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Research on Evaluation Index System for Low-Carbon Development of China's Automotive Industry

Zhao Fuquan[1,2], Liu Feiqi[1,2], Liu Zongwei[1,2], Hao Han[1,2]

1. Tsinghua Automotive Strategy Research Institute, Tsinghua University, Beijing 100084, China
2. State Key Laboratory of Automotive Safety and Energy, Tsinghua University, Beijing 100084, China

Abstract: Energy security and climate have become global issues of increasing importance. China, as a major political and economic power, has a responsibility for energy conservation and emissions reduction. However, the automotive industry is facing severe emissions reduction challenges while following the low-carbon process. The trend of total expansion of China's automotive industry is inevitable, and transformation of the vehicle energy structure is also imminent. Realizing low-carbon development of China's automotive industry in the future will require effective determination of the low-carbon development gap between China and other automotive powers and removal of the key influencing factors. In this study we used an analytic hierarchy process to analyze the factors influencing the low-carbon development of China's automotive industry, and we compared China with other countries. This study provides a reference for future low-carbon development of the automotive industry in China.

Keywords: automotive industry; low-carbon development; evaluation index system

1 Introduction

Energy security and greenhouse gas (GHG) emissions have gradually become global problems. Developing a low-carbon economy has become an inevitable choice for the future development of all countries in the world. In 2015, after comparing current temperature fluctuation levels to pre-industrial levels, countries signed the *Paris Agreement* to control the average global temperature fluctuations to within 2 °C [1]. At the same time, the global landscape is becoming increasingly complex, and the conflict between developing countries and developed countries on the sharing of responsibilities and obligations is becoming increasingly prominent, which further increases the difficulty of global low-carbon development. Decarbonization has gradually changed from an environmental problem to a complex economic and political problem. In particular, as a developing country, faced with an increase in energy demand brought by economic development, China is not likely to sacrifice economic development to achieve energy saving and decarbonization; however, as a world power, China must bear the corresponding responsibility of reducing emissions. Faced with such intense pressure, the Chinese government has chosen to respond positively: committing to a 40%–45% cut in 2020 CO_2-GDP intensity from 2005 in accordance with the Copenhagen Agreement at COP15 of 2009. In 2014, in the *China-US Joint Statement on Climate Change*, China pledged to achieve peak CO_2 emissions in 2030, with non-fossil fuels accounting for approximately 20% of primary energy consumption. In 2015, in the *Paris Agreement*, China promised a 60%–65% cut in 2030 CO_2-GDP intensity from 2005 [1–3]. After the United States announced its withdrawal from the *Paris Agreement* in 2017, China fully demonstrated its due responsibility, set a good example, and actively promoted the low-carbon industrial and economy development [4].

As the pillar industry in the national economy, the automotive industry is closely related to the development of the country's overall industrial low-carbon economy. With the development of

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Corresponding author: Hao Han, Tsinghua University, Assistant Professor. Major research field is analysis of low-carbon transportation systems. E-mail: hao@tsinghua.edu.cn

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the national economy and improvements in living standards, the increase in traffic volume will be an inevitable trend for future development. More travel demands have led to the expansion of the automotive market. In 2016, China's dependence on foreign oil exceeded 65%. Road vehicles account for 90% of the country's gasoline consumption and 45% of its diesel consumption, which not only seriously threatens national energy security, but also limits China's low-carbon development [5–6]. Therefore, to meet the needs of China's overall low-carbon development, the low-carbon development of the automotive industry is an inevitable. Controlling total energy consumption of the automotive industry, changing energy consumption structure, and promoting the development of new and renewable energy sources will all be important to reduce carbon emissions [7].

A country that achieves low-carbon development in its strong automotive industry will become a leading power in the automotive industry. Low carbon is not only a core demand and an important means of building a strong country, but also an all-round, comprehensive, and systematic index that covers many aspects and various links needed to transform China into a country with a strong automotive industry. At the same time, the automotive industry is a complex system with multiple interrelated factors. Several problems cannot be addressed solely by depending on the development of the automotive industry, but require joint efforts of the manufacturing industry, energy industry, and other industries to achieve a breakthrough. The automotive industry should not be liable for all responsibilities concerning decarbonization and emissions reduction. Therefore, it is necessary to establish a complete evaluation index system and to determine the automotive core elements that impact decarbonization of the automotive industry. It is also necessary to define the responsibilities of the automotive industry in low-carbon development for guiding the construction of China's automotive industry in the future.

This study used the analytic hierarchy process (AHP) to analyze the influential factors in low-carbon development of China's automotive industry. We determined the low-carbon development gap between China and other countries by analyzing and mining the influential factors and making international comparisons. We identified lessons from foreign countries' development experiences to serve as a reference for future low-carbon development of China's automotive industry.

