Systems Engineering Study on the Decarbonization of Automobiles in China

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Abstract: In line with the commitment made in the *Paris Agreement* to reduce CO_2 emissions, the automobile industry in China aims to lower its CO_2 emissions to contribute towards achieving this goal. We have thus developed a model for predicting CO_2 emissions from automobiles based on (1) a framework for the decarbonization of automobiles, (2) the current state of emissions over the automobile life cycle, and (3) the predicted sales of automobiles in China in 2030. Using this model, we were able to predict the amount of CO_2 that automobiles in China will emit in 2030, and the total amount of CO_2 emitted by automobiles will be predicted to peak in 2025–2030. We also analyzed the proportion of CO_2 emitted by automobiles to the total amount of CO_2 emitted in China. A system for evaluating the CO_2 emissions of automobiles in China was established, and comprehensive suggestions for realizing a low-carbon technology roadmap in China are presented in this paper.

Keywords: decarbonization; fuel consumption regulations; automobile technology; life cycle; technology roadmap

1 Introduction

Decarbonization is a core principle in the development of China's national economy and in the formulation of national strategies. Consequently, the greatest challenge faced by the Chinese automobile industry is successfully reducing CO_2 emissions. According to a report by the Intergovernmental Panel on Climate Change (IPCC), to prevent a global rise in temperature beyond 2 °C, CO_2 emissions globally must be restricted to 3.15×10^{12} t. As of today, 2×10^{12} t of CO_2 has already been emitted. To address this issue, 195 countries, including China, have signed the *Paris Agreement*. In this agreement, China committed to curb its CO_2 emissions and reduce its CO_2 emissions per unit of GDP by 60%–65% below 2005 level by 2030. Therefore, it is essential to consider the challenge of decarbonization in the formulation of a sustainable development strategy for China's automobile industry. This strategy is expected to play an important role in helping the automobile industry transition toward a low energy consumption–low carbon paradigm [1]. Studies on

the decarbonization development of China's automobile industry are thus highly significant, given the present need to restrict CO_2 emissions [2]. The objective of this work is to systematically study the decarbonization of the automobile industry based on its life cycle. The various phases involved in the automobile industry include research and development, production, and manufacture, automobile sales, automobile usage, and automobile recycling. Each phase of this life cycle involves and affects various fields, including raw materials, mechanics, electronics, energy, finance, services, and infrastructure construction.

2 Systems engineering study on the decarbonization of China's automobile industry

This systems engineering study encompasses six different aspects: a systems framework for reducing carbon emissions from automobiles, the current state of automobile CO_2 emissions, a predictive model for automobile CO_2 emissions, prediction of the total CO_2 emissions of automobiles, the proportion of CO_2

emitted by automobiles to the total CO_2 emitted by China, and the evaluation of automobile CO_2 emissions.

The systems framework for decarbonization consists of seven different phases: mining of energy resources, processing of energy resources, transportation of energy resources, manufacture of automobile materials, manufacture of automobiles, usage of automobiles, and recycling of automobiles.

According to statistical data from the National Bureau of Statistics of China, the usage phase accounted for 75% of all automobile CO_2 emissions in 2015; the manufacture of materials, the manufacture of automobiles, maintenance, and recycling phases accounted for the remaining 16%, 6%, 1%, and 2% of the emissions, respectively (Fig. 1). In developed countries, the usage phase usually accounts for approximately 60% of the total CO_2 emitted by automobiles. Thus, the emission intensity of China is higher than that of developed countries in every phase involved in the automobile industry, from the oil wells to wheels.

The CO_2 emissions of China's automobiles in the usage phase were 3.2×10^8 t in 2000, 6.1×10^8 t in 2008, and 8.6×10^8 t in 2015. It is apparent that the carbon emissions due to the automobile industry have risen rapidly over time [3]. In contrast, the emissions due to automobiles in Japan were 2.37×10^8 t in 2000 [4], 2.23×10^8 t in 2008, and 2.01×10^8 t in 2014, indicating that CO_2 emissions due to the Japanese automobile industry have decreased every year.

