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Abstract- **The use of hybrid electric vehicles (HEVs) as an alternative to traditional petroleum-powered cars has risen due to climate change, air pollution, and fuel depletion. The usage of fossil fuels in transportation is giving rise to growing environmental concerns. The transportation sector is the second largest energy-consuming sector that accounts for 30% of the world's total delivered energy and about 60% of world oil demand. In 2008, the transportation sector accounted for about 22% of total world CO_2 emissions. Within this sector, road vehicles dominate oil consumption and represent 81% of total transportation energy demand. This review discusses opportunities to reduce energy consumed and greenhouse gases in this sector and briefly discusses the Hybrid electric vehicles as a solution to improve fuel economy and reduce emissions. Also, the Classification of Hybrid Electric Vehicles, and the General architectures of hybrid electric vehicles and their subtypes have been discussed. Hybrid electric vehicle system components, system analysis, and fuel economy benefits are also explained. As the comparison results proved that the benefits of improved engine thermal efficiency outweigh the losses caused by longer energy transmission paths and showed that hybridization can improve fuel economy by about 24% in typical urban cycles. This study offers a thorough analysis of hybrid electric vehicles, including information on the designs, and energy management systems, created by different researchers. According to the thorough analysis, the current systems can execute HEVs rather effectively, but their dependability and autonomous systems remain not satisfactory. As a result, several variables, difficulties, and issues related to the future generation of hybrid cars have been highlighted in this research.**

Keywords: ***Hybrid electric vehicles; Emission; Internal combustion engine; Gasoline fuel; Diesel fuel; Greenhouse gas emissions***

I. Introduction

Many factors affect the automotive industry and research development such as Global warming, the danger of exhaust gases emissions on the environment and the fossil fuel crisis which supplies are rapidly consumed, so it's expected that the world will run out of energy soon, besides the huge environmental threatening of exhaust gases such as nitrogen oxides, hydrocarbons, carbon monoxides, etc.[1, 2]. The transportation sector is one of the primary suppliers of greenhouse gas (GHG) emissions [3, 4]. The United States Environmental Protection Agency (EPA) reported that CO_2 is the primary GHG emitted through human activity due to fuel burning [5, 6]. So, governments worldwide have to legislate stricter fuel economy and emission regulations. Europe announced the most progressive emissions legislation thus far with an intended target of 95 g of CO_2/km in 2021 [7, 8]. and China set a target of 117 g/ km by 2020 [9].

Automotive manufacturers are taking on many strategies to reduce the usage of fossil fuels to meet these regulations such as raising combustion efficiency, downsized engines, lower rolling resistance tires, powertrain electrification, using lightweight materials that have been developed intensively over past times, and using sustainable and environmentally friendly sources of energy[10-13]. Hybridization is a step toward powertrain electrification. The idea of using a hybrid powertrain dates back to 1898 when Ferdinand Porsche built his first hybrid car, the Lohner Electric Chaise, which was driven by both a gasoline engine and an electric motor [14, 15]. The main purpose of the hybrid powertrain in the early stage was to improve the performance of launching by using the electric motor to assist the internal combustion engine (ICE). Due to the cost and performance limitations of battery packs, hybrid vehicles had not been accepted by the retail market until the late 1990s.

The additional source of power allows for greater flexibility in engine usage while meeting the driver's demand [16]. Moreover, supernumerary systems such as regenerative braking and engine shutdown offer different methods for achieving better fuel economy and emissions reduction. Appropriate energy management among different power sources is essential to exploit the fuel-saving potential of hybrid electric vehicles (HEVs) because it enables appropriate power distribution between the engine and the battery.

Various studies have reviewed the available configurations of the hybrid powertrain, including the powertrain analysis and component location and size as essential factors for achieving better fuel economy and emission reduction [17, 18]. In general, three configuration types are used based on the mechanical connections and power flow among the powertrain components: parallel, series, and Series-parallel multi-mode configuration[19]. Automotive manufacturers apply different configurations as each type has unique strengths and weak points.

The contributions of this paper are mainly twofold: (1) Vehicles energy flow consumption and exhaust emissions restrictions, (2) HEV configurations obtained at the market are comprehensively studied and are divided into three types according to their characteristics: parallel, series, and Series-parallel multi-mode configuration. The mechanism and the advantages and limitations of each type are comparatively discussed.

II. OVERVIEW OF TRANSPORTATION ENERGY CONSUMPTION AND EMISSIONS IN THE WORLD

Energy is consumed in the transportation sector to move people and goods by air, rail, road, water, marine, and pipeline. Road transport includes heavy-duty vehicles, such as large trucks used for moving freight and buses used for passenger travel, and light-duty vehicles such as automobiles, sport utility vehicles, minivans, small trucks, and motorbikes as well as medium. The transportation sector occupied the second largest place in energy consumption in the USA because it consumes about 28% of total delivered energy consumption from 2012 to 2021[20], the industrial sector sets in the first place as can be seen in Fig. 1.

A. Energy consumption by the transportation sector

Globally, energy consumption by the transportation sector accounts for about 30% of the world's total delivered energy[21]. Transportation sector's share of world total liquids consumption is increased from 50% in 2002 to 53% in 2007 and expected to reach 61% in 2035, which is equal to 87% of the total increase in global liquid fuels consumption [21, 22]. Total world liquids consumption, transportation consumption, and other sectors' consumption from 2020 to 2040 are shown in Fig. 2. Road vehicles are consuming most of the transportation oil demand. It represents about 89% of transportation energy demand in 2020. Light-duty vehicles consumed the highest amount of energy (57%) in the world as presented by the previous research [20, 21, 23].

