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Study on the Application of Hydrogen Fuel Cells in Passenger Cars and Prospects

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Abstract. The increasing demand for clean and sustainable energy sources has driven extensive research and development in the field of hydrogen fuel cell technology. This article provides an in-depth analysis of the advancements in hydrogen fuel cell technology and its potential application in passenger cars as a widely available, clean, and efficient energy source. By reviewing the current status of hydrogen fuel cells and national policies governing their implementation, this study aims to shed light on the development characteristics of China's hydrogen fuel cell industry, while also drawing comparisons with international hydrogen fuel cell policies and applications. Additionally, the article evaluates the performance of existing hydrogen fuel cell passenger cars in the market and proposes the application of future cutting-edge technologies to further enhance their capabilities. Through meticulous paraphrasing and enrichment, this scholarly work offers a comprehensive overview of hydrogen fuel cell technology, delves into the intricate landscape of the industry, and explores the promising prospects for its continued advancement. By encompassing a wide array of aspects related to hydrogen fuel cell technology, this article contributes to the academic discourse surrounding sustainable and efficient energy solutions for the transportation sector.

1 Introduction

Of all the mineral fuels and commercial energy sources worldwide, about 91% are derived from coal and oil, of which the proven reserves of oil amount to only 1.4 trillion tons, enough for about 41 years of extraction. In the coming decades, the international community will confront a pressing energy predicament resulting from the exhaustion of oil reserves. Furthermore, coal and natural gas reservoirs are encountering comparable challenges, while mineral resources are not a viable long-term solution to fulfill humanity's energy needs [1]. Consequently, a global quandary regarding energy supply looms on the horizon. At the same time, the environmental problems caused by the burning of mineral resources cannot be ignored, for example, emissions from burning coal, including organic matter, sulfates, and black carbon, are the main components of PM2.5 pollutants. These pollutants can cause air pollution, which in turn affects human health, lowers resistance, and increases the incidence of disease. Compared with the fossil energy era represented by coal and oil that opened the first two energy revolutions, the new global energy revolution is more revolutionary, presenting a series of new features and trends different from the fossil energy era. Among the many emerging energy technologies, hydrogen energy technology has achieved rapid development and breakthroughs in recent years, supporting the development of the hydrogen energy industry as an important direction for energy transformation. In recent years, hydrogen fuel cells have become a key focus of research, development, and demonstration promotion in the automotive industry, and the hydrogen fuel cell industry is now facing a new stage of rapid commercialization from experimental research and development.

Compared to other new energy sources, hydrogen has many advantages, mainly reflected in the following aspects [2]:

1. Good environmental friendliness. Hydrogen fuel cells only emit water and do not produce other harmful substances, making it highly environmentally friendly as a vehicle. The promotion of this type of vehicle plays a crucial role in environmental protection.

2. Almost zero emissions. Hydrogen fuel cells do not produce greenhouse gas emissions, which can effectively reduce pollution and improve air quality.

3.No noise pollution. Compared with renewable energy sources such as wind power, which produce noise pollution during the generation process, hydrogen fuel cells have excellent quiet performance. Therefore, compared with traditional internal combustion engine vehicles, hydrogen fuel cell vehicles are quieter.

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4. Short refueling time for hydrogen gas. The hydrogen fuel cell power unit refuels quickly, comparable to traditional internal combustion engine vehicles and faster than pure electric vehicles.

5. The range of hydrogen fuel cell vehicles is the same as that of fossil fuel vehicles. Unlike electric vehicles, hydrogen fuel cell vehicles are not significantly affected by external temperatures and do not reduce their driving range in cold weather.

6. High comfort for passengers. Compared with traditional vehicles, hydrogen fuel cell vehicles have advantages such as high stability, low noise, and excellent comfort.

Therefore, a deep analysis of the application of hydrogen fuel cells is crucial for their industrial development. In this article, we first review the current status of hydrogen fuel cells and national policies and analyze the development characteristics of China's hydrogen fuel cell industry by comparing hydrogen fuel cell policies and applications at home and abroad. Finally, we compare the performance of existing hydrogen fuel cell passenger cars on the market and propose the possible application of future cutting-edge technologies.