In Japan, low emissions, mostly due to technological advancements, in the usage phase have contributed to the stabilization and gradual decrease in the overall amount of CO_2 emitted. The amount of CO_2 emitted by automobiles in China, on the other hand, is increasing rapidly, in tandem with the rise in car ownership. A large quantity of CO_2 is released during the manufacturing phase; however, the rise in CO_2 emissions is, at present, gradually plateauing. In 2013, Japan produced half the number of automobiles as China, but only emitted 1/9 of the amount of CO_2 emitted by China [5]. The amount of CO_2 emitted
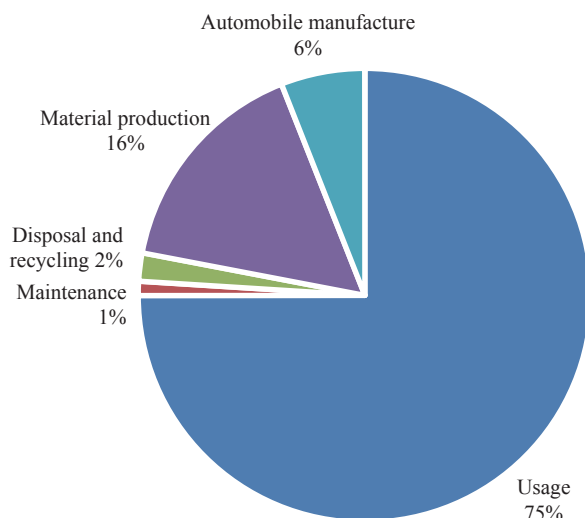
during the production of a car by a foreign automobile company can be as low as approximately 0.7 t per car. In China, although the amount of CO_2 emitted during the car manufacturing phase is decreasing every year, there is still significant room for improvement as Chinese companies still emit approximately 2.9 t of CO_2 per car in this phase. China also emits more CO_2 than the United States in the production of materials for automobile manufacturing. The production of steel that is required for each car produces emissions of 3.27 t in China, whereas in the United States, only 2.49 t of CO_2 is emitted. Similarly, aluminum production produces 1.46 t of CO_2 per car in China, but only 0.28 t of CO_2 per car in the United States.

Based on the automobile life cycle, a carbon emissions model was constructed for automobile usage, manufacture, materials, maintenance, and disposal/recycling phases. Notably, the CO_2 emissions of the automobile usage phase also include CO_2 emissions of the fuel production phase.

Total CO_2 emission, $M\mathrm{co_2\_tot} = M\mathrm{co_2\_road} + M\mathrm{co_2\_manuf} + M\mathrm{co_2\_maint} + M\mathrm{co_2\_dis} + M\mathrm{co_2\_mat}$

In this equation, $M\mathrm{co_2\_tot}$, $M\mathrm{co_2\_road}$, $M\mathrm{co_2\_manuf}$, $M\mathrm{co_2\_maint}$, $M\mathrm{co_2\_dis}$, and $M\mathrm{co_2\_mat}$ are the total CO_2 emissions, CO_2 emissions of automobile usage, automobile manufacture, automobile maintenance, automobile disposal/recycling, and material manufacture phases, respectively.

The life cycle CO_2 emission of automobiles is the sum of CO_2 emissions of automobile usage, automobile manufacture, automobile maintenance, automobile disposal and recycling, and the production of automobile material phases.

The CO_2 emitted by automobiles during their usage on roads is given by:

$M\mathrm{co_2\_road} = \Sigma G_r \times A_k / A_r \times e_k \times m_k \times e_t \times C_k \times l_k$

where G_r is fuel consumption over a reference year, i.e., the fuel consumption of a known year; A_k is the predicted number of cars in the future, i.e., the number of cars in the forecast year; A_r is the number of reference cars, i.e., the number of cars of a known year; m_k is the correction factor for the average annual mileage; e_k is the correction factor for the automobile fuel consumption of a future year; e_t is the traffic efficiency factor; C_k is the CO_2 emission coefficient per unit mass of fuel; l_k is the CO_2 emission coefficient over a life cycle.

In this model, corrections to the theoretical fuel consumption was made based on the total annual fuel consumption to avoid issues due to the inconsistencies between the actual and theoretical fuel consumptions and because it is impossible to calculate the actual fuel consumption. The CO_2 emission of the automobile manufacturing phase may be expressed as:

$M\mathrm{co_2\_manuf} = M\mathrm{quantity} \times C\mathrm{co_2\_quantity}$

In this equation, $M\mathrm{quantity}$ is the number of cars produced and $C\mathrm{co_2\_quantity}$ is the average CO_2 emitted to produce each car.