B. Emissions of the transportation sector and GHG emissions standards

The number of vehicles on the road has increased after the Second World War to nearly a billion vehicles and is expected to exceed two billion in the following 15 years[21]. It's expected that about 8.6 billion metric tons of carbon dioxide will be released into the atmosphere from 2020 to 2035 [24, 25].

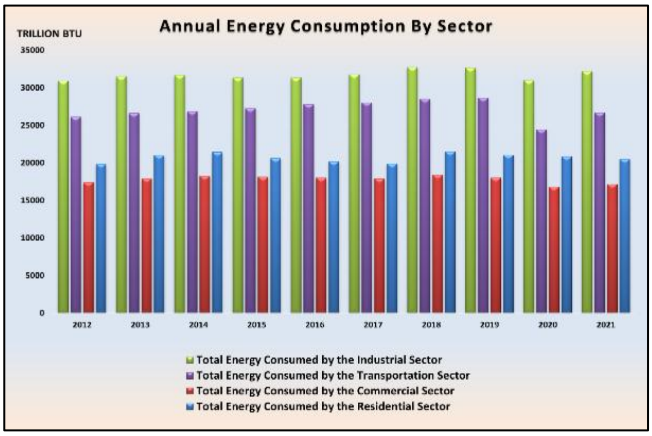

Figure 1. Energy consumption by sector in USA [20].

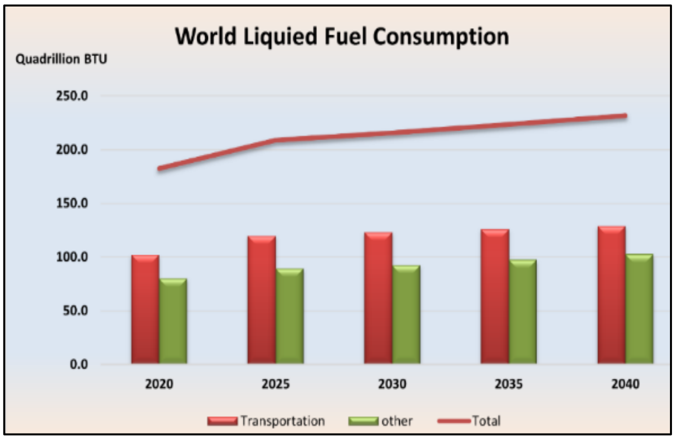

Figure 2. World Liquids Consumption [20]

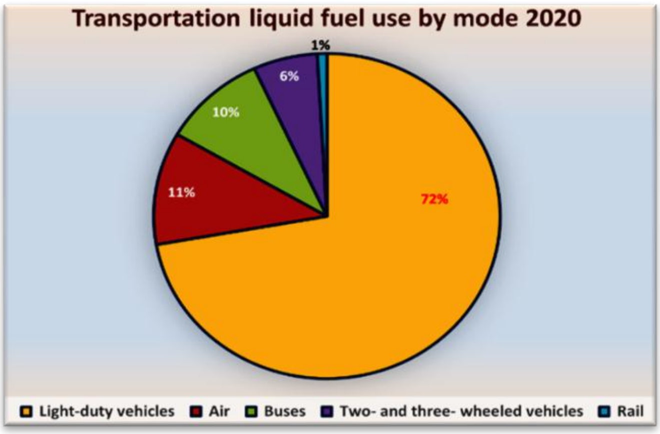

Figure 3. Transportation liquid fuel use by mode [20, 21, 23]

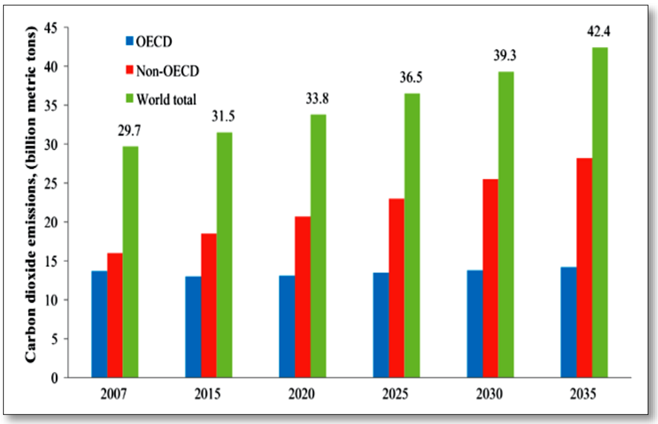

Figure 4. Total world carbon dioxide emissions trend [21]

This is estimated to be increased by about 43% for the projected period. Carbon dioxide emission trends for OECD and non-OECD countries between 2007 and 2035 are shown in Fig. 4. [21]. Carbon dioxide (CO2) is the major GHG emission in the transportation sector, it accounts for 95%. The transportation sector also produces carbon monoxide (CO), and aerosols[26]. But these emissions are not counted as greenhouse gases although they are believed to have an indirect effect on global warming [27]. United Nations' Intergovernmental Panel on Climate Change (IPCC) showed that the Transportation sector was responsible for about 23% in 2004 and 2007 and 22% in 2008 of total world CO2 emissions. Road transportation accounts for 10% of global

GHG emissions. About 45% of Road transportation total emissions have been produced by passenger vehicles [21].