2 Fuel Cells

2.1 Types of fuel cells

There are many types of fuel cells, and they are usually distinguished according to the type of cell electrolyte: alkaline fuel cells, phosphoric acid fuel cells, molten carbonate fuel cells, solid oxide fuel cells, proton exchange membrane fuel cells, etc. [3].

As shown in Figure 1, the operating temperatures of fuel cells are very different, and they can be distinguished according to the operating temperature. Alkaline fuel cells and proton exchange membrane fuel cells have an operating temperature of no more than 200°C and belong to low-temperature fuel cells; phosphoric acid fuel cells are medium-temperature fuel cells and their operating temperature is between 200-750 °C, and solid oxide fuel cells belong to high-temperature fuel cells and their operating temperature is more than 750 °C [3]. Therefore, in an environment such as passenger cars, where occupant comfort and vehicle thermal management capabilities need to be considered, fuel cells that operate at too high a temperature are clearly inappropriate. Therefore, for this type of passenger car environment, only proton exchange membrane fuel cells and phosphoric acid fuel cells can be considered. Next, the electrolyte types of these two fuel cells will be analyzed and compared.

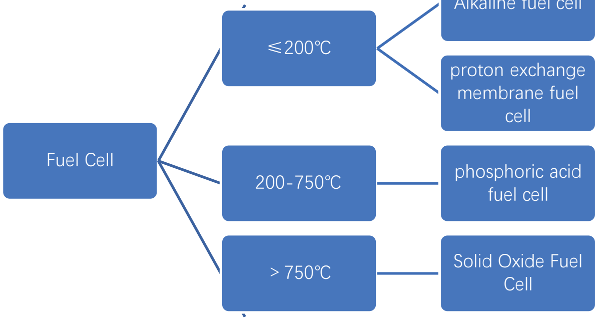

Fig 1. Types of fuel cells (picture credit: original)

The electrolyte of alkaline fuel cells is usually sodium hydroxide solution, because their fuel cell electrolyte is alkaline, the permeability of the fuel will be lower and the current density of the electrolyte will be higher. Usually, platinum, a precious metal, is used as the catalyst, so the cost is higher. But its operating temperature is lower. Generally speaking, it has relatively good working performance at 80 ºC, and it has the characteristic of fast corresponding speed [4]. However, its energy density is low, compared with the proton exchange membrane fuel cell under the same operating temperature, its energy density is only a tenth of the proton exchange membrane fuel cell. Because its electrolyte is alkaline, it has certain requirements for oxidant and needs pure oxygen as an oxidant. And if the oxygen is impure, the actual lifetime is affected by impurities in the air such as carbon dioxide. Therefore, although its operating temperature is better, its cost as well as operating conditions are high, and its energy density is not high enough for commercial applications.

Compared to the harsh conditions of alkaline fuel cells, proton exchange membrane fuel cells with high energy are currently the most promising for electric vehicle applications. Inside the fuel cell, protons pass from the anode through the exchange membrane to the cathode, thus forming a circuit with the external circuit. Its operating temperature is low, typically below 100 degrees Celsiusand the fuel is environmentally friendly, emitting products of water and water vapor. The energy conversion rate is high [5]. And the power can be flexibly adjusted according to reality, without noise during operation and with a fast start-up rate. The characteristics of each fuel cell are shown in Table 1.

Table 1 Comparison of the main properties of each fuel cell

	Alkaline fuel cell	Proton exchange membrane fuel cells	Phosphoric acid fuel cell	Solid Oxide Fuel Cells
Operating temperature	≤200°C	≤200°C	200°C-750°C	≥750°C
Usual fuel	Hydrogen	Hydrogen, natural gas, methanol, etc.	Hydrogen, natural gas, methanol, etc.	Hydrogen, natural gas, methanol, gas

Catalyst	Platinum	Non-precious metals	Platinum	Non-precious metals
Features	Low energy density and requires pure oxygen as oxidant	High energy conversion efficiency and fast start-up rate.	The cost is lower compared to alkaline fuel cells, but the operating temperature is high.	The actual power of the single cell is limited and can only produce 1V.

The main working principle of the proton exchange membrane cell is introduced, as shown in Figure 2 below. During operation, the anode catalyst induces the fuel to dissociate into hydrogen ions, which then cross the proton exchange membrane to the cathode and release electrons, doing work on the external circuit; the cathode catalyst reduces the oxidizer and synthesizes water with hydrogen ions and electrons.

