Comparative study of corporate average fuel consumption regulations based on curb weight and footprint benchmarks

Zongwei Liu, Haoyi Zhang, Han Hao & Fuquan Zhao

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ORIGINAL PAPER

Comparative study of corporate average fuel consumption regulations based on curb weight and footprint benchmarks

Zongwei Liu[1,2] · Haoyi Zhang[1,2] · Han Hao[1,2] · Fuquan Zhao[1,2]

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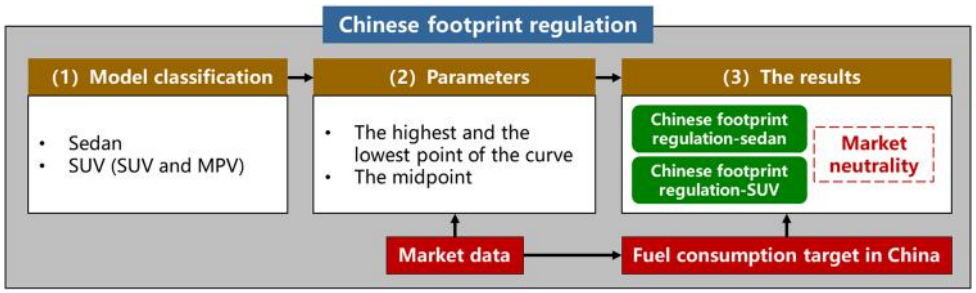
Abstract

In recent years, the rapid development of the automotive industry has brought about several environmental and energy issues worldwide. Many countries have established fuel consumption regulations. Among them, fuel consumption regulations based on the curb weight or footprint have been put forward in China and the US. This paper mainly compares the effect of the application of footprint-based and curb weight-based regulations in China. To compare the effect of these two different benchmarks, a Chinese footprint-based fuel consumption regulation is designed based on the principles of the American footprint regulations and the actual conditions of the Chinese passenger car market, and fuel consumption data from 14 enterprises are also used. It is found that regulations help maintain market neutrality if the target value is separated into two curves according to the type of vehicle. Additionally, footprint regulations are more conducive to vehicle lightweighting than curb weight regulations. Finally, policy recommendations are drawn: to maintain market neutrality, there should be two target value curves in the fifth stage of the weight regulation: one for sedans and one for SUVs. Meanwhile, footprint regulation adaptation should be considered in the future to promote vehicle lightweighting in the Chinese market.

Graphic abstract



Keywords New energy vehicle · Regulatory design · Fuel consumption · Policy suggestion

Abbreviations

CAFC	Corporate average fuel consumption
CAFE	Corporate average fuel economy
NEDC	New European Driving Cycle
JC08	Japanese Driving Cycle
SUV	Sports utility vehicle
MPV	Multi-purpose vehicles

✉ Fuquan Zhao
zhaofuquan@tsinghua.edu.cn

[1] State Key Laboratory of Automotive Safety and Energy, Tsinghua University, Beijing 100084, China

[2] Tsinghua Automotive Strategy Research Institute, Tsinghua University, Beijing 100084, China

Introduction

Vehicles affect fuel consumption and energy security in China

The automobile industry is a mainstay industry of the national economy in China, and the development of the automobile industry provides strong support for sustainable

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economic growth (Zhao, Liu 2014). China's automobile market has grown rapidly in recent years (Hao and Wang 2011). According to the China Association of Automobile Manufacturers (CAAM), 20.806 million cars were sold in China in 2019. China exceeded the USA in vehicle sales in 2009, becoming the largest vehicle market in the world (Huo et al. 2012). Since then, China has remained the largest vehicle market for ten years (Xinhua net 2019). However, the rapid growth of the automotive industry has resulted in increasing fuel consumption in China. According to research conducted in 2014, 720,000 more cars were produced in 2013 than in 2012, which led to an increase in fuel consumption of 27 million tons and in crude oil demand of 35 million tons (Zhang 2014). In addition, in 2018, 69.8% of the oil consumption in China depended on imports (CNPC 2011). It is predicted that by 2030, the dependence rate will exceed 70% (Zhao et al. 2016). Since the main cause of fuel consumption in China is vehicles and transportation, vehicle energy-saving technology relates to energy security in China (Liu et al. 2017). The huge amount of fuel consumption has also caused significant emissions and environmental issues in China (Lyu et al. 2015). Carbon emissions from the automotive industry accounted for 8% of national emissions in China in 2017, which is roughly equivalent to the carbon emissions of the construction industry in 2016 (Ma et al. 2019). Nearly 20% of the carbon emissions in China are produced by these two industries.

In particular, the passenger car market has continued to grow in recent years as the main part of the vehicle market in China (China Energy Research Society 2016), and the sales volume was 22.351 million in 2018 (China Passenger Cars Association 2018). Therefore, increasingly restricted fuel consumption regulations for passenger vehicles are a necessary strategy for China (Wang et al. 2018). It is believed that without such a clear policy signal, technology development and deployment in China will not develop rapidly (He and Bandivadekar 2013). In addition, the tightening of fuel consumption restrictions will not be delayed, although it is hard for some companies (Zhao and Liu 2015). China adopted fuel economy standards beginning in 2004, and its fuel economy standards are now more stringent than those of the US, Canada and Australia (Zhou et al. 2013). These regulations will have a profound impact on fuel consumption and greenhouse gas emissions in the future (Ma et al. 2012). The Chinese fuel consumption regulation mentioned below is one of the most effective methods to solve the problem, alongside car emission standards (Zhao and Liu 2014).

Regulations for passenger car fuel consumption in major countries

The USA took the lead in setting the CAFE (corporate average fuel economy) fuel consumption standard for vehicles in 1975 (Yu 2016). Then, Japan (1979) and Europe (1980) established their own fuel consumption regulations (Zheng 2010). In 2004, China promulgated its first mandatory standard for controlling automobile fuel consumption. Afterward, it has been updated constantly, and the fourth stage of CAFC (corporate average fuel consumption) regulation was established in 2016.

The standards in these countries have been updated several times, and two kinds of benchmarks are adopted: the curb weight of the car or the area of the footprint (wheelbase × gauge), as shown in Table 1, China, Japan and the European Union adopt fuel consumption regulations based on the curb weight benchmark (Zheng 2010) (hereafter referred to as "weight regulations"). According to the draft of China's fifth-phase (2021–2025) fuel consumption regulations released recently by the China Automotive Technology and Research Center, the target value curve will be changed from stepped to linear in the fifth stage of the fuel consumption regulation, which means that the target value has a linear relationship with the curb weight of the model rather than divided into groups based on curb weight to improve the accuracy of the regulation. Stricter targets are set to ensure that the national goals of passenger car energy conservation are met (Rong et al. 2015).