In Europe, the Transportation sector is also responsible for a large share of urban air pollution and noise nuisance also[28]. Moreover, Emissions of greenhouse gases (GHGs) from transport (excluding international transport) increased by 20%, between 1990 and 2001, and an additional increase by about 25% between 2001 and 2015 as shown in Fig.5. [21]. In the USA, in 2008, the transportation sector is the second largest source of GHG emissions after the electric power sector, it accounts for nearly 30% of total U.S. greenhouse gas emissions as shown in Fig.6. [21]. The USA is believed to contribute to about 25% of total world **CO_2** emissions [29]. In USA, carbon dioxide (CO2) grew by about 27.65% from 1990 to 2007, then decreased by about 4.7% in 2008 [20].

In the USA, passenger cars are believed to produce (36%), light trucks produce (19%), heavy trucks (16%), other (11%), aircraft (10%), marine (5%), rail (2%) and buses (1%) of transportation GHG emissions as shown in Fig. 7. [21].

C. *Passenger-vehicle fuel economy and greenhouse gas emission standards*

There are many methods to enhance fuel economy and reduce the **CO_2** emission of vehicles [21, 30]. These methods include: Innovate new technologies and developing the automotive industry, using alternative fuels such as natural gas, hydrogen fuel cells, and advanced biofuels as alternatives to oil [24, 31], and using different power plants such as fuel cell vehicles (FCV) and hybrid vehicles (HEV), legislation vehicle taxation and charges relative to emissions performance and offering motivations for low emission vehicles to inspire investments in emission reduction technologies[32].

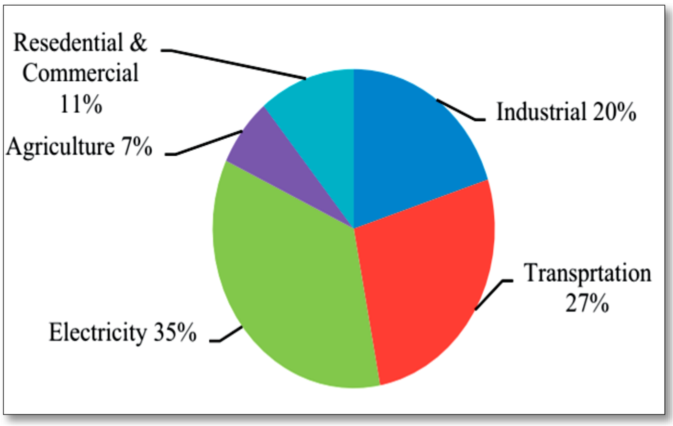

Figure 6. U.S. greenhouse gas emissions by sector [21]

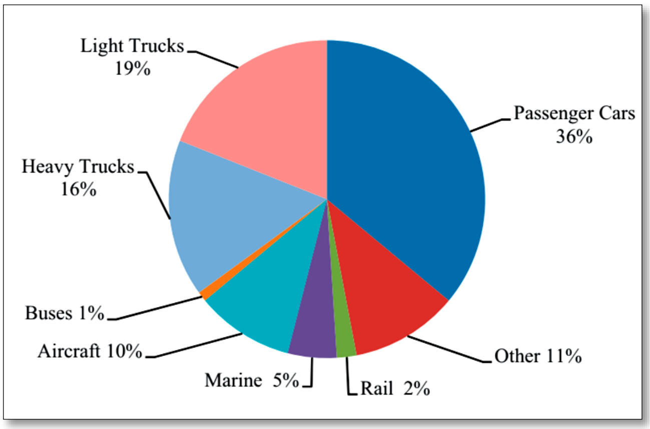

Figure 7. Percentage transportation GHG emissions by mode [21]