2 Evaluation index system

We developed an evaluation index system for a low-carbon automotive industry. It was based on comprehensive consideration of experts' opinions and literature research. It allowed for automotive comprehensive evaluation and quantitative comparisons at the development level of the automotive industry. The system includes seven first-level indicators (i.e., product, energy, infrastructure, travel, policy, and culture), 32 secondary indexes, and 37 third-level indexes. Quantitative and qualitative indicators were combined to clarify the key elements and important functions of the automotive industry, as well as the gaps between China and other developed countries.

The automotive low-carbon evaluation index system was based on the following three basic principles [8]:

(1) Representativeness: Because the automotive industry features long industrial chains and covers numerous fields, the evaluation index must cover all the related fields and fully represent the various key elements required for a low-carbon industry.

(2) Independence: There are many factors influencing a low-carbon automotive industry, many of which are interrelated. Similar elements should not be listed as different evaluation indicators. Therefore, selected indicators must not be substituted for each other. Moreover, the number of indicators must be reduced as much as possible to clearly describe the low-carbon development of the automotive industry of one country.

(3) Guidance: The purpose of establishing the low-carbon evaluation index for the automotive industry was to clarify interrelated factors and their relationships that influence low-carbon development. We considered lessons from the low-carbon development of automotive industries in foreign countries to find pathways for the future low-carbon development of China's automotive industry.

The first-level indicators were divided into seven aspects, including decarbonization of the industry, product, energy, infrastructure, travel, the policy environment, and culture. Table 1 illustrates the seven primary indicators of the low-carbon evaluation index system for the automotive industry.

These seven primary indexes connect, influence, and restrain each other. There are complex logical relationships interwoven with each other, with short-term factors that affect the low-carbon development of the current automotive market and automotive industry and long-term factors that influence low-carbon development trends in the future. There are issues waiting to be solved by the government, difficulties for enterprises to overcome, requirements to change consumers' consumption awareness, mobility to promote development of the automotive market to achieve goals, and challenges requiring all parties' joint efforts. As shown in Fig. 1, decarbonization of the industry serves as the basis for decarbonization of other aspects. Decarbonization of products, energy, infrastructure, and mobility are the specific manifestations of the decarbonization of each link. Decarbonization of the policy environment and culture also determines the development trends and atmosphere of decarbonization of the whole society. For example, the development of energy saving and new energy vehicles requires guidance from national policies, such as mandatory fuel consumption standards and required proportions of new energy vehicles, as well as effective supervision. Automotive enterprises are required to proactively promote the development of energy savings and new energy vehicle technology to meet government regulations and to optimize the structure of market products to provide con-

Table 1. Low-carbon evaluation index system for the automotive industry.

Name of index	Connotation of index	Investigation factors
Decarbonization of the industry	The life cycle of automobiles includes "design–manufacture–use–service–scrap." Decarbonization of the industry does not mean low carbon for one link, but all the elements in the whole industry cooperate and coordinate with each other to achieve low-carbon development of the entire automotive industrial chain.	Decarbonization of design (power system, transmission system, mass reduction, low resistance); decarbonization of manufacturing (popularization of energy-saving equipment, processes, and technologies; comprehensive utilization and recycling of resources; intelligent manufacturing); decarbonization of use, service, and scrap (scrap and recovery of auto parts, materials, and batteries)
Decarbonization of products	This index considers the impacts of the composition of products in the automotive market on the decarbonization of the auto industry.	Analyze the proportion of car ownership and sales of various vehicle models in the auto market. Consider the impact of vehicle aging on decarbonization of vehicles
Decarbonization of energy	The life cycle of automotive energy includes preparation–transportation–storage–use. The cleanliness of energy development will have direct impacts on the decarbonization of transportation. Decarbonization of energy needs to consider future developmental trends of carbon emissions of various automobile fuels, and it should strive to achieve the optimal ratio of carbon emissions for automobile fuels.	Consider impacts of traditional fuels and hydrogen (the links of manufacturing, storage and delivery), power (source, distribution and use; V2G optimization), and Internet of energy on decarbonization of automobile fuels
Decarbonization of infrastructure	The influence of decarbonization in infrastructure construction coordinates with the decarbonization of vehicle operation, so that the infrastructure construction can adapt to or moderately advance the development of vehicle technologies. This will keep decarbonization of vehicles at an optimal state.	Consider the influence of traditional infrastructure, charging infrastructure, and intelligent network infrastructure on the low-carbon development of automobile infrastructure, including the influence of its own materials, coverage, and utilization conditions on decarbonization
Decarbonization of travel	Low-carbon travel needs to be optimized from both the demand side and the supply side to encourage the effective combination of transportation and to reduce carbon emissions from travel. Decarbonization of travel involves the influence of many factors such as urban planning and traffic structure. The direct feedback is residents' travel choices.	Since we were unable to compare the development of low-carbon travel directly through measuring urban planning, we chose to compare the travel sharing rate of different transportation modes, public transportation ownership, annual vehicle mileage, turnover rates for passenger and cargo transportation, driving habits, and so on, to give feedback on travel.
Decarbonization of policy	Decarbonization of policy environment requires both incentive policies and support of standards to realize appropriate subsidies and law-based punishment.	Consider the national incentive policies for energy-saving and new energy vehicles, regulations for fuel consumption, policies for recycling and scrapping, low-carbon energy policies, road rights management, public transportation promotion policies, etc.
Decarbonization of culture	From the perspective of enterprises and consumers, enterprises need to have a proactive awareness of low-carbon research and development to guide the consumer market; consumers need to have low-carbon consumption awareness and change their traditional consumption concepts. Only by forming a low-carbon culture can we promote the decarbonization of the automotive industry.	Enterprises' awareness of low-carbon R&D; consumers' awareness of low-carbon purchases and travel; promotion of low-carbon cultures, etc.

