boost the growth of NEVs.

Therefore, in our study, we assume three different substitution speeds for the three clusters. The percentage of NEVs in 2035 will account for 25%, 15% and 5% for clusters 1, 2 and 3, respectively. The results are shown in Table 8. Under the substitution scenario, China's automobile fuel demand in 2035 is 652.58 Mt. The fuel demand for clusters 1, 2 and 3 are 132.13, 183.10 and 337.35 respectively. Besides, it is also shown in Table 8 that the average fuel demand for each province in cluster 2 is much higher than two other clusters, which points out a feasible direction for future fuel demand control.

Compared to that without substitution, the fuel demand in China in 2035 can be reduced by 94.11 Mt, which is equivalent to 26.3% of China's net oil imports in 2016. This proportion will further expand as the speed of fuel vehicle exit increases. Therefore, the exit of fossil fuel vehicles will greatly reduce China's foreign oil dependency and thus ensure China's energy security.

Table 6 Indicators for cluster analysis

Interpretation	Indicator
Policy restrictions	Policy (D=1 if restricted policy is implemented, and D=0 if not)
	Population density
State of supporting facilities	Urban rate
	GDP per capita

Table 7- Summary of clusters

cluster	province	N	Density (peo./km ²)	Urbanity	perGDP (2010 RMB yuan)	Policy
1	BJ, TJ, HE, ZJ, GD, HI, GZ, SH	8	1206.4	82.59%	179281.4	1
2	JS, FJ, SD, HB, CQ SX, IM, LN, JL, HL, AH, JX, HA,	5	531.35	83.19%	213693.8	0
3	HN, GX, SC, XZ, SN, GS, QH, NX, XJ, YN	18	199.22	71.26%	73064.7	0

Table 8 Fuel demand with different substitution in each cluster

Scenario	Fossil fuel vehicle ownership (million)	Fuel demand (Mt)	Fuel demand				
			Diesel	Gasoline	Passenger vehicles	Trucks	
Baseline (no substitution)	666.61	746.69	390.28	356.41	414.23	332.46	
CHN	578.12	652.58	344.03	308.55	358.83	293.75	
Cluster 1 (25% substitution)	Total	132.35	132.13	60.23	71.90	83.42	48.71
	Mean	16.54	16.52	7.53	8.99	10.43	6.09
Cluster 2 (15% substitution)	Total	168.91	183.10	90.75	92.34	105.75	77.35
	Mean	33.78	36.62	18.15	18.47	21.15	15.47
Cluster 3 (5% substitution)	Total	276.86	337.35	193.04	144.30	169.66	167.69
	Mean	15.38	18.74	10.72	8.02	9.43	9.32

5 Robustness analysis of different substitutions

We further calculate automobiles fuel demand in 2035 under three scenarios with slow, medium and fast substitution. Assuming that under the three scenarios, the proportions of NEVs substitution for the provinces in Cluster 1, 2, and 3 in 2035 are (25%, 15%, 5%), (30%, 20%, 10%), (35%, 25%, 15%), respectively. The results are shown in Table 9 and Figure 8. Under the three scenarios with slow, medium and fast substitution, China's automobile fuel demands in 2035 are 653, 615 and 578 million tons, respectively. Compared with the case without substitution, the total amount of gasoline and diesel demand can be reduced by 94, 132, and 169 million tons respectively, which is equivalent to 118, 165, and 211 million tons of crude oil assuming 80% of the refined oil extraction ratio. These amounts account for 32.9%, 46.1%, and 59.0% of China's net crude oil imports in 2016, respectively.

The robustness analysis shows that China’s fuel demand will decrease more under faster NEVs substitutions, which is likely to happen when government implement more favorable policies for NEVs and stricter policies for fossil fuel vehicles.

