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Review

Sustainable Development of the Automobile Industry in the United States, Europe, and Japan with Special Focus on the Vehicles' Power Sources

Naoya Shigeta and **Seyed Ehsan Hosseini** *

Combustion and Sustainable Energy Laboratory (ComSEL), Department of Mechanical Engineering, Arkansas Tech University, 1811 N Boulder Ave, Russellville, AR 72801, USA; shosseini@atu.edu
* Correspondence: seyed.ehsan.hosseini@gmail.com; Tel.: +1-(479)-964-0877

Abstract: In this paper, various modern power engines developed by the American, Japanese, and European automobile industries will be compared. Specific data, including the efficiency, emission rate of nitrogen oxides (NO_x), fuel consumption, and electronic vehicle technology, will be developed. Since the first invention of the automobile engine in the late 19th century, companies came up with unique innovations, including its structure, control systems, and additional mechanical installations to improve efficiency and reduce emissions. Numerous companies, including Ford, Toyota, and Mercedes-Benz, compete in the automobile industry to improve their engine's efficiency and emission rates to create a clean environment. In addition, each country has its regulations on emission rates and automobile structure. Therefore, to meet these regulations, the structure and the system of the engines vary between companies in different countries. A variety of variable valve timing (VVT) systems, which is a mechanical part installed in the engine, are being developed by several companies. The VVT controls the opening and closing of the air inlet valve and the exhaust valve, which improves the reduction of fuel consumption and thermal efficiency. Furthermore, changing the engine structure is also another method that automobile companies are developing. Changing the engine's shape can improve the vehicle's performance (e.g., the engine vibration while running, the power output, and the smoothness of driving). Due to the emissions caused by petrol and diesel engines, the electrified vehicles have been developing to achieve a cleaner environment. This includes battery electric vehicles, hybrid electric vehicles, plug-in hybrid electric vehicles, and fuel cell electric vehicles. By comparing these features in the engine, it is possible to understand what the companies in the US, Japan, and the European countries are working on to improve their engines and provide a clean environment.

Keywords: efficiency; emission; variable valve timing; electrified vehicles

Citation: Shigeta, N.; Hosseini, S.E. Sustainable Development of the Automobile Industry in the United States, Europe, and Japan with Special Focus on the Vehicles' Power Sources. *Energies* **2021**, *14*, 78. https://dx.doi.org/10.3390/en14010078

Received: 28 November 2020
Accepted: 20 December 2020
Published: 25 December 2020

1. Introduction

The development of automobile power sources has been drastically changing due to several engineers' new ideas. This is achieved by understanding the customer's demand for their vehicles from different countries. This includes not only their likes and dislikes of the vehicle's appearance but also the varying environment, road condition, and regulations in their area [1]. Leading countries in the automobile industry, including the United States of America, European countries, and Japan, have strived to improve their vehicles by combining their technology and the customer's demand. Though many companies have similar goals and expectations, they have unique characteristics and strengths, which put them in the top competitors.

Climate change also has been impacting the development of the automobile power source. One hundred ninety-five nations established goals at the Paris Agreement in December 2015 to combat global warming issues. It was estimated that the emission rate of CO_2 from the transportation sector in 2020 would increase by 92%, compared to 1990 [2].

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To achieve these goals, manufacturers have been developing vehicles with a high-efficiency power source and a clean output [3]. As a result, several types of power sources and technology have been created. These include electric vehicles, hybrid electric vehicles, and fuel cell hybrid vehicles. These vehicles have contributed significantly to reducing tailpipe emissions. Though each type of technology has its advantages, it has some disadvantages, which degrades its quality. However, automobile industries have been improving these vehicles to overcome their problems.

Restrictions vary in each country, and it dramatically influences the quality of their vehicles. There are several restrictions in each country to solve climate change and road conditions, other than the goals established in the Paris Agreement. America, Europe, and Japan have different laws and restrictions on emission. Therefore, each country has a different technology to satisfy its target goal. An example is the ethanol-gasoline blended fuel. By mixing ethanol with gasoline, it contributes to the reduction of greenhouse gas [4].

This paper aims to understand how manufacturers in the US, Europe, and Japan are developing their vehicles' power sources. By considering the customer demand, vehicle performance, emission rate, and regulations, several improvements and developments have been made to achieve these goals. These include adding additional mechanical components such as the variable valve timing, changing engine structure, and changing the power source as in the electric and hybrid vehicles. Moreover, by comparing their technological development, the manufacturers' goals and achievements can also be understood.

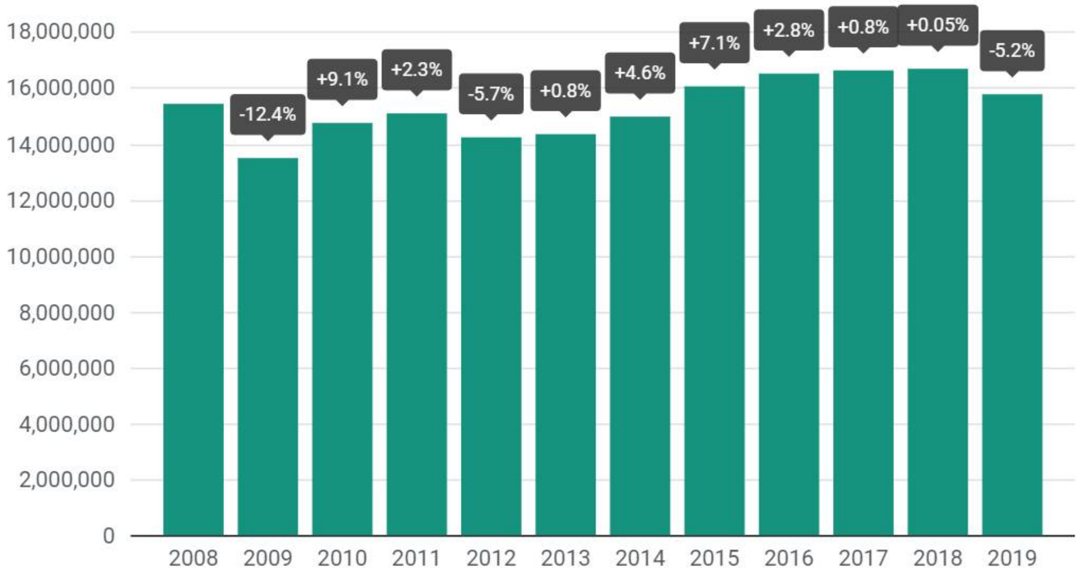
2. The History of the Automobile Industries

Right after Germany built the world's first gas-powered vehicle in the late 1800 s, the United States rapidly built their first car as well. From the early 20th century to the 1980 s, the US was known as the world's largest automobile producer [5]. The first gas-powered vehicle in the US was built in 1893 by the brothers Charles and Frank Duryea [6]. Three manufacturers, including Ford, General Motors, and Chrysler, dominated the automobile sector for several years. However, as foreign auto manufacturers started exporting and designing different vehicles to match American customer demand, American produced cars' popularity declined [5]. Yet, the production of American automobile has been gradually increasing each year, where it was 5.6 million in 2009, which increased to 11.3 million vehicles in 2017. From 2011 to 2017, approximately 130,000 automaker and auto supplier jobs were added in America. Currently, there are 46 automobile assembly plants in the US. It contributes almost $6 billion to America's gross domestic product (GDP) when 200,000 vehicles are produced at a single plant. In 2017, the American automakers, including the Fiat Chrysler Automobiles Group, Ford, and General Motors represented 77% of its sales in the US. This shows that American auto manufacturers are meeting the American customer demands. Approximately one million American vehicles have been exported to different countries every year, which indicates the US's outstanding role in the automobile industry in the world [7]. Today, American manufacturers are installing clean systems to their vehicles without sacrificing their performance, thus keeping their customer demand. Figure 1 demonstrates the export of the American vehicles' scenario from 1996 to 2020.

Figure 1. Export of American vehicles from 1996 to 2020 [8].

In Europe, the first automobile built with an internal combustion engine was in the late 1800 s, by two German engineers, Karl Friedrich Benz and Gottlieb Wilhelm Daimler [9]. As soon as this revolutionary technology was invented, France established its world-first automobile manufacturing company. Henry Ford installed a belt-conveyer assembly line that drastically reduced cost and assembly time [10]. Data from June 2020 states that 13.8 million Europeans are working directly and indirectly in the auto industry, which covers 6.1 percent of the total EU jobs [11]. In 2018, about 5.4 million cars produced by European manufacturers were exported around the world. This was worth more than €127 billion, approximately $150 billion [12]. Automobile industries contribute greatly to innovation. Therefore, the EU spends 28 percent of its total spending on the automotive sector [11]. To solve emission reduction problems, manufacturers started improving the building of electric vehicles, and every year, the popularity of electric cars is increasing. To achieve an all-electric vehicle society, manufacturers in Europe are developing various types of clean vehicles that will increase their number of customers by understanding their demands. Though there is a lot of competition between countries, European countries are one of the top automobile producers. Figure 2 depicts the production rate of passenger cars and motor vehicles in various EU countries.

Since 1907, when a Japanese engineer first built the entire gasoline-powered car, Japanese manufacturers have invented and designed various automobile types. However, Japanese cars were not popular in the first several years. By the end of the 1950 s, manufacturers started exporting their products to different countries. As automobile industries in Japan began to improve their technology to meet their customer demand, several brands became internationally known for their quality and cheapness. Toyota, Honda, and Nissan are examples of these manufacturers. Their small-sized engine and fuel efficiency became widespread [13]. Today, Japan is one of the largest automobiles producing countries in the world. In 2017, about 19% of Japan's export value was in the automotive sector, which reached 60.7 trillion yen (Over $560 billion). This includes both four and two-wheeled vehicles and their auto parts [14]. It also covered 8.7 percent of the total employment, 5.5 million employees, in 2017 [15]. Every year, Japan achieves a tremendous amount of automobile production and sales, contributing significantly to the Japanese economy. Japanese manufacturers are now developing a vehicle with better quality, better fuel economy, and a clean car to satisfy their customers. Figure 3 illustrates a summary of Japanese vehicle production from 1996 to 2020.



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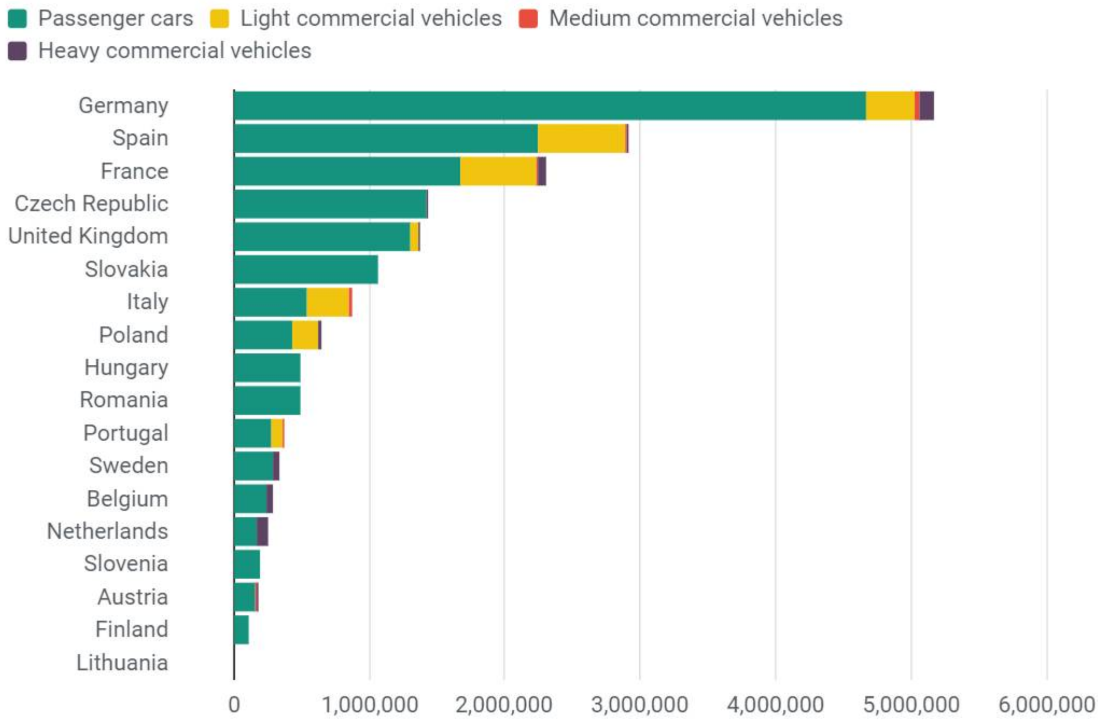

(**b**)

Figure 2. (**a**) Export of American vehicles from EU production of passenger cars, (**b**) EU production of motor vehicles by countries [16].