sumers with better choices [9]. In terms of electric vehicle (EV) development, there are new requirements for clean power; and battery energy storage has also provided some solutions for the uneven distribution of power in time and space. Low-carbon infrastructure is closely related to low-carbon travel, which directly affects consumers' purchasing choices and travel choices. In the primary index, each factor is crucial to the decarbonization of the automotive industry, and a gap in any index will affect the overall level of decarbonization of the automotive industry.

3 Evaluation method

We used AHP to evaluate decarbonization of the automotive industry. After determining the evaluation index system according to the principles of representativeness, independence, and comprehensiveness, we constructed a comparative matrix for indicators at the same level combined with experts' opinions; we then determined the relative weights of various elements. We used the maximum eigenvalue to test the consistency of the comparison matrix, and we used the normalized feature vector corresponding to the largest characteristic root of the comparison matrix as the weight vector. According to the characteristics of the evaluation index, we classified indicators as quantitative or qualitative. For the quantitative indicators, we first collected data, conducted the dimensionless process on the indicators, and then determined the score line to grade the indicators. For the

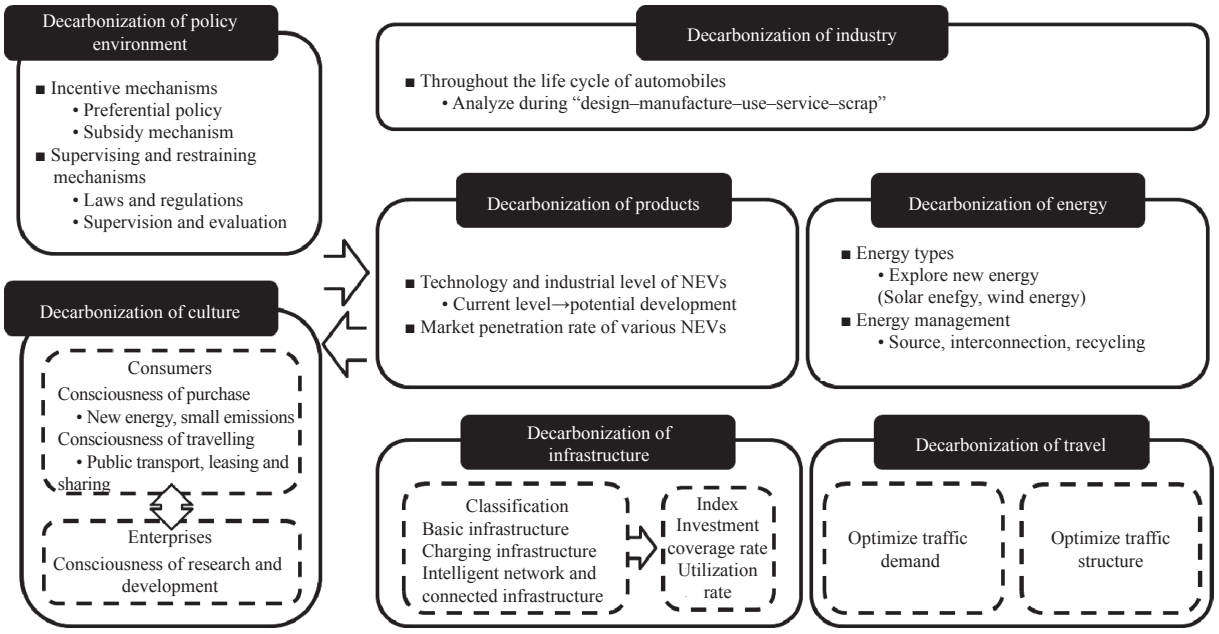

Fig. 1. Relationships between the primary indictors.

qualitative indicators, we determined the score for each country through expert marking and then considered the weights and points of the indicators to obtain evaluation results [10–12].