The following assumptions were made according to the proportion of an automobile's life cycle CO_2 emissions accounted for by each phase in other countries.

Fig. 1. Statistical analysis of automobile CO_2 emissions in China.

The ratio of maintenance-related CO_2 emissions to usage-related CO_2 emissions is $0.008:0.769$; the ratio of material-production-related CO_2 emissions to automobile-manufacturing-related CO_2 emissions is $0.131:0.068$; the ratio of disposal-and-recycling-related CO_2 emissions to usage-related CO_2 emissions is $0.022:0.769$.

The inputs of our model include forecasted nationwide automobile sales in 2020, 2025, and 2030 (30 million, 35 million, and 38 million, respectively) and the energy consumption reduction targets listed in the *Technology Roadmap for Energy-saving and New Energy Vehicles*, calling for 20%, 35%, and 50% reductions in the energy consumed to produce each car compared with 2015 levels in 2020, 2025, and 2030, respectively. The CO_2 emissions of automobiles in China were thus forecasted using our model and the aforementioned inputs and assumptions. It was shown that a large reduction in CO_2 emissions will be achieved in the automobile usage phase and overall automobile life cycle by 2030 (Fig. 2), which indicates that target CO_2 emission levels will be achieved ahead of schedule. At present, the CO_2 emissions of the automobile manufacturing phase are already beginning to decrease; however, the greatest contribution to CO_2 emission reduction is expected to originate from the automobile usage phase. The decrease in CO_2 emissions in the automobile manufacturing phase will help the automobile industry save energy and reduce emissions. The reduction of CO_2 emissions in the automobile usage phase may be attributed to two causes: ① the fuel and power consumption of cars is continuously decreasing over time in accordance with regulatory requirements; ② annual car sales, car disposal, and car ownership will stabilize after 2025. However, if CO_2 emissions of the usage phase cannot be controlled, it will become very difficult to maintain a steady increase in the nationwide car sales up to 2030.

The proportion of CO_2 emissions due to road transportation to the total CO_2 emissions globally and that to China are shown in Figs. 3 and 4, respectively [6]. CO_2 emissions in road transportation account for 17% of the world's total CO_2 emissions, whereas China's CO_2 emissions account for 4.6%, 5.3%, and 7.0% of the world's total CO_2 emissions in 2005, 2010, and 2015, respectively. Although CO_2 emissions in road transportation account for a relatively smaller proportion of China's emissions (owing to the high CO_2 emissions of China), this proportion has increased significantly from 2005 to 2015 and is continuing to increase rapidly. A significant quantity of CO_2 is therefore produced by automobiles in China.

We constructed a system for evaluating the decarbonization of the automobile industry from a systems engineering perspective on automobile decarbonization, which contains seven first-level indicators and 32 second-level indicators. The first-level indicators include industry decarbonization, product decarbonization, energy decarbonization, infrastructure decarbonization, travel decarbonization, decarbonization of the policy environment, and the development of a low-carbon culture, as shown in Fig. 5.

The evaluation was conducted by assigning weights to each indicator and having experts score the indicators. In terms of the overall level of automobile decarbonization in each country, Japan and Germany have attained the highest scores, and there is a sizeable gap between China and other developed countries. Based on these scores, Japan and Germany occupy the first tier of development (in terms of decarbonization) as they have both attained scores above 8.5. China is in the third tier of development as it has attained a score lower than 7. Other than the decarbonization of its policy environment, China has attained lower scores for all the other indicators as compared to other developed countries. The *Paris Agreement* mandates that each country must measure, predict, and control its carbon emissions as they see fit. Some countries have proposed to stop selling
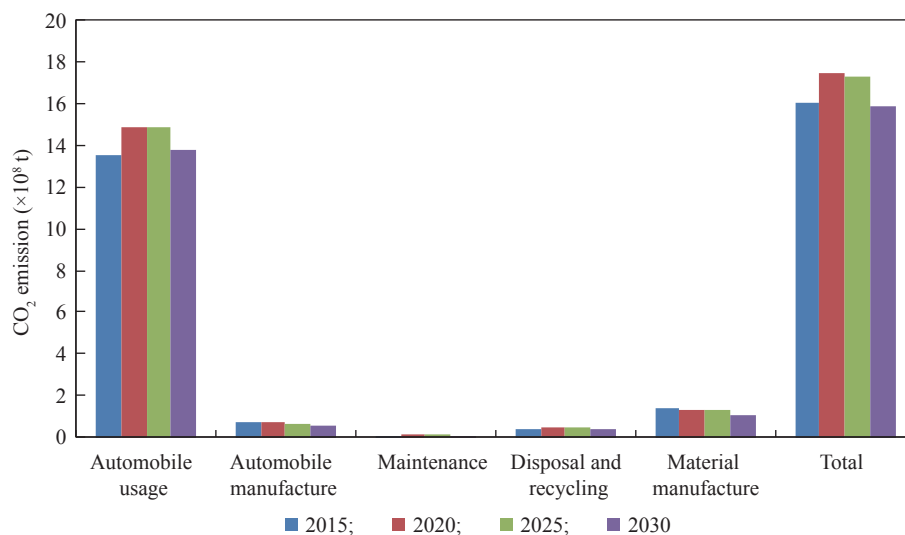