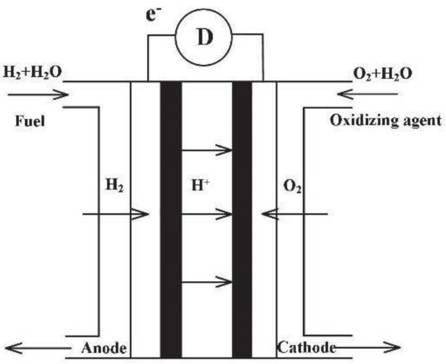

Fig. 2. Proton Exchange Membrane Fuel Cell Schematic (Picture credit: Original)

The electrochemical reactions of the proton exchange membrane fuel cell are as follows:

$$\text{Anode:}\ 4H^+ + 4e^- = 2H^2 \qquad (1)$$

$$\text{Cathodes:}\ O^2 + 4H^+ + 4e^- = 2H_2O \qquad (2)$$

$$\text{Total response}: 2H_2 + O_2 = 2H_2O + Calories \quad (3)$$

For an application environment like passenger cars, for fuel cells, compared to other types of fuel cells, proton exchange membrane fuel cells are currently the most suitable fuel cells for passenger car applications.

2.2 Efficiency advantages of fuel cells

The internal combustion engine is generally around 30% of the efficiency of the current mass-produced automotive internal combustion engine because of the influence of the Carnot cycle. The higher energy utilization efficiency of fuel cell is one of its biggest advantages.

In practice, the maximum amount of energy in a fuel that can be converted into electrical energy is the Gibbs free energy [6]:

$$H_2 + 1/2O_2 = H_2O(l)\Delta_f G_l = -237.13kJ/mol = -118.6kJ/g \qquad (4)$$

$$H_2 + 1/2O_2 = H_2O(g)\Delta_f G_g = -228.57kJ/mol = -114.3kJ/g \qquad (5)$$

Theoretical maximum energy conversion efficiency of hydrogen fuel cell under standard condition:

$$\eta_{el,max,HHV} = \frac{-\Delta_f G_l}{HHV} = 0.83 \qquad (6)$$

$$\eta_{el,max,LHV} = \frac{-\Delta_f G_g}{LHV} = 0.95 \qquad (7)$$

After considering the internal resistance generated by various phenomena of activation polarization and mass transfer polarization inside the fuel cell, the actual effective output efficiency of the fuel cell is calculated based on the voltage at which the fuel cell actually operates [6]:

$$\eta_{el,HHV} = \frac{Electricity\ output}{Input\ energy} = \frac{Electrical\ power\ output}{Energy\ input\ per\ unit\ time} = \frac{UI}{HHV \cdot \frac{dn}{dt}} = \frac{UzF\frac{dn}{dt}}{HHV \cdot \frac{dn}{dt}} = \frac{U}{HHV/zF} \qquad (8)$$

$$E^0_{HHV} = \frac{HHV}{zF} = \frac{\frac{285.85kJ}{mol}}{2\times\frac{96485C}{mol}} = 1.48V \qquad (9)$$

$$E^0_{LHV} = \frac{LHV}{zF} = \frac{241.82kJ/mol}{2\times 96485C/mol} = 1.25V \qquad (10)$$

So the power generation efficiency of the fuel cell can be simplified as:

$$\eta_{el,HHV} = \frac{0.6}{1.48} = 0.41 \qquad (11)$$

$$\eta_{el,LHV} = \frac{0.6}{1.25} = 0.48 \qquad (12)$$

$$\eta_{el,HHV} = \frac{0.8}{1.48} = 0.54 \qquad (13)$$

$$\eta_{el,LHV} = \frac{0.8}{1.25} = 0.64 \qquad (14)$$

From the above calculation, it can be obtained that the energy conversion efficiency of the fuel cell is high. And for the energy module applied in passenger cars. Basically, the energy conversion efficiency of the hydrogen fuel cell is similar to that of an accumulator battery. The biggest advantage of hydrogen fuel cell compared with the storage battery is the fuel refilling speed, and hydrogen fuel cell can generally refill the required energy within a few minutes.