4 Low-carbon evaluations of the automotive industries from various countries based on the index evaluation system

We comprehensively evaluated the levels of decarbonization in Germany, the United States, Japan, France, Italy, the United Kingdom (UK), South Korea, and China using our evaluation index system. All levels of indicators were graded and quantified. To clarify the comparison of low-carbon development of the automotive industry in different countries, the overall scores were divided into three sections based on our results. Countries with more than 8-points belonged to the first group; countries with 7–8 points were placed in the second group; countries with less than 7-points were placed in the third group. The results are shown in Fig. 2.

Among the eight countries, Japan and Germany scored more than 8-points, ranking in the first group for low-carbon development of the automotive industry. France, Italy, the UK, South Korea, and the United States scored between 7- and 8-points, ranking in the second group. China, with less than 7-points, ranked in the third group. China was still far behind Japan, Germany, and other leading automotive manufacturers in the low-carbon development of the automotive industry.

5 Analysis of the automotive industry's low-carbon development gap between China and other countries

Our analysis showed that Japan and Germany had the highest decarbonization; the United States, France, Italy, South Korea, and the UK had moderate decarbonization; and China had the least decarbonization of the automotive industry. As a country with a strong automotive industry, Japan vigorously promotes the development of fuel-efficient vehicles, with a high promotion of intelligent manufacturing equipment, efficient use of resources, and high vehicle recycling. It has achieved significant advantages through links of the vehicle life cycle. China's automotive industry started later, and its technologies are not as mature. Meanwhile, the weak development of China's manufacturing industry also limits the low-carbon development of China's automotive industry.

Our analysis found that Japan had the highest decarbonization of products, placing it in our first group, while all other countries were in our second group. Due to the free circulation of automotive products in the global market, there is no significant difference in the decarbonization of products in various countries. Japan advocates the development of small cars and is committed to the promotion of its local light-duty sedans, so its market structure is significantly better than other countries. The decarbonization of American products is slightly less than other countries because American consumers prefer larger-sized vehicles and the domestic brands emphasize power development. In contrast, vehicles are upgraded quickly in China due to the rapid development of China's automotive industry. In addition, subject to regulations for the mandatory scrapping of vehicles, the structure of vehicles in service is relatively good and the decarbonization of products is at a moderate level.

Our analysis found that Japan had the highest decarbonization of energy; other countries in our analysis had moderate levels of decarbonization and they were placed in our second group. China had lower decarbonization of energy, placing it in our

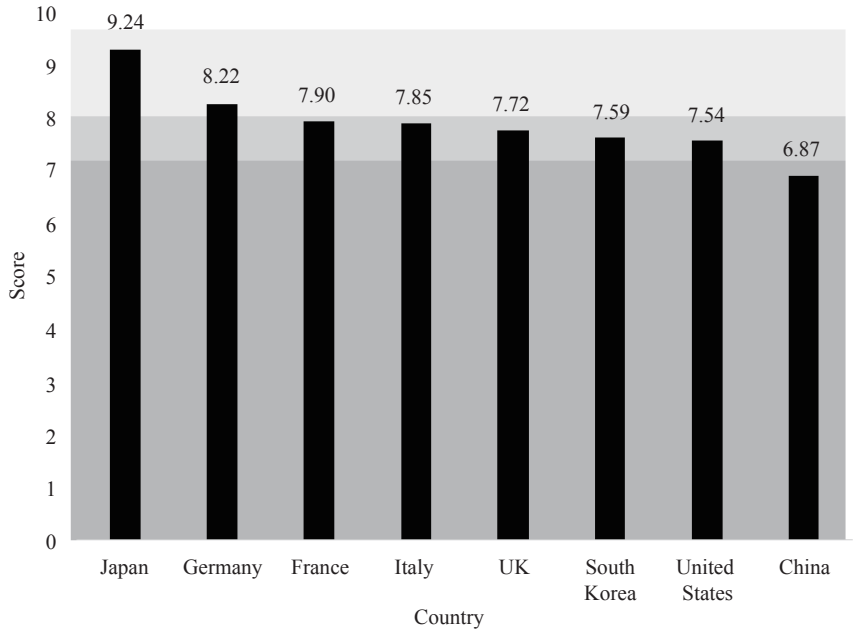

Fig. 2. Evaluation results of decarbonization of the automotive industries in various countries.

third group. However, Japan is limited by geographical conditions and is short of energy resources. Owing to its lack of energy supply, Japan has vigorously developed nuclear power, making its power structure better than the power structure of other countries. Subject to resources and guided by policies, European countries have vigorously developed renewable energy, maintaining a lower carbon energy structure. Although China is increasingly dependent on oil, its own oil production is still affected by mining processes and technologies, with high energy consumption and little decarbonization. At the same time, China's power structure relies on thermal power generation. Although it is gradually transforming to non-fossil fuel power generation, achieving a big transformation in a short time is still a challenge.

