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Challenges, Potential and Opportunities for Internal Combustion Engines in China

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Abstract: With the increasing pressure on the automotive industry due to energy consumption, environmental pollution and climate change, internal combustion engines, which occupy a dominant position in traditional automotive powertrains, are facing considerable challenges from battery electric powertrains. This paper presents an in-depth analysis and objective interpretation of the challenges, potential and opportunities for internal combustion engines in this point. Specifically, the global automotive industry is approaching the "Power 2.0 era", and multiple powertrains will coexist for a long time. The relationships between the various powertrains are complementary rather than simply competitive in China. Only by optimizing the product and technology combination can the best solution be obtained to meet the increasingly stringent regulations and the escalating needs for mobility. At the same time, internal combustion engines will continue to play an important role in the development of the automotive industry, and they have the potential for further improvement in plenty of areas, such as thermal efficiency, emissions and electrification. Internal combustion engines will undergo an important evolution toward high efficiency through fixed-point operation, system simplification and cost reduction. In addition, the electrification of powertrains, the upgrading and diversification of fuel designs, and the development of intelligent and connected technologies will bring unprecedented opportunities for making the internal combustion engine more efficient, green and clean to better serve society in the near future.

Keywords: internal combustion engine; Power 2.0 era; challenges; potential and opportunities; China

1. Introduction

With the increasing pressure of energy consumption, environmental pollution and climate change on the automotive industry [1,2], the internal combustion engine (ICE), which occupies a dominant position in traditional automotive powertrains, is facing increasing challenges [3]. At the same time, battery electric vehicles (BEVs) have greatly improved and have become the focus in China and all over the world, which poses a great threat to vehicles with traditional internal combustion engines [4]. It has been reported that some countries and regions are introducing policies to ban the sale of internal combustion engine vehicles (ICEVs), and some automakers have proposed plans to stop the production of pure ICEVs at some point [5]. Although some of this information interpreted by the media is inaccurate, the impact on the internal combustion engine industry is obvious. Among this information, the media article "The death of the internal combustion engine", published by The Economist in 2017 [6], caused considerable uproar and the debates around the future of internal combustion engines perplexed stakeholders all over the world. However, is it really the end of the internal combustion engines in transport? What is the future of the internal combustion engines and transport powertrain patterns? Systematical and critical analysis should be conducted to interpret the future of ICEs and prospect the trend of powertrains.

Extensive research has studied the technology potential of ICEs from perspectives of thermal efficiency and alternative fuels [7–13]. Numerous famous scholars, such as Daisho et al., and institutes, such as Oak Ridge National Laboratory (ORNL), conducted extensive research on developing advanced low-emission and fuel-efficient engine technologies, which indicated that the thermal efficiency of internal combustion engines is far from the physical limit, and there is still much space for the improvement in fuel savings [7–11]. As far as emissions are concerned, Zhao systematically discussed the relevant engine technologies in his book, *Technologies for Near-Zero-Emission Gasoline-Powered Vehicles* [12]. Kalghatgi reviewed the current transport fuels and looked ahead to the demand and supply for transport energy. He concluded that high antiknock quality fuels will enable future spark-ignition engines to reach their full potential [13].

Some studies have compared diversified powertrains from various aspects [14–22]. Yu et al. reviewed the energy density of various energy sources and discussed the effect on the payload and driving range of vehicles. They concluded that hydrocarbon fuel will still be a preferable energy source in the transportation sector. Battery electric powertrains are suitable to be applied in light duty vehicles, while fuel cell systems show potential in heavy duty applications. In addition, hybrid vehicles show promise to overcome the environmental impact without sacrificing overall vehicle performance [17]. Zhao et al. appraised the powertrain technologies from the perspectives of energy-saving and new energy strategies, aiming to apply China's fuel consumption regulations, and drew the conclusion that new energy vehicles are not yet capable of competing with ICEVs, and that hybrid electric vehicles (HEVs) are appropriate for the technological transition from conventional vehicles to new energy vehicles [18]. Liu et al. compared the main technology pathways in China and illustrated that ICEs will be simpler in the future as a result of electric motor coupling, and battery electric vehicles (BEVs) and fuel cell vehicles (FCVs) are still faced with multiple challenges [4]. Numerous scholars compared the conventional vehicles and electric vehicles from the perspective of life cycle emissions or cost [19–22]. The results show that the carbon emissions of electric vehicles are highly dependent on the source of electricity and battery production. In addition, electric vehicles exhibit the potential for significant increases in human toxicity, freshwater eco-toxicity, metal depletion impacts and so on [19].

