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Comparative Study on the Performance of Traditional Engines and Various Substitutes

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Abstract. As the global climate starts to change due the exploitation of natural resources by human, internal combustion engines are no longer the favorite son of mankind. Instead, alternatives such as hybrid power systems and electric motors have drawn the attention of various car manufacturers and numerous scholars from worldwide. At the same time, the automobile industry has not given up internal combustion engines yet, and kept producing innovative engine designs aiming to minimize the negative impact of fossil-fuels on the environment. By researching, analyzing, and comparing data and information from various sources, this article will discuss the fundamentals and working basics of internal combustion engines, hybrid power systems and electric motors, the iconic innovations on internal combustion engines by several car manufacturers, and will compare traditional engines and its alternatives through various aspects. This essay will mainly focus on internal combustion engines and some of the more environmentally friendly alternatives available today, as well as a comparison between them and their advantages and disadvantages.

Keywords: Traditional engines, Working basics, Internal combustion engines, Hybrid power systems.

1. Introduction

As the global climate starts to change due the exploitation of natural resources by human, internal combustion engines are no longer the favorite son of mankind. Instead, alternatives such as hybrid power systems and electric motors have drawn the attention of various car manufacturers and numerous scholars from worldwide [1]. At the same time, the automobile industry has not given up internal combustion engines yet, and kept producing innovative engine designs aiming to minimize the negative impact of fossil-fuels on the environment. By researching, analyzing, and comparing data and information from various sources, this article will discuss the fundamentals and working basics of internal combustion engines, hybrid power systems and electric motors, the iconic innovations on internal combustion engines by several car manufacturers, and will compare traditional engines and its alternatives through various aspects [2].

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This essay will mainly focus on internal combustion engines and some of the more environmentally friendly alternatives available today, as well as a comparison between them and their advantages and disadvantages.

2. Traditional heat engines

As the main energy source for transportation, the internal combustion engine is remarkably used in areas such as automobiles, locomotives, and ships. Mostly all engines of the vehicle are in the form of internal combustion engines. the historical breakthrough by Nicolaus Otto (1876) and Rudolf Diesel (1892) in the development of the Spark Ignition (SI) engine and Compression Ignition (CI) engine is globally praised [3]. However, at present, there is a pressing need to develop advanced combustion engines that maximize engine efficiency and totally mitigate exhaust emissions [1]. This report will specifically investigate the working principles of SI engines and an analysis of the performance improvement of turbocharging will also be included [3].

In general, the working principle of internal combustion engines (IC engines) is to convert chemical energy from the fuel to thermal energy from the combustion of the fuel mixture. As the result, the thermal energy is then transformed into mechanical energy. The IC engine is well-known for its high efficiency, compact structure, potent mobility, simple operation, and maintenance. The internal combustion engine has been developed for a century and a half of history. The earliest internal combustion engine was invented in Reno, France, a gas engine fueled by gas, which replaced the steam of a compound steam engine [4]. In 1883, Omler and Karl Benz developed the internal combustion engine spontaneously according to the theoretical principles of Otto. Human transportation tools had yet again taken another epoch-making step when the world’s first car was equipped with the horizontal two-stroke engine back in 1886 [5].

The number of the internal combustion engine in the world greatly exceeds that of any other thermal engine and occupies a significantly important position in the national economy. In 2016, Throughout 2016, the total retail sales of passenger cars in China showed double-digit growth, driving up the overall sales of domestic automotive gasoline engines. According to the statistics of the China Automobile Association [3], in 2016, 49 enterprises completed the sales of 22,156,363 vehicles, with a year-on-year growth of 14.68%.

However, due to the variability of domestic climate, topography, and other factors, the present gasoline engine is now facing unprecedented difficulties. The boom of the automobile industry has led to problems such as oil shortages, greenhouse gases effect, and so forth [6]. Therefore, energy saving and environmental protection will be the two themes of the global automobile industry, which is also the dual purpose of the development of the automobile internal combustion engine. Early in 2016, the China Ministry of Environmental Protection introduced the law limiting greenhouse gas (GHG) emissions [4]. The limits for carbon monoxide emissions were reduced to 700 mg/km, and the standard emissions limitations are getting more rigorous, requiring the emissions of carbon monoxide to be reduced by 20 percent by 2023. the traditional IC engine has no choice but to make adjustments (downsize and fuel economy improvement) to maintain its marketing competitiveness. Some may think that IC engines have little potential but it is not the case. As spark ignition and diesel engine technology evolve, these engines continue to show substantial improvements in efficiency, power density, degree of emission control, and operational capacity. Changes in engine operation and design are steadily improving engine performance [7]. New materials become available and more knowledge-based design offer the potential for continuing to reduce engine weight, size, and cost, for given power output, and for different and more efficient internal combustion engine concepts.