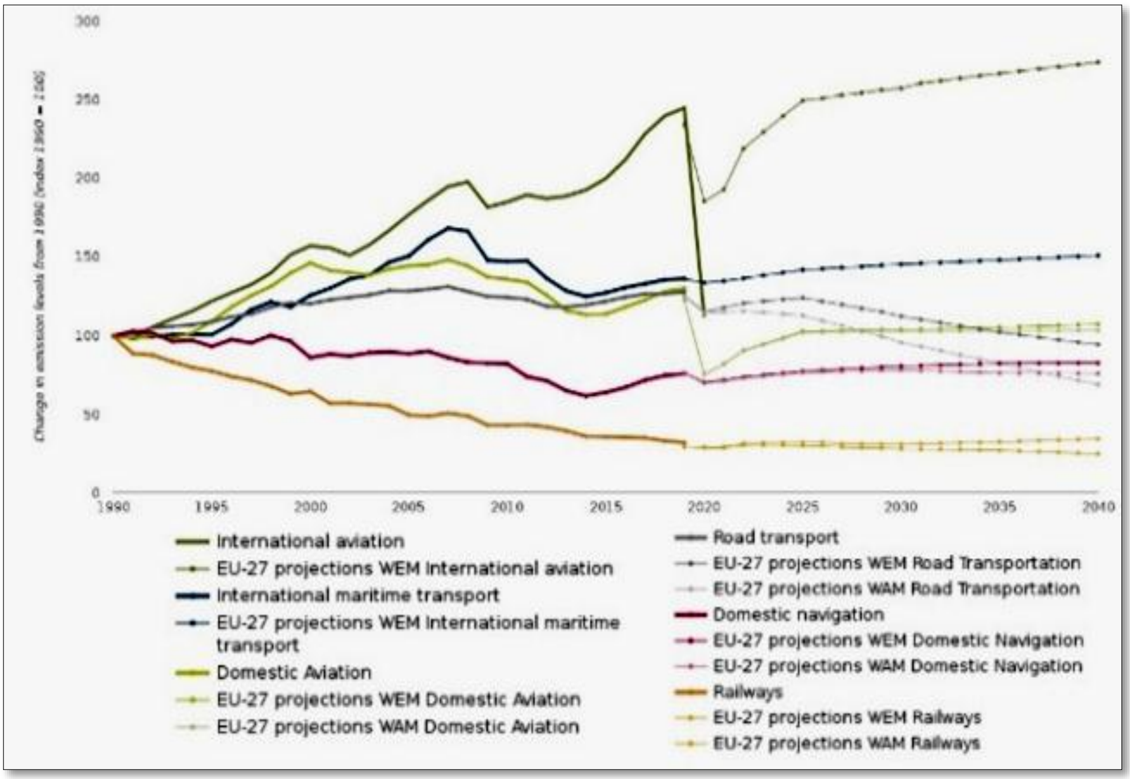

Figure 5. Total greenhouse gas emissions from transport [21]

Table I. Fuel economy and GHG standards for vehicles around the world [30].

Country/region	Type	Measure	Structure	Test method	Implementation
European Union	**CO_2**	g/km	Overall light-duty fleet	EU NEDC	Voluntary
United States	Fuel	mpg	Cars and light trucks	U.S. CAFE	Mandatory
Canada	Fuel	l/100 km	Cars and light trucks	U.S. CAFE	Voluntary
Australia	Fuel	l/100 km	Overall light-duty fleet	EU NEDC	Mandatory
Japan	Fuel	km/l	Weight-based	Japan 10–15	Mandatory
China	Fuel	l/100 km	Weight-based	EU NEDC	Mandatory
Taiwan/South Korea	Fuel	km/l	Engine size	U.S. CAFE	Mandatory

Table II. Comparison of the US, Europe, and Japan FE test cycles [34, 35]

Test cycle	Duration, s	Length, km	Average speed, km/h	Maximum speed, km/h	Max. acceleration m/s2 %	Idle time
NEDC	1180	11.01	NA	120	0.833	23.4
EPA highway	765	16.45	77.4	96.4	1.475	0
EPA city	1371	17.85	31.7	91.3	1.475	17.4
Japan10–15	660	4.16	22.7	73.5	NA	31.4
JC08	1204	NA	24.5	81.6	1.70	NA

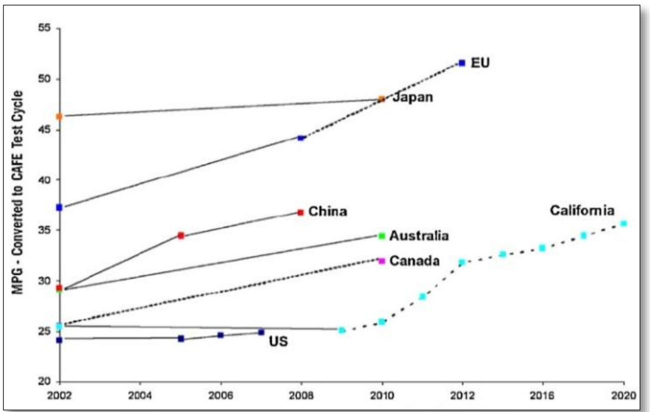

Figure 8. Comparison of fuel economy standards mpg normalized by CAFÉ

Automobile fuel economy standards have proven to be one of the most useful ways to regulate oil demand and greenhouse gas (GHG) emissions in several counties all over the world for the transportation sector[33]. There are main regions around the world that have applied fuel economy and greenhouse gas (GHG) emission standards. These regions include European Union, USA, Canada, Australia, Japan, China, Taiwan, and South Korea. Table I provides a summary of vehicles' fuel economy and GHG standards around the world [21, 30, 34].

D. Fuel economy testing methods

Fuel economy measuring is based on a driving cycle with regulations for testing submission of the vehicles. The driving cycle is planned to represent the real driving model on road. Europe, Japan, and The US have developed their techniques to measure vehicle emissions and fuel consumption. Other countries have applied these testing methods fully or partially with modifications to match their driving conditions. Table II shows a comparison of the US, Europe, and Japan fuel economy test cycles[34, 35].

A new methodology has been developed by Sauer in 2004, to compare different fuel economy and greenhouse gas emission standards around the world to better understand them. They found that Japan and Europe took the lead with the strictest regulations. Japanese standards were expected to be the lowest fleet average greenhouse gas emissions all over the world (125 g **CO_2**/km) by 2015. China also is moving ahead. However, U.S. automobile fuel economy standards took a place after them but could move in front of Canada, Australia, and South Korea up to 2020 [21, 36, 37]. The summary of their findings is shown in Fig. 8.

III. HYBRID ELECTRIC VEHICLES AS A SOLUTION TO IMPROVE FUEL ECONOMY AND REDUCE EMISSIONS

Nowadays most automotive industry companies are interested in the electrical power train and how to use it to get better performance, lower fuel consumption, and more environmentally friendly emission characteristics. But till now electric vehicles are difficulty spreading because of the shortage of electric fast charging stations which need a very high cost to be established. Thus, a Hybrid electric powertrain is a good solution as it is the transient phase between traditional petroleum-fueled vehicles and full electrified vehicles, it uses an electric motor in addition to an internal combustion engine to drive the vehicle and charge batteries with no need to stop the vehicle. Especially for vehicles used in the urban environment where higher accelerations and lower average speeds make the internal combustion engine run at a lower efficiency point, so, the most important property of hybrid vehicle systems is that fuel economy can be noticeably increased to meet increasingly stringent emission standards besides drivability requirements. Thus, hybrid vehicles could play a vital role in saving the world environment and the problem of growing energy insecure needs.