2.3 Current Research Status of Proton Exchange Membrane Fuel Cells

The main commercial problem of proton exchange membrane hydrogen fuel cells (PEMFC) at this stage is the high price, and the main problem facing the commercialization of hydrogen fuel cell vehicles is also the high cost and poor durability of the cells. Therefore, the key factor is to develop membrane electrode assemblies (MEA) with high performance, low cost, and high lifetime. As the core component of PEMFC, the membrane electrode assembly consists of a catalytic layer, a proton exchange membrane and a gas diffusion layer in a sandwich structure. The cost of a membrane electrode is about more than 50% of the total cost of the cell, in which the catalyst is the main source of membrane electrode cost, while the fuel cell life issue mainly depends on the material life and stability of the membrane electrode. The following three parts: catalyst, ionomer, and catalytic layer structure design will be investigated and analyzed for the latest research on proton exchange membrane fuel cells [7].

(1) Catalyst: Fuel cells are mainly oxygen reduction reactions and hydroxide reactions. The high reaction energy barrier required for O=O bond cleavage results in a slower oxygen reduction reaction at the cathode. Therefore the help of a catalyst is needed. The older technique is to use a large carrier amount of platinum catalyst at the cathode, but this approach makes the overall price of the fuel cell high and leads to the collapse of the electrode pore structure with poor mass transfer performance. Therefore, research in catalysts and platinum-based catalysts is currently the main research direction. These include mainly platinum carbon catalysts, platinum alloy catalysts, and core-shell catalysts. The main research objective is to improve the electrocatalytic kinetic properties while reducing the cost by adjusting the catalyst material structure [8].

(2) Ionomer: Ionomer is the key material of the catalytic layer, and mainly needs to have these properties:1. be able to transfer protons from inside the anode catalytic layer to the interface of the catalytic layer and proton exchange membrane, and from the interface of membrane and catalytic layer to inside the cathode catalytic layer. 2. have certain gas diffusivity, allowing the reaction gas to enter the reaction site. 3. have sufficient thermal and chemical stability to ensure the long-term stability of membrane electrode operation.

Currently, most of the proton exchange membranes use perfluorosulfonic acid ionomers. The main characteristic of these ionomers is that the electrode properties are not good enough, which makes the service life of membrane electrodes not long enough. Therefore, researchers are currently improving the performance of the ionomer mainly by means of some methods to optimize the modification of membrane electrodes. Jinnouchi [9] et al. at Toyota Central Research Institute designed a high oxygen permeability ionomer with a ring-shaped structural skeleton. Ahn [10] et al. developed a supercritical fluid-based, homogeneously dispersed ionomer in hydroalcohol by some physical methods to obtain a highly permeable oxygen ionomer catalytic layer.

(3) Catalytic layer structure design: The ordering of catalytic layer is crucial and is a hot research topic in the field of membrane electrode preparation technology. A reasonable structural design can effectively improve the reaction interface of the membrane electrode, reduce the resistance to mass transfer of protons, electrons and reactants, and improve the utilization of the catalyst. In 2002, Middelman [11] designed an ideal membrane electrode with a vertically oriented catalyst-coated electron conductor, a vertically oriented proton conductor and a vertically oriented through-hole structure.

Table 2 Hydrogen fuel cell car parameters comparison

Types of Hydrogen Vehicles		Toyota Mirai II	Hyundai NEXO
Maximum range		402miles (646.96km)	612km
Maximum speed		175km/h	179km/h
Fuel cell power reactors	Maximum output power density (kW/L)	4.4kW/L	3.1Kw/L
	Maximum output power (kW)	128kW	93.3kW
Maximum motor output power		134kW	118.4kW
Number of hydrogen storage tanks and the amount of hydrogen stored		3 Hydrogen storage tanks，5.6kg Hydrogen	3 Hydrogen storage tanks，4kg Hydrogen

Table 3 Hydrogen fuel cell car parameters comparison （continued）

Types of Hydrogen Vehicles		Changan SL03 Hydrogen Electric Edition	Honda Clarity
Maximum range		730km（CLTC Work conditions）	750km（J08 Work conditions）
Maximum speed		170Km/h	165km/h
Fuel cell power reactors	≥4Kw/L	3.1Kw/L	3.1Kw/L
	-	103kw	93.3kW
Maximum motor output power		160kW	130kW
Number of hydrogen storage tanks and the amount of hydrogen stored		2 Hydrogen storage tanks，4.7kg Hydrogen	3 Hydrogen storage tanks,5kg Hydrogen

The data used in this investigation are limited, and only parameters such as range, maximum speed, amount of hydrogen stored, and performance of the electric stack are investigated and compared. Therefore, only these aspects are discussed and analyzed.