Nowadays, internal combustion engines have become quite mature and reliable, and technological advances are becoming more and more detailed, such as EFI for gasoline engines, high-pressure common rail for diesel engines, etc. In addition, the current direction of human research due to the influence of social development has produced a great deviation [8]. On the one hand, most internal combustion engine research is biased toward environmental protection and emission reduction. On the other hand, the economic orientation of scientific research is too strong, resulting in breakthroughs in

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materials, processing methods, and energy utilization methods for human science and technology and industrial systems to have a long-term role in promoting basic science has not been too much progress.

For the internal combustion engine, today's technology has made it difficult for the internal combustion engine to progress further. In order to reduce the damage to the environment, many technologies are applied to improve the efficiency of internal combustion engines, such as turbines and increased compression ratios [9]. A greater compression ratio usually means higher thermal efficiency and lower fuel consumption, but fuel consumption is not the only pursuit of engine performance. In a typical gasoline engine, oil and air are mixed right at the intake tract into the cylinder and then ignited by spark plugs. Usually, the compression ratio in the case of gasoline engines, the intake tract on the mixed oil and gas mixture once ignited will burn quickly, a large compression ratio will lead to more intense combustion of gasoline, causing the engine to burst, not only affect the combustion effect, but the body will also be damaged [10]. With the popularity of gasoline engine direct injection technology, the gasoline engine in the cylinder directly injected gasoline, pre-mixed with air before being ignited. The gasoline engine's gas mixture is changed from a homogeneous mixture to a partially premixed mixture, which makes the gas more “pressure-resistant”, so the compression ratio can also be increased to improve output performance and thermal efficiency.

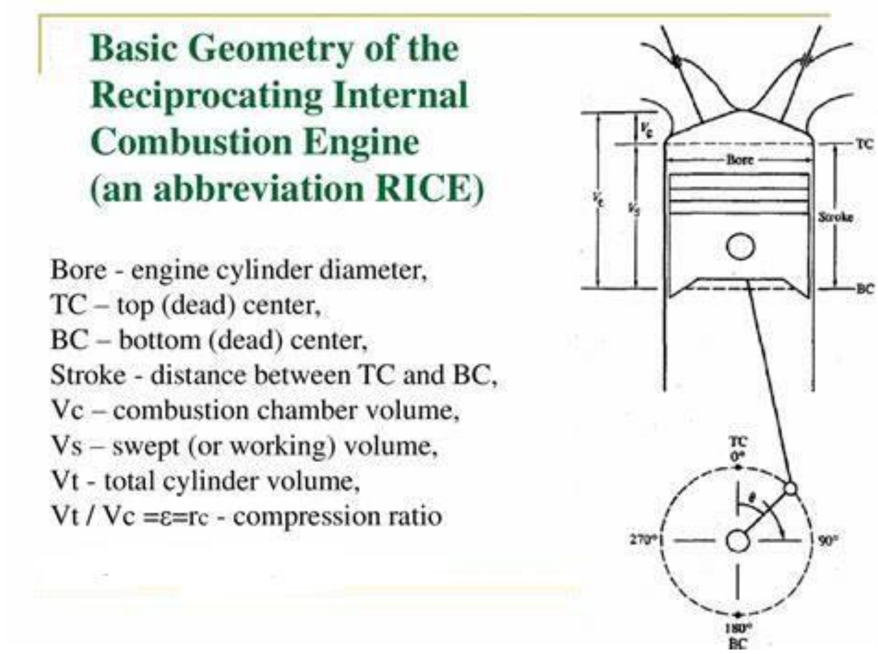

Figure 1. Basic geometry of the reciprocating internal combustion engine [2].