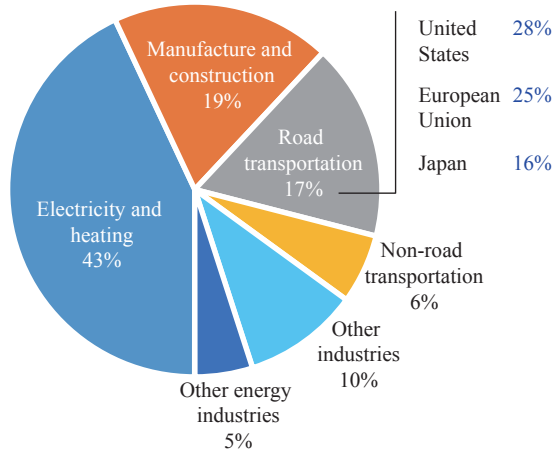**Fig. 2.** Forecasted total CO_2 emissions by automobiles in China.

Fig. 3. Proportion of CO_2 emissions produced by road transportation to the total CO_2 emissions of the world.
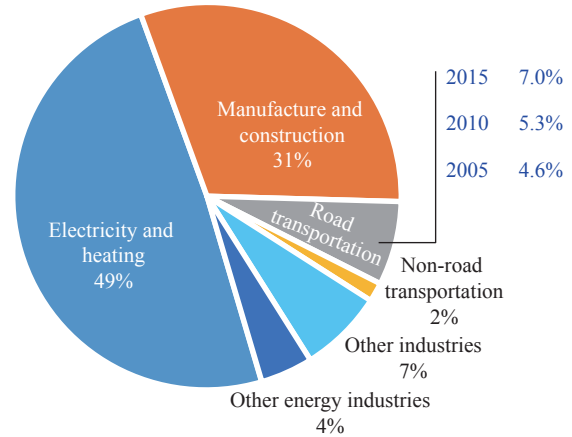
Fig. 4. Proportion of CO_2 emissions produced by road transportation among the total CO_2 emissions of China.
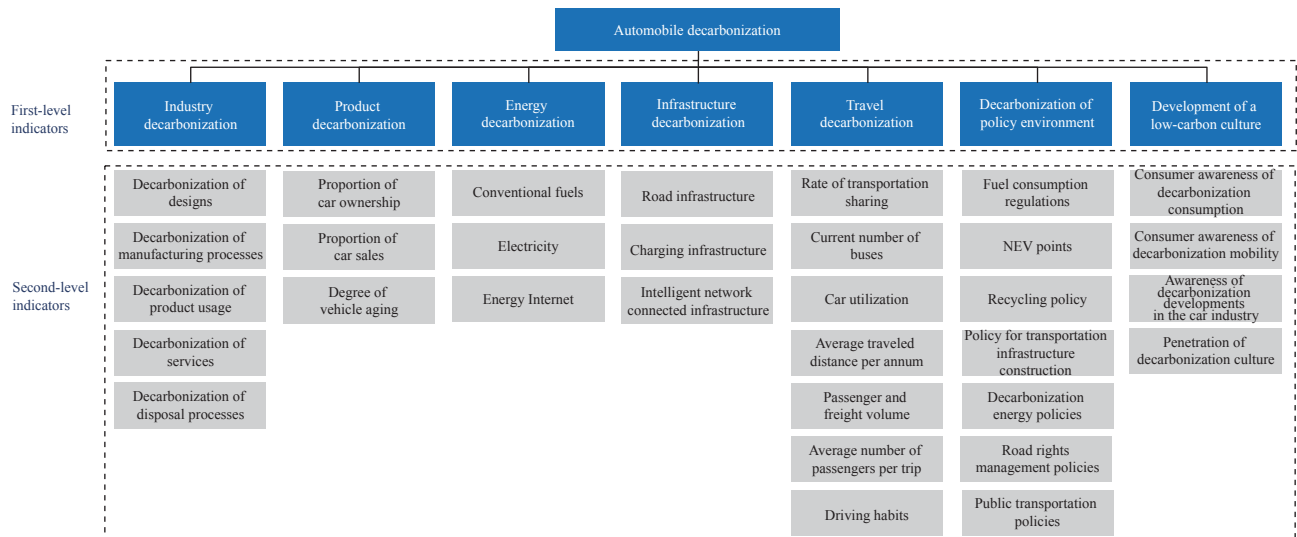