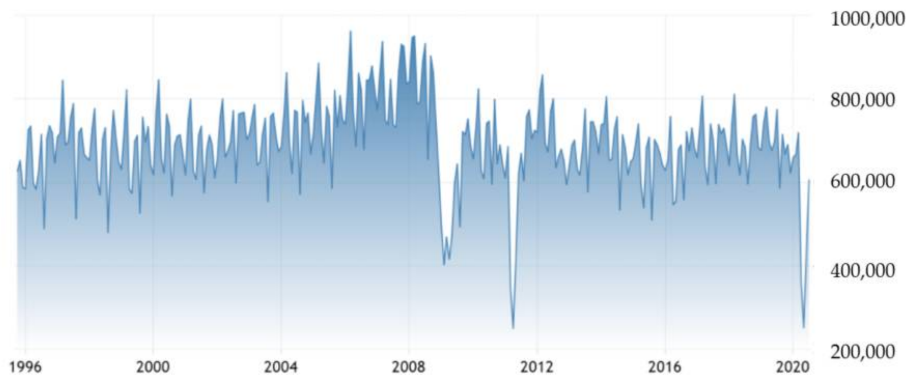

Figure 3. Production of Japanese vehicles from 1996 to 2020 [17].

Though there are many automobile companies in different countries, the industries in the US, Japan, and the European countries are some of the most significant contributors to car engines' development. The first car had an engine with a maximum of only 21 miles per gallon (mpg). Since then, automobile companies have worked on improving the fuel efficiency of their engines. In 2000, the Prius hybrid car made by Toyota was an achievement in the development of an engine that reached over 50 mpg on the highway. Furthermore, each country has different standards of emission rate, fuel economy, and other regulations. Therefore, companies come up with different ideas to meet those standards. One of the mechanical parts that many industries are focusing on is the timing of the opening and closing of the inlet and exhaust valve. By installing technology relating to this timing, they can improve the car's thermal efficiency and fuel economy. Almost every company has its valve timing system installed in their vehicle. Moreover, several engine structures have been created to improve stability, vibration, and horsepower (hp). For example, designs, including the inlet engine, V engine, and the boxer engine, all have unique benefits that improve the engine performance.

3. Customers' Demand

The demand for engine performance from customers in each region differs due to their needs. In the US, the three highest market shares in 2019 were the Ford F-Series, Ram Pickup, and the Chevrolet Silverado, which all have potent engines [18]. This shows that American customers demand vehicles with strong engines. On the other hand, Japanese customers demand a higher fuel economy; therefore, hybrid, electric, and other compact cars are popular. Japanese companies mainly focus on building small, light-weighted engines for vehicles. The popular passenger cars in Japan in 2019 with internal combustion engines were Toyota Prius, Nissan Note, and Honda Freed [19]. These cars are all compact cars with either gasoline or hybrid engines. Although the customer demand for diesel engines decreases in Europe, the percentage of diesel engine market sales is higher than in the US and Japan. In 2018, 35.9% of the market share was diesel in Europe [20]. Diesel fuel is cheaper than petrol fuel automobiles in Europe and can produce a higher efficiency rate. Similar to Japanese customers, European customers also demand compact cars because of their road conditions. Volkswagen Golf, Renault Clio, and 208 were popular passenger cars sold in 2017 in Europe [21]. These cars can either have a diesel or petrol engine and they are all compact. Since the customers from each region have their own demand, local car companies focus on manufacturing to satisfy their customers. Moreover, manufacturers also change their design and specifications to satisfy customers in foreign countries as well. For example, Toyota made the V6 engine Toyota Highlander which debuted in the US, to satisfy American customers.

4. Environmental Issues and Emissions Regulations

There are various laws and regulations in the US, Japan, and Europe to regulate pollution emissions to make a clean and healthy environment. By following these regulations, automobile companies can adjust and develop engines that will achieve these standards. Additionally, ethanol-gasoline blended fuel is also used to reduce the amount of HC and CO emissions. Several kinds of research and results have been introduced, showing ethanol-gasoline fuel's significance [4].

In 1990, the US established a law called the "Clean Air Act". This law is to regulate pollutant emission, including NO_x, sulfur dioxide (SO_2), and particulate matter (PM). To achieve limited emission, manufacturers must build cleaner engines, provide cleaner fuel, and provide maintenance services [22]. In 2018, research showed that the average NO_x emission rate from the light passenger vehicles in the US was 0.18 g/km for gasoline engines and 0.095 g/km for diesel engines [23]. In the US, every state has its law to reduce emissions. One example is the "California Diesel Risk Program" that was established in California to set a goal to reduce 75% of diesel PM emissions by 2010 and 85 percent by 2020 for all vehicles, including trucks, buses, and waste collection vehicles. The goal was achieved by new development in the diesel engine, other programs that reduced emissions, and various measuring tools. According to this law, vehicles also cannot exceed more than 20 percent of nitrogen dioxide (NO_2) emission [24]. Figure 4 illustrates the estimated US average vehicle emissions rates of light-duty vehicles using gasoline [23].

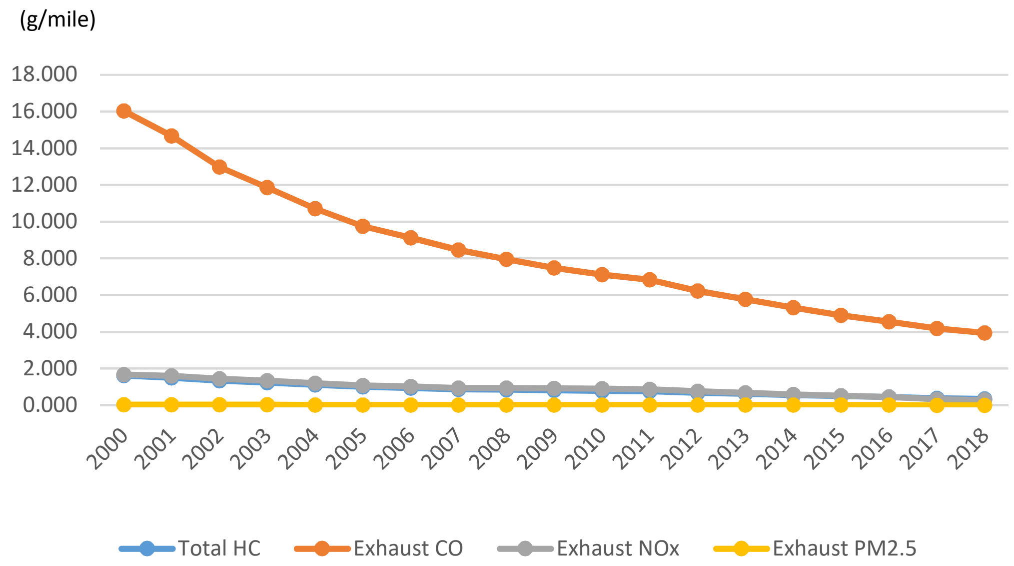

Figure 4. Estimated US average vehicle emissions rates of light-duty vehicles using gasoline [23].

Compared to the US, the Japanese automobiles' average NO_x emission measured in 2018 is lower. For light passenger vehicles that use gasoline, it was calculated that there is 0.05 g/km, and for diesel engines, it was 0.15 g/km. Japan established a law in 1992, and it was last amended in 2007 called the "NO_x and PM law". One hundred ninety-six communities in five metropolitan areas affected by the NO_x and PM emission were selected to reduce the emission rate [25]. Research indicated that the regions with this law have 2 to 2.5 times less NO_x emission than the areas without this law. Another result that they collected is the number of children getting asthma. Data from 618,973 children were collected, and investigation showed that the number of children getting asthma decreased every year by 0.073% when the NO_x and PM law is active [26]. This covers heavy-duty vehicles, including buses, trucks, and vans. Passenger cars that use diesel engines are also included in this law. For passenger diesel cars, the standard was set to 0.48 g/km for NO_x emission and 0.055 g/km for PM emission. If vehicles did not achieve the emission standard, they were not allowed to drive in the area. To satisfy the standard, cars need to be renewed with a cleaner engine or old vehicles retrofitted with devices to control the emission [25].

European countries are strict with the emission rates because of the high usage of diesel engines. Investigations indicate that Europe's light passenger vehicles emitted an average NO_x of 0.06 g/km for gasoline engines and 0.6 g/km for diesel engines per year. They established a law that strictly restricted CO_2 emissions. From 2015 to 2019, the EU set their goal for CO_2 emission to 130 g/km. This corresponds to 5.6 L (1.48 gallons) per 100 km for the petrol engine and 4.9 L per 100 km for the diesel engine. After 2019, they set the goal even lower to 95 g/km, which correlated with 4.1 L/100 km for petrol engines and 3.6 L/100 km for diesel engines. To monitor each vehicle's emission rate, many European countries, including Germany, the United Kingdom, and the Netherlands, made a program called the "Low Emission Zone Program." In this program, they selected cities and towns where vehicles must meet the EU air quality standards. Cars that do not satisfy the emission standard are restricted in this area, and if the vehicle needs to enter the zone for some reason, the driver will likely get charged or be given the option to retrofit [27]. New results have come up that the emission rates tested in the laboratory and the emission rates tested on roads differ. The measured NO_x emission was 80 mg/km in the laboratory, whereas the on-road test using the real driving emission (RDE) was 168 mg/km. From 2020, the limit for NO_x emission would be 120 mg/km, which will be tested using the RDE [28].

Ethanol-gasoline blended fuel has been introduced to decrease the amount of exhaust gas created by the SI engine. By blending ethanol in gasoline, it increases the oxygen content because ethanol contains 35% oxygen content. Ethanol is also a clean and renewable source produced by fermenting biomass sources, including sugar cane, corn, and sugar beet. The fuel also has a significant influence on the rural economy since ethanol is a low-cost fuel. Another advantage of ethanol is that the Research Octane Number (RON) is higher than gasoline. As a result, it can withstand high pressure and temperature before ignition [4]. Most ethanol-gasoline blended fuel contains 10% ethanol, which is represented as E10. Other fuels have a varying amount of ethanol to satisfy the performance of specific vehicles. Some examples are the E85 and the ED95. The E85 contains between 65% to 85% ethanol and is used for flexible-fuel vehicles (FFV). The ED95 contains an ethanol level of 95%, and it can be used on a heavy-duty vehicle [29]. Liquified petroleum gas (LPG) vehicles have also significantly contributed to supporting a clean environment. LPG fuels form propane and butane made from methane, the most straightforward carbon and hydrogen molecule [30]. LPG vehicles emit 20% less CO2 and 90% less PN than petrol vehicles and emit 98% less NO_x and 81% fewer PN than diesel vehicles [31].