First of all, in terms of the power structure of the vehicle, the cars of various manufacturers are basically similar. The main principle of operation is that hydrogen is stored in a hydrogen storage tank, and the hydrogen enters the hydrogen fuel cell reactor through a pipe with oxygen from an air compressor to produce electricity for the vehicle's energy. At the same time, the surplus electricity is usually stored in a high-voltage battery with a capacity of several tens of kW, which is used as an auxiliary energy source for passenger cars.

Among the four hydrogen fuel cell vehicles investigated, the actual maximum range and top speed of all four vehicles are similar. The main difference lies in the maximum output power density and hydrogen storage capacity of the fuel cell reactors of the four vehicles. In a compact platform such as a passenger car, the fuel cell reactor needs to meet the need to produce more energy in as small a volume as possible. In this regard, Toyota's Mirai fuel cell stack has the best performance, achieving a power density of 4.4kW/L. This is mainly due to its proton exchange membrane with Gore's ePTFE structural optimization and chemical additive technology. This proton exchange membrane makes it thinner without being considered mechanically strong and stable itself, and the addition of expanded polytetrafluoroethylene (expanded-PTEE, ePTEE) into the proton exchange membrane achieves an increase in fuel cell power density [12].

Through the survey, on the commercial side, hydrogen fuel cells can already be applied in platforms like passenger cars. However, in the category of new energy vehicles, compared with the more mature pure electric vehicles, there are still many technical shortcomings of hydrogen fuel cell vehicles. First of all, due to the large size of hydrogen fuel cell reactors and hydrogen storage tanks, the overall comfort of hydrogen fuel cell passenger cars is poor, and the space inside the car is crowded. Secondly, in terms of price, due to the expensive price of fuel cells, the cost of the whole vehicle remains high, and even after the government subsidies in various countries, the price of the whole vehicle is still high, generally around 100,000 US dollars. In contrast, the price of pure electric vehicles with the same technical parameters is much lower, only 1/3 of the price of hydrogen-fueled vehicles [13].

3 Existing problems and solutions

3.1 Hydrogen storage technology and its safety

The hydrogen storage system is an energy storage unit of hydrogen fuel cell vehicles, which mainly includes two kinds of on-board hydrogen storage solutions: high-pressure gaseous hydrogen storage and liquid hydrogen storage. However, from the current technology maturity analysis, high-pressure gas hydrogen storage is the most mature and the lowest cost, which is the main application of hydrogen storage technology at this stage. With the development of technology, high-pressure hydrogen storage bottles for vehicles will be based on the transition from Type III 35MPa to Type IV 70MPa gas hydrogen storage bottles.The 70MPa hydrogen storage bottle can store more hydrogen to ensure a longer battery life and the type IV 70MPa hydrogen storage bottle also has better safety [14].

3.2 Crash safety of hydrogen fuel cell vehicles

At present, due to the way of storing hydrogen energy in high-pressure gas containers, the high pressure of 70MPa makes the collision safety of hydrogen fuel cell vehicles also need to be studied. Due to the inherent nature of hydrogen as the lightest element, when hydrogen leaks, its diffusion rate is much higher than that of petroleum fuels. At present, the general solution to this problem is to install a hydrogen leak alarm device in the passenger car, when a hydrogen leak occurs in the car, the device gets the leak signal and cuts off the hydrogen supply. The protection of hydrogen tanks is another major issue in crash safety. In the market, the fixed brackets and steel belts of hydrogen storage bottles have been generally upgraded, and materials with better strength, stiffness, and toughness have been used to ensure that the hydrogen storage tank will not be excessively displaced in the event of a collision.

3.3 Hydrogen storage bottles are expensive to produce

Carbon fiber is commonly used in the production of hydrogen storage bottles around the world, and the cost of high-pressure hydrogen storage bottles used in passenger vehicles is estimated to be about 55,000 yuan from the volume and quality of hydrogen storage bottles. The cost of carbon fiber materials is more than half of the overall cost. In the production process of hydrogen storage bottles, the research level of carbon fiber winding equipment still needs to be improved, and the intelligence and automation of processing equipment are also gradually developing. The high cost of carbon fibers, hydrogen storage alloys, and some carbon nanometer materials also limits the development of fuel cell vehicles.