An HEV is a complicated system of electrical and mechanical components. Its drivetrain control problems are complex and usually have conflicting requirements, many design objectives are so difficult to formalize, and many variables which are of major concern cannot be measured. The HEV system control is fundamentally a multivariable problem with many actuators, sensors, and performance variables. It is important to get the advantage of these interactions with multivariable designs; so, multivariable designs may cause less robust parameter variation and uncertainties of control strategies, and it will be more difficult to calibrate.

Earlier, a hybrid powertrain design was used to improve launching performance, as the electric motor was used to assist the internal combustion engine (ICE). Lohner Electric Chaise was Ferdinand Porsche's first car that uses a hybrid powertrain system powered by both an electric motor and a gasoline engine, this car dates back to 1898, but because of the high cost and low efficiency of battery packs, the hybrid powertrain systems had not been succeeded to get a place at the retail market until the late of 1990s[14, 15].

A. Classification of Hybrid Electric Vehicles

To cover most automotive needs, many hybrid electric vehicle concepts have been developed and proposed. Nowadays hybrid electric vehicles can be classified according to the level of electrification, such as micro hybrid, mild hybrid, full hybrid, or plug-in hybrid electric vehicles as well as fully electric vehicles. These types of hybrid electric vehicles are described briefly in the following sections.

The analogous functional block diagrams are shown in Fig. 9, where the mechanical connection (which includes the clutches and gears) is bidirectional while the hydraulic connection is unidirectional. The ability to link the ICE and generator to generate power for solely electric propulsion is the essential characteristic of the series hybrid, whereas the ability to couple the ICE and electric motor to move the wheels is the important feature of the parallel hybrid. The parallel and series hybrids are directly combined to form the series-parallel hybrid. The complex hybrid can provide extra and flexible working phases in addition to the series-parallel hybrid operation[38].

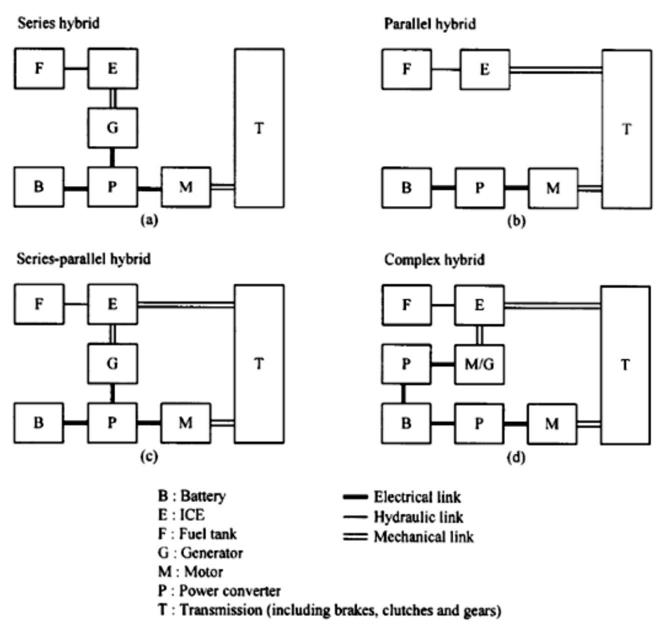

Figure 9. Classification of HEVs [38]

B. Micro Hybrid Electric Vehicles

Micro HEVs are usually operated at low voltages, often between 12 V and 48 V. so, the maximum electric power capability is often about 5 kW [39], and thus micro-hybrid electric vehicles mainly have auto start-stop functions. while braking and idling conditions, the internal combustion engine is automatically shut off, so fuel economy can be enhanced by 5–10% [40] during city driving circumstances. Because of increasing the power capability of a 12 V battery, some micro-hybrid vehicles have several degrees of regenerative braking capability and store the recovered energy in the battery. Most micro-hybrid electric systems are applied by developing the alternator–starter system, as the conventional belt layout is improved, and the alternator is enhanced to have the ability to start the engine and recharge the battery. Valve-regulated lead–acid batteries (VRLAs) such as absorbent glass mat (AGM) batteries and gel batteries are often used in this type of hybrid electric vehicle. Lower cost is the biggest advantage of the micro-hybrid vehicle, while the main weakness is the inability to recover energy through regenerative braking.

C. Mild Hybrid Electric Vehicles

In comparison to micro-hybrid electric vehicles, a mild type of hybrid electric vehicle normally has an independent electric drivetrain that provides about 5–20 kW of electric propulsion power, the operating voltage of the electric drive system is typically between 48 V and 200 V [40, 41]. The electric motor may assist the ICE at aggressive acceleration phases and recover regenerative energy while decelerating phases. Therefore, mild hybrid electric vehicles can optimize fuel economy and vehicle performance improving driving comfort. Mild hybrid electric architecture depends on the degree of hybridization. The belt starter–generator is mechanically coupled with the alternator belt as micro hybrids and the starter generator and mechanically coupled with the engine crankshaft. Lithium-ion and Nickel–metal hydride batteries are the energy storage in mild hybrid electric vehicles. One of the mild hybrid electric vehicles' main characteristics is that the vehicle does not have zero emissions driving mode. Shutting down the engine when the vehicle stops and using electrical power to initially start the vehicle can be optimize engine operational points and minimize engine transients. It saves about 15-20% of fuel consumption [19, 40].