Fig. 5. System of evaluative indicators for the decarbonization of a nation's automobile industry.

fossil-fuel-powered cars by 2030 to satisfy the demands of ecologically sustainable development. Our research shows that China will achieve peak automobile CO_2 emissions by 2028, with China's total CO_2 emissions being restricted to 1.5×10^9 t. Automobile CO_2 emissions will account for 12% of China's total CO_2 emissions at this point.

3 Technology roadmap for the decarbonization of passenger cars in China

China has passed highly stringent regulations for automobile fuel consumption (Fig. 6) to restrict automobile CO_2 emissions [7]. These mandatory regulations on CO_2 emissions from passenger vehicles must be implemented immediately by car manufacturers in China. Moreover, these mandatory regulations will soon also be applied to commercial vehicles. In the past,

although pollutant emissions were restricted by laws and regulations, fuel consumption was dictated purely by market forces. CO_2 emissions are now a major priority for China, as reflected by the passage of stringent fuel consumption regulations to control CO_2 emissions from passenger cars. These fuel consumption laws have three sets of requirements. The first is "admittance," which requires a manufacturer to fulfil certain conditions to gain permission to sell cars in China. The second is the restriction of the manufacturer's fleet emissions below a certain level. The third pertains to fuel consumption targets: if the cars sold by a manufacturer cannot achieve the mandated fuel consumption targets, the manufacturer must purchase carbon allowances. Chinese fuel consumption regulations (CO_2 regulations) affect all industries, and they are the strictest set of rules applying to the country's automobile industry. These regulations will ultimately determine the survival of Chinese industries. The stringency of

these regulations is an indication of the importance the Chinese government places on reducing CO_2 emissions from the automobile industry. Fig. 6 shows that a 27% reduction in fuel consumption is required between Phase III and Phase IV; a further decrease, greater than 20%, is required by Phase V.

The reduction of CO_2 emissions and energy consumption from the automobile industry is the collective responsibility of society as a whole, including the government, industry, and consumers. As a decrease in fuel consumption will lead to an increase in product costs, the willingness of customers to pay for more expensive cars that satisfy fuel consumption regulations will be crucial for the survival of the automobile industry. According to willingness to pay (WTP) surveys based on product life cycle returns, passenger car customers are only willing to

pay for increased purchase costs if these can be ameliorated by savings in fuel consumption within three years. The cost required to reduce fuel consumption by 0.1 L was obtained as shown in Fig. 7; an A0-class car requires additional 230 CNY to achieve this target, whereas a C-class car requires additional 474 CNY for the same. These cost increases must be borne by the industry if emissions reduction targets are to be achieved. Therefore, the Chinese automobile industry must confront the cost pressures imposed by technological innovations as it strives to achieve Phase IV fuel consumption ratings by propagating fuel-saving technologies. Cost pressures are therefore a major constraint in the electrification of the automobile industry.