Several experts and scholars also had retorted the "death theory" of ICEs and argued for the importance and potential improvements of ICEs from different perspectives [3,23–25]. The most representative is the editorial of the International Journal of Engine Research (IJER) in 2019, in which 37 experts from the US, Japan and Europe stated the continuing importance of ICEs to meet the world's mobility and power needs [3]. Fossil energy is the only affordable and reliable energy source, especially for poor countries, and transportation infrastructure is largely based on ICEs and would require decades and huge expense to replace. In addition, proposed alternatives, such as electric vehicles, are still facing cost, electric range, security and other limitations nowadays, let alone those powered by renewable energy such as wind and solar energy. A number of professors from Wissenschaftliche Gesellschaft für Kraftfahrzeug- und Motorentechnik e.V. (WKM), an association of prestigious professors from German, Austrian and Swiss universities, also pleaded that a ban on ICEs would have negative effects on fighting climate change. The role of combustion engines as the driving force for mobility, freight transport, and mobile machinery can be complemented, but not replaced. Combustion engines are ideally suited for alternative synthetic and biogenic fuels and will have a long-lasting need [23]. Kalghatgi also concluded that the life cycle greenhouse gas (GHG) of battery electric vehicles (BEVs) would be worse than that of ICEVs if the energy used for battery production and electricity generation is not sufficiently decarbonized, and air quality in terms of particulates, nitrogen oxides and sulfur dioxide would get worse if coal is used for power generation. Transport will be powered by ICEs for decades to come, especially for commercial transport, and alternatives are unlikely to make up much more than 10% of the total transport energy demand by 2040 [25].

However, most analyses have focused on the specific technologies of ICEs or comparisons between different powertrains. There is little literature which assesses the future of ICEs from the aspects of technology, industry and market comprehensively and states the logical relationship between various powertrains clearly. What is more, few studies have taken the Chinese market and some key factors, such as the diversification of fuel designs and intelligent and connected technologies, into consideration specifically. Undoubtedly, the automotive industry is undergoing unprecedented restructuring, and one of the main driving forces is the energy revolution [13,23–25]. Furthermore, the demand for energy is an ongoing topic, and the history of energy utilization has always been a process of continuous progress and alternating growth. Therefore, determining the future of vehicle powertrains is not a simple tradeoff problem that can be solved by sweeping approach, and a comprehensive analysis of the future of ICEs is needed.

To fill these research gaps, this paper attempts to present a thorough analysis and objective interpretation of the challenges, potential, advantages and opportunities for internal combustion engines considering complex factors and the relationships between diversified powertrains during this historic period of industrial transformation. Furthermore, the analysis not only considers the industrial aspects of internal combustion engines, which have a long history of more than 100 years, but also discusses the future roadmap of the entire automotive industry, aiming at providing a reference and picture for the future sustainable development of internal combustion engines and the whole automotive industry. This paper is organized as follows. Section 2 analyzes the present challenges for ICEs from perspectives of regulations and technologies. Sections 3 and 4 analyze the potential, advantages and opportunities of ICEs respectively. Section 5 presents the prospects for diversified powertrain technologies in China. Section 6 draws conclusions from the whole study and proposes recommendations for the government and manufacturers.

2. Challenges for Internal Combustion Engines

2.1. Increasingly Stringent Fuel Consumption Regulations

Currently, with the increasing ownership of vehicles globally, the petroleum consumed by automobiles is increasing daily and countries have continued to upgrade laws and regulations to limit fuel consumption. According to the latest data, China's crude oil imports reached 505.72 million tons in 2019, and its dependence on foreign oil has risen to 70.8%, far exceeding the international energy security warning line of 50% [26,27]. Currently, oil consumption by the automotive industry accounts for approximately one half of the total oil consumption in China [28]. For this reason, China's fuel consumption regulations have been tightened continuously. Taking the corporate average fuel consumption (CAFC) regulation as an example, the fuel consumption target of the fourth phase is 5 L/100 km and it will be reduced to 4 L/100 km in the fifth phase (MY 2020–2025) and then to 3.2 L/100 km in the sixth phase (MY 2025–2030) [18,29]. Increasingly stringent fuel consumption regulations not only bring about a significant increase in technology costs but also pose a serious practical challenge to the thermal efficiency of internal combustion engines [30]. It is increasingly difficult to comply with the standards by purely optimizing internal combustion engines.

2.2. Increasingly Upgraded Environmental Standards

Global environmental protection pressure is becoming increasingly serious, and many cities are currently suffering from particulate matter and haze [31]. Environmental protection is not only an important development strategy in the long term but also an urgent political task in the near future. On the one hand, for the automotive industry to reduce harmful gas and particulate matter emissions effectively, China has been accelerating automotive emission regulations upgrades. The upcoming "Limits and measurement methods for emissions from light-duty and heavy-duty vehicles (CHINA 6)" is regarded as one of the most stringent emission regulations in the world. It not only extends the basic content of European standards but also adds some assessment indicators from American standards, and many cities will implement it ahead of schedule [32,33]. More advanced postprocessing technology must be added to ICEVs to make it possible to meet the new standard, which also brings about a significant increase in cost [7]. In addition, to alleviate traffic congestion, regions and cities are increasingly implementing or planning to implement policies to limit traffic and even the sale of ICEVs based on environmental considerations. On the other hand, carbon dioxide emissions have become the focus of global attention because of climate change. As the largest carbon emitter, China made an official commitment about carbon emissions reduction in the Paris Agreement [34]. However, it is also a tough problem for traditional ICEVs. These increasing requirements have resulted in great challenges regarding the survival of ICEVs.