For SI engines, the piston in the cylinder will move back and forth and transform power from the burning gases in the combustion chamber through the connecting rod mechanism to the drive shift. It is noticeable that for a whole 4 stroke process, the angle will be 720 degrees, this will be again explained later. The piston will move back and forth and reach TC and BC for which the cylinder volume is minimum or maximum respectively. When the piston reaches TC, the volume between the piston and cylinder head is called combustion chamber volume (Vc). The ratio of Vt (total cylinder volume) to Vc is the compression ratio which is a vital parameter that show the degree to which the reaction gas is compressed [11].

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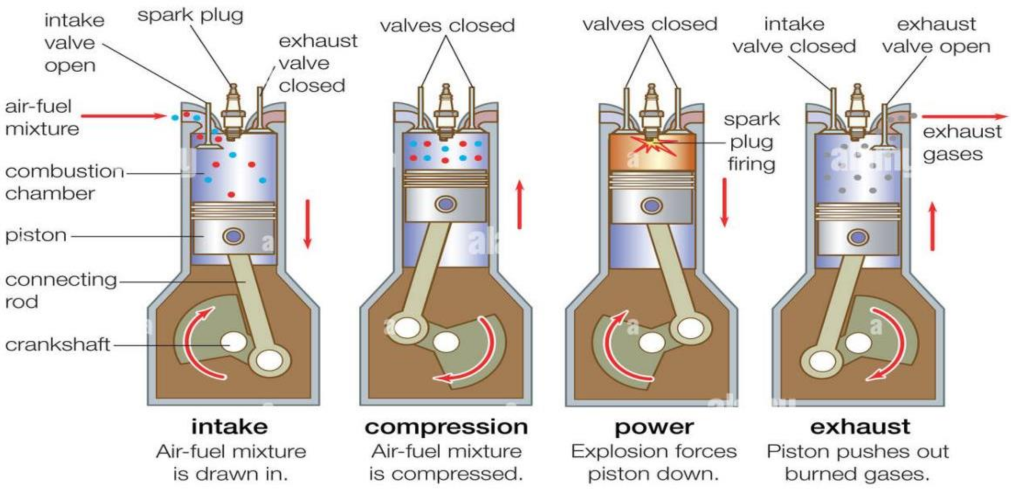

Figure 2. 4 stroke process [4].

Mostly all SI engines operate on process known as 4 stroke process. Each cylinder requires four strokes of its piston—two revolutions of the crankshaft—to complete the sequence of events that produces one power stroke.

1. Intake stroke. During intake stroke, the inlet valve is opened and the outlet valve is closed, the piston starts from TC to BC. As the result, the air-fuel mixture is drawn in onto the cylinder.

2. Compression stroke. Both the inlet valve and outlet valve are closed which provide an isolated system. The piston starts from BC to TC, which compressed the mixture to a small proportion of its initial volume. In the cylinder the temperature and the pressure increase rapidly [4].

3. Power cycle. It is also called expansion stroke. At the end of the compression stroke the spark plug ignites, the temperature rises up (can increase to 200degrees if compression ratio is 10). high-pressure gases (for SI engines which can reach 5MPa) push the piston down and force the crank to rotate. The outlet valve opens to originate the exhaust process.

4. Exhaust stroke. The piston starts from BC to TC and exhaust the remaining gas through the opening outlet valve. Through which the process the temperature in the cylinder can reach 600degrees~800degrees.

During a 4-stroke cycle or an otto cycle, there are two crankshaft revolutions for each cycle. Here is the p-v diagram of otto cycle.

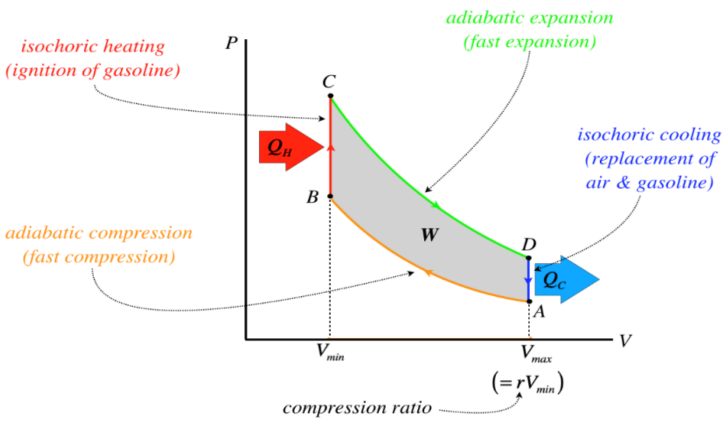

Figure 3. P-v diagram of otto cycle.