Here some of the technologies that could be used to achieve the CO_2 emissions targets are discussed for each phase of the
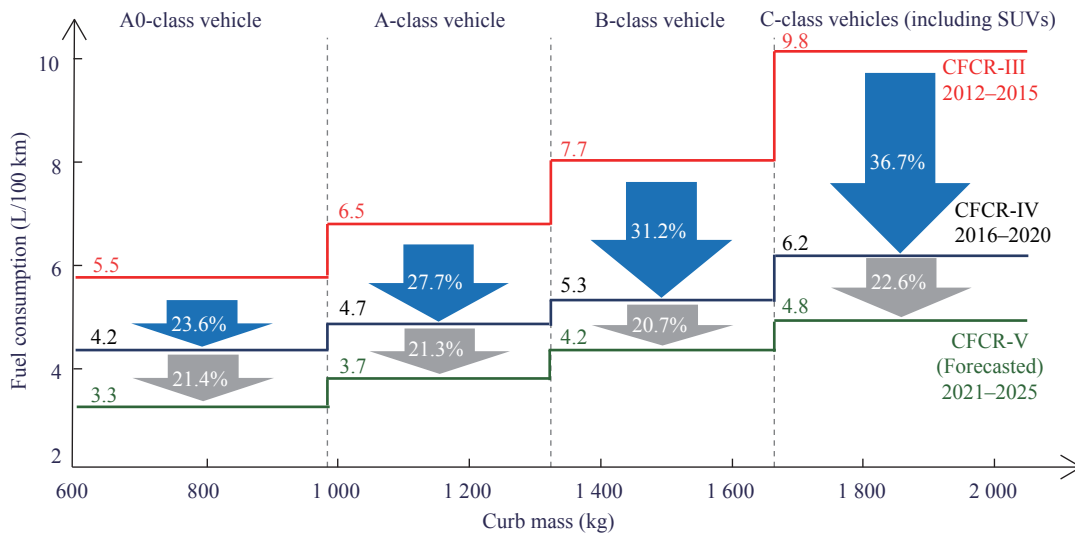

Fig. 6. Fuel consumption regulations for passenger cars in China. CFCR: combined fuel consumption rating.
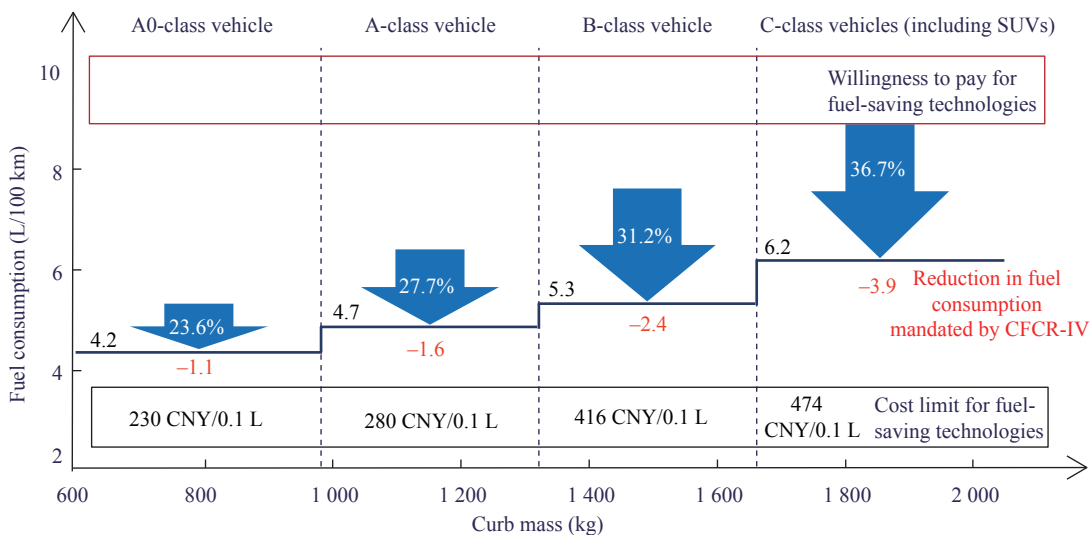

Fig. 7. Estimated cost of reducing the fuel consumption of passenger cars in China. CFCR: combined fuel consumption rating.