Table 9 Fuel vehicles and fuel demand under different substitution scenarios

Scenario		Vehicle ownership (million)	Fuel demand (Mt)
Baseline		666.61	747
CHN		578.12	653
Slow	Cluster 1-25%	Total	132
		Mean	17
	Cluster 2-15%	Total	183
		Mean	37
	Cluster 3-5%	Total	337
		Mean	19
CHN		544.78	615
Medium	Cluster 1-30%	Total	123
		Mean	15
	Cluster 2-20%	Total	172
		Mean	34
	Cluster 3-10%	Total	320
		Mean	18
CHN		511.45	578
Fast	Cluster 1-35%	Total	115
		Mean	14
	Cluster 2-25%	Total	162
		Mean	32
	Cluster 3-15%	Total	302
		Mean	17

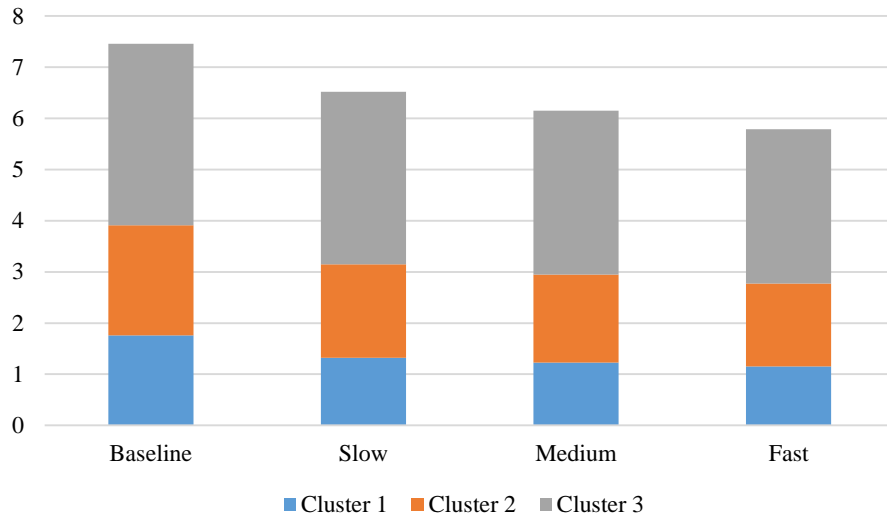


Figure 8 Fuel demand under different substitution scenarios (hundred million tons)

6 Conclusion

Vehicle ownership is one of the most important factors in determining fuel demand. As China's vehicle ownership is still in a period of rapid growth and has not reached saturation, detailed and appropriate forecast of China's vehicle ownership is necessary for the accurate prediction of oil demand in China. Due to the vast territory of China and the large differences in provincial economic development, current vehicle ownership and its future trends among provinces are also quite different.

This paper takes into account the provincial differences in population density, urbanization rate, and economic development, and combines the experience of developed countries with China's historical data to estimate the saturation level and parameters in the Gompertz prediction model to calculate the China's future vehicle ownership. Based on that, we made provincial predictions about China's fuel demand under three different scenarios in 2035, and more carefully evaluated the impact of NEVs substitution on oil demand in China.

Our analysis shows that the relationship between the vehicle ownership rate and real GDP per capita in China conforms to the S-shape trend. Currently, most provinces are at a stage of accelerated growth. According to our results, there are gaps between the saturation levels of vehicle ownership rate among provinces, but they are acceptable compared to the time difference among provinces to reach the inflexion points. In 2035, the predicted vehicle ownership rate varies greatly across various provinces, among which Jiangsu, Chongqing and Zhejiang are the top three provinces with the highest vehicle ownership rates at the level of 654, 621 and 612 vehicles per thousand persons respectively. Besides, the total vehicle ownership of China will reach 667 million in 2035. And the top three provinces with the greatest vehicle ownership will be Guangdong, Shandong and Jiangsu, with 78.26, 59.23 and 51.84 million vehicles respectively. Without considering the impact of NEVs substitution, the total fuel demand of China's automobiles is expected to be 746.69 Mt in 2035. Guangdong, Henan and Shandong are the three provinces with the most demand for automobile

fuel, which are 76.76, 64.91 and 63.95Mt respectively. Taking the substitution effects of NEVs into consideration, China's automobile fuel demand in 2035 is 652.58 Mt. And the amount replaced by NEVs is 94.11 Mt, which is equivalent to 26.3% of China's net oil imports in 2016.