For an ideal gas, the ideal gas law is always applicable: pv=nRT

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A-B isentropic process. isentropic compression of the working fluid occurs as the piston moves from BC to TC.

B-C isochoric process. with the SI, a rapid burning occurs inside the piston; therefore, the heat addition takes place at a constant volume.

C-D isentropic process. in this process, the working fluid expands is entropically and produces useful work for the cycle.

D-E isochoric process. heat removal at constant volume. In fact, The actual exhaust and intake stroke has been replaced by this process.

For the otto cycle, the efficiency is defined as, where r represents the compression ratio of the engine. Y represents the ratio of specific heat which is the ratio of C_p to C_v. From the equation, we can know that to a certain extent, the efficiency will be positively related to the compression ratio as Y will be regarded as constant. In general, the efficiency of the otto cycle can reach 25% but never exceeds that of the efficiency of the Carnot cycle.

$$\eta = 1 - \frac{1}{r^{y-1}} \tag{1}$$

The Carnot cycle is regarded as the ideal reversible process. Here is the p-v diagram of it.

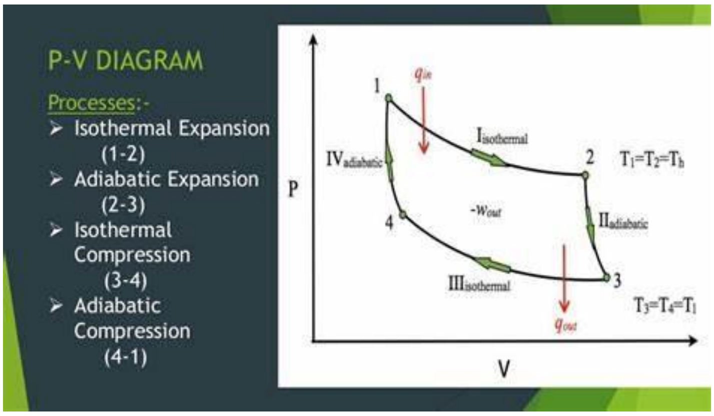

Figure 4. The Carnot cycle.

3. Innovative heat engine technologies

In 2020, lots of e-powered vehicles were produced by innovation brand companies, it seems like a proposal to change the living style to go out. This section will review what tech creation on the internal combustion engine, mostly in the 2000s.

This section will focus on some brands at first, most vehicles brand are born in the end of 20th century, the beginning of 21st century, such as Honda, Mazda, and Nissan. These brands came up with various state-of-the-art heat engine developments that were and still are technologically advanced.

Firstly, in the 1990s, Honda introduced a well-known technology called VTEC. It's been 30 years since the technology was introduced. Conventional engine cam shapes are fixed and the valve opening height is fixed regardless of the states of the engine. Honda engineers came up with a way to design two sets of cams with different shapes deployed on the same camshaft, which became VTEC. The most famous engine that deployed VTEC is the k20c. It is capable of precise controls of the exhaust valve opening height and time, the intake efficiency of the K20C is improved. Furthermore, the exhaust gas discharge is relatively thorough, which can avoid knocking. In other words, the K20C can use a higher compression ratio to improve fuel economy. Of course, EGR can also be achieved by controlling the size and time of exhaust valve opening. Thus, the emissions, fuel consumption, and power are excellent.

Secondly, Mazda’s Spark Controlled Compression Ignition is another excellent innovative advancement for traditional heat engines. SKYACTIV-X compression engine, in simple terms, can be understood as a “hybridization” of gasoline engine and diesel engine, which not only retains the mode

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of spark plug ignition of gasoline engines but also incorporates diesel engines' compression ignition. Mazda's previous launch of the SKYACTIV-G engine has a compression ratio of 13:1, which is already high for fuel engines, but the new SKYACTIV-X compression-ignition engine is even more extreme than it, reaching 15:1. It's just like at first it was a gasoline mode, and after it works a while, it will become a diesel engine, but the fuel is the same type.

The last one is a variety of volumes of the cylinder, named VC, according to the definition of the compression ratio, it seems very simple to change the compression ratio. There are many solutions that can be achieved in theory. In fact, in the past few decades, many engineers from many manufacturers have tried various schemes to achieve variable compression ratios, such as the 2000 Geneva Motor Show, Saab released the SVC engine, which achieves a variable compression ratio by deflecting a certain angle around the center of the crankshaft with an integrated cylinder head, but in the end, these solutions have not been successfully mass-produced, until Nissan's VC (Variable Compression) – Turbo engine is introduced. Only in the history of the automobile was the first mass-produced variable compression ratio engine.