In the United States, 94% of ethanol is obtained from corn starch. The E10 fuel was brought due to the Clean Air Act Amendment of 1990 and other established laws [32]. More than 98% of gasoline in the US contains 10% ethanol and 90% gasoline (E10), and it is sold in every state [33]. This achieves in satisfying the renewable fuel standard (RFS). Figure 5 shows the target goals of the RFS volume requirement, set by the Energy Independence and Security Act of 2007 (EISA). Moreover, there are specific goals set for specific ethanol-blended fuel categories. For example, conventional biofuel (fuels contained from starch feedstock including corn and grain sorghum) must demonstrate a 20% reduction of the greenhouse gas, and advanced biofuel (fuels contained from cellulosic and advanced feedstock including sugar cane and sugar beet) must demonstrate a 50% reduction of the greenhouse gas [34].

European countries have also provided E10 fuel from 2009 to reduce tailpipe emission. E10 is available for most European cars built after 2000, and it is currently available in 14 EU countries [29]. An Italian emission laboratory, Istituto Motori of National Research Council, has researched and experimented with the use of ethanol-gasoline blended fuel. They used a four-stroke SI engine motorcycle for their experiment. While testing different fuel sources with varying percentages of the ethanol-gasoline mixture, several results have shown up. By blending 20% of the ethanol content (E20), the most reduction of emission was reported.

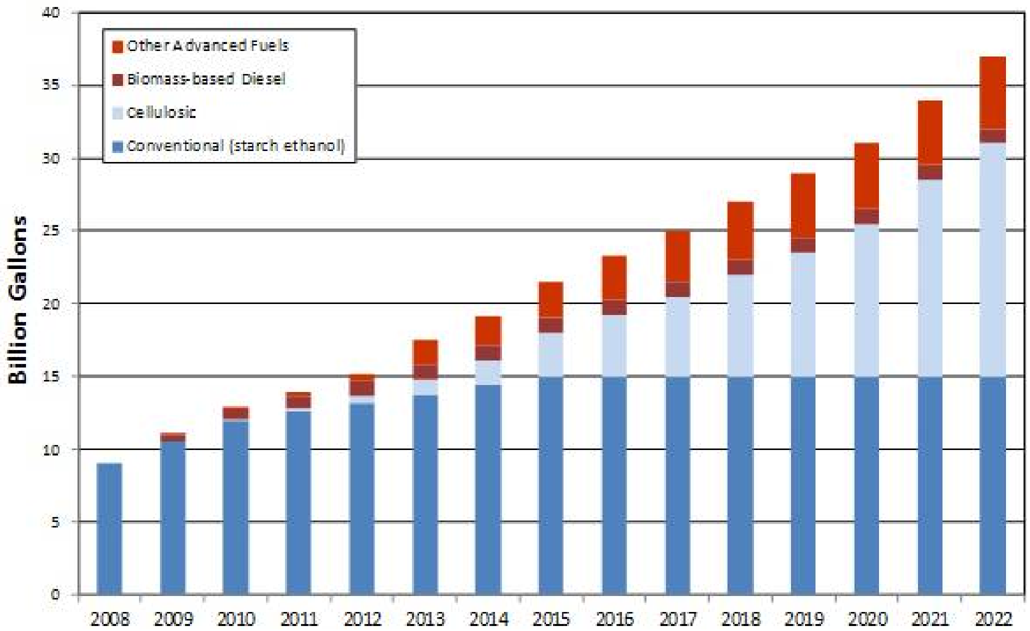

Figure 5. RFS volume requirements set by the EISA [34].

Additionally, the flame temperature is lower for E20 and E30, which leads to a lower exhaust temperature. Thus, it has a lower quantity of NO_x production. However, during the cold-transient phase, the emission rate increases due to the high fuel it needs to achieve complete combustion. This leads to a low mixture and burns in the combustion chamber. As shown in Figure 6, E20 emits the fewest emission of CO (6.5 g/km) [2]. LPG vehicle is also an automobile using renewable fuel sources. They are the most used passenger cars in Europe, which uses alternative fuel. There are approximately 8 million LPG vehicles in Europe, and more than 31,000 refueling stations are available for this vehicle [31].

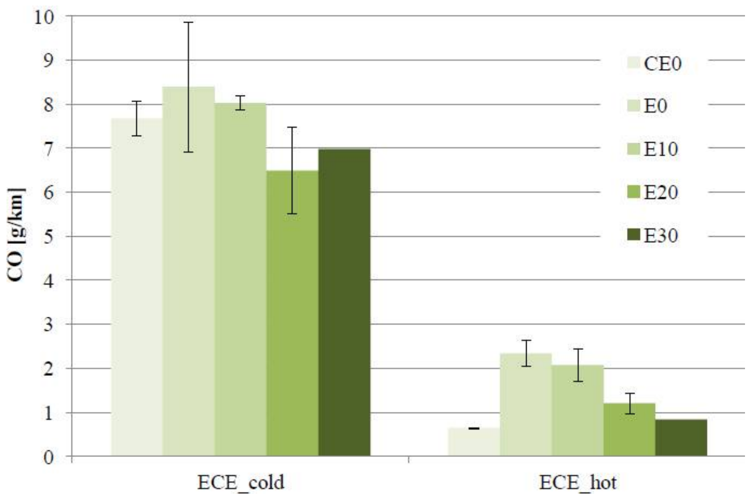

Figure 6. CO emission for various fuel source during cold and hot transient phase [2].

Though ethanol-gasoline blended fuels are not as popular compared to other countries, researchers consider the use of biofuel energy for vehicles. Japan's government has permitted the E10, and Bio-Ethyl Tert-Butyl Ether (ETBE) blended gasoline sales in 2012. Because of the limited amount of crop production and the less effect on the decline of

CO_2 emission, not much development has been achieved in Japan. Due to the limited amount of space, Japan has a low self-sufficiency rate for ethanol production, and it is mainly imported. About three million liters of ethanol are produced from ethylene, where one million are for industrial chemicals, and two million are for fuels. In 2014, 523 million liters of ethanol fuel were imported, all from Brazil, which is 500 times more than Japan's production. Therefore, Japanese industries focus on cellulosic ethanol technology, which does not use food [35]. In 2018, Toyota Brazil introduced its prototype of the world's first hybrid FFV in Brazil, which uses renewable biofuel. Toyota expects that the Hybrid FFV technology development will help lead to their goal for the "Toyota Environmental Challenge 2050". One goal is to reduce the global CO_2 emission by 90% from Toyota's 2010 international level [36].

5. Recent Development in Automobile Engines

5.1. Variable Valve Timing (VVT)

To improve the engines' efficiency and fuel consumption, companies install additional mechanical parts in the engine. To improve the engine, many automobile industries have focused on the valve's opening and closing timing. The VVT is connected to the camshaft, and it controls the speed of rotation of the camshaft by monitoring the vehicle's performance. As the vehicle detect performance differences, it changes the four-valve events' timing, which includes the opening and closing of the intake and exhaust valve [37]. Although every VVT has a similar process, individual companies have their own unique valve timing system that improves the engine's efficiency and performance.

5.1.1. Ford Ti-VCT

Ford has developed a variable timing system to support its V engine called the Twin Independent Variable Camshaft Timing (Ti-VCT). This was created to improve higher fuel efficiency and reduce emission rates. It controls the two camshafts with four phases that control the inlet valve and the exhaust valve either together or independently. The unique feature of Ti-VCT is that it can replace the Exhaust Gas Recirculation (EGR), which is a mechanical component that reduces gas emission by sending the exhaust gas back to the inlet valve for reuse purposes [38].

5.1.2. Toyota VVT-i

Japanese companies also have a unique variable valve timing system. One example of the VVT is the Valuable Valve Timing-Intelligence (VVT-i) developed by Toyota. The VVTi (Figure 7) is known to improve fuel efficiency by 6%. There is the single and the dual VVT-i where it only controls the intake camshaft and controls both intake and exhaust camshaft for the dual. There are three essential parts to make the component functional: the Electronic Control Unit (ECU), Oil Control Valve (OCV), and the VVT pulley. Depending on the engine performance and condition, the ECU detects and calculates the valve's timing and sends instructions to the OCV 6, which controls and sends hydraulic pressure to the VVT pulley. This pulley, in the end, changes the valve timing. Like the Ti-VCT, the EGR is no longer needed in the engine process by installing this component. This machine component increases the fuel economy and reduces NO_x and hydrocarbon emissions [39].

5.1.3. Porsche VarioCam

The VVT invented by Porsche called the VarioCam (Figure 8) also has a unique feature. This machine component has two stages of valve lifting, the outer and the inner lifter, and two different sized cams. As the driver's input varies, the pin that is controlled by the hydraulic pressure inside the hydraulic tappet locks or unlocks the inner lifter to the outer lifter. When the pin locks the two lifters, it performs usual driving because the bigger cam will control the valve's opening and closing. However, when the pin is unlocked, it causes a small lift of the valve because the smaller cam controls it. By this process, the timing of the opening and closing of the inlet valve and exhaust valve overlaps at the exhaust process;

some exhaust gas will go into the inlet manifold, which can be reused and reduces the pollutant emission. Research of the VarioCam shows that the fuel consumption reduction and the emission rate improved by 10% [40].

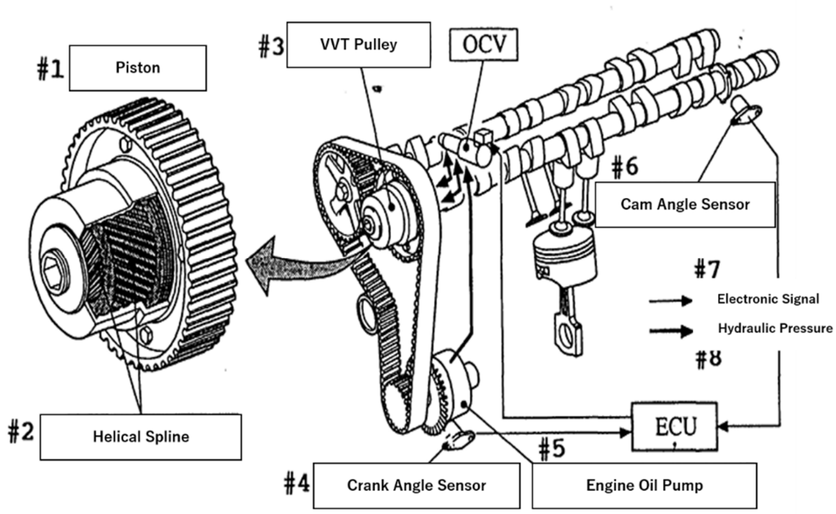

Figure 7. Diagram of the VVT-i [39].

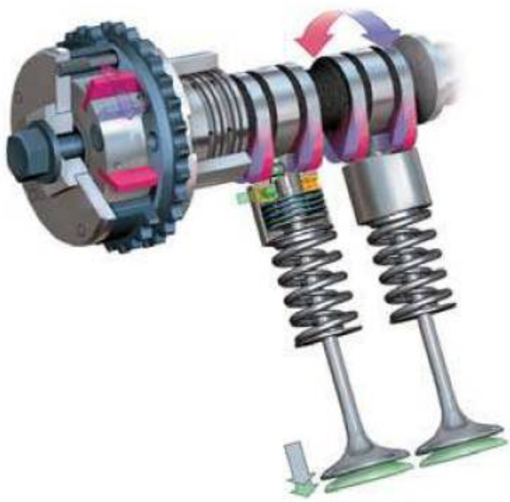

Figure 8. Diagram of the VarioCam (Note: To improve the fuel efficiency and to reduce the amount of emission, the pin unlocks the two lifters) [40].