The study contributes to the literature by using a detailed bottom-up prediction model with consideration of provincial heterogeneity in China, which help generate more accurate forecast results. Different from previous studies which assume homogenous saturation levels of each province, we take into account the provincial differences and relate the growth pattern with provincial population density, urbanization rate, and economic development. For a country like China with vast regional disparity, this analysis can help policy makers formulate and implement more targeted and effective policies. Furthermore, the method can be applied to other countries or regions with dramatic heterogeneity. The paper also has important policy implications. Our evaluation results under the scenario of NEVs substitution imply that the exit of fossil fuel vehicles will greatly reduce China's foreign oil dependency, thus ensuring China's energy security.

It should be pointed out that we assume the future fuel economy in China improves at the average rate between 2004 and 2014 in our study, which makes it possible that the accelerated technological progress may result in a lower actual fuel demand than our forecast. In addition, this paper does not discuss the possible future changes in people's vehicle purchase behavior. If great progress is made in the technology, price, and supporting facilities of NEVs, or if new restrictive policies of fossil fuel vehicles are introduced, such as car purchase restriction and subsidies for NEVs, the proportion of NEVs will not be negligible any more, and the growth of automobile fuel demand in the future will also be lower than our forecast results.

Based on our conclusions above, we propose the following two suggestions:

Firstly, according to the forecast results, China's automobile fuel demand will continue growing at an accelerated speed in the future if there is no control, which will exacerbate China's environmental problems and raising its dependency on foreign oil. In order to overcome such a situation, relevant policies can be introduced to address the petroleum safety problems that may arise from the excessive growth of vehicle ownership. Such policies may proceed from the perspective of promoting the adjustment of automobile stock and fuel structure, and the improvement of fuel economy.

Secondly, corresponding policies should be developed considering the provincial differences. As it has been demonstrated above, Guangdong, Henan, Shandong and some other provinces are the main driving forces for China's automobile fuel demand growth in the future. These provinces are usually regions with rapid economic growth and large population base. Therefore, more focus ought to be put on these regions to effectively alleviate the rapid growth of automobile fuel demand in China.

References

- Auffhammer, M., Wolfram, C.D., 2014. Powering up China: Income distributions and residential electricity consumption. *Am. Econ. Rev.* 104(5): 575-580.
- BP (British Petroleum Public Limited Company), 2017. BP statistical review of world energy. (Available at) <<https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html>>.
- CATARC (China Automotive Technology & Research Center), 2015. Annual Report on Automotive Energy-saving in China (2015). Beijing: Posts & Telecom Press, 15-19.
- Cherif, R., Hasanov, F., Pande, A., 2017. Riding the energy transition: Oil beyond 2040. International Monetary Fund.
- Dargay, J., Gately, D., 1997. Vehicle ownership to 2015: implications for energy use and emissions. *Energy policy*, 25(14-15): 1121-1127.
- Dargay, J., Gately, D., Sommer, M., 2007. Vehicle ownership and income growth, worldwide: 1960-2030. *Energy J.*, 143-170.
- Del Campo, C., Monteiro, C. M., & Soares, J. O., 2008. The European regional policy and the socio-economic diversity of European regions: A multivariate analysis. *Eur. J. Oper. Res.*, 187(2): 600-612.
- Dong, Q., Miao, W., 2018. Minister of MIIT: China's new energy automobiles are expected to account for 10% of the total. (Available at)<<http://www.itdcw.com/news/focus/0313Y5132018.html>>.
- ExxonMobil, 2016. The outlook for energy: A view to 2040.
- Gately, D., Dargay, J., 1999. Incomes effect on car and vehicle ownership. *Transp. Res. Part A: Policy & Pract.* 33(2): 101-138.
- Gu, J. B., Qi, F. F., Wu J.L., 2010. Forecasting on China's civil automobile-owned based on Gompertz Model. *Technol. Econ.* 29(1): 57-62.
- He, K., Huo, H., Zhang, Q., et al., 2005. Oil consumption and CO₂ emissions in China's road transport: current status, future trends, and policy implications. *Energy policy* 33(12):1499-1507.
- Huo, H., Wang, M., Johnson, L., et al., 2007. Projection of Chinese motor vehicle growth, oil demand, and CO₂ emissions through 2050. *Transp. Res Record: J. Transp. Res. Board* 2007 (2038): 69-77.
- Huo, H., Zhang, Q., He, K., et al., 2007. Vehicle-use intensity in China: Current status and future trend. *Energy Policy* 43: 6-16.
- IEA (International Energy Agency), 2017. Oil market report 2017.
- Jiang, Y., 2017. Bloomberg forecasts EVs to be one third of global vehicle ownership by 2040.