Overview of the Chinese fourth-stage CAFC regulations

China is currently applying a fourth-stage fuel consumption regulation, called the CAFC regulation (2016–2020). This regulation applies to all passenger cars in the Chinese

Table 1 Regulations for passenger car fuel consumption in major countries

Country	Indicators	Continuity	Benchmark	Driving cycle	2020 target (L/100 km)
US	Fuel economy rating (mpg)	Linear	Footprint (ft^2, Wheelbase × gauge)	CAFE	4.74
EU	Carbon emissions (g/km)	Linear	Curb weight (kg)	NEDC	3.8
Japan	Fuel economy rating (km/L)	Step	Curb weight (kg)	JC08	4.5
China	Fuel consumption per hundred kilometers (L/100 km)	Step	Curb weight (kg)	NEDC	5.0

market, and the average fuel consumption of each company is calculated to determine whether it meets the target value for each company. The application of energy-saving technologies and the market development of new energy vehicles are strongly encouraged. Enterprises should pay attention to both energy-saving technologies and the development of new energy vehicles (Hua et al. 2015) because doing so is necessary to continuously meet the target. Compared with that in the third stage, the fuel consumption target value has been tightened significantly in the fourth stage to further reduce passenger car fuel consumption. Since the implementation of the first phase of fuel consumption regulation in China, the average fuel consumption of passenger cars has been 7.97 L/100 km based on the fuel consumption data released by the government (MIIT 2016), and the average fuel consumption of passenger cars in China has improved by 14.7% in the past eight years, according to a report published by the Innovation Center for Energy and Transportation in 2017 (iCET 2016).

The significance of studying Chinese footprint regulations

In China, the currently applied curb weight fuel consumption regulations are similar to European regulations, but the distribution of the market in China is similar to that of the US; two main types of cars are sold. This contrast leads to several problems in the current weight regulation:

1. It is not conducive to fleet development toward vehicle lightweighting and miniaturization.
2. It is difficult for large vehicles such as SUVs to meet the standards, which affects market neutrality.

These issues affect the development of the Chinese car market. The maximum trend of the car model affects the average fuel consumption restrictions in China, which means that the progress of fuel-saving technology may not be reflected in the average fuel consumption or even seems to be worse. Therefore, a solution should be found to address these problems, a new regulation that is not based on curb weight should be considered, and the effect on car models should be studied. The car market in the USA is enormous, similar to that in China, and it has abundant management experience regarding fuel consumption regulation. To maintain market neutrality, a footprint regulation is proposed with the design of two target value curves, and two different types of car models are managed separately in the USA. However, there is no similar design in China.

Although a comprehensive study was conducted before promulgating the current regulations, until now, there have been no studies about the application of footprint-based regulations in China or comparative studies about footprint regulations and weight regulations. Therefore, it is necessary to determine whether it is worthwhile for China to learn from the US fuel consumption regulations.

This paper is the first to study the footprint regulation application in China and show all its benefits compared to weight regulation. It is suggested that the Chinese government should follow three steps to apply a footprint regulation gradually.

The remainder of this paper is organized as follows: Section two explains the method of comparing footprint regulations and weight regulations. Section three studies the principle of designing footprint regulations in the USA. Then, following the principle and the current fuel consumption regulations in China, the process of designing a footprint regulation and a weight regulation with double curves that are suitable for the Chinese market is described in Section 4. Newly designed regulations are compared together with current regulations in Section five. In Section six, some conclusions are summarized, and policy recommendations are made.

Methodology

This paper mainly studies the effect of footprint regulations and weight regulations on the Chinese market, including the impact on vehicle miniaturization and vehicle lightweighting and the different effects between regulations with a single curve and those with two curves. First, the design ideas for the US footprint regulations are presented. Then, based on the current situation of the Chinese passenger vehicle market, a footprint regulation considering the Chinese market is designed. To compare the effects, the fuel consumption regulation with a curb weight benchmark and two curves based on different types of models are designed (hereafter referred to as the Chinese double-curve weight regulation). A comparative analysis is conducted to compare the effects of two regulations on models and auto companies. Data on curb weight, footprint area, and fuel consumption from 8 Chinese automakers and 6 foreign automakers are used. The proportion of compliance models among all models represents is used to show whether regulations help maintain market neutrality, and quantitative analysis on the difference in the compliance rate of different types of vehicles is conducted. Finally, the advantages and disadvantages of the two regulations when applied to the Chinese market are found. The role of footprint regulations in guiding model development towards miniaturization and vehicle lightweighting is also presented.

The process of designing a Chinese footprint regulation and a double-curve weight regulation is an important part of this research. To design a footprint regulation for China, the design ideas of US footprint regulations are studied in this paper, as shown in Fig. 1. It is known that there are many pickup trucks and large SUVs in the US car market (Jiang

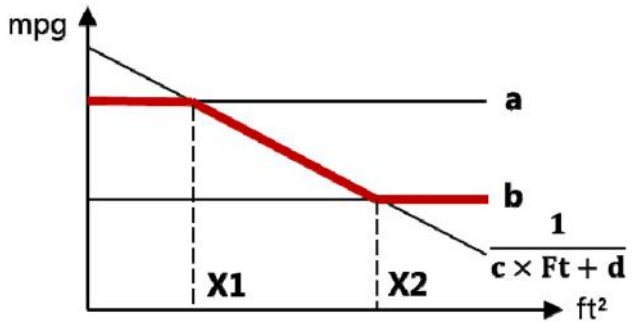

Fig. 1 A simplified model of US footprint regulations

2015). Under the first stage of fuel consumption regulations, the target values for different vehicle models were the same. Auto companies that mainly produced small cars (such as Suzuki) complied with the regulations more easily (Ling 2010). For car manufacturers that produce large cars, compliance was much harder (Tong and Wu 2009) unless more fuel-saving technology was applied to their models, which dramatically increased their manufacturing costs. This issue was resolved after the implementation of the second phase of the US regulations. In the new regulations, there were two target value curves for passenger cars and other large vehicles. The target value for light trucks (including pickup trucks and some large SUVs) was set to be looser than that for passenger cars; thus, the fuel consumption standard for large vehicles was easier to be met. In this paper, a footprint regulation for China is designed based on the design of US footprint regulations, and the design method is shown in Fig. 2.