5.1.4. Other Strategies

Manufacturers have been introducing strategies other than the VVT system to improve the fuel consumption and emission rate. These strategies include Downspeeding, Downsizing, and Fuel Stratified Injection.

(A) Engine Downspeeding

Engine Downspeeding strategy allows the engine to operate at a lower speed while achieving the same power output to reduce the friction, which improves the fuel consumption. This system greatly impacted the automobile industry, especially heavy-duty trucks.

According to the North American Council for Freight Efficiency (NACFE), this strategy saves 2 to 3 percent of fuel when operated alone and saves 3 to 6 percent when it is combined with other powertrain technologies. It also has the benefit of reducing engine noise since the engine speed becomes slower [41]. However, by reducing the engine speed, it generates higher torque. For example, if the speed is reduced from 1450 rpm to 1125 rpm, it increases the torque by 29%. The combination of technologies has contributed to overcoming a high torque environment and achieves a better engine performance. DANA developed an axle called the Spicer AdvanTEK 40 Tandem Axle, which can handle a higher input torque by developing faster axle ratios. This allows the overall efficiency to increase up to 2%, and over a five-year time span, trucks operating in a linehaul duty cycle can save more than 2700 gallons of diesel fuel [42]. DANA also developed the SPL 350 driveshaft and the SPL 250 inter-axle shaft to handle the high torque during severe duty. It is capable of carrying 40% more torque than its competitive designs [43].

Volvo was the first automobile industry to introduce the downspeeding concept in 2011. Volvo found out that by decreasing the speed from 1350 to 1150 rpm, the fuel consumption improves by about 3% [44]. However, the new Volvo D13TC engine's development achieved a reduction of fuel consumption by 11%. The Volvo D13TC is a turbo compound engine, where the excess heat recovers in the turbo compound unit. Which then activates the gear link, pushing the crankshaft. This leads to greater efficiency, better fuel consumption, and performance. The dynamic torque system is also installed in this engine, which detects the weight of the vehicle and the road condition. It then automatically sets the right torque level for better performance [45].

(B) Engine Downsizing

Engine downsizing reduces the engine size to improve fuel economy and lower emission rate [46]. It is known as the most straightforward strategy to achieve its goals. However, it is not as popular since it is considered to have a limit. Most small engines have an additional powertrain combined, such as the turbocharger, to produce and match the power output [47].

Volkswagen achieved the downsizing of their engine for their model, Golf, which offers a 1.0 L 3-cylinder gasoline engine. However, Volkswagen has no plan to reduce the size smaller than the current 1.0 L gasoline engine and its 1.6 L 4-cylinder diesel engine. This is because smaller engines require more work and often consume more fuel to produce maximum power than larger engines [47]. Car manufacturers, regulators, and green groups found out that small size engines emit much higher CO_2 and NO_x according to an official test lab result [48].

Toyota has developed a downsized engine, which is the 2.8 L 1GD-FTV diesel engine. It uses the thermo swing wall insulation technology (TSWIN), the world's first technology. TSWIN achieves the maximum thermal efficiency of 44%. Compared to its predecessor, the KD engine, a 3.0 L engine, maximum torque improved by 25% while low-speed torque enhanced by 11%. The fuel efficiency also increased by 15%. The selective catalyst reduction (SCR) system is also installed in the engine, which can eliminate 99% of NO_x emission [49].

(C) Fuel Stratified Injection

Fuel stratified injection (FSI) is similar to the standard direct fuel injection. However, FSI directly injects the fuel in the combustion chamber during the compression stroke, while direct fuel injection injects the fuel during the intake stroke. This allows a better fuel economy without losing any power output [50]. While many countries use the standard direct fuel injection for their engine, several European manufacturers are developing and installing advanced FSI systems to their engines.

Audi inputs the FSI system to all their gasoline engines. They successfully developed the world's first turbocharged direct-injection engine called the turbo fuel stratified injection (TFSI) in 2004 [51,52]. It has the advantage of producing higher power output and more significant engine response while providing better fuel efficiency and reduction of emission gas [52]. The benefit of this combination is by directly injecting the fuel. It swirls in the combustion engine, which cools the combustion chamber walls, which overcomes the issue of knocking. This achieves a high compression ratio, which improves the quality of combustion, thermodynamic efficiency, and engine efficiency [51].

Mercedes-Benz as well uses the FSI system, called the BlueDirect. This system has a variety of operating modes, including the homogeneous stratified combustion (HOS) and the homogeneous split (HSP). The HOS mode is the combination of the standard direct fuel injection and the FSI. It first creates a homogenous mixture by injecting fuel in the intake phase while the throttle valve is open. Then by injecting fuel at the compression phase, it achieves an extension of the lean-mixture operation. The HSP mode injects more than 95% of the fuel, which is followed by a small injection before ignition. This mode stabilizes the combustion process, and it is beneficial during difficult combustion conditions [53].

5.2. IC Engine Structures

Changing the structure of the engine makes significant changes in the engine's performance, as well as its fuel consumption. These structures include inline, V, and the flat engine. Comparing similar engine types developed by the US, Japan, and the European countries would give a good understanding of the fuel economy and spec difference and why each company in each country uses their unique structures.

5.2.1. Inline Engine

Inline engines (Figure 9) are engines that have cylinders that are aligned horizontally. This is a typical structure for most vehicle engines, and it can either have four cylinders or six cylinders where six cylinders engines have a higher power output and less vibration.

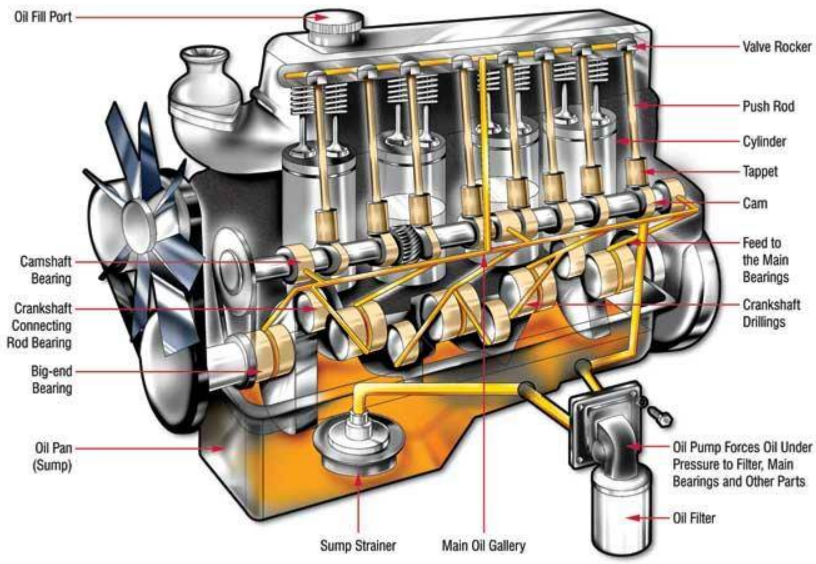

Figure 9. Inline four-cylinder engine [54].

Vehicles with a capacity of 3.0 L or less have a four-cylinder inline engine. This structure's advantage is that it is compact, light, and can easily be manufactured and maintained. However, the disadvantage is that it does not have the right balance, and it has a high center of gravity, which is detrimental to smooth driving [55]. Several subcompact cars in the US, Japan, and European countries use inline four-cylinder engines. The Chevrolet Sonic, Honda Fit, and the Fiat 500 are all gasoline subcompact cars with four-cylinder inline engines. The three engines' capacity is 1.4 L for the Fiat 500, 1.5 L for Honda Fit, and 1.6 L for the Chevrolet Sonic. Though all three cars are subcompact and there are not many differences in their engine capacity and size, each engine's spec varies.

The 2017 Chevrolet Sonic uses the "Four-Cylinder Turbo 1.4 L Ecotec" engine (Figure 10), in which its output power is 138 hp. This engine's fuel economy is 25 mpg for city road and 33 mpg for highway road [56]. The unique feature of the engine is the turbocharger, which inputs more air in the cylinders. This results in producing a more substantial output power [57]. The "Four-Cylinder 1.5 L Earth Dreams Technology" engine used in the 2017 Honda Fit has a power output of 130 hp. The fuel economy is 29 mpg for the city and 36 mpg for the highway [58]. A VVT system called the variable valve timing, and electronic control system (VTEC) is attached to the engine to switch between Otto cycle and Atkinson cycle, which achieves less fuel consumption and reduces emission [59]. When the vehicle is during the Atkinson cycle, the expansion stroke occurs longer than the compression stroke. This achieves higher efficiency and much fewer tailpipe emission [60]. The 2017 Fiat 500 1.4 L four-cylinder engine has a power output of 101 hp. The fuel economy is 31 mpg for the city and 38 mpg for the highway [61]. Comparing these three engines used for subcompact cars, there are significant differences in their specs. The Chevrolet Sonic has the most robust output while it has the lowest fuel economy than the Honda and the Fiat engine. In comparison, the Fiat has the lowest power output but has the highest fuel economy. The spec for the Honda Fit engine is right in between these two engines. Most Japanese and European vehicles use this structure because it fits with their compact cars. Table 1 summarizes the essential characteristics of various inline engines.

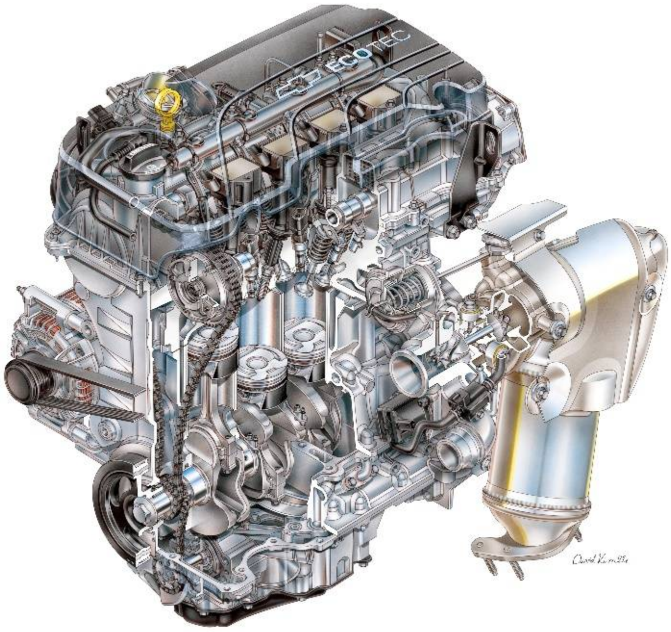

Figure 10. Four Cylinder Turbo 1.4 L Ecotec [62].

Table 1. The essential characteristics of various inline engines.

	Engine Type	Fuel Economy (City/Highway) [mpg]	Horsepower [hp]
2017 Chevrolet Sonic (US)	Four-Cylinder Turbo 1.4 L Ecotec engine	25/33	138
2017 Honda Fit (Japan)	Four-Cylinder 1.5 L Earth Dreams Technology engine	29/36	130
2017 Fiat 500 (EU)	1.4 L four-cylinder engine	31/38	101

5.2.2. V Engine

The V engine is another structure for an internal combustion engine (Figure 11). The benefit of this structure is its compact size and its lightweight. This allows more cylinders to be input, producing higher horsepower and torque output [55]. Another advantage of this engine is that it has a lower center of gravity than the inline engine.