D. Full Hybrid Electric Vehicles

Full Hybrid Electric Vehicles are also called strong hybrid electric vehicles. The electric drive system of full hybrid electric vehicles (HEVs) usually has more than 40 kW of electric power and operates on a voltage level above 150 V [41]. The electric powertrain of a full hybrid electric vehicle can propel the vehicle exclusively when the combustion engine has lower efficiency, and the battery is designed to be able to store the regenerative energy during various deceleration scenarios. These vehicles can be driven in zero emissions mode to meet some special requirements such as driving in tunnels and indoors or silent cruising in certain areas. Full Hybrid Electric Vehicles are widely used as city buses and delivery trucks. In comparison to traditional vehicles, the overall fuel economy of a full hybrid electric vehicle in urban driving could be improved by up to 40% [19, 40].

E. Plug-in Hybrid Electric Vehicle

Plug-in hybrid electric vehicles (PHEVs) merge the characteristics of both full hybrid electric vehicles and all-electric vehicles when charging the battery through a grid AC outlet. The electric powertrain of PHEVs generally has an 80–150 kW electrical power to allow the vehicle to operate in zero emissions mode for a range of 20–60 miles on daily driving routes.

Then the internal combustion engine starts to generate electric power to supply the motor and charge the battery, regenerative braking energy is to improve fuel economy and reduces emissions also. Table III shows a comparison between types of hybrid electric vehicles and their main distinctions.

Table III. Comparison between micro, mild, full, and plug-in HEVs

Function or component parameters	Types of HEV			
	Micro	Mild	Full	Plug-in
Idle Stop/Start	◆	◆	◆	◆
Electric Torque Assistance		◆	◆	◆
Energy Recuperation		◆	◆	◆
Electric Drive			◆	◆
Battery Charging (during Driving)	◆	◆	◆	◆
Battery Charging (from Grid)				◆
Battery Voltage (V)	12-48	48-200	> 150	200-400
Electric Machine Power (kW)	5	5-20	> 40	80-150
EV Mode Range (km)			5-20	30-100
CO2 Estimated Benefit	5-6%	7-12%	15-20%	> 20%

F. General Architectures of Hybrid Electric Vehicles

Hybrid electric vehicles are classified into three major architectures depending on power train configuration and control strategy, hybrid vehicle types are:

G. A Series HEV

The serial type of Hybrid vehicles relies on the electric motor to drive the power wheels, and the internal combustion engine is just coupled with an electric generator that supplies power to the electric motor and charges batteries, Fig.9. shows the configuration of the series of hybrid vehicles [16]. The energy storage system (ESS) charging or discharging is controlled to achieve optimal fuel economy, while the electric motor drives the vehicle realizing vehicle performance requirements. Simply, a series hybrid vehicle is an electric vehicle with a Genset supplying electrical energy when the ESS deficiencies energy to drive the vehicle. the simplicity of dynamic control is the main reason for using this type of hybrid vehicle in a wide range, especially in the category of heavy/medium-duty trucks and shuttle buses[19]. In this type of system, the main function of the Genset is to extend the range of the electric vehicle beyond the range of the battery alone. The series hybrid powertrain is simpler compared with other types, including configuration and energy management[42].

Only a few vehicles in the market use the series configuration of hybrid systems[43]. Lately, some manufacturers have developed electric cars with a range of extended techniques. The most successful model of this type in the market is the BMW i3, which offers a gasoline-powered range extender unit [16, 44]. Another example is the Nissan e-Power, which has a 1.2 L gasoline engine that acts only as a generator to charge batteries[45]. However, high energy conversion losses can occur because all of the engine output must first be converted into electricity. The fuel economy of series HEVs is still better than conventional vehicles. The motor and generator have relatively high efficiency and the ICE operates at a maximum efficiency point[16].

H. A Parallel HEV

In the opposite of a series HEV, a parallel HEV principally combines ICE output power with electric motor/generator output power. The parallel HEV configuration has been shown in Fig.10. [16], both the ICE and Motor/Generator are linked mechanically with the output shaft and can provide power instantaneously to drive the vehicle. The vehicle also can be driven by the electric motor or the combustion engine separately. The maximum power of the electric powertrain is usually smaller than that of the engine powertrain in a parallel hybrid vehicle[46].

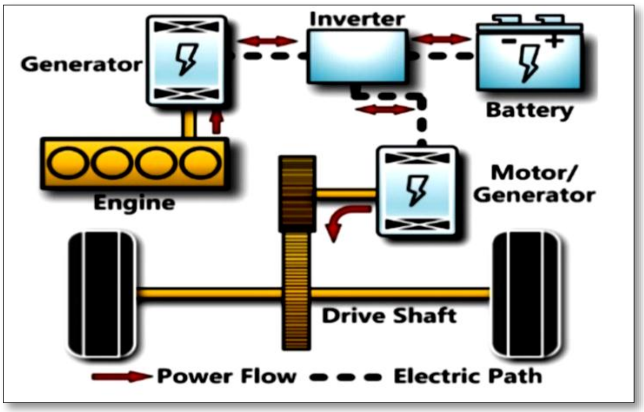

Figure 9. Configuration of series HEV [16].