(Available at)<<http://finance.sina.com.cn/roll/2017-07-10/doc-ifyhweua4640386.shtml>>.

Johansson, O., Schipper, L., 1997. Measuring the long-run fuel demand of cars: separate estimations of vehicle stock, mean fuel intensity, and mean annual driving distance. *J. Transp. Econ. Policy*, 277-292.

Muraleedharakurup, G., MCGordon, A., Poxon, J. et al., 2010. Building a better business case: the use of non-linear growth models for predicting the market for hybrid vehicles in the UK. *Ecol. Veh. Renew. Energies*. (Available at)<<https://www.researchgate.net/publication/228998926>>.

National Bureau of Statistical of China, 2016. *China Energy Statistical Yearbook (2016)*. Beijing: China Statistics Press.

National Bureau of Statistics of China, 2017. *China Statistical Yearbook (2017)*. Beijing: China Statistics Press.

Palencia, J.C., Otsuka, Y., Araki, M., et al., 2017. Scenario analysis of lightweight and electric-drive vehicle market penetration in the long-term and impact on the light-duty vehicle fleet. *Appl. Energy* 204:1444-1462.

Peng, T., Ou, X., Yuan, Z., et al., 2018. Development and application of China provincial road transport energy demand and GHG emissions analysis model. *Appl. Energy* 222: 313-328.

Qi, F. F., 2010. Forecasting research on the consumption demand of civilian vehicle in China based on panel data model. *University of Science and Technology of China*, 29-30.

Reuters, 2017. China studying when to ban sales of traditional fuel cars: Xinhua. (Available at)<<https://www.reuters.com/article/us-china-autos/china-studying-when-to-ban-sales-of-traditional-fuel-cars-xinhua-idUSKCN1BL01U>>.

Shen, L., Xue, J.J., 2011. Development path choice and strategy framework of China's energy security. *China Popul. Resour. & Environ.* 21(10):49-54.

Wang, H., Ou, X., Zhang, X., 2017. Mode, technology, energy consumption, and resulting CO₂ emissions in China's transport sector up to 2050. *Energy Policy* 109: 719-733.

Ward, J. H., 1963. Hierarchical grouping to optimize an objective function. *J. Am. Stat. Assoc.* 58(301): 236-244.

Wu, T., Zhao, H., Ou, X., 2014. Vehicle ownership analysis based on GDP per Capita in China: 1963-2050. *Energies* 7: 7454-7482.

Yuan, Y., Cai, W.J., Can, W., & Wang, S.Q., 2012. Regional allocation of CO₂ intensity reduction targets based on cluster analysis. *Adv. climate change Res.* 3(4): 220-228.

Zhang, Q., Tian, W., Zheng, Y., et al., 2010. Fuel consumption from vehicles of China until 2030 in energy scenarios. *Energy Policy* 39: 6860-6867.

Zhang, Q., Zhao, S.C., 2016. Factors influencing private vehicle ownership in China. *Transp. Res.* 2(3):1-5.

Zhao, C., Liu, G.Y., Chen, B., 2015. Advances in theories and methods of energy forecasting and early warning. *Acta Ecologica Sinica* 35(7): 2399-2413.

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