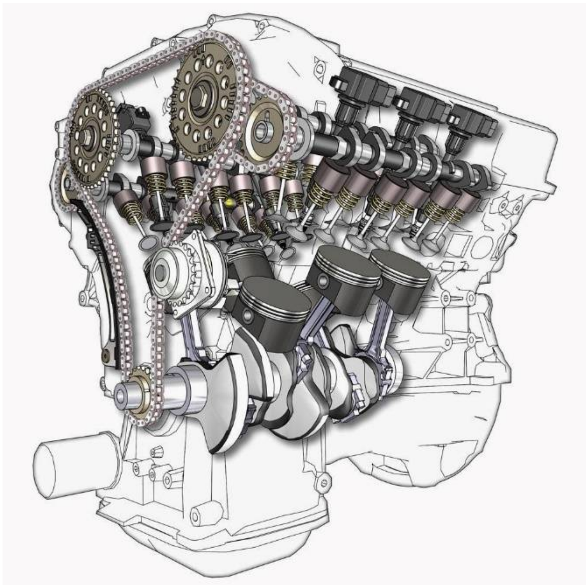

Figure 11. Diagram of the V Six-Cylinder Engine [63].

The V engine's downside is that it is not stable, and it emits a tremendous amount of gas. There are the six-cylinder and the eight-cylinder V engine versions [55]. This engine is usually used for large vehicles, and the engine capacity is equal to or over 3.0 L. Therefore, many American vehicles such as the Ford cars have this engine installed in their vehicle. In contrast, not many Japanese vehicles use this engine because of the low demand from Japanese customers. The Ford F150 "3.5 L EcoBoost Twin-Turbocharged V6", Toyota Highlander, and the Volkswagen Atlas all use the V6 engine. The Ford F150 "3.5 L EcoBoost Twin-Turbocharged V6" (Figure 12) engine produces 375 hp and 400 lb-ft of torque. The fuel economy is 18 mpg for the city and 25 mpg for the highway. The unique technology developed in this engine is the Turbocharger, which produces as much or more torque than the torque that the V8 engine produces.

Figure 12. Ford 3.5 L EcoBoost Twin-Turbocharged V6 Engine [64].

The "3.5 L V6 DOHC Engine" in the Toyota Highlander debuted in the US to satisfy the American consumers. This engine is also powerful, where the horsepower is 295 hp and 263 lb-ft for torque. The fuel economy is 20 mpg for the city and 27 mpg for the highway [65].

The Volkswagen Atlas also uses the V6 engine called the "3.6 L VR6". The engine produces 276 hp and 266 lb-ft, where the fuel economy is 18 mpg for the city and 25 mpg for the highway [66]. Thus, the horsepower and torque are much more powerful compared to the inline engine. The Ford F150 has a potent engine compared to the other two cars. This shows that strong engines are in demand from American customers. Nevertheless, the fuel economy between the three engines has fewer differences. The characteristics of various V engines have been summarized in Table 2.

Table 2. The main characteristics of various V engines.

	Engine Type	Fuel Economy (City/Highway) [mpg]	Torque [lb-ft]	Horsepower [hp]
Ford F150 (US)	3.5 L EcoBoost Twin-Turbocharged V6	18/25	400	375
Toyota Highlander (Japan)	3.5 L V6 DOHC Engine	20/27	263	295
Volkswagen Atlas (EU)	3.6 L VR6	18/25	266	276

5.2.3. Flat Engine

The flat engine, also known as the boxer engine, is a unique structure where cylinders are aligned horizontally evenly facing the opposite direction (Figure 13). The advantage of this structure is that it has a low center of gravity compared to the inline and the V engine, reducing vibration and improving balance that leads to smooth driving. The structure's disadvantage is that it is complex and expensive to manufacture since there are more machine components required [67]. Not many companies put this engine in their vehicle because the vehicles are not designed for the structure. American automobile does not use any boxer engines, whereas some Japanese and European companies use them. The Porsche 911 series and the Subaru Outback have a six-cylinder flat engine.

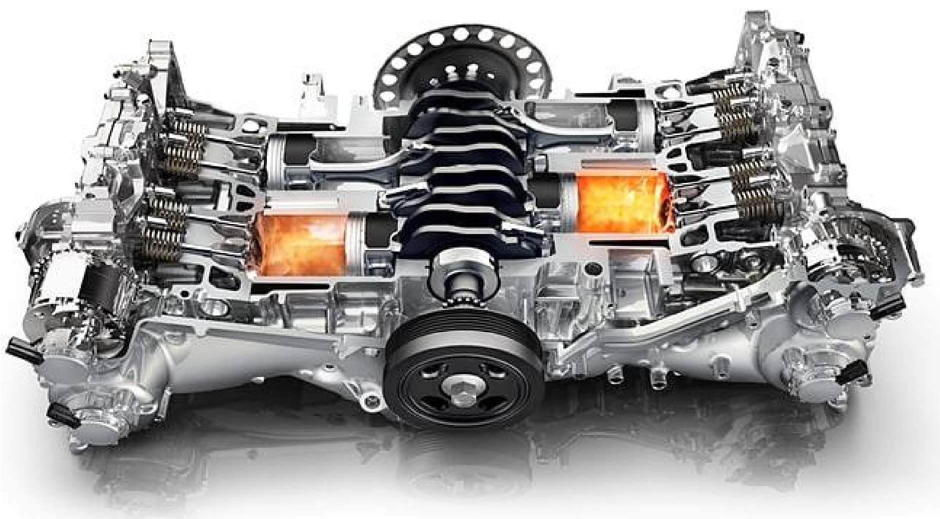

Figure 13. Flat four-cylinder engine [68].

The 2017 Porsche 911 engine, "Six Cylinder Turbo 3.0 L" has a powerful output of 370 hp (Figure 14). This is because the primary purpose of the car is for sports usage. Additionally, the fuel economy is 10 mpg for the city and 29 mpg for the highway [69]. The VarioCam system is attached to the engine to control fuel efficiency and power output.

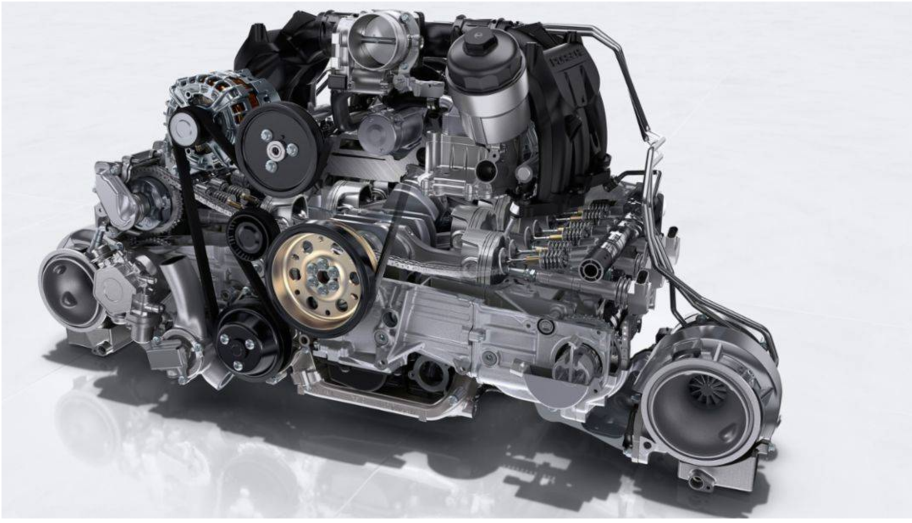

Figure 14. Porsche Six Cylinder Turbo 3.0 L [70].

The 2017 Subaru Outback has a 3.6 L six-cylinder flat engine which has a production of 256 hp. The fuel economy is 25 mpg for the city and 32 mpg for the highway [71]. Flat engines are not a typical structure used in vehicles, and Subaru and Porsche are the leading companies that use this engine. Moreover, using this engine for both companies is different, where Porsche cars with the flat engine are sports cars, and Subaru cars are mainly daily passenger use cars. Therefore, Porsche cars have too high horsepower compared to the Subaru engine, and the fuel economy for Subaru is higher compared to the Porsche flat engine. Table 3 indicates the essential characteristics of various flat engines.

Table 3. The main characteristics of various flat engines.

	Engine Type	Fuel Economy (City/Highway) [mpg]	Horsepower [hp]
2017 Subaru Outback (Japan)	3.6 L six-cylinder flat engine	25/32	256
2017 Porsche 911 (EU)	Six Cylinder Turbo 3.0 L	10/29	370

5.3. Clean Vehicles

To achieve a clean environment, automobile manufacturers are developing their technologies by changing their power source. In 2015, an agreement was signed at the Paris COP21 by 195 nations to deal with climate change to create a sustainable low carbon future [3]. While clean vehicles were developing during the past several years, this agreement was a massive trigger for rapid innovation in the automobile sector. Electrified vehicles, also known as xEV, have been developing and improving very rapidly. xEV includes battery electric vehicles, hybrid electric vehicles, plug-in hybrid electric vehicles, and fuel cell electric vehicles [72]. Manufacturers from the US, Japan, and countries from Europe have been significantly contributing to creating a clean environment while providing a performance that satisfies their customers' demand. Figure 15 demonstrates the world automobile new car sales transition by different powertrain [73].

5.3.1. Battery Electric Vehicles

Today, the battery electric vehicle (BEV) is one of the trending automobile technologies around the world. The main advantage of an electric powered engine is that it produces zero-emission gas [74]. The first electric vehicle (EV) on the road was during the 1800s, but EV declined as soon as the petrol engine vehicle got popular and the number of gas stations increased. During the late 1960s and the early 1970s, there was a gas shortage, which provoked EV [75]. However, because of its expense, a limited number of charging stations, and lack of power supply, it was unpopular [76]. Though this technology has several advantages, it also has a few negative points. Unlike refueling petrol or diesel gas, EVs can take a while to charge their battery fully. At this current stage, finding a charging station can be difficult as well [77]. Figure 16 shows a schematic of a BEV and its main components [78]. Moreover, Figure 17 summarizes the top reasons why people do not buy an electric vehicle [76].

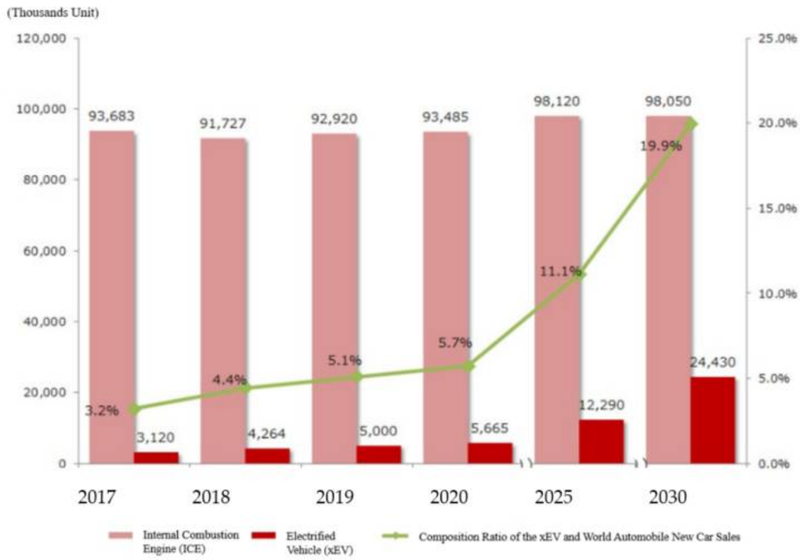

Figure 15. World automobile new car sales transition by different powertrain [73].