Japan, France, Germany, and the United States had the highest decarbonization of infrastructure, placing them in our first group. Japan, France, and Germany have comprehensive public transport infrastructure, the United States and France have comprehensive road infrastructure, and Germany has comprehensive EV charging infrastructure. China is a developing country, and although its infrastructure development has been rapid, its basis is still weak, and it is still less mature than other countries. The growing mobility demand brought by China's growing population has also led to greater needs for infrastructure.

From the perspective of low-carbon mobility, Japan had the lowest decarbonization of mobility, placing it in our first group. However, the United States is clearly behind other countries. As mentioned above, Japan has vigorously promoted and implemented low-carbon mobility, delivering a high level of decarbonization to the whole society. Subject to geography and culture, the development of public transportation in the United States has been weak, which has led to lower development of low-carbon mobility in the United States than in other countries. At present, China has growing transportation demand. First-tier cities are affected by factors such as right-of-way regulations and road congestion, so public transport use remains high. For second-and third-tier cities restricted by economic development, private car ownership is low but growing. Therefore, optimizing the structure of transportation will directly affect carbon emissions from travel in the future.

From the perspective of low-carbon policies, the United States and Japan have implemented the most low-carbon policies, placing them in the first group and other countries are second. South Korea's low-carbon policies are relatively weak. The United States has actively promoted fuel consumption laws at the national and state level. Meanwhile, the promotion of EVs and charging infrastructure has gained support from the government of the United States. Although Japan has few EV promotion policies, the technical policies for energy-saving vehicles, low-carbon development of energy, and the promotion of public transportation are all in place and effective. China has also actively promoted the development of energy-savings and new energy vehicles and encouraged the development of clean energy. The right-of-way management has become an effective method to reduce the carbon emissions.

From the perspective of low-carbon culture, Japan, Germany, France, and Italy had a low-carbon culture, placing these countries in our first group. South Korea, the UK, the United States, and China did not have a strong low-carbon culture and were placed in our second group. Consumer awareness will mainly

affect the composition of the market and travel mode choices, which is one of the most important factors affecting decarbonization in vehicle use. At present, influenced by family structure, vehicles in China's market tend to be large. Moreover, China's consumers regard vehicles as a symbol of wealth. Chinese domestic automotive companies are vigorously developing sports utility vehicles (SUV) to meet consumer preferences and to expand their market share. However, along with promotion of new-energy vehicle (NEV) policies, China's domestic brands have also increased research and development (R&D) and promoted EVs to actively respond to the national policies; they are expected to surpass other countries in technology development.

6 Strategies for low-carbon development of China's automotive industry

6.1 Projections for timing of low-carbon development of China's automotive industry

A comparison with several major countries with strong automotive industries showed that there is a low-carbon development gap between China and other countries. However, at the same time, China has good performance in low-carbon products, transportation, and policies, and the gap between it and other countries has narrowed. Based on an in-depth analysis of China's automotive industry, as well as a study and analysis of the trends, we projected the timing of low-carbon development of China's automotive industry, as is show in Fig. 3.

We projected that from 2015 to 2020, China will move from the third group to the second, reaching 7-points by 2020. From 2020–2035, it is expected that China will experience a period of high-speed growth in low-carbon development of its automotive industry. If all aspects of development control are in place, with the aid of the manufacturing industry and the continued development of low-carbon energy, China's automotive industry is expected to complete the transition from the second group to the first group during this period. China will reach 8-points by 2030 and enter the first group, which is in-line with China's strategic goal of reaching peak GHG emissions by 2030. From 2035 to 2050, China's low-carbon development of the automotive industry will enter a difficult period, and the speed of growth will gradually slow and enter a period of steady growth. During this period, China will remain in the first group and gradually develop into a global leader in a low-carbon automotive industry.

In general, the progress of low-carbon development of China's automotive industry will experience a trend of rapid development and then slower development, which will likely be due to pressure from China's domestic policy environment and international political responsibilities. Because China is required to achieve rapid reduction of GHG emissions in the short-term and decarbonization of China's automotive industry is poor, it is relatively easy to realize emissions reduction at the early stage. However, after realizing these goals, the margin for improvements will continuously narrow and the challenge of emissions reduction will increase, so progress will slow. Finally, the low-carbon progress of China's automotive industry will be on par with other countries with advanced automotive industries.