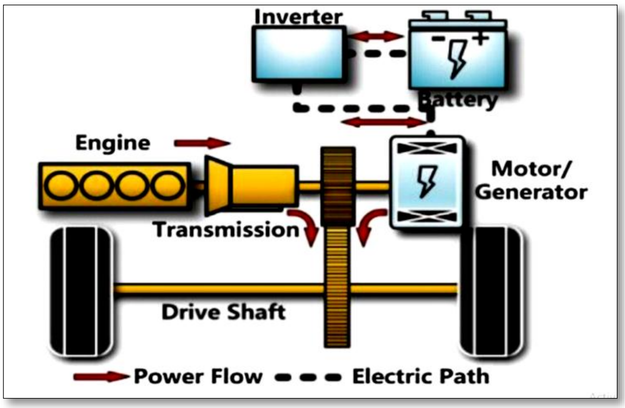

Figure 10. Configuration of parallel HEV [16]

The electric motor and ESS should provide the required power to move the vehicle. In addition, parallel hybrids must include a transmission to be able to supply sufficient torque which can be smoothly and efficiently coupled with the torque of the electric motor to meet vehicle propelling requirements. The engine could be frequently turned on and off in response to the system control strategy. The electric motor works as a generator recharging the batteries during regenerative braking or when the engine produces more power than is needed to drive the vehicle.[19, 47].

The parallel configuration can be deemed as a gradual addition to a traditional powertrain and its design needs little investing and engineering effort relatively. Parallel hybrid powertrains can be categorized into five subtypes according to the Motor/Generator location and size [48]. The P0 Subtype refers to the configuration in which the motor is attached to ICE by a belt. So, it is also known as a belt-driven starter/generator HEV. Due to the torque limitation of the belt, the starter/generator is always small and can achieve only the start-stop function [16, 49]. The P1 subtype refers to the configuration in which the motor is coupled with the crankshaft of the engine. Here, the motor is always described as a combined starter generator (ISG) [19, 50]. The location of the ISG always limits its size; this limitation does not allow the ISG to deliver high torque to operate the vehicle. Only some functions can be achieved such as start-stop, regenerative braking, and acceleration assist. Fig.11. describes Configurations of subtypes P0 and P1 in parallel HEVs.

Subtypes P2 and P3 are the general variations of parallel HEVs. In these configurations, the motor is installed on the input and output of the transmission, respectively. The motor in P2 and P3 is bigger than that in P0 and P1 and can run the vehicle separately at high speeds [47, 51]. A lot of European and Korean auto manufacturers have published P2-type HEVs as the Volkswagen Passat hybrid and the Hybrid Hyundai Sonata and in China, BYD used the P3 subtype in the BYD Qin [16]. Configurations of subtypes P2 and P3 in parallel HEVs are shown in Fig. 12.

The P4 subtype discusses a parallel hybrid in which the motor is attached directly to the drive shaft or is integrated into the hub of a wheel using in-wheel motor technology as shown in Fig.13. P4 is generally not used individually but is combined with other parallel subtypes, P2 and P3, particularly in four-wheel drive (4WD) vehicles [16, 52]. A comparative study through DP [53] also showed that P2 is proved to have better fuel economy than P1 due to its larger motor, and P2 and P3 have similar fuel economy subsidies.

I. A series-parallel HEV (combined type)

To get the benefits of both series and parallel HEVs, the series-parallel Hybrid vehicle is somewhat more complicated and costly. However, this system has been embraced by some modern HEVs, as advanced control techniques that can be applied. A series-parallel Hybrid vehicle can run with just an electric motor, or internal combustion engine or run with a combined strategy of control[54, 55]. Batteries are charged when the combustion engine is ON or by an external charging system. The combined hybrid powertrain system can be developed by adding clutches to a parallel configuration, which can behave as any of the other hybrid configurations with the same powertrain. It is also referred to as the operating mode.

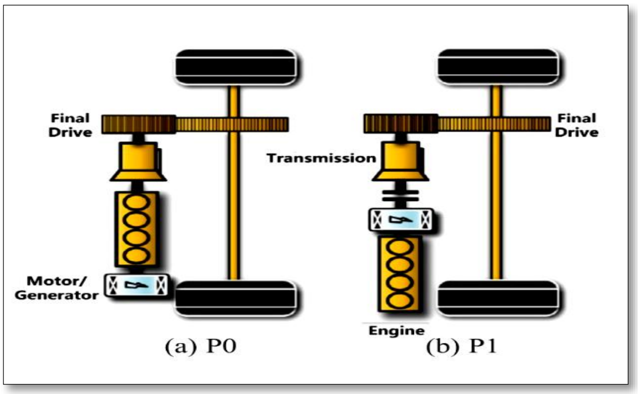

Figure 11. Configurations of subtypes P0, and P1 in parallel HEVs [16]

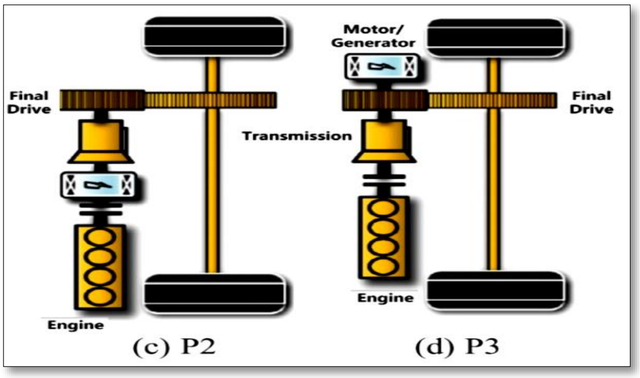

Figure 12. Configurations of subtypes P2 and P3 in parallel HEVs [16]