4. Hybrid power systems

Basically, the word "hybrid" means it has two power systems, a gas engine, and an electric motor. The wheels are powered by the engine and electric motor. In this system, the gas engine can also charge the battery. There are two distinct types of hybrid vehicles -- hybrid Electric vehicles (HEV) and plug-in hybrid Electric vehicles (PHEV). There is a big difference between the two types.

HEVs' powertrains are electric and gasoline-powered, but they are not charged from the grid like pure electric vehicles. The HEV provides power through regenerative braking or the engine while the vehicle is moving. By using both electric motors and engines, these vehicles can use relatively small engines. The battery can also be used to power other appliances in the vehicle such as fans, which is why these vehicles are fuel efficient.

PHEVs are also powered using electric motors and Gas engines, but unlike HEVs, PHEVs have a charging port so the battery can be recharged. While the battery can still be recharged through regenerative braking or through the engine on the road, this ability to charge off the grid means PHEVs drive more like battery-electric vehicles, relying only on battery range before running out of power and then switching to the Gas Engine when needed. The range of a purely electric PHEV is usually close to 50km at most, much lower than that of an electric car.

A conventional fuel engine and an electric motor are integrated into the plug-in hybrid, and both can work independently or in tandem. Hybrid cars are characterized by small battery capacity and do not need to be charged externally, so there is no need to worry about the battery running out of power affecting the range. At the same time, it is paired with an engine and an electric motor, the battery charge is driven by the car's electric motor, through the recovery of braking energy, to help the car start and stop, improve the vehicle's low-speed power output, and, to reduce fuel consumption has a certain help effect. And, plug-in hybrid models cost more, and its structure is also more complex, such as the engine and electric motor, as well as the transmission and drivetrain cannot be less, the body weight is also heavier than the traditional fuel car, due to its current pure electric range is not very good. Therefore, if the battery power is low, the hybrid vehicle will even consume more fuel.

The extended-range electric vehicle is another example of hybrid vehicle. In this vehicle, the wheels are driven by two motors. There is a lithium battery in the car. There is also a gasoline engine in it. However, this engine is not used to drive the wheels, but to charge the battery. In this process, the generator generates electric current through electromagnetic induction. Finally, the current in the battery drives the electric motor to drive the wheels.

Compared with traditional electric vehicles, this car can have a longer range., especially in remote areas. People can directly use the gasoline engine to charge the battery. And in daily use, people can directly charge the vehicle for use. This can save some of the cost of use. But this approach can only reduce carbon emissions at some level, and its economic efficiency is limited. This does not completely avoid the use of gas to drive a vehicle. Gasoline engines are always working. This can only be used to make up for the shortcomings of electric cars, such as short battery life. In most cases, the extended-range electric vehicle is powered by fuel to electric energy, and it goes through an energy conversion process, plus the weight of the vehicle is on the heavy side. In some operating conditions, the extended-range electric vehicle does not save fuel, such as on highways, the extended-range electric vehicle will consume more fuel, which is a disadvantage of the tandem power method in hybrid. At the same time, the manufacturing cost of the vehicle will be higher.

Table 1. Performance comparison of different vehicle types.

Features/Types	Gasoline vehicles	HEV	PHEV	EREV
Range	Long	Long	Long	Long
Charging/Fueling Convenience	Easy	Moderate	Moderate	Moderate
Charging/Fueling speed	Fast	Slow	Slow	Slow
Manufacturing Cost (relatively)	Low	High	High	High
Maintenance Cost (relatively)	High	High	High	High
Tax	High	Low	Low	Low
Energy Price	High	Low	Low	Low
Performance(relatively)	High	Low	Low	Low

By comparison, for hybrid vehicles, the biggest limitation is the inconvenience of charging. And that's one of the advantages of the fuel car. At the same time, for hybrid vehicles, the advantage of the battery is not able to be obvious. But due to the policy, their advantages can be reflected in the price, such as tax. For performance, hybrid vehicles use smaller engines due to space constraints, so in comparison, they don't perform as satisfactory as traditional gas cars.