3.3 The durability of the catalyst is insufficient

When the hydrogen fuel cell is running in the vehicle, the catalyst will attenuate, such as the agglomeration, migration and loss of Pt nanometer materials under the action of potentiodynamic. The reduction of catalyst efficiency greatly affects the operating stability of fuel cells [15].

3.4 Hydrogen refueling stations have not been scaled up

Problems such as equipment and the land area of the hydrogenation station determine that the construction and use cost of the hydrogenation station is higher than that of gas station. At the same time, hydrogen refueling stations are faced with the problem of transporting hydrogen and supporting various equipment. According to data, the construction cost of a hydrogen refueling station is about four times that of an ordinary gas station, and the operating cost needs to be higher.The high construction cost has become a severe obstacle to the popularization of hydrogen refueling station construction.

3.5 Suggestions for hydrogen fuel cell application in passenger vehicles

In order to accelerate the development of hydrogen fuel cells and make hydrogen fuel cell passenger cars get further industrial production, this paper puts forward some suggestions on the existing problems at the present stage. (1) Strengthen research on hydrogen production and further reduce the cost of hydrogen fuel use. (2) Focus on the development of new high-stability, high-activity low-PT, or non-PT catalysts to reduce preparation costs and improve the stability of fuel cells. (3) Explore the preparation of new materials for hydrogen storage bottles to get rid of the limitation of the high cost of carbon fiber materials, or strengthen the research on carbon fiber materials to reduce their production costs. (4) Formulate industrial planning and increase investment to build a complete policy support system [15].

4 Conclusion

This paper systematically describes the application research of hydrogen fuel cell in passenger vehicles, through the introduction of the environment and the introduction of fuel cell types, it is concluded that proton exchange membrane fuel cell is more suitable for passenger cars such as small mobile platform fuel cells, and several existing hydrogen fuel cell vehicles were investigated. Finally, combined with the previous research and practical application process, the existing problems of hydrogen fuel cell application in passenger vehicles are put forward. There are three main problems: (1) Safety, hydrogen is a flammable and explosive gas, so when it is applied to passenger cars, it needs to be considered for safety according to preparation, transportation, filling, storage of passenger cars and collision safety. (2) Promotion, at present, new energy vehicles are still dominated by pure electric vehicles. The fuel of hydrogen fuel cells needs to be filled by filling stations, although the gas stations of traditional fossil energy companies are transforming into hydrogen filling stations, this is undoubtedly a long process, and the specific implementation also needs the implementation of the policies of governments around the world and the development of technology to promote. (3) Technical, at present, hydrogen fuel cell vehicles still have technical problems, such as low-temperature cold start technology, which limits the application environment of hydrogen fuel cell vehicles.

The development potential of hydrogen fuel cell passenger vehicles is huge, and the future energy architecture must also develop in the direction of carbon removal and hydrogen. However, at present, the application of hydrogen fuel cells in passenger vehicles has many problems. Compared with other types of similar new energy vehicles, in terms of performance parameters, the hydrogen fuel cell power structure is immature, the fuel cell energy system is large, and the passenger space is compressed. At the same time, the technology of pure electric vehicles and hybrid vehicles based on electric storage is developing rapidly and the supporting industry is more perfect, and the latest pure electric vehicles on sale have surpassed hydrogen fuel cell vehicles in terms of driving range. Hydrogen fuel cell vehicles are only slightly better at filling energy speed, but the development of fast charging technology has led to this advantage becoming more and more diluted. Moreover, the high research and development cost and manufacturing cost of hydrogen fuel cell vehicles, the lack of popularization of hydrogen refueling stations and safety issues determine that it is doomed to be difficult to promote at this stage. However, it is foreseeable that hydrogen energy, as an absolutely clean energy source, will gradually mature in the future technology and a more perfect hydrogen energy environment. Hydrogen energy passenger cars will have better development and will serve mankind more cleanly.

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Author Contribution: All the authors contributed equally and their names were listed in alphabetical order.

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