To design a Chinese double-curve weight regulation, the current regulation should be considered, and the target value curve is set based on the actual situation in the Chinese car market. The data for sedans and SUVs are fitted linearly to obtain the double curve, and this double curve will then be moved up or down simultaneously to let the average fuel consumption for all vehicles meet the national goal of average fuel consumption. Finally, the Chinese double-curve weight regulation is obtained. Based on these two regulations, the actual effects of the two types of regulations on automobile miniaturization, vehicle lightweighting, and market model orientation in China are considered.

Design ideas of US footprint regulations

Method of footprint regulation design

The parameters of the US footprint regulations are determined mainly based on market conditions or predictions. The target values for passenger cars and light trucks in the regulations are set to satisfy the following mathematical formulas (National Highway Traffic Safety Administration 2012a).

(1) For passenger cars, assume that the fuel consumption target value is Target1 and that the footprint area is Ft1.

$$Target1 = MAX\left(\frac{1}{MIN\left(MAX\left(c1 \times Ft1 + d1, \frac{1}{a1}\right), \frac{1}{b1}\right)}, \frac{1}{MIN\left(MAX\left(g1 \times Ft1 + h1, \frac{1}{e1}\right), \frac{1}{f1}\right)}\right) \quad (1)$$

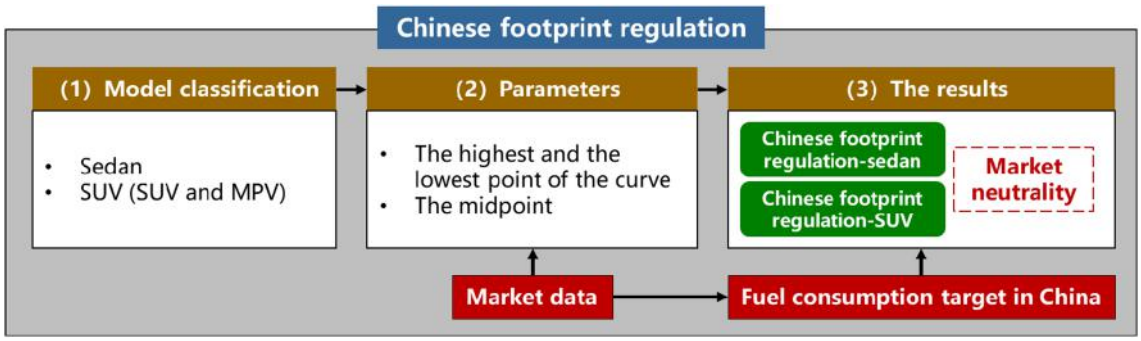

Fig. 2 Design of Chinese footprint regulations

(2) For light trucks, assume that the fuel consumption target value is Target1 and that the footprint area is Ft1.

$$Target2 = MAX\left(\frac{1}{MIN\left(MAX\left(c2 \times Ft2 + d2, \frac{1}{a2}\right), \frac{1}{b2}\right)}, \frac{1}{MIN\left(MAX\left(g2 \times Ft2 + h2, \frac{1}{e2}\right), \frac{1}{f2}\right)}\right) \quad (2)$$

a1–d1 and a2–d2 have no physical meaning; these are parameters based on the market situation or the prediction of it, and they are used to represent the highest value, the lowest value, the slope, and intercept of the middle segment (National Highway Traffic Safety Administration 2012b), as shown in Fig. 1. e1–h1 and e2–h2 are the parameters designed based on the technical utilization rate, air conditioning efficiency, power, and many other factors of each model. To simplify the design process, these parameters are not considered when designing the footprint regulation for China.

As shown in Fig. 1, the shape of the curves will be determined by the four parameters "a", "b", "X1", and "X2". "a" and "b" are determined according to the national fuel consumption target values and markets; they will not be

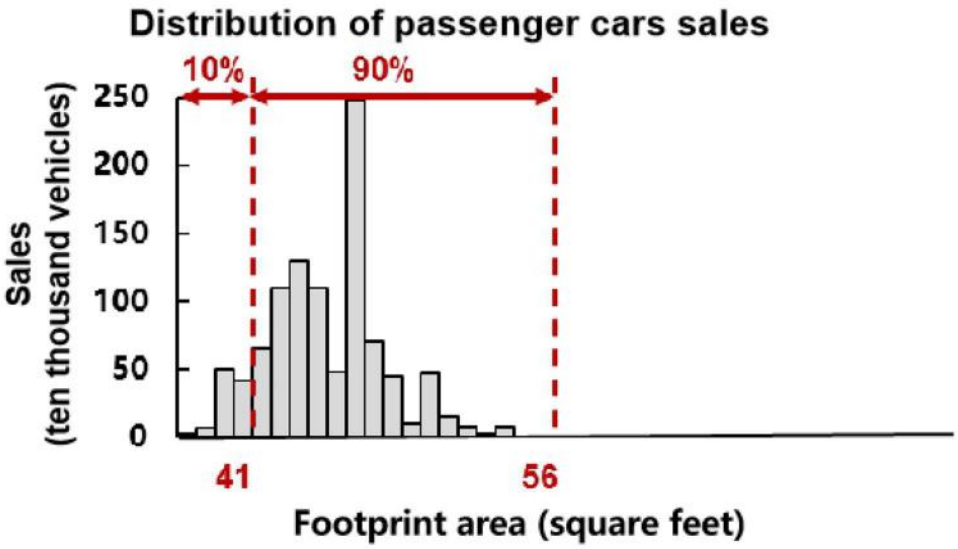

Fig. 3 Distribution of US passenger cars sales (2017)