2.3. Challenges from New Technologies

With the rapid development of new energy and hybrid vehicle technologies, internal combustion engines are no longer the only option for vehicle powertrains. Therefore, regardless of whether ICEVs can meet future fuel consumption and environmental regulations, the use of increasingly complex internal combustion engines is no longer the best commercial option from the perspective of the technology economy. NEVs driven by electrical energy not only help to reduce oil dependence and harmful pollution but also have no emissions in the use stage; thus, they have been highly valued globally. At the same time, the potential of renewable energy generation and hydrogen production is enormous for countries establishing low-carbon energy systems, which will also provide an important driving force for the development and industrialization of electric powertrains. In the future, with the increasing number of electric vehicles and the gradual maturity of V2G (vehicle-to-grid) technology, EVs will serve as energy supply and storage devices for the peak shaving and valley filling of the electricity grid. Especially in China, the development of NEVs has become a national strategy. The government has issued many industrial policies, such as the NEV credit policy, which promotes the marketization of NEVs and requires automakers in China to produce a certain proportion of NEVs [35–37]. Some experts hold the opinion that NEVs will soon reach the tipping point and achieve high-speed development [38,39], which means that a dramatic change will occur in the automotive power source. The rapid progress of electric technologies and the maturity of the related infrastructure and business models will pose great challenges to the survival of internal combustion engines.

3. Potential of Internal Combustion Engines

Despite severe challenges, the potential of internal combustion engines should not be underestimated, and it is analyzed from the following four perspectives:

3.1. The Thermal Efficiency of Internal Combustion Engines Is Far from the Limit

The peak thermal efficiency of engines plays a determinate role in reducing fuel consumption and carbon emissions. According to the public data of various automakers in China, the highest peak thermal efficiency of gasoline engines in mass production has reached 41%, and in laboratory tests, it is higher than 50%. The peak thermal efficiency of diesel engines in mass production has reached 50%, and in laboratory tests, it is higher than 55%. According to the research of Japan Science and Technology Agency, for spark ignition gasoline engines, the peak effective thermal efficiency can be increased to 50.35% by the combination of exhaust gas recirculation (EGR), lean burn, lean boost, long stroke, low friction, high T/C efficiency, tumble + H_2 addition, and heat insulation. For compression ignition gasoline engines, the peak effective thermal efficiency can be increased to 51.05% by the application of multiple premixed compression ignition (MPCI), boost + EGR, combustion system optimization, and Miller cycle engines with low friction, low cooling heat loss and high compression ratios (CR = 18) [8]. Thus, the thermal efficiency of internal combustion engines is far from the physical limit, and there is still much room for improvement in fuel savings.

3.2. Internal Combustion Engine Vehicles Can Reach Near-Zero Emissions

At present, the technology of ICEVs can achieve near-zero emissions of nitrogen oxides and particulates at lower and lower cost [12]. In the future, through further optimization of internal combustion engines by the electrification of the power system, the deployment of advanced postprocessing technologies, and sustainable decarbonization strategies (such as CO_2 capturing and recycling technologies), ICEVs are expected to achieve zero pollution. That is, the emission of pollutants can be reduced to a level that does not damage the environment or negatively impact air quality. The exhaust emissions of the vehicles are cleaner than the air. According to the calculation of the real-time air quality detection model in Stuttgart, Germany, the total pollution of vehicles meeting the European 6d-TEMP standard is approximately 0.2–0.5 $\mu g/m^3$ [40], which is almost negligible. The technology path of ICEVs to meet the more stringent emission standards in the next phase is clear and feasible, and the main factor that needs to be considered is cost.

3.3. The Carbon Emissions of Internal Combustion Engine Vehicles Are not Necessarily Higher than Battery Electric Vehicles

The comparison of carbon emissions of different vehicles must be based on the calculation over the whole lifecycle rather than only the usage stage. Electricity is a secondary energy source. Although the carbon emissions of electric vehicles are zero in the usage stage, the electricity from different sources produces various levels of carbon emissions. In addition, carbon emissions from vehicle production and recovery should also be considered. Extensive research has evaluated and compared the carbon emissions of different vehicles in China, especially battery electric vehicles [15,16,20–22,41–44]. According to these studies, some consensuses have been reached gradually in recent years. On the one hand, the carbon emissions of electric vehicles with long ranges are not lower than those of gasoline vehicles from the whole lifecycle perspective [41–45]. Figure 1 shows the equivalent carbon emissions of different vehicles in the Chinese market in 2017 [43]. According to the results, electric vehicles with medium and short driving ranges certainly have lower carbon emissions than gasoline vehicles, but it is still difficult to achieve the level of strong HEVs. The carbon emissions of electric vehicles may be higher if regional and seasonal differences are considered [44]. In addition, in the production stage, the carbon emissions of electric vehicles are significantly higher than those of gasoline vehicles because the carbon emissions of battery manufacturing are much higher than those of internal combustion engines [21,22,43].