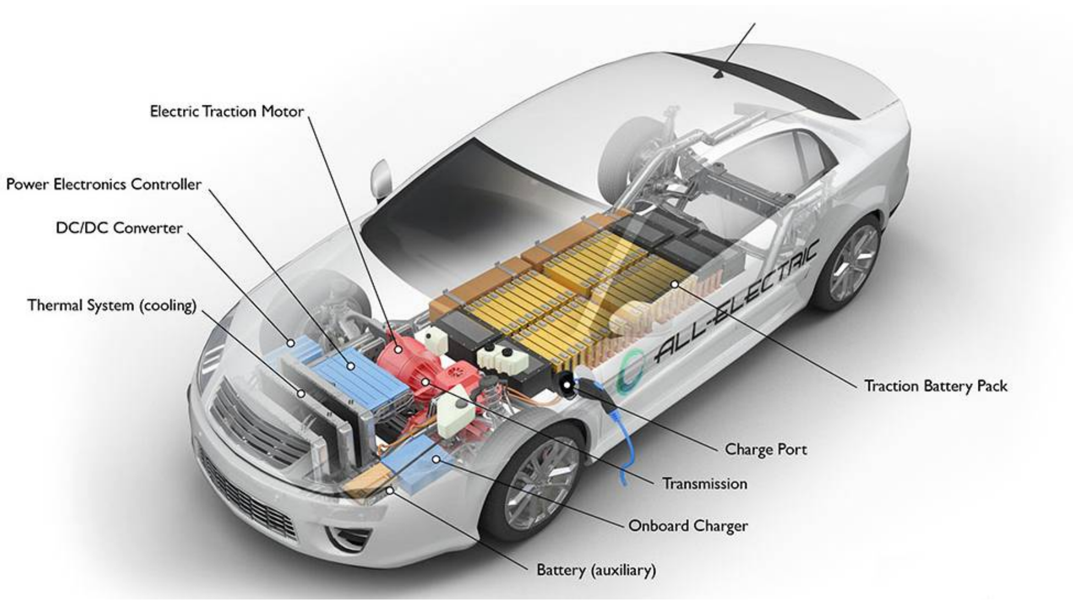

Figure 16. Schematic of a battery electric vehicle [78].

Today, BEV cars have potent batteries. Lithium-ion is mainly used for its battery, which is small, light-weighted, and durable [79]. American, European, and Japanese automobile industries are among the leading countries that contribute to EV technology. The first successful electric vehicle was built in 1890 [75]. The best-known manufacturer producing EV is Tesla due to its limited line-up on electric cars [80]. Tesla built the Model S, which is the world's first all-electric sedan. It is known as the top class EV, driving the most extended range compared to any other electrical car [81]. The vehicle can go up to 402 miles in range, and it can drive 163 miles when charged for only 15 min at a supercharger. It also only takes 30 min to charge 80 percent of the battery. Currently, there are 1971 supercharger stations with 17,467 superchargers located around the world [82]. Compared to the previous model, Model S 100D, it had an almost 20 percent increase in range without changing its battery pack design. They successfully created this long-range EV due to a significant reduction in its mass. Changing the car's design and minimizing the components' weight in the battery pack and drive unit helped achieve this goal [80]. Today, Tesla is one of the largest EV producing manufacturers globally, and their sales and demand are increasing each year around the world.

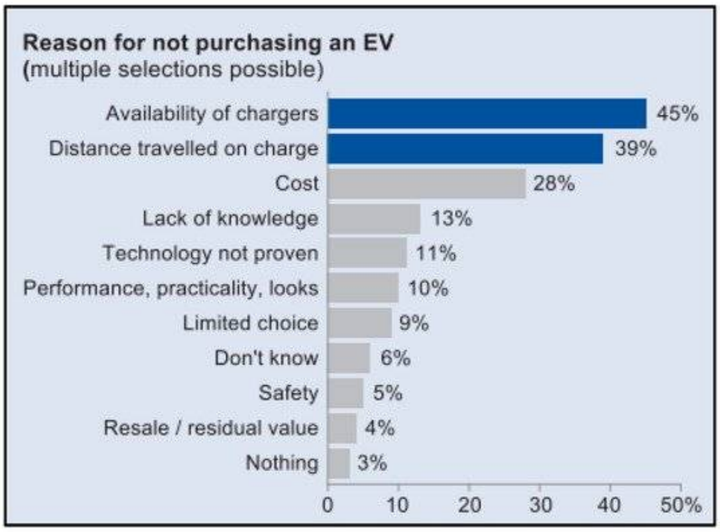

Figure 17. Top reasons why people do not buy an electric vehicle [76].

European industries have actively been improving their electric vehicle to achieve a 100 percent EV society. In one town in France, Renault provided their fully electric-powered car, New ZOE, to every household to experiment and prove that EV can achieve harmonious living. New ZOE can drive up to a range of 245 miles [83]. Though EV produces a small amount of life cycle emissions, it emits zero direct emissions, including CO_2, NO_x, and PM10 [84,85]. It also can be charged by three different methods, which are home wall box, public charge, and DC rapid charger [86]. Another EV from Europe is the family sedan, BMW i3. The battery can be charged within six hours using a BMW Wallbox. It can drive up to 153 miles, where a range extender can be installed, which adds a driving range of up to 200 miles. It produces a power output of 168 hp and a torque of 250 lb-ft. Additionally, the car itself is environmentally friendly, but the plant where the vehicle is produced is also eco-friendly. The BMW Leipzig Plant, where BMW i3 is produced, uses 100 percent renewable energy, and it has been developed such that it reduces its energy usage and water consumption [87].

Currently, not many all-electric cars are produced in Japan due to low demand from customers and the rapid development of hybrid technologies. Nissan Leaf is a popular 100 percent electric motor with a lithium-ion battery, and it is known as the bestselling highway-capable electric car [88]. This vehicle produces no tailpipe emission. The motor has a production of 107 HP, which does not have much difference between the Japanese gasoline inline engine vehicles. In 2010, when Nissan launched the Nissan Leaf, the driving range was 124 miles per charge. However, in 2017, the range increased to 248 miles [72]. The Honda Clarity Electric is also a Japan-made electric car. Though the Clarity series moved to HEV and PHEV in 2020, it is still a competitive electric sedan. The electric battery offers 161 hp and 221 lb-ft of torque. The driving range is 89 miles, which is shorter than most EVs [89]. Several Japanese manufacturers are currently building electric vehicles. Toyota has announced six EV models planned to be launched between 2020 to 2025 [90]. The main characteristics of various BEV engines have been mentioned in Table 4.

Table 4. The essential characteristics of various BEV engines.

	Battery Type	Driving Range (Fully Charged) [mile]	Charging Time at a Fast Charging Station (Up to 80%)
Tesla Model S (US)	100 kWh 400 V lithium-ion	402	30 min
Nissan Leaf (Japan)	40 kWh 350 V lithium-ion	124	40 min
Honda Clarity Electric (Japan)	25.5 kWh lithium-ion	89	30 min
Renault New ZOE (EU)	Z.E. 50 battery 52 kWh lithium-ion	245	1 h 05 min
BMW i3 (EU)	42.2 kWh 352 V lithium-ion	153	35 min

5.3.2. Hybrid Electric Vehicles

(A) Full Hybrid

Hybrid Electric Vehicle (HEV) is a vehicle that is powered by an internal combustion engine and an electric motor (Figure 18). This helps reduce emission gas while giving a better fuel economy without sacrificing its performance [91]. The first hybrid car was invented in 1896 by an Austrian-German engineer, Ferdinand Porsche. He developed a motor which is operated by the battery since petrol vehicles are smelly and noisy. The finalized car was the Lohner-Porsche Elektromobil [92]. Today, it is one of the leading innovations on the road. Batteries, flywheels, and ultracapacitors are mainly used for its power source and storage solution [93]. Adding an electric motor allows for a smaller engine, which results in a lighter weight. There is no need to charge the battery because it is set by the internal combustion engine and the regenerative braking [91].

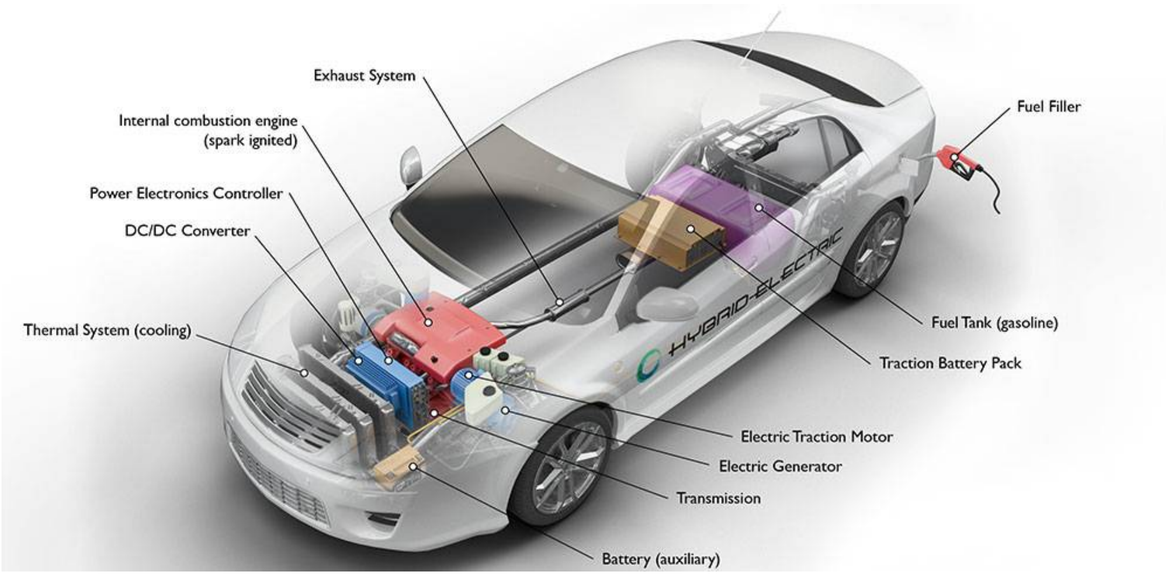

Figure 18. Schematic of a hybrid electric vehicle (HEV) and its main components [91].

Volvo is an example of a European manufacturer that builds hybrid cars. The Volvo hybrid technology reduces fuel consumption and lowers tailpipe emission for both petrol and diesel fuel. It also increases power acceleration by boosting the Integrated Starter Generator, supporting the combustion engine, using recuperated electrical energy. The battery is charged when braking, improving fuel efficiency. The XC90 Twin Engine is one of the Volvo produced vehicles that use this technology. The family SUV can drive up to 24 miles when it is set on Electric mode. The vehicle can be put on Pure mode, powered by the motor consuming as little fuel as possible to achieve a minimal CO_2 emission [94].

The CO_2 emission is about 7 g/km. Similar to the American mild-hybrid technology, it also incorporates a stop/start function, which helps reduce fuel consumption and tailpipe emission. The engine is a four-cylinder diesel twin-turbocharged engine that produces a brake horsepower of 232 bhp [95].