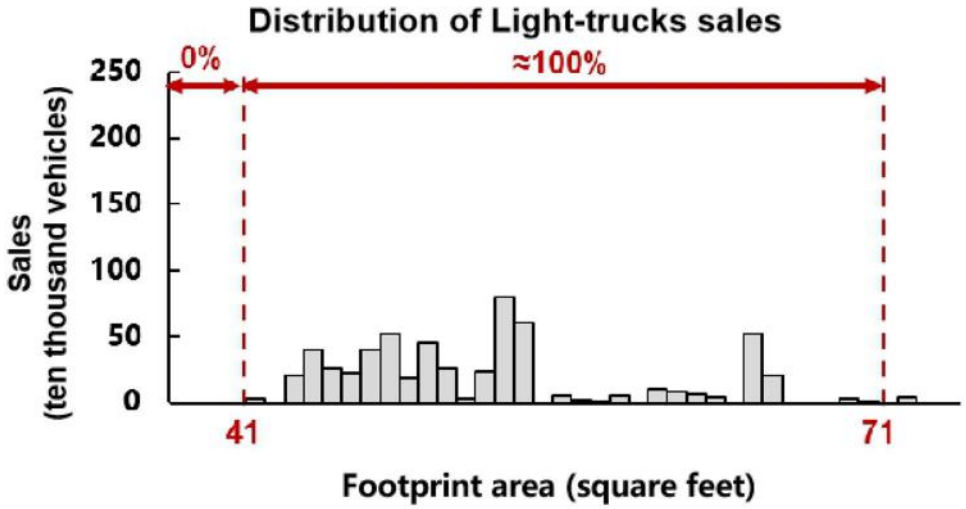

Fig. 4 Distribution of US light trucks sales (2017)

described in detail here. "X1" and "X2" are determined based on the distribution of the footprint area in the current US market; for passenger cars, 10% and 100% points of sale are selected, respectively. The footprints are 41 square feet and 56 square feet, as shown in Fig. 3. For light trucks, the 0% and 100% points (approximation) of sale are selected (National Highway Traffic Safety Administration 2012a), as shown in Fig. 4. Finally, the shape of the curve in the footprint regulations can be determined according to "a", "b", "X1", and "X2".

Design of the footprint regulation and double-curve weight regulation in China

Chinese footprint regulation design

This paper learns from the classification method of the US footprint regulation and classifies vehicles in China based on the market distribution in China. Due to factors such as the Urban Limitation Policy for Commercial Vehicles in China, the number of vehicles that meet the US classification standard for light trucks in the Chinese market is very small. Thus, this paper designs a regulation consisting of two target value curves separately based on two models, sedans and SUVs (SUV + MPV), which have significant differences in fuel consumption and large sales volumes. Then, following the design method of the US footprint regulations shown in Section three, the target curve of the Chinese footprint regulation can be determined by the parameters X1, X2, the midpoint P (the average of all vehicle models), and the slope K, as shown in Fig. 5. These parameters are designed based on data from the Chinese market. Finally, the two curves are translated to meet the national goals, and a footprint fuel consumption regulation for China (hereafter referred to as the Chinese footprint regulation) is obtained.

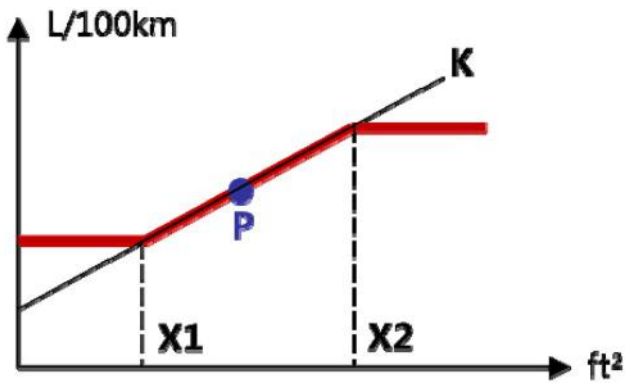

Fig. 5 Simplified model of the Chinese footprint regulation

According to the design method of the Chinese footprint regulation, data for 6 foreign brand car manufacturers and 8 Chinese brand car manufacturers in 2017 are used (only models with more than 500 units of sales were considered). These models are used to represent the situation of the Chinese passenger car market (including the average fuel consumption, average curb weight, and average footprint area). A total of 15.5 million vehicles are included, covering more than 60% of passenger vehicle sales in China, which is highly representative. The statistical results are shown in Figs. 6 and 7. The final results for the Chinese footprint regulation are shown in Fig. 8.

Design of the Chinese double-curve weight regulation

This paper compares the effect of the Chinese footprint regulation and a weight regulation on aspects of the Chinese vehicle market, such as miniaturization, vehicle lightweighting, and market distribution. According to the draft of the Chinese fifth-stage fuel consumption regulation (shown in Fig. 9), the classification method of models and data for

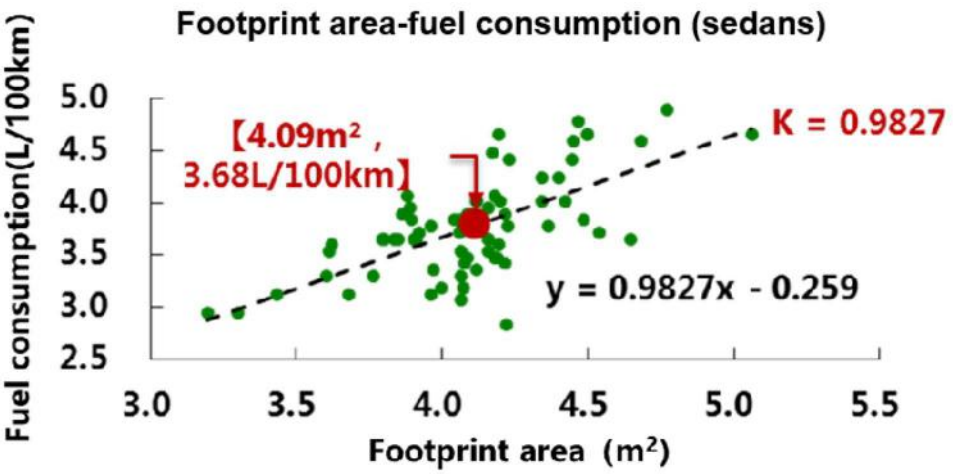

Fig. 6 Statistical results for footprint area-fuel consumption (sedans)