6.2 Strategies for low-carbon development of China's automotive industry

6.2.1 National actions

To conform with the global low-carbon development trend, low-carbon development of the automotive industry is an inevitable choice. Promoting low-carbon development of the automotive industry will help China achieve its goal of reaching peak GHG emissions by 2030. It could effectively alleviate China's dependence on oil resources, promote rapid development of

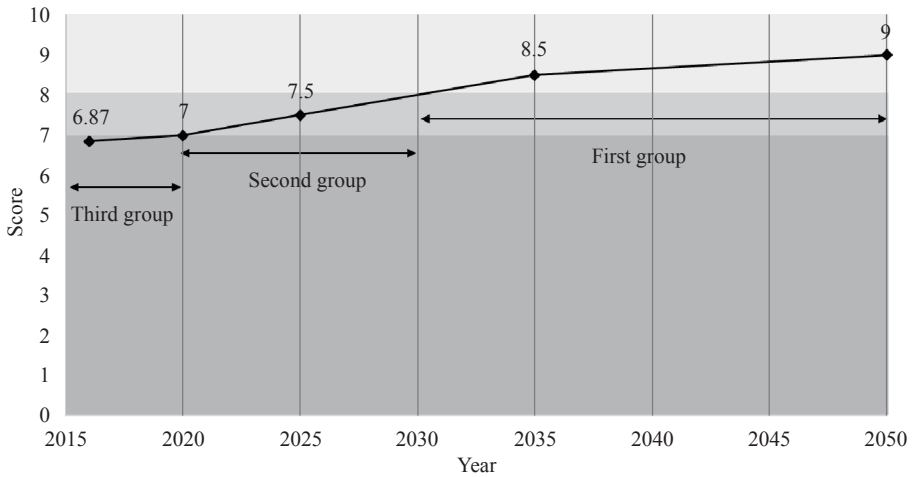

Fig. 3. Projections for index evaluation of decarbonization of China's automotive industry.

renewable energy in China, and effectively improve China's medium- and long-term energy structure.

As shown in Fig. 4, it is still necessary to continue to promote the development of new energy vehicles for the automotive industry, discover NEV models that are most suitable for China's national conditions, realize a combination of policy-driven and economic approaches, and improve the product structure of China's automotive market. At the same time, the government also needs to further improve legislation and effective enforcement of laws and regulations for fuel consumption and emissions standards. China's automotive market is in transition, but it is still dominated by conventional fossil fuel vehicles. Promoting the rapid introduction of energy-saving technology and promoting the progress of automotive enterprises through laws and regulations are future priorities for the government. Finally, China's automotive market should gradually shift from being driven by policies to being driven by the market; it should shift from being supported by subsidies to being supported by free choices of the market. The automotive industry will also be gradually integrated into the trade of carbon emissions quotas, and carbon emissions from the automotive industry will gradually be under market management [13].

Owing to the high investment cost and long payback period for infrastructure construction, it is necessary to rely on national policies and financial support for initial promotion. Coordinating the time, development pace, and product quality of infrastructure construction will be a key measure for urban planning [14]. In particular, the government must formulate effective and feasible plans for coordinated development of EVs and intelligent networks and connected vehicles (and corresponding infrastructure) to meet the needs of the future, rapidly developing automotive industry. With gradual improvement of the automotive market, policy-driven development will gradually relax and will be changed to market-driven development.

Like infrastructure construction, energy also faces the risks of high investment and long cycles. China's energy structure is presently undergoing a transformation. The construction of renewable energy power stations and ultra-high voltage power grids cannot be separated from large capital investment and land acquisition. At the same time, as energy is related to national security, energy cooperation with neighboring countries must be controlled by the state in a unified way to control the input and output of energy and realize the optimization and transformation of the energy structure while alleviating China's energy crisis. Finally, the government should formulate relevant policies and strategies and make good use of the large energy storage characteristics of EVs and the portable characteristics of such energy in the future; this will harmonize regional electricity use and effectively achieve off-peak power consumption [15]. China's power companies should consider making full use of EVs to coordinate power grids in small areas.