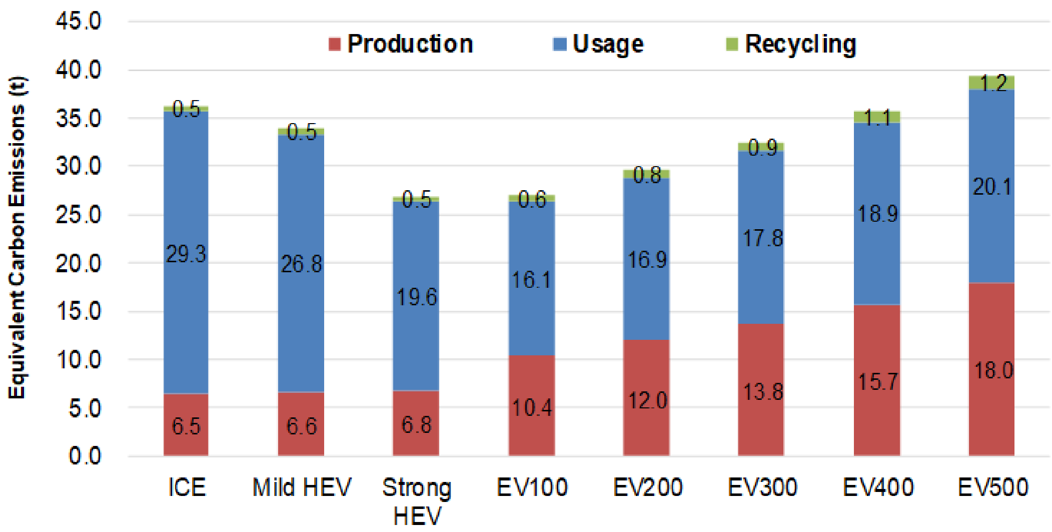

Figure 1. Equivalent carbon emissions of different vehicles in China [43].

Of course, the above results, which are mainly affected by two key factors, are not invariable. One factor is the increase in the battery energy density, and the other is the cleanliness of external electricity [22,43–45]. China's energy structure has been dominated by coal-fired power, which is a considerably high-carbon energy, and the structure is hard to completely transform in the short term [43,44]. After all, the introduction and effective use of renewable energy cannot be achieved overnight. In this case, it is impossible to achieve a low-carbon society by a "de-internal combustion engine". Of course, the advantages of electric vehicles will become increasingly clear in the long run, but in the near future, it is harmful to the low-carbon development of the industry to focus only on the development of electric vehicles and ignore the technology development of internal combustion engines.

3.4. Changes Brought by Electrification

In fact, the internal combustion engine is an important participant in this round of the automotive revolution rather than a bystander. Through the electrification of traditional powertrains, the form, direction and capability of internal combustion engines will be changed greatly. In the past, the internal combustion engine had to work in a wider range to satisfy complex working conditions. To improve thermal efficiency, various technologies were needed to expand the optimal working area, which also brought about a significant increase in cost. Furthermore, increasing demands will inevitably lead to more complex systems and higher costs until the physical limit of the thermal efficiency of internal combustion engines is reached. In addition, the final thermal efficiency of internal combustion engines is the average value of each working mode, and its maximum thermal efficiency has not been effectively reflected [11]. Therefore, it will be increasingly difficult for ICEVs to meet future fuel consumption and emission regulations.

However, the internal combustion engine can gain potential with the help of electrification [3]. In the future, the internal combustion engine will be effectively combined with the electric motor in the powertrain [14]. Due to the coupling of ICE, battery and motor, battery charging and discharging can be used to adapt to different working conditions. Then, internal combustion engines can always work in narrow and fixed thermal efficiency ranges, and they can even work only at the maximum thermal efficiency point [46]. In this way, the internal combustion engine will be greatly simplified, and the cost will be significantly reduced, which can compensate for the increased cost introduced by the battery and motor. Essentially, this route can achieve variable power output by means of electromechanical coupling, i.e., ICE + α (where α represents motor), as shown in Figure 2.