The technology of hybrid cars in Japan became a hit as Toyota developed one of the first HEV markets. The best-known HEV created in Japan is the Toyota Prius [96]. The fuel efficiency for the 2020 Prius is 54 mpg on city road and 50 mpg on highway road. The estimated driving range is 610 miles on city road and 565 miles on the highway [97]. The engine is a 4-cylinder inline engine that produces an output of 121 hp when combined with the electric motor [98]. This is not a powerful car compared to the Ram 1500. However, it is enough to transport the driver since the fuel economy is superb. The Honda Insight LX and EX is also a fuel-efficient HEV. The Atkinson cycle four-cylinder engine with its electric motor provides 55 mpg on city road and 49 mpg on highway road. This is achieved by the selection of ECON Mode [99].

(B) Mild Hybrid

The mild hybrid electric vehicle (MHEV) is a vehicle that assists only its engine. It cannot power the car itself. It has a smaller engine, which leads to a lighter weight, and it is considered cheaper compared to the full hybrid vehicle [100]. Mild hybrid vehicles have a smaller battery than a usual full hybrid car. Therefore, it does not achieve good fuel saving compared to a complete hybrid vehicle. However, it supports its output power by quickly restarting the motor whenever the stop/start system is activated [101].

The American automakers' hybrid cars are successfully improving, where sales increase every year [102]. American auto manufacturers brought in the mild hybrid to achieve a better efficiency without sacrificing any power output loss. An example of this system is the eTorque system developed by Fiat Chrysler. The 2019 Ram 1500 incorporates the eTorque. The battery is as small as a small suitcase. It has either a V6 with an output of 305 hp or a V8 engine with a 395 hp output [103]. The eTorque uses a cold-blowing air-conditioning system to activate the stop/start system. This system operates the vehicle using electric power. Therefore, it has a smooth start, which is hard to detect in the cabin whenever the vehicle restarts. The fuel economy for the V6 engine is 20 mpg for the city and 25 mpg for highway road, while for the V8 engine, it is 17 mpg for city and 22 mph for highway road [104].

European manufacturers mainly produce plug-in hybrid electric vehicles and the mild-hybrid to compete with the Japanese hybrid technology [105]. The Volkswagen eTSI models use the mild-hybrid technology, which has a small electric motor and battery to assist its engine. The motor gains energy as the car brakes and uses it when accelerating to improve fuel efficiency. According to official tests, the first eTSI vehicle has a fuel economy of 49.6 mpg, and the 1.5 L engine produces 150 hp, which emits between 130 to 134 g/km depending on the trim level [106].

(C) Plug-in Hybrid Electric Vehicles

Plug-in hybrid electric vehicles (PHEV) are the combination of BEV and HEV, where they can be powered by its internal combustion engine or the electric motor itself (Figure 19). Therefore, the battery can be charged by plugging it into the electric charger, or it can be charged the same way as HEV charges its battery. The advantage of this vehicle is the fuel economy [107].

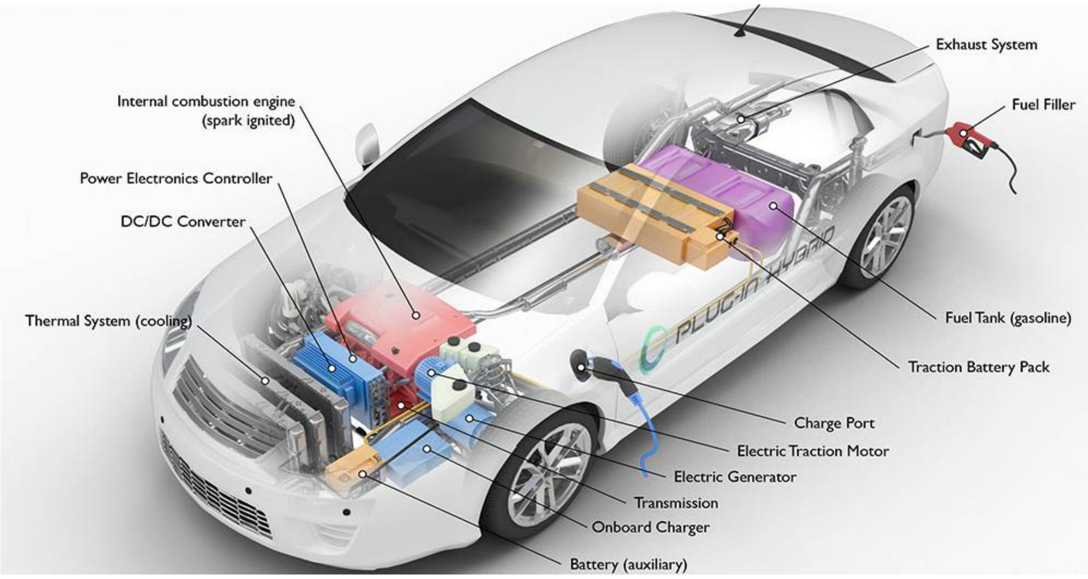

Figure 19. Diagram of a plug-in hybrid electric vehicle (PHEV) and its main components [108].

The development of PHEV in the US has improved drastically. The Chevrolet Volt is one example of the PHEV in the US. The car can drive up to 53 miles with 100% electricity, while when it is in hybrid mode, it can go up to 420 miles [109]. The fuel economy for this car is 43 mpg for city roads and 42 mpg for highway roads. The battery can be charged in approximately 2 h and 15 min when using a 7.2 kW charger. It will take 13 h to fully charge when charging at a 130-volt household outlet, while it takes two hours and 20 min when charging at a 240-volt outlet. The power output of this vehicle is 149 hp [110]. The Ford Fusion is also a plug-in hybrid that helps create a friendly environment and excellent fuel efficiency and performance. The 2020 Ford Fusion has an estimated driving range of up to 610 miles when the vehicle is fully charged with gasoline. The estimated driving range when it is operated with 100 percent electricity is 26 miles. This is less than half the driving range compared to the Chevrolet Volt. The fuel economy is 43 mpg for the city and 41 mpg for highway road while producing a power output of 188 hp [111]. It has an assist called the SmartGauge, which gives driving feedback in real-time, efficiently going for the driver [112]. Drivers can experience three different modes of operation: The Auto EV mode, the EV Now mode, and the EV Later mode. Each mode depends on the amount of electricity used or saved for later usage [113].

The Mercedes-Benz E 300 de is the third diesel-electric plug-in hybrid, where the other two cars are also European, Volvo V60 and Audi Q7. It has four different modes of operation, which are Hybrid, E-Mode, E-Save, and Charge, which is controlled by the car itself [114]. The water-cooled onboard charger's installation can charge from 10 to 100 percent in approximately 1.5 h using a Mercedes-Benz Wallbox. By using other sockets, it will take five hours to charge for the same amount. This car can achieve a zero-emission drive up to 30 miles. When both sources power it, the fuel economy is between 176.6 to 201.8 mpge with a CO_2 emission of 41 g/km. This is also a powerful car that can provide an output of 306 hp. Many systems are put into the vehicle as well to improve its fuel saving. An example is the ECO Assist. This assist gives the precise calculation of when drivers should come off the accelerator [115]. The BMW 330e plug-in hybrid is a sedan that achieves an efficient and excellent driving performance for the customer. It can drive up to 41 miles without any gasoline usage with a 288 hp output [116]. The car incorporates a TwinPower Turbo technology, which increases its system torque by driving its sources together with the electric motor. A convenient system is installed where the nearby charging station will pop up on display and the control system making it easier for the driver to charge [117]. The 2021 BMW 330e PHEV has a fuel economy of 75 mpge, which is about 40% of the fuel economy of the Mercedes-Benz E 300 de [118].

In Japan, the Honda Clarity PHEV was launched in 2018, providing an excellent environmental performance and highly efficient driving. It incorporates a 2-motor hybrid system, the Sport Hybrid Intelligent Multi-Mode Drive (i-MMD), a two-motor system that instantly provides smooth and powerful acceleration. It also has three different modes: EV Drive, Hybrid Drive, and Engine Drive. Like HEV, it shifts between modes as the car decides its performance to achieve a higher efficient driving [119]. During the beginning of the development of the PHEV with Sport Hybrid i-MMD system, it only reached a driving range of 13 miles in EV mode [120]. Many improvements have been made to the vehicle, which now can drive up to 47 miles in EV mode [121]. The engine installed is the 1.5 L Atkinson-cycle DOHC i-VTEC, which results in better fuel efficiency and a high maximum thermal efficiency of 40.5% [119]. The full combined gasoline-electric driving range is 340 miles, where the fuel economy is 110 mpge when powered by electricity and gasoline. Again, because it is a plug-in vehicle, it will take a while to charge the battery, which is 2.5 h using a 240-volt charger to charge fully. The HV mode allows charging, which results in regenerating up to 48% of battery capacity [122]. Honda also achieved in the development of a one-motor system (intelligent Dual-Clutch Drive, i-DCD) and a three-motor system (Super Handling—All Wheel Drive, SH-AWD) [123]. The Mitsubishi Outlander PHEV is also a competitive vehicle, which was the best-selling PHEV in Europe according to the data in January 2018 [124]. This SUV can be driven using a hybrid system, while the battery can be charged using regenerative power. It is one of the first plug-in vehicles with DC Fast Charging [125]. The 2020 Outlander can be charged using a household 120-volt plug overnight or using a 240-volt home charger, which takes under 3.5 h to charge [109] entirely. When it is in EV mode, operated with 100 percent twin electric motors with zero-emission, it can drive up to 22 miles. While Hybrid mode provides additional power, achieving a driving range up to 310 miles [126]. The twin electric motors have an instant acceleration system, which provides an immediate torque offering an acceleration without emitting any gas. The engine can also switch between the Otto cycle, which is for power, and Atkinson cycle, which is for efficiency [127]. The comparison between various characteristics of the HEVs is given in Table 5.

Table 5. The main characteristics of various HEVs.

	Hybrid Type	Fuel Economy While Hybrid Mode (City/Highway) [mpg]
Volvo XC90 (EU)	Full Hybrid	25 (* combined city/highway)
Toyota Prius (Japan)	Full Hybrid	54/50
Honda Insight LX and EX (Japan)	Full Hybrid	55/49
Fiat Chrysler (EU)	Mild Hybrid	20/25 (* V6 engine) 17/22 (* V8 engine)
First Volkswagen eTSI (EU)	Mild Hybrid	45 (* combined city/highway)
Chevrolet Volt (US)	PHEV	43/42
Ford Fusion (US)	PHEV	43/41
Mercedes-Benz E 300 de (EU)	PHEV	51.5 (* combined city/highway)
The BMW 330e (EU)	PHEV	NA/36
Honda Clarity (Japan)	PHEV	42 (* combined city/highway)
Mitsubishi Outlander (Japan)	PHEV	25 (* combined city/highway)

5.3.3. Fuel Cell Electric Vehicles

Fuel cell electric vehicles (FCEV) are vehicles powered by hydrogen (Figure 20) [128]. Hydrogen has been proven as a powerful source of energy. It has been used in powering spacecraft, forklifts, and submarines [129]. This vehicle is more efficient than the internal combustion engine and does not produce any tailpipe gases, and only water vapor is produced. It uses the same technique as the EV, but the difference is that the hydrogen converts electricity. Unlike the other electric cars, FCEV can be fueled in a short time like the internal combustion engine vehicles. It can also charge its battery using the regenerative braking system. The most common type of fuel cell used in an FCEV is the polymer electrolyte membrane (PEM) [128].