China fuel consumption regulation (CFCR) while maintaining economic viability. The technologies that could be used to achieve Phase IV targets before 2020 (a gasoline engine thermal efficiency of 38 % and 5 L/100 km) include Miller cycle engines, start-stop systems, variable valve lift, integrated exhaust manifolds, high-efficiency superchargers, and low-friction and lightweighting technologies. Phase V fuel consumption targets for 2025 require a fuel consumption of 4 L/100 km and gasoline engines with a thermal efficiency of 42 %. The technologies that could be used to achieve these goals include variable valve actuation (VVA), thermal management, 48 V hybrid electric or plug-in hybrid electric vehicles (HEV or PHEV, respectively), electric superchargers, exhaust gas recycling, cylinder deactivation, variable compression ratios (VCRs), waste heat recovery (WHR), water injection system, and lean-burn engines. Phase VI fuel consumption reduction for 2030 requires a thermal efficiency of 45 % and fuel consumption of 3.2 L/100 km; this will require costlier technologies, such as low-temperature combustion, high stroke-to-bore ratios, WHR, adiabatic engines, motor electrification, and HEV/PHEV technologies.

By combining these technologies with existing new energy electrification, China FAW developed the concept of engine electrification, which simultaneously accounts for the costs and fuel-saving potential of engine electrification. The first generation of FAW hybrid engines utilizes a belt-driven starter generator (BSG), whereas the second generation innovates upon the first by electrifying other engine accessory components (Fig. 8).

Further technological innovations may be pursued through electrification of the transmission, which allows for full and plug-in hybridization. The core purpose of such innovations is the integration of the electric motor and transmission. Phase IV

fuel consumption targets may be achieved in B-class vehicles using 48 V mild-hybrid systems, which are more cost-effective than high-pressure hybrid systems. Phase IV targets for B/C-class hybrid electric vehicles may be achieved using hybridization technologies based on electrified transmission. For B/C-class vehicles to attain Phase V fuel consumption targets, PHEV technology will be required.

Electric vehicles are expected to contribute very significantly toward the achievement of fuel consumption targets during each regulatory phase. A single A0-class electric vehicle can offset the fuel consumption of 7.9 units of conventional B-class cars during Phase IV or 2.3 units of B-class cars in Phase V. Alternatively, an A0-class electric vehicle offsets the fuel consumption of 6.1 units of conventional C-class cars in Phase IV or 2 units of C-class cars in Phase V. The potential for entirely-electric cars to balance current corporate average fuel consumption (CAFC) regulations is, given the policy for passenger cars, expected to increase several fold in the near future.

A comparative study of the three existing types of hydrogen fuel cell vehicles, i.e., the energy supplementing, hybrid, and fully fuel-cell-powered types, concluded that the third is the most suitable in terms of contributions towards decarbonization. A fully fuel-cell-powered vehicle does not require external charging as it uses a rapidly hydrogenated fuel cell stack that performs at a level comparable to conventional internal combustion cars. These vehicles, therefore, represent a mainstream technological trend in the development of low-carbon vehicles.

4 Technology roadmap for decarbonizing commercial vehicles in China

Commercial vehicles are facing a major challenge from fuel
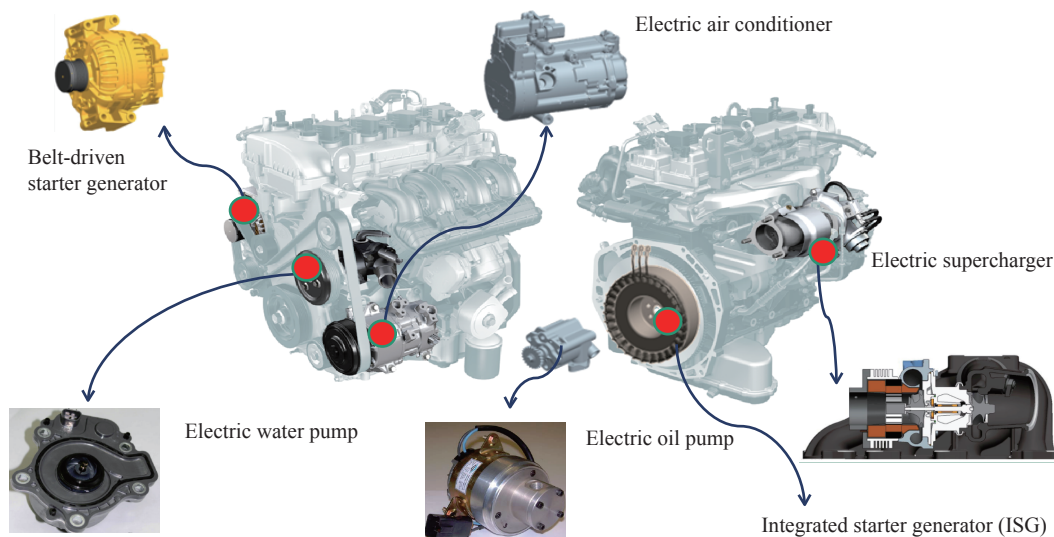