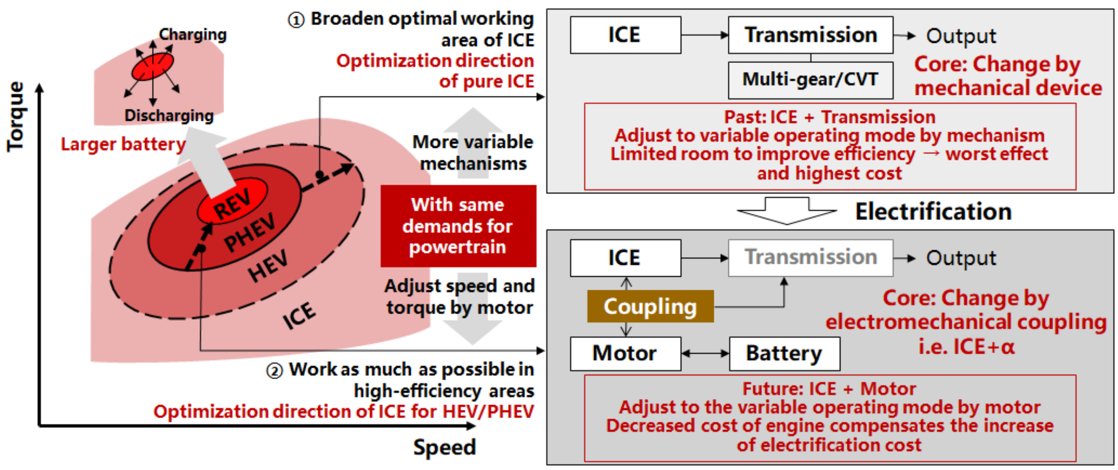

Figure 2. Electrification of internal combustion engines.

The electrification of the traditional internal combustion engine will be a gradual process that will be accelerated as regulations become more stringent and the electrification technology continues to progress. As a result, enterprises will optimize internal combustion engines according to the requirements of various electromechanical coupling powertrains, such as HEVs, plug-in hybrid electric vehicles (PHEVs) and range-extended electric vehicles (REVs). Of course, automakers also need to evaluate the tradeoff between the battery and motor cost increases and the cost savings of internal combustion engines. Different automakers will have different choices at different times and with different technical bases. However, the internal combustion engine will still undergo a great change, which will revitalize the internal combustion engine and greatly expand the potential for energy savings, emission reduction and carbon reduction. In addition, to fulfill the requirements for electromechanical coupling, much research is still needed on the internal combustion engine.

4. Advantages of Internal Combustion Engines and Future Opportunities

Internal combustion engines not only have great potential but also have many advantages that can help electric vehicles to overcome their shortcomings. First, the main barriers of electric vehicles are the battery cost and driving range. The battery cost cannot be reduced in the short term, and in the long run, it will be affected by the relationship between the supply and demand of raw materials [47,48]. However, there will be a sharp increase in costs by adding batteries to increase the driving range without a mature infrastructure. In addition, even if the cost of batteries is significantly reduced in the future, a large number of batteries is still unfavorable for energy conservation and carbon reduction because batteries are heavy and the production of batteries produces heavy carbon emissions. In this case, if we can fully tap the potential of internal combustion engines and coordinate the battery and motor, then we can effectively control costs and easily resolve range anxiety.

Second, there are still significant limitations to electric vehicle usage, and these limitations are determined by the battery properties and are difficult to solve comprehensively. Generally, when the temperature is below −15 degrees Celsius, the performance of electric vehicles declines sharply. In China, the average temperature during the day in approximately 5% of the territory is below −15 degrees Celsius in winter, and approximately 35% of the territory is below −15 degrees Celsius at night in winter [49,50]. There is no doubt that electric vehicles in these areas face additional challenges. In contrast, the internal combustion engine has strong adaptability and can operate normally in extreme conditions such as severe heat and cold. In areas where batteries are difficult to adapt, it is better to make full use of the advantages of internal combustion engines to ensure the operation of electric vehicles through the effective combination of internal combustion engines and batteries. In some areas where it is particularly cold all year, it is not suitable to promote electric vehicles. The use of ICEVs can meet the needs of transport. In fact, the high-reliability application of internal combustion engines in some harsh conditions is far from being replaced by other technologies. Even if new technologies can be found to meet these conditions, it will take a long time to tackle various problems.

Finally, after more than 100 years of development, the internal combustion engine has a complete industrial chain, a clear division of labor and profound accumulation. Because of the solid industrial foundation, it is difficult to replace the internal combustion engine, which is highly reliable and inexpensive—especially in countries such as China, which has a vast territory [3]. Given the varied natural conditions and uneven economic development, it will be difficult to replace internal combustion engines. In addition, as the most complex powertrain in automobiles, the manufacture of internal combustion engines involves a large number of key technologies, including process and material technologies. These technologies have effectively supported the continuous progress of the ICEVs in the past and will continue to support the electrification of the automotive powertrain in the future.

In addition, extensive studies and predictions have been conducted on the future market share of different powertrains, most of which, as Figure 3 shows [51–57], have indicated that the global market share of plug-in electric vehicles (PEVs) will be approximately 40% in 2035 and 50–60% in 2050, and passenger vehicles with ICE as a partial or whole powertrain will still account for about 80% of the global passenger vehicle market in 2035. Even so, most studies have not taken plenty of future opportunities for ICEs into consideration.