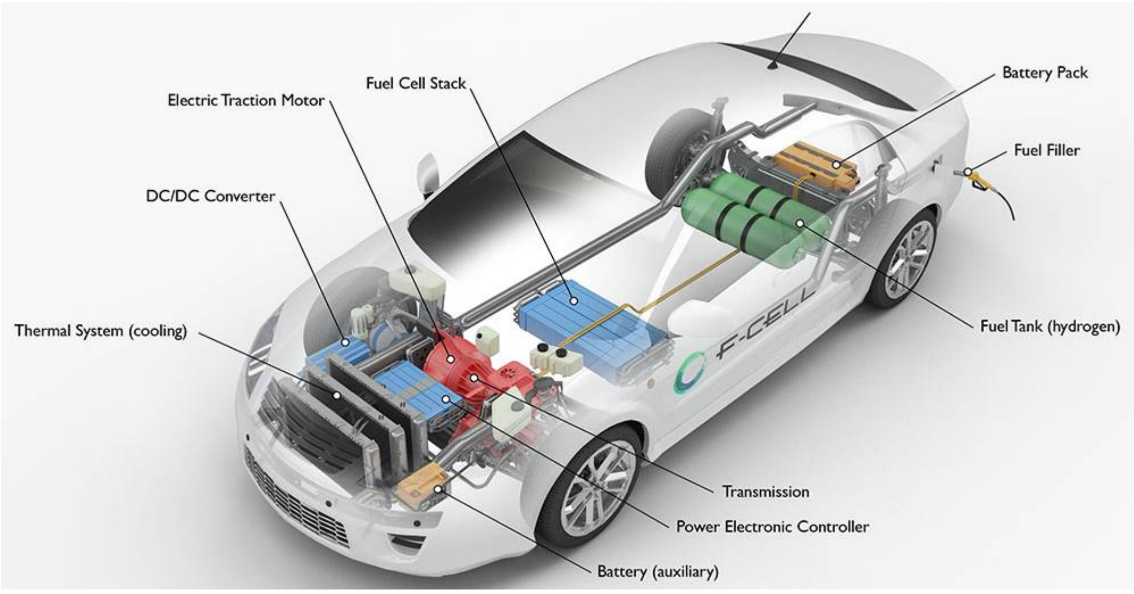

Figure 20. Diagram of a Fuel Cell Electric Vehicle (FCEV) and its main components.

At the end of 2014, Toyota launched the Mirai sedan [130] in Japan. The 2020 Mirai emits zero-emission, and it only takes five minutes to refuel its tank with an estimated driving range of 312 miles [131]. The estimated fuel economy is 67 mpg for both city and highway roads, producing a 153 hp output [132]. This vehicle uses a world-first 3D proper mesh flow channel to generate electricity efficiently. The Toyota Fuel Cell System, also known as TFCS, provide a stable driving environment. For example, they placed the fuel-cell stack, high-pressure hydrogen tank, and other components under the vehicle floor to achieve a low center of gravity. The fuel-cell stack produces a maximum output of 114 kW, and it uses the world's first 3D acceptable mesh flow channel, which helps generate electricity efficiently [133]. Honda also launched Clarity with a fuel cell power source. The 2020 Clarity also does not emit any tailpipe emission. The estimated driving range is 360 miles, which is further than the 2020 Mirai, and it is designed to have minimal wind resistance. The fuel cell activates the electric motor, which creates instant acceleration by converting hydrogen to electricity. The fuel-cell stack is small, which can fit under the hood. As a result, creates a spacious interior for five passengers [134].

In Europe, the Mercedes-Benz GLC F-CELL is the world's first fuel cell system containing a plug-in battery vehicle. This system's feature is that it can be powered only by hydrogen or electricity and emits zero-emission. Therefore, it can be refueled in two different stations: hydrogen station and charging station. Another feature is that it can be operated in four different modes. These are HYBRID, BATTERY, F-CELL, and CHARGE. The system also detects the road condition and decide the percentage of power usage produced by the fuel cell and the battery [135]. The maximum output from the battery is 155 kW, which is higher than the Toyota Mirai. It takes only three minutes to refuel hydrogen, and the driving range during full hydrogen operation is about 248 miles [136]. The battery provides an additional 31 miles [137]. The main characteristics of various FCEVs have been mentioned in Table 6.

Table 6. The main characteristics of various FCEVs.

	Driving Range [mile]	System Maximum Output [kW]
Toyota Mirai (Japan)	312	114
Honda Clarity (Japan)	360	130
Mercedes-Benz GLC F-CELL (EU)	248	155

5.3.4. Other Clean Vehicles

There are several types of electrified vehicles that have been developed to reduce tailpipe emissions. Manufacturers are also developing vehicles that install solar panels. Toyota Corporation is testing its Prius Plug-in Hybrid powered by solar energy with Sharp Corporation and the New Energy and Industrial Technology Development Organization (Figure 21) [138].

Figure 21. Picture of the Prius Plug-in Hybrid with solar cells [139].

They have been testing several times using the solar panel, and it is showing its improvement. The result shows that the new solar panel can produce almost five times the power produced in the previous panel, and seven times more of the range can be driven [140]. The advantage of this type is that its drivers do not need to find a charging station. However, it cannot move far compared to other vehicles with a different power source [138]. It could drive up to 35 miles when the vehicle is driven in BEV mode. The solar panels, a total of about 1100 cells, are mounted on the roof, hood, rear hatch door, and other vehicle parts. Sharp develops its solar battery cells, which are known for its world-class high efficiency. The conversion efficiency is 34 percent-plus. It can deliver 860 watts of power and it can be charged while it is driving [139]. There are currently 33 hydrogen-powered public buses operating in Japan manufactured by Toyota and are planning to increase their number. It is also expected to see more fuel cell buses made by other automobile manufacturers in the future [141].

In 2015, 42% of the total passenger cars in the EU were diesel vehicles. Currently, the emission rate from new models matches the emission standards, but older vehicles do not reach their target. Therefore, European manufacturers are retrofitting the old diesel vehicles to reduce the amount of tailpipe gas emission. One of the strategies is the installation of a diesel particulate filter (DPF) [142]. The DPF is a filter that captures and stores soot, which will be burned off during the regeneration process. However, this system is not suited for people who drive a short distance at a low speed because it blocks the filter [143].

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Another strategy is to install the Selective Catalyst Reduction (SCR) system. The SCR system converts NO_x into nitrogen and water by adding ammonia, such as AdBlue [142]. These new technologies improve the reduction emission rate from a diesel vehicle, and it is available to install these systems in older diesel vehicles.

6. Future Plans

In Japan, eight automobile manufacturers, including Toyota, Honda, and Nissan, one research institution, and several Japanese universities worked together to improve the engine's thermal efficiency and reduce CO_2 emission. The outline of the achievement of the 50% thermal efficiency is presented in Figure 22.

A project called the "Efficient Additivated Gasoline Lean Engine" (EAGLE), created by a European research group, is developing a gasoline engine that will achieve 50% efficiency. To succeed in this goal, they focus on decreasing thermal losses by applying insulation coating, reaching ultra-lean combustion while emitting fewer pollutants, and developing technology to reduce NO_x emission [144]. Furthermore, in Europe, automobile industries announced their plan to release 200 new EV models with better performance and lower cost [145].

Suggestions have been made where the sales for petrol and diesel engine vehicles will be banned within 10 to 15 years. Most vehicles will be shifting to electric vehicles [146]. Electric cars are expected to grow 43.13 percent in growth rate between 2019 to 2030 [147]. Though the average amount of CO2 emission from a passenger car decreases in the United Kingdom, they introduced their target goal of zero carbon emission by 2050. They set their goal by 2035 and are planning to ban hybrid and plug-in hybrid from achieving this target. Several issues need to be solved including the number of charging stations, cost, and battery technology development. Honda and Nissan are planning to withdraw their diesel vehicle production from Europe's market sale by the mid-2020s. They will be aiming to develop electric vehicles to comply with the emission regulations of Europe [148].

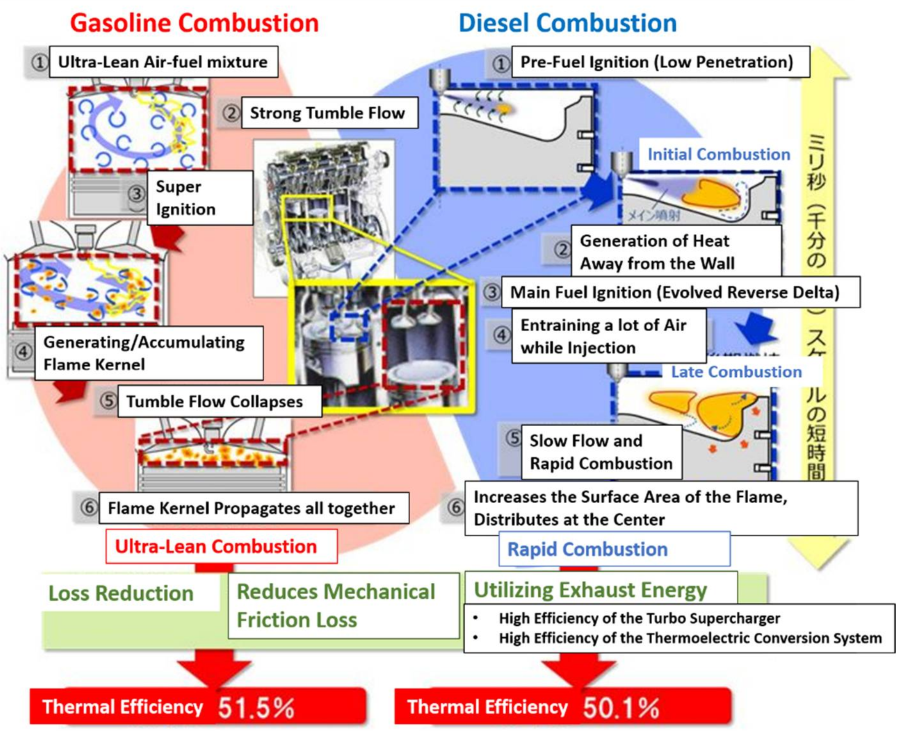

Figure 22. Outline of the achievement of the 50% thermal efficiency [149].

7. Conclusions

Various automobile companies in the US, Japan, and Europe have different features that make their engine unique. This includes developing a modified VVT system, adjusting the engine's structure, and creating a new technology to reduce tailpipe emission. By comparing various engines, it could be understood that American engines are powerful, having high horsepower and torque output compared to Japanese and European engines. This is achieved by using the V engine and by adding additional devices such as the Turbocharger. However, Japanese and European engines are more fuel-efficient, having a higher fuel economy than American engines. To improve fuel efficiency, companies developed and added different VVT systems to their engines.

Additionally, comparing the innovation of EVs, it can be understood that manufacturers from each region are significantly contributing to the reduction of emission gas. The strengths, weaknesses, and several features can be seen by comparing different automobile manufacturers' other models. Due to the strict regulation of tailpipe emission and electric vehicles' development, the characteristics produced in the three regions can potentially become similar to each other. However, like petrol and diesel vehicles, customers from the US, Europe, and Japan have different demands. Thus, manufacturers would be focusing on their production considering the customer demand and the road condition and environment. Manufacturers can focus on the output horsepower or power efficiency and charging time. Comparison between the countries shows that the goal or focus for automobile manufacturers in these countries varies due to their customers' demand, which results in different specs.

Author Contributions: Conceptualization, both authors; methodology, S.E.H.; investigation, both authors; writing—original draft preparation, N.S.; writing—review and editing, S.E.H.; visualization, S.E.H.; supervision, S.E.H. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Acknowledgments: The authors would like to appreciate "Arkansas Department of Transportation" and the higher administration of Arkansas Tech University for their valuable support.

Conflicts of Interest: The authors declare no conflict of interest.

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