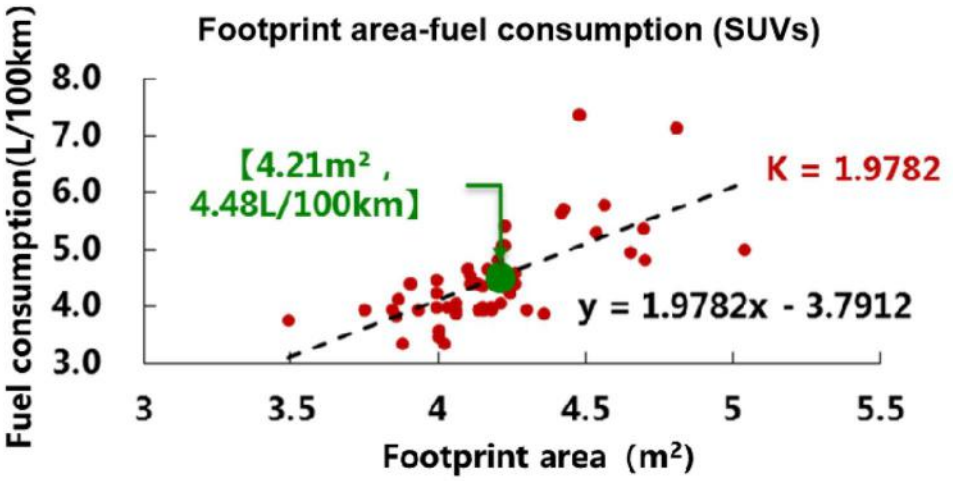

Fig. 7 Statistical results for footprint area-fuel consumption (SUVs)

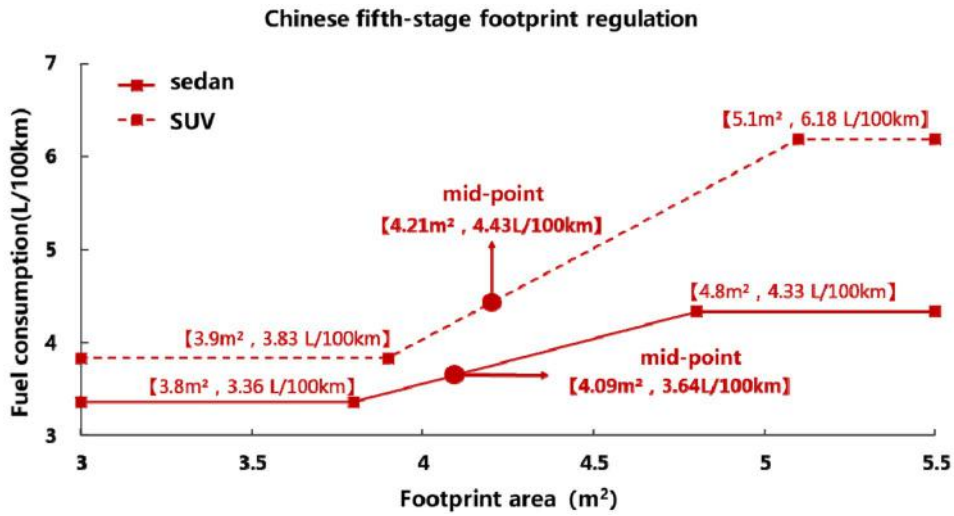

Fig. 8 Design of the Chinese fifth-stage footprint regulation

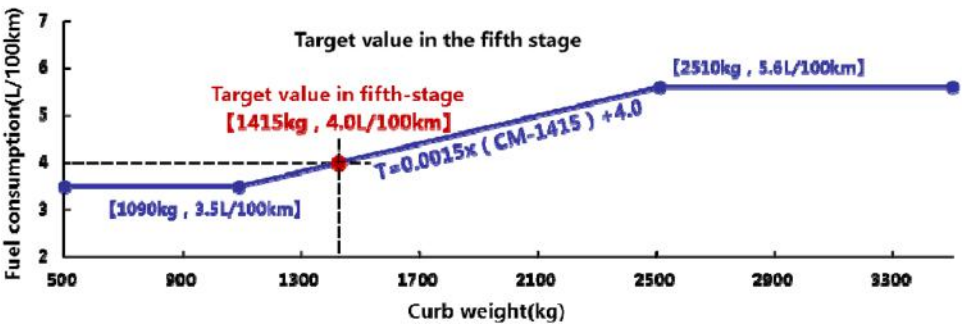

Fig. 9 Fifth-stage passenger car fuel consumption regulation (draft)