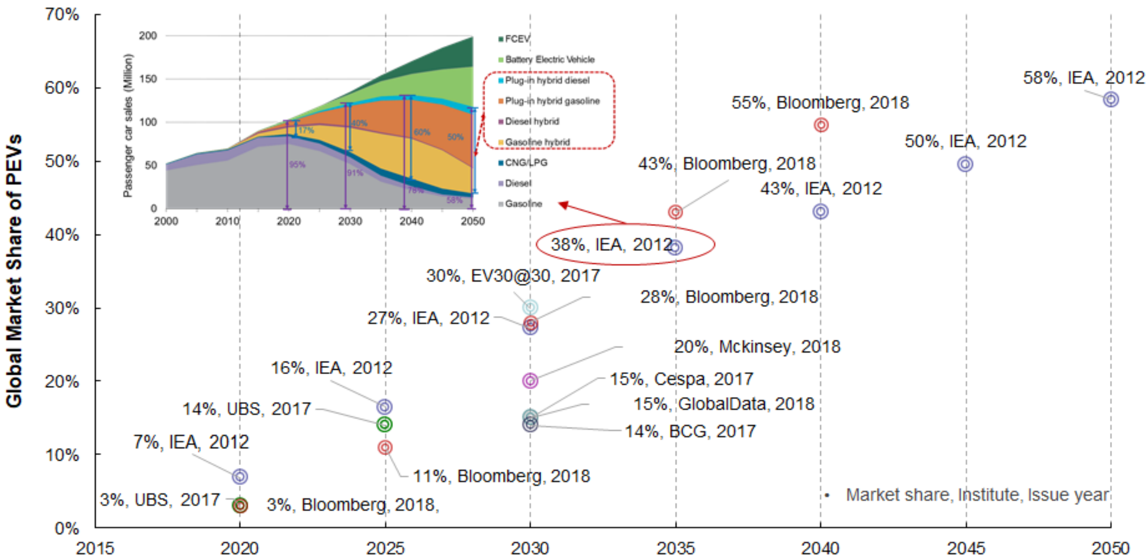

Figure 3. Overview of predictions on global market share of plug-in electric vehicles (PEVs).

In fact, while facing severe challenges, internal combustion engines are also facing unprecedented optimization opportunities, which will pose a great impact on the future pattern of vehicle powertrains.

- Opportunity for the electrification of powertrains. The great potential of improving the thermal efficiency of internal combustion engines will be fully realized after they are effectively combined with batteries and motors. The current peak thermal efficiency of the internal combustion engine still has room for improvement by more than 10%. By narrowing the high thermal efficiency range of the internal combustion engine and running at a single point, the comprehensive thermal efficiency can be further improved by more than 20% (absolute value). In this process, a variety of variable mechanical technologies will gradually be eliminated, which will decrease the cost. With the electrification of the automotive powertrain, the internal combustion engine will play an important role as a part of the electromechanical coupling system for a long time. Thus, the existing mode, performance requirements and development concept of internal combustion engines will change fundamentally. In the future, internal combustion engines will evolve toward high efficiency, fixed operating conditions, simplicity and low cost, and they will be closely integrated with high-efficiency motors, transmissions and batteries, which will bring new development opportunities to the entire industry.
- Opportunities for the upgrade and diversification of fuels. Fuel upgrading and diversified use are also important trends, and the internal combustion engine is an important part of the global fuel revolution. After more than 100 years of development, the internal combustion engine is technically mature enough to use almost any kind of fuel effectively through the coordinated improvement and control of the combustion process and fuel characteristics. In the future, through further optimization and intelligent control of the combustion system and modified fuel designs, increasingly more types of fuel, especially carbon-neutral, low-octane and renewable-energy fuels, will be used by internal combustion engines, making them more efficient, green and clean and prolonging their life.
- Opportunity for the development of intelligent and connected technologies. At present, automobiles are being developed toward low-carbon emissions, networking and intellectualization, and the application of intelligent networking technology is not limited to the vehicle level. The automotive powertrain can achieve more effective and optimized control with the help of intelligent networking technologies. Obviously, this is not only conducive to the optimal operation of electric powertrains but is also urgently needed for the complex electromechanical coupling required to incorporate an internal combustion engine. In the future, the powertrain will acquire real-time vehicle and traffic

environment information through the network and implement highly intelligent and precise control based on the perception and prediction of the internal and external states of the vehicle, which will directly minimize its energy consumption and emissions.