Fig. 8. Engine electrification.

consumption targets in China as the country intends to implement Phase III and Phase IV regulations by 2020 and 2025, respectively. This will impose a mandatory 15% reduction in fuel consumption on vehicles. In comparison, the United States intends only to implement Phase II regulations by 2021, whereas the European Union is still collecting CO_2 emissions data and is only expected to announce emissions limits for commercial vehicles in 2022.

Commercial vehicles currently account for 53% of the CO_2 emissions from all automobiles, whereas passenger cars only account for 47% of the same. Chinese reliance on imports for 65% of its petroleum needs, and the majority of this is used for commercial vehicles. Enhancing the fuel economy of commercial vehicles will involve two steps, with the first being the development of a commercial vehicle engine with a 47% thermal efficiency. Commercial vehicles are still largely reliant on diesel engines, as electric vehicle batteries do not currently have sufficient capacity to serve as a viable alternative for highway transport vehicles. The required thermal efficiency may be achieved if the combustion processes of diesel engines is improved. The key to this goal lies in the improvement of three crucial aspects: the combustion chamber, common rail, and supercharger. One of the most important milestones for this goal is the creation of a common rail injection system with variable injection rates. To this end, China FAW has developed a dual rail injection system with separate high- and low-pressure rails. Three different fuel injection rates can be obtained by combining these rails using a control system, and a national patent has been granted for this system. The reduction of NO_x emissions and fuel consumption are the most important priorities in the optimization of combustion processes. A supercharger must be highly efficient at both low and high speeds, and the best technological solution, in this regard, is the dual-channel asymmetric supercharger developed by China FAW.

The second step is to utilize clean fuels, which is an important step towards reducing carbon emissions from commercial vehicles. For example, China-adapted World Transient Vehicle Cycle (C-WTVC) test cycles show that natural-gas engines could reduce CO_2 emissions significantly by approximately 7%. Commercial vehicle engines developed in the future should be based on natural gas engines and diesel engines should be considered alternate variants. This type of development would represent a major innovation in the automobile industry.

Phase IV mandates a thermal efficiency of 50% in diesel engines. One of the most important technological pathways toward this goal is WHR; it has the potential to increase thermal efficiency by 2%–4%.

The use of hybrid power systems is another important low-carbon technological pathway for commercial vehicle development, as hybrid systems could reduce CO_2 emissions by 7%–10%. The "smartization" of commercial vehicles also has tremendous potential to reduce fuel consumption: road conditions could be predicted via intelligent prediction technologies, and smart formations could reduce wind resistance. The latter has the potential to reduce fuel consumption by approximately 20%.

5 Suggestions

In this work, systems engineering study of the decarbonization of automobiles in China was conducted. Based on results and other issues discovered while performing this study, following suggestions are listed to decarbonize automobiles in China and accelerate the country's progress in this regard.

(1) A decarbonization automobile industry system, including the establishment of a decarbonization database, decarbonization industrial chains, and a management system for decarbonization development, should be established.

(2) The energy and automobile industries should be developed in a coordinated manner. For example, the development of power installations, hydrogen energy, and alternative fuels should be coordinated with those of electric cars, hydrogen fuel cell vehicles, and commercial vehicle technologies, respectively.

(3) A decarbonization strategy should be formulated for commercial vehicles. CO_2 emissions reductions may be achieved via improved thermal efficiency and the use of low-carbon fuels, and energy transformations and decarbonization may be achieved simultaneously through the use of hydrogen fuel cell technology.

(4) Green manufacturing should be implemented to reduce CO_2 emissions and promote green production processes in the automobile industry. A recycling system that matches the scale of the automobile industry should also be established, and the use of recyclable raw materials promoted on a wide scale.

(5) The development of intelligent networked vehicles should be promoted to accelerate the development of smart cars, accelerate infrastructure development, and further expand industrial cooperation.

(6) Big data, the Internet, and artificial intelligence should be used to reduce CO_2 emissions during automobile usage.

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