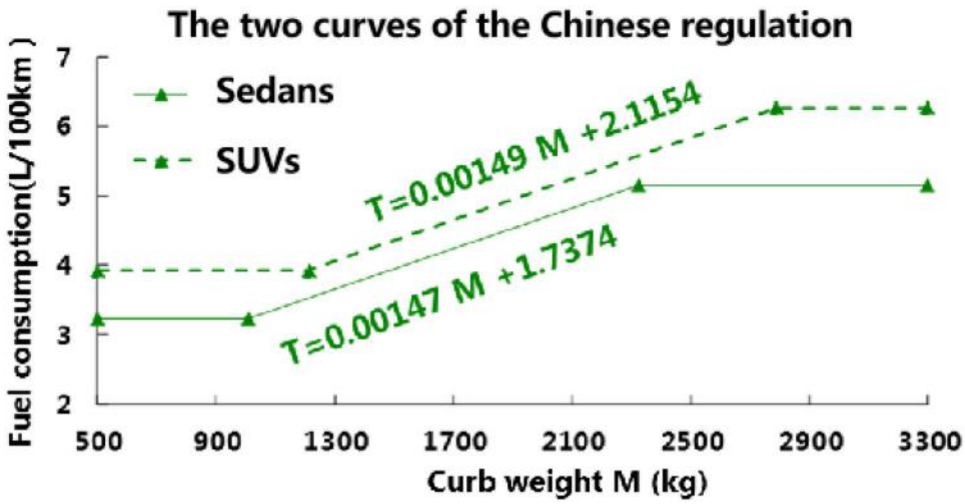

Fig. 10 The Chinese double-curve weight regulation

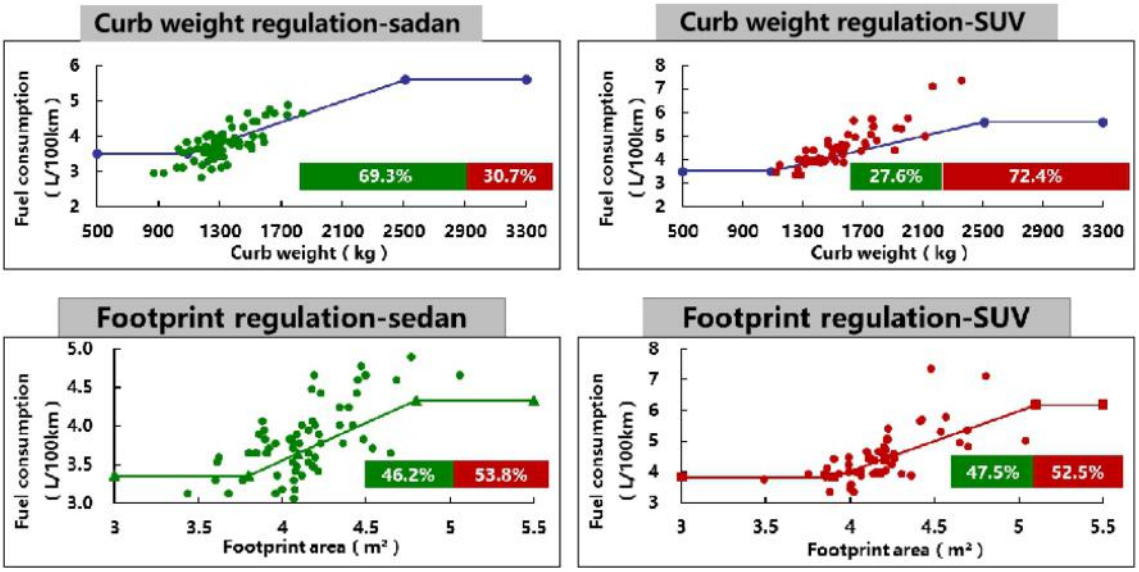

Fig. 11 Fuel consumption distribution

Table 2 Statistics for the compliance rate

	Sedans		SUVs	
	Compliance (%)	Noncompliance (%)	Compliance (%)	Noncompliance (%)
Weight regulation	69.3	30.7	27.6	72.4
Footprint regulation	46.2	53.8	47.5	52.5

14 auto companies, the double-curve weight regulation is designed, as shown in Fig. 10.

Comparative analysis of the three different fuel consumption regulations

Effect of footprint regulation on car models

This section is based on the Chinese scenario. First, the difference effect of the regulations based on the weight or footprint on market neutrality and vehicle lightweighting is studied. Then, a scenario analysis is carried out to study the effects of curve rotation and translation on car manufacturers.

Effect on maintaining market neutrality

All data from the 14 auto companies are combined with the curves of the footprint regulation and the fifth-stage weight regulation (shown in Fig. 11) to calculate the compliance rate (shown in Table 2). The difference in the compliance rate between the two kinds of models is used to represent market neutrality.

After switching from the one-curve weight regulation to the footprint regulation, the compliance rate dropped from 69.3 to 46.2%, and the compliance rate of SUVs increased from 27.6 to 47.5%. The difference between the two types dropped by approximately 43.0%, which means that the footprint regulation with a double curve makes the difficulty of compliance more similar for the two types of vehicles; therefore, the double-curve regulation is better at maintaining market neutrality.

Effect on vehicle lightweighting

The effects of the weight benchmark and footprint benchmark on lightweighting for the two types of models are compared.

According to the middle segment of the target value curves in the double-curve weight regulation, for every 100 kg of weight reduction for sedan or SUV models, the target value for these models tightens by approximately 0.147 L/100 km and 0.149 L/100 km, respectively.

By studying the data on the weight, footprint area and fuel consumption for the 14 auto companies, it is found that for every 100 kg of curb weight reduction for sedan or SUV models, the fuel consumption will decrease by approximately 0.191 L/100 km or 0.270 L/100 km, respectively.

In the double-curve weight regulation, the target value is stricter when the curb weight is reduced, while the target value remains unchanged after vehicle lightweighting in the footprint regulation. Therefore, under the same weight reduction, the footprint regulation is more beneficial for compliance and thereby better for promoting vehicle lightweighting.

Effect on vehicle miniaturization

In the process of the Chinese fuel consumption regulation, the target value curves were gradually tightened in the first three stages of the regulations; for example, in the fourth stage (2016–2020), the target value curve was rotated clockwise around the midpoint by 70% (the slope multiplied by 70%) after translation. This rotation made it more difficult for heavy vehicles to comply with the regulation but easier for small vehicles, which means that the rotation of the footprint regulations had a function of promoting miniaturization.