5. Prospects for Powertrain Technologies in China

Because of the challenges and also the potential and opportunities for ICEs, the automotive industry is entering an energy diversification era where ICEVs, HEVs, PHEVs, REVs, BEVs and FCVs will coexist for a long time, as shown in Figure 4 [4,18,51,58]. They will have different market shares and gradually develop over time. The various types of powertrains have their own advantages and disadvantages. Regulations will be the most important factor promoting this trend. Because of the high incremental cost of technology, it will be difficult to meet the fuel consumption target of 4 L/100 km in China by simply relying on internal combustion engines. ICEVs will gradually approach the application limit around the year 2025, after which HEVs will have a large market share. Almost all internal combustion engines will match the battery and motor system to form a hybrid form of "ICE + α". With the help of the battery and motor, the working range of the internal combustion engine will be adjusted to improve efficiency and reduce fuel consumption. With the further strengthening of regulations, HEVs will also face a fuel-saving limit, and PHEVs and REVs will grow rapidly. In this process, the batteries of PHEVs will become larger to meet the increasingly stringent regulations. Furthermore, internal combustion engines will evolve in a new design direction to further improve the comprehensive thermal efficiency through working in fixed ranges and even fixed points, and the system costs will be reduced by simplifying the design. For PHEVs, the cost reduction achieved by simplifying the design of the internal combustion engine compensates for the cost increase brought about by the introduction of large batteries to some extent. For REVs, the introduction of an internal combustion engine will address the tradeoff between the driving range and battery cost [59,60]. Due to the increasingly stringent laws and regulations, the proportion of BEVs and FCVs will also increase steadily. The speed of BEVs and FCVs depends not only on the technology but also on the pace of cost reduction and infrastructure construction [15,61]. The PHEVs and REVs will finally withdraw from the market after the cost of batteries has dropped dramatically and the charging infrastructure has been fully popularized.

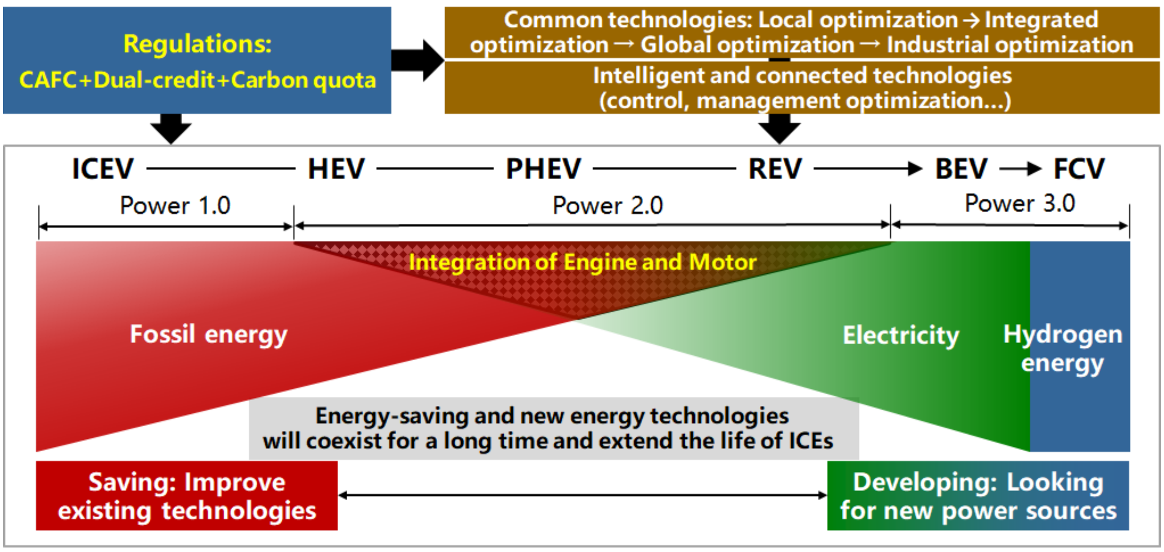

Figure 4. Forecast of the technology trend of powertrains in China.

Although there will be fewer and fewer vehicles driven by internal combustion engines alone, the internal combustion engines will not be withdrawn from the historical stage. The market share of HEVs, PHEVs and REVs that are equipped with internal combustion engines will gradually expand.

In the foreseeable future, there will still be far more automobiles with internal combustion engines than those without them. Therefore, although internal combustion engines in automotive powertrains have declined in dominance, they are still vital. The country, industry and academia should have a clear understanding of the potential advantages of internal combustion engines and the industrial basis required. Internal combustion engines have played and will continue to play an important role in the sustainable development of automobiles, and this fact should not be denied. From a national perspective, the abandonment of the internal combustion engine industry would be a huge waste of social resources and would have a negative impact on the national economy. Therefore, it is necessary to be cautious in introducing policies to restrict the development of internal combustion engines and automobiles nationwide. Similar measures taken by other countries according to their own conditions should also be fully evaluated. Otherwise, the aim of saving fuel and reducing carbon emissions will not be achieved immediately, and inappropriate measures will affect the healthy development of the automotive industry and many related industries. Automakers should consider the different technologies, product portfolios, brand price bearing capacities and development periods. It should be emphasized that automakers may have different perspectives and strategies based on their situations and interests regarding the future development of various power technologies. Decision-makers and researchers should evaluate automotive powertrain technologies systematically, comprehensively and objectively over the whole product lifecycle from the perspective of technology maturity, cost, progress speed, key investments, industrial support, policies and other dimensions to guide the healthy and sustainable development of the industry.