5. Electric motors

Electric motors are one of the main alternatives to heat engines. Electric motors harness the electromagnetic force produced by the current and magnetic field.

The above is a brief design of an electric motor. A coil (black square-like conductor) is placed in a uniform magnetic field. According to Fleming’s left-hand rule, if the current flowed through the coil downward electromagnetic force can be acquired at the left end and upward electromagnetic force can be acquired at the right end. The design of the bottom of the electric motor was made to maintain the directions of currents by creating gaps between itself and exterior current conductors.

Heat engines and electric motors both have advantages over each other and their own drawbacks. The section below will compare the two types of power systems.

6. Comparison, Discussions, and Evaluations

Heat engines have excellent energy storage since fossil fuel don’t vanish easily; heat engines are easier to repair due to their clear mechanical display; heat engines on daily cars are economical compared to an electric motor, since it does not need to be recharged every day; heat engines are safer compared to electric motors since it does not have problems like overrides or short circuits. However, heat engines’ efficiencies are limited by Carnot efficiency due to irreversibility during combustion processes; heat engines use a non-renewable energy source, which not only is finite but also produces pollutants and greenhouse gases; also, compared to electric motors, heat engines are far larger.

Electric motors can have very high efficiencies since they are not limited by Carnot efficiency; they partially use renewable energies, which is theoretically infinite and unpolluting; electric motors’ sizes and weights are much smaller compared to heat engines, which lowers energy consumption; However, electric motors have poor storage of energies and thus less economical compared to heat engines; sometimes, electric motors may cause safety risks due to overloading or short circuit.

Furthermore, there are some real-life factors that people might consider when choosing between electric and fossil fuel vehicles. Cars with heat engines are easier to get an insurance quote since they

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are safer on average; fossil fuel vehicles experience less overall depreciation. On the other hand, petrol or diesel car owners need to pay fuel duty and congestion fees, which is a considerable amount of extra expenditure.

Electric car owners, luckily, can not only save on congestion and fuel duty but also receive tax credits from the government; also, in some countries, electric cars can use bus lanes. Nevertheless, the payments are harsher on maintenance, insurance quotes and re-sales.

To make this article more convincing, three real life hatchback models were found for comparison.

Table 2. Data provided by manufacturer official sites.

/	**VW Golf 2018** (Heat engine)	**Peugeot 308 GT Hybrid 2021** (Hybrid)	**BMW i3 2018** (Electric fuel cell)
0-100kmph	7.7s	7.5s	7.3s
Torque	199Nm@1600rpm	250Nm@1750rpm	250Nm@184rpm
Horsepower	170HP	178HP	170HP
Top speed	198.6kmph	235kmph (claimed)	150kmph*1
Range	612km	3333km(claimed)	155.2km (without range extender*2)
l/100km	8.11l/100km	1.2l/100km	2.1l/100km (equivalent)

The BMW i3 is the best in acceleration and torque since it is full-scale electric. Admittedly, the Peugeot has the same maximum torque, but the BMW can attain maximum torque at a lower engine rpm, which is more practical in any aspect. The main brilliance of the electric motor is its high low-rpm torque. The reason is that electrons move at very high speeds inside the conductor if there is an electric field. Thus, maximum torque can be achieved almost instantly when the driver put their foot down.

However, in the rest aspects, the hybrid was the best. A part of the reason is that it has two engines and overall higher power output, so it has the highest top speed; another part is that it is “smarter”. It is claimed by Peugeot that the 308GT hybrid can switch between electric or heat engines for different driving situations and retrieve heat energies from brakes for better fuel economy.

7. Conclusion

In conclusion, the traditional gasoline car has been difficult to produce new changes due to the limitations of technology. However, due to the convenience of fuel, gasoline cars are still difficult to be replaced. For hybrid vehicles, an important core of them is still the internal combustion engine. The internal combustion engine provides sufficient range and is able to recharge the battery. Hybrid vehicles are a measure of environmental protection, but still do not completely avoid the problem. With the developing technologies, more and more alternatives of heat engines will emerge. However, it is still believed that heat engines are still going to be the predominant engines used in various fields. Although it is not exactly efficient, but its excellent energy storage, reliability, and technological advancements are nonnegligible. Though electric motors still present problems such as electricity storage, they have proved their potentials as an alternative to heat engines as well as their great prospect.

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