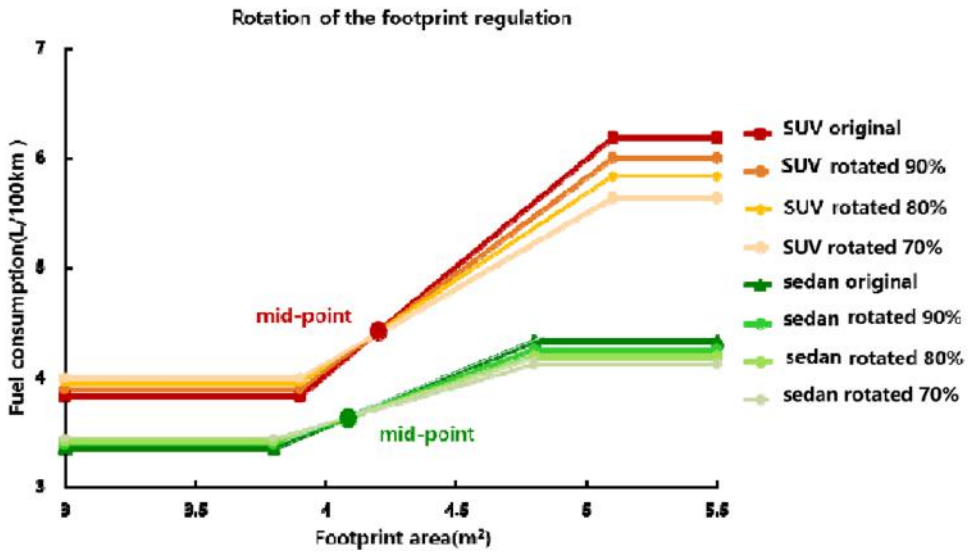

Fig. 12 Various situations of footprint rotation

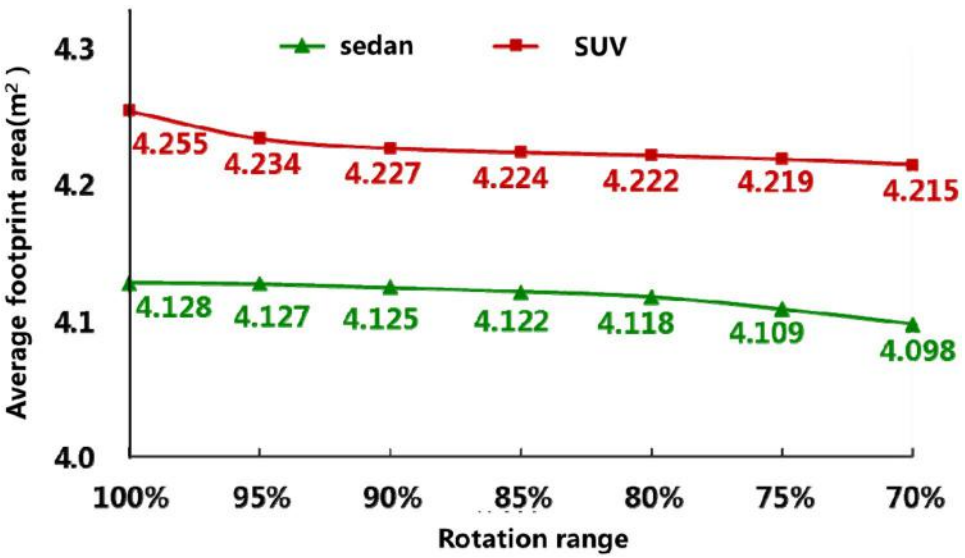

Fig. 13 Effect of footprint regulation rotation on vehicle miniaturization

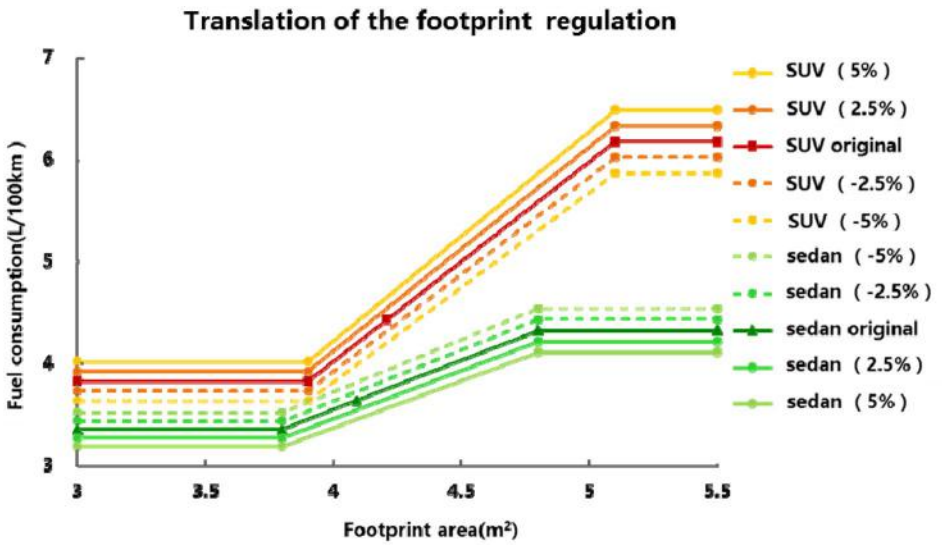

Fig. 14 Various footprint situations

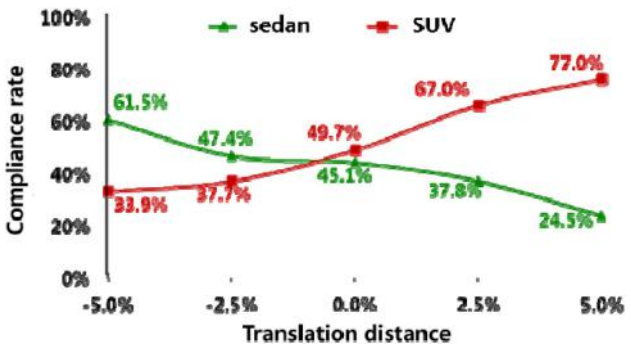

Fig. 15 Compliance rates under different distant translations

Analysis of the rotation of the target value curve was conducted. This curve rotation is studied between the original curve and curve rotated 70%. These curves are shown in Fig. 12. The average footprint area of all compliant models is calculated under each target value curve and shown in Fig. 13, representing the miniaturization effect. The results show that the rotation of the footprint regulation curve can promote vehicle miniaturization. When the curve is rotated by 70%, the average footprint of sedans is reduced by approximately 0.03 m^2 and that of SUVs is reduced by approximately 0.04 m^2. Relevant research indicates that auto manufacturers will have incentives to reduce vehicle size only if the consumer's preference for vehicle size is lower than the acceleration performance (Kate and Steven 2012), which is why footprint regulations are needed to promote vehicle miniaturization.

Guideline effect of footprint regulations on vehicle model types

The main purpose of the double-curve feature in the footprint regulation is to ensure market neutrality, and the difficulty of complying with the regulation is similar for the two types of models. However, if curves in the double-curve regulation are lowered or raised, the difficulty of compliance will change, making it possible for the government to guide the proportions of the two model types distributed.

The original curve represents the best regulation curve for maintaining market neutrality, as shown in Fig. 14. The percentage represents the distance that the curve moves. A positive number represents an increase in distance. The compliance rates of the two types of vehicles are calculated, as shown in Fig. 15. It is clear that shortening the distance is more conducive to the development of sedans and negatively affects SUVs, while increasing the distance has the opposite effect. This paper finds that the guiding effect is characteristic of a double-curve regulation. This function is achieved in the Chinese footprint regulation and the Chinese double-curve weight regulation designed in this paper.

Therefore, it is clear that the double-curve regulation can maintain market neutrality; moreover, it provides the government with a way to manage the automotive market. If the Chinese footprint regulation or the Chinese double-curve weight regulation is adopted, then the government can manipulate the market distribution of the two vehicle types in the market by adjusting the distance between the two curves according to the expectations of the car market. In this process, the overall fuel consumption target will remain unchanged.

Analysis of the effect on typical auto companies

To compare the effects of the three different regulations on auto companies, the compliance difficulties for the 14 auto manufacturers mentioned above are quantified under these regulations, as represented by the compliance rate. The original weight regulation, the Chinese double-curve weight regulation and the Chinese footprint regulation are referred to as "weight regulation 1", "weight regulation 2" and "footprint regulation", respectively.