In fact, internal combustion engines will make the electromechanical coupling system play a more important role in the automotive industry. Conversely, the progress of electrical technology has also broadened the possibilities for internal combustion engines. Therefore, the relationship between internal combustion engines and electric powertrains is complementary rather than separated and exclusive. We must recognize that the electrification of automotive powertrains is an irreversible trend. The direction of technical research and industrial applications for internal combustion engines must be adjusted to maximize the value in the new era. At the same time, researchers of NEVs should not underestimate the importance of internal combustion engines. They should understand that there is still a long way to go for batteries to reach maturity. Therefore, NEVs should adopt the internal combustion engine to supplement their own shortcomings, provide products with better cost performance and consumer experience and gain time for their own development. In short, there is absolutely no need for the two sides to argue and deny each other, nor for them to stand in line and be hostile to each other. In the changeover period from old technologies to new technologies, we should not only consider the development of new innovations with an open mind but also see the previous developments with an objective attitude. Most importantly, both sides must learn from each other and make up for their weaknesses.

6. Conclusions

This paper aims to systematically and critically appraise the challenges, potential, advantages and opportunities for internal combustion engines during this historic period of industrial transformation. The analysis not only considers the industrial aspects of internal combustion engines, but also discusses the future powertrain roadmap of the entire automotive industry, aiming at providing a reference and picture for the future sustainable development of internal combustion engines and the whole automotive industry. Our analysis suggests that although they are facing severe challenges, internal combustion engines still have great potential and opportunities in the future. Internal combustion engines will continue to play an important role in the development of the automotive industry and undergo an important evolution toward high efficiency, system simplification and cost reduction, and also benefit from the electrification of powertrains, upgrading and diversification of fuel designs, and rapid development of intelligent and connected technologies.

The automotive "Power 1.0 era" has been dominated by internal combustion engines for almost 100 years, and the "Power 2.0 era", where multiple powertrains coexist, is approaching. Looking toward the future, humans may eventually enter the "Power 3.0 era", which will be dominated by pure electric powertrains. However, this is a long-term goal, and it is likely that the mainstream technology at that time will not be not today's lithium battery system but solid-state batteries, hydrogen fuel cells, or other new types of batteries that are still unknown [62,63]. In the development of energy-efficient and new energy technologies, the "saving" and "developing" of energy should both be emphasized. The relationships of various powertrains are complementary rather than competitive. Only by optimizing the product combination can we obtain the best solution to meet the increasingly stringent regulations and escalating travel needs. In addition, as an indispensable part of various electromechanical coupling systems, internal combustion engines still have great potential to continue to play an important role in the development of the automotive industry. This also means that the internal combustion engine will undergo a major transformation and will be developed toward a new direction of fixed-point efficiency, system simplification and cost reduction in the future.

Therefore, both the government and manufacturers must attach great importance to the optimization and upgrading of internal combustion engines. On the one hand, we must make full use of the industrial foundation, the advantages and technical potential of internal combustion engines to scientifically formulate short-term, medium-term and long-term technology routes by combining different power forms, in view of their evolution direction. On the other hand, we should also provide basic support and continuous investment to excavate the extensive potential of internal combustion engines. In addition, practical measures should be taken to engage people with the internal combustion engine industry and to prevent brain drain in this industry. Only in this way can we effectively support the sustainable development of the automotive industry.

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Abbreviations

AER	All-Electric Range
BEV	Battery Electric Vehicle
CAFC	Corporate Average Fuel Consumption
CAFE	Corporate Average Fuel Economy
CR	Compression Ratio
EGR	Exhaust Gas Recirculation
EV	Electric Vehicle
FCV	Fuel Cell Vehicle
GHG	Greenhouse Gas
HEV	Hybrid Electric Vehicle
ICE	Internal Combustion Engine
ICEV	Internal Combustion Engine Vehicle
IJER	International Journal of Engine Research
MIIT	Ministry of Industry and Information Technology
MPCI	Multiple Premixed Compression Ignition
NEDC	New European Driving Cycle
NEV	New Energy Vehicle

NHTSA	National Highway Traffic Safety Administration
OEM	Original Equipment Manufacturer
PC	Passenger Car
PEV	Plug-in Electric Vehicle
PHEV	Plug-in Hybrid Electric Vehicle
PM	Particulate Matter
REV	Range-extended Electric Vehicle
V2G	Vehicle to Grid
WKM	Wissenschaftliche Gesellschaft für Kraftfahrzeug- und Motorentechnik
ZEV	Zero-emission Vehicle

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