6.2.2 Industrial actions

The relationship between the automotive industry, energy, transportation infrastructure, and other industries must be well coordinated to achieve decarbonization; then, the whole life cycle of vehicle energy conservation and emissions reduction can be achieved. As the automotive industry involves a wide range of fields and a long industrial chain, it is also necessary to clarify the automotive industry's responsibilities in energy conservation and emissions reduction and not blindly assume their obligations for emissions reduction. For example, the automotive industry is promoting new energy vehicles, but cleaner energy requires the joint efforts of energy companies and power companies for a breakthrough. To realize decarbonization of the manufacturing industry, enterprises need to introduce advanced equipment, processes, and technologies. However, the efficient and low-energy

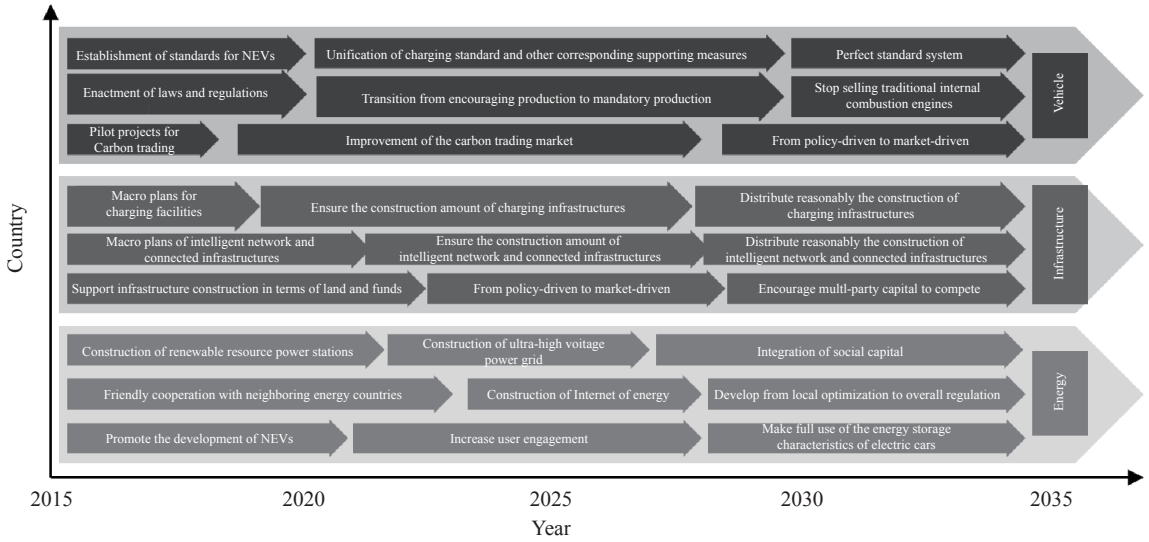

Fig. 4. Strategies for low-carbon development of China's automotive industry.

operation of equipment requires the joint efforts of the entire manufacturing industry.

The automotive industry must rely on the cooperation and coordination of various industries for effective development and operation of a low-carbon automotive industry. However, many problems cannot be effectively solved, and a breakthrough cannot be achieved by solely depending on the industry. In the future, effective coordination of industrial relations, mutual promotion of technological progress between industries, and clear responsibilities for carbon emissions will be key for China's low-carbon development.

6.2.3 Enterprise actions

As shown in Fig. 5, enterprises must first achieve a low-carbon vehicle life cycle, including application of lightweight materials (design), replacement with energy-saving equipment (manufacturing), improvement of aftermarket services (service), and increasing vehicle recycling and reuse (scrap). For products, enterprises need to follow national policies that promote energy-saving technologies for traditional fuel vehicles. Enterprises should also increase investment in the R&D and industrialization of NEV technologies; in particular, domestic automotive companies should use NEVs, a technical breakthrough, to decarbonize products. Both traditional automotive enterprises and new companies should increase development of intelligent networks and connected vehicles. Building intelligent transportation systems and realizing efficient use of vehicles will become important for intelligent networks and connected vehicle development in the future. Finally, with the promotion of car sharing, new requirements for the automotive industry will arise because of changing business models. Popularity of time-share rentals and car sharing in the future will improve vehicle use and avoid waste of idle resources. Meanwhile, it will also accelerate the updating of vehicles and optimize the market structure for vehicles in service. Taken together, automotive enterprises need to constantly improve traditional automotive manufacturing, energy saving and NEV technologies, intelligent networks and connected vehicles, and business models to promote low-carbon development of the automotive industry.

6.2.4 Consumer actions

As buyers and users of automobiles, consumers directly affect the product structure of the automotive market. As shown in Fig. 6, consumers should change their consumption awareness to impact automotive energy conservation and emissions reduction, rather than viewing automobiles as a symbol of wealth. Consumers should replace old and worn vehicles and purchase energy-saving vehicles and NEVs for energy conservation and emissions reduction [16]. Consumers should change their mobility awareness, prioritize public transportation and car sharing, reduce the frequency and distance of daily trips, and reduce travel carbon emissions. For energy use, consumers can use EV battery energy storage for staggered power use to relieve pressure on the power grid.