The distribution of the fuel consumption target values for all auto companies under the three regulations is summarized. These results are shown in Figs. 16 and 17. In general, compared with weight regulation 1, weight regulation 2 and the footprint regulation impose stricter requirements on fuel consumption for foreign brands, and the fuel consumption

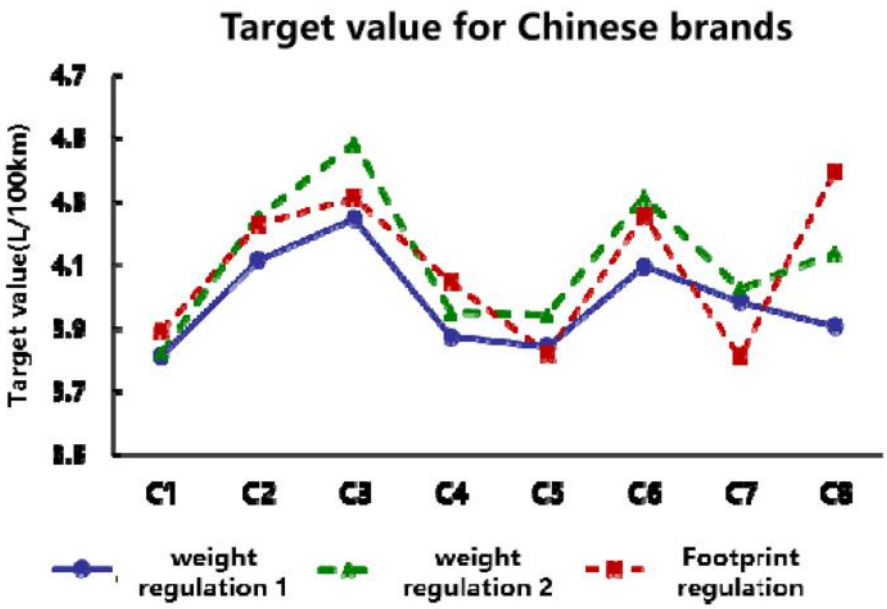

Fig. 16 Target value for Chinese brands

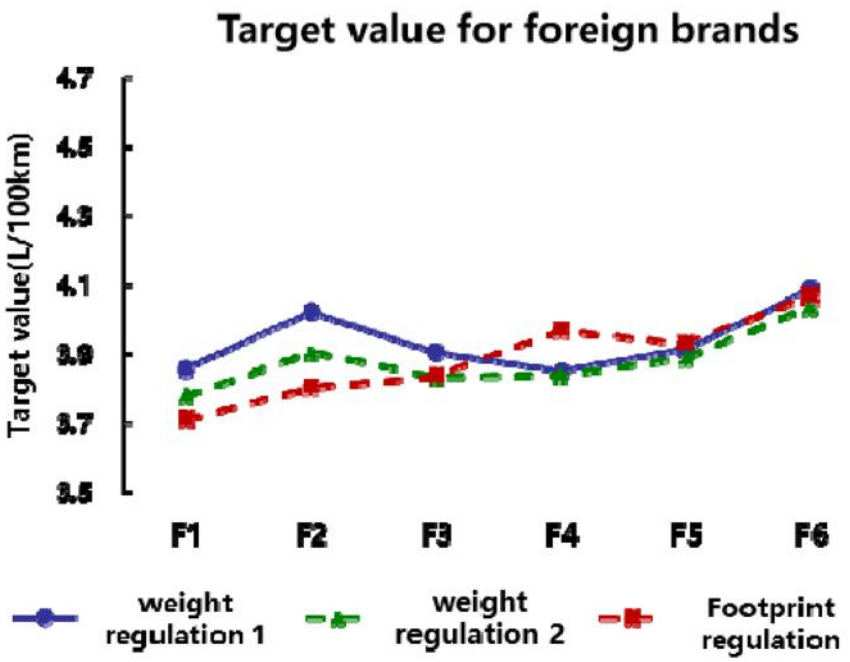

Fig. 17 Target value for foreign brands

requirements of Chinese brand auto companies are relaxed. Furthermore, the comparison of weight regulation 2 and the footprint regulation shows that the fuel consumption requirements of Chinese brand car companies are stricter under the footprint regulation.

The reason for this phenomenon is that Chinese brand companies produce far more SUVs, while foreign brand companies produce more sedans; thus, after switching to the double-curve regulation, the target value for SUVs will rise, and the target value for sedans will drop. In summary, the three regulations have different effects on auto companies, and double-curve regulations are better at maintaining market neutrality, which benefits the auto companies that produce mainly SUVs. In addition, compared with the weight regulations, the footprint regulation is more conducive to promoting vehicle lightweighting.

Conclusion and suggestions

This paper studies US footprint regulations and China's weight regulations. Footprint regulations are more conducive to vehicle lightweighting than curb weight regulations. At the same time, the rotation of the target value curve also helps promote vehicle miniaturization. It is also found that both the Chinese footprint regulation and the Chinese double-curve weight regulation can help maintain market neutrality by classifying different types of models and setting two different target value curves. In addition, adjusting the distance between the two curves also has a certain effect of guiding the change in market share between sedans and SUVs.

In summary, regulations based on footprint have some obvious advantages, which can better promote both lightweighting and miniaturization. By adopting a double curve in footprint and weight regulations, the government can choose between maintaining market neutrality and guiding the market share between sedans and SUVs when necessary.

Currently, the fourth stage of fuel consumption regulation is adopted in China, and according to a draft, the fifth-stage (2021–2025) fuel consumption regulation will still be based on the curb weight, but the target value curve will change from stepped to linear. Based on this information, it is recommended that the change will be too rapid and will difficult for companies to follow if a footprint regulation is adopted in the fifth-stage regulation. Thus, the application of a footprint regulation could be divided into three steps:

1. First, a double-curve weight regulation should be applied. The advantages of a double-curve regulation are described above, and the trend of model maximization caused by consumers' preference for SUVs can be controlled. In this period, the Chinese government could first adjust the distance between two target value curves to have a certain effect of controlling the market share and then study the relationship between the distance of

curves and the guiding effect on the market share during this period of application.

2. Second, a footprint regulation could be adopted, exploiting the advantages of a footprint-based regulation as well as a double-curve weight regulation. For the Chinese government, the market share guiding effect will be roughly predictable by both the government and companies, making this period of application smoother and more effective.
3. Finally, further research on the actual effect of the footprint regulation on the market should be done based on the data collected in the first two steps. Then, more flexible measures are available, such as two target value curves that can be moved upward or downward separately, and the slope, the highest point and the lowest point of the curve can change separately.

Given that the auto industry is a large-scale and complex industry, a fuel consumption regulation is needed with targeted restrictions for different kinds of models, a controllable guiding effect on the market share between different kinds of models and multiple parameters designed to have a controlling effect on variable indicators. Therefore, it is clear that footprint regulation will perform relatively better than other regulations, and further research about the effect of different parameters of footprint regulations should be done.

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