7 Conclusions

By establishing a model to evaluate low-carbon development of China's automotive industry, this study quantitatively evaluated the level of low-carbon development of the automotive industries in eight countries. According to the research results, the comprehensive functions of the advanced manufacturing industry, a clean energy structure, and universal awareness of decarbonization make Japan and Germany leaders in the low-carbon development, while China still lags, and other countries have moderate low-carbon development and are placed in the second group. China's industry is quickly transforming towards decarbonization, and automotive products are under continuous improvement. However, subject to development levels of the manufacturing industry and energy industry, large improvement

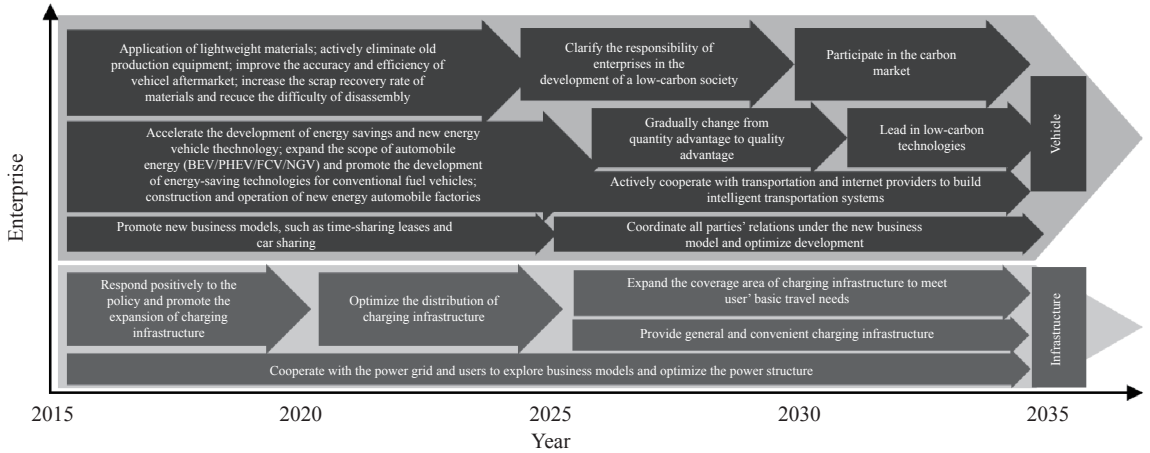

Fig. 5. Enterprise strategies for low-carbon development of the automotive industry.

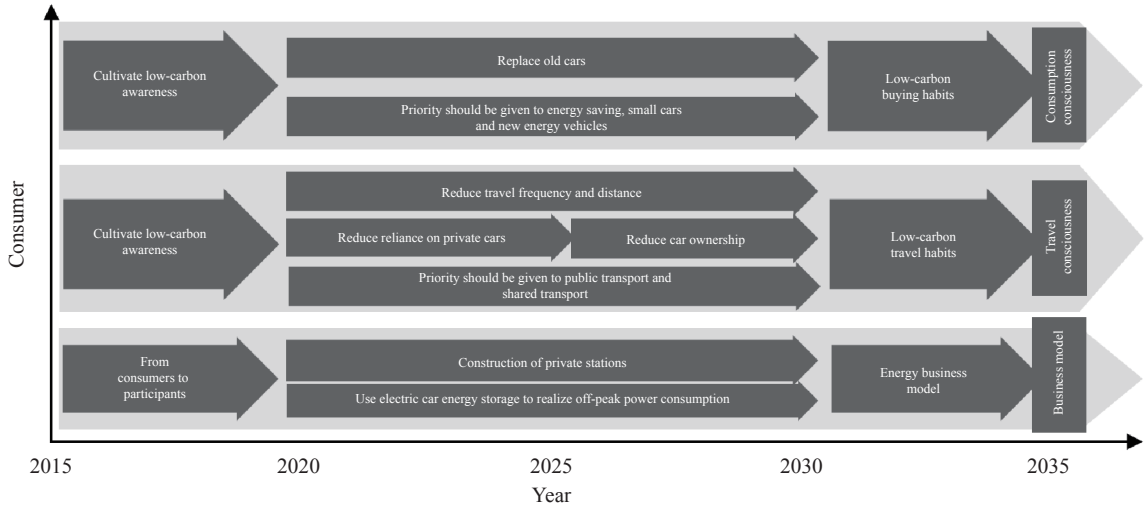

Fig. 6. Consumer behaviors for low-carbon development of the automotive industry.

in decarbonization can occur in the future; this would require coordinated development of multiple industries. At the initial stage of development, it still needs national strategic guidance and financial support. Later, the government can gradually reduce its support and prioritize the market in low-carbon development. The evaluation index system can guide China's automotive industry to understand its own weaknesses and seek breakthroughs in low-carbon development; it can be a reference for automotive industry development planning in the future.

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