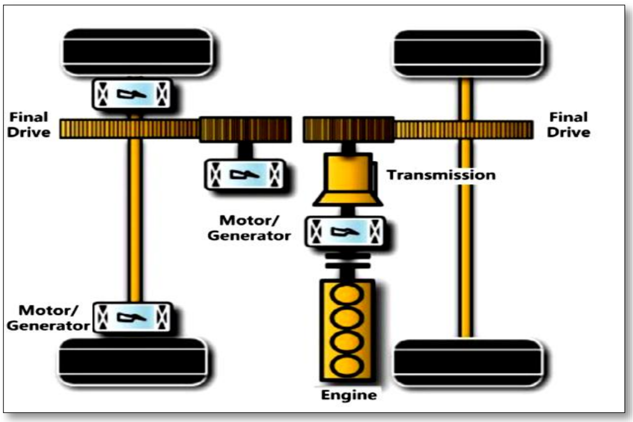

Figure 13. Configurations of subtype P4 in parallel HEVs [16]

The freedom to choose from different modes makes it possible to achieve higher energy efficiency and performance than that realized by using the other HEV configuration types introduced above[56, 57]. The series-parallel type has been shown in Fig.14. The first model of this kind was introduced by Honda in 2014 in its i-MMD system, which is installed in the Accord plug-in hybrid. Two MGs are used in this configuration: One is fully coupled with the ICE, and the other connects directly to the drive shaft [16, 58, 59]. A clutch is employed to disengage the connection between the ICE and output shaft, which enables three operating modes: EV, series, and parallel. The mode shift strategy avoids inefficient engine operation: The EV mode is used when the battery SOC is high, and the series and parallel modes operate only at low and high vehicle speeds. A regular transmission is no longer required to reduce the powertrain cost. Since a mechanical connection still exists between the ICE and the output shaft in the parallel mode, ICE cannot operate in its most efficient area at all vehicle speeds[60, 61].

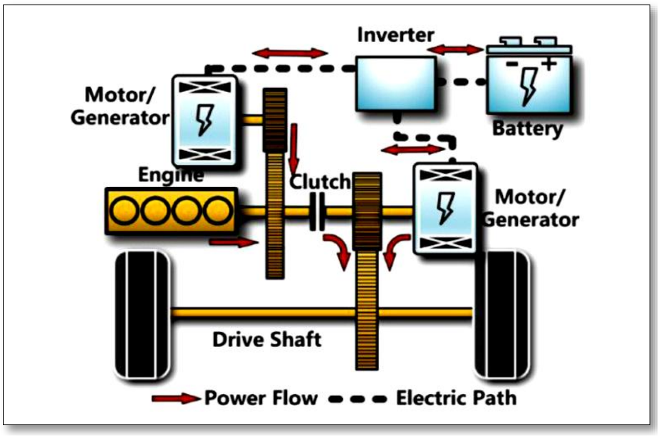

Figure 14. Configuration of series-parallel hybrid powertrain [16]

J. *Hybrid Electric Vehicle System Components*

Batteries, electric motors, and power electronics components such as converters and inverters, and transmission systems are the main components of a hybrid vehicle system. The ESS (Batteries): In hybrid vehicle applications, Batteries must have a high energy density, deep cycle low internal resistance, and long life. Batteries directly affect the performance and efficiency of the vehicle. High power density batteries are mainly used for plug-in HEVs and may have a combination of ultracapacitors that lasts indefinitely and has extremely high charge and discharge rates[62]. For providing the surges required for accelerating an electrically powered vehicle and for accumulating charges during regenerative braking. This combination has advantages of both power and energy density and also decreases the size of the entire ESS. On the other hand, to reduce manufacturing costs, lithium-ion (Li-ion) batteries have been the best choice for hybrid and purely electric vehicles[63].

Transmission: Hybrid vehicle systems carry need specific requirements for transmission design[64]. Generally, it must be able to manage ICE, electric motor, and combinations of both to drive the vehicle. it also must be able to support functions of regenerative braking, auto start-stop ICE, and shifting the operation range of ICE; the transmission must also be able to modify its parameters to match the actual drive scenarios. thus, a hybrid vehicle system primarily relies on the transmission to fulfill an optimal performance for multiple types of drive cycles [65].

Electric motors: Efficient, lightweight, powerful electric motors also play an essential role in hybrid technology. Brushless DC, and (AC) induction motors can be selected for HEVs depending on the design objectives [66]. The electric motor can be used as the main power device, a load-sharing device, or a small transient torque source due to the architecture of an HEV. Electric motors also run well in the 'normal' mode, in which the motor produces constant torque through the rated speed range. Then the motor goes into its 'extended' mode, in which torque decreases with speed. In this [67], the electric motor is mainly designed to provide the necessary torque for sufficient acceleration during its normal mode before it shifts to its extended mode for steady speeds. The second purpose of electric motors is to get the energy of regenerative braking. The electric motors for HEVs need to have the ability to operate regularly as a generator when driven by some external rotational force[68].

The regenerative braking system and control strategy are important technologies to improve the fuel economy of a hybrid vehicle as stop-start urban driving requires frequent acceleration and deceleration. Using the brake pedal in an HEV usually sends signals to the control system for the motor to generate negative torque, turn off the ICE or let the vehicle's energy drive the electric motor via the drivetrain to convert the mechanical energy of the vehicle to electrical energy[69], and then recharge the battery system.

The control system also has to optimize the regenerative braking strength and activate the conventional hydraulic braking system according to the force applied to the brake pedal. Quite a deceleration generally maximizes the use of the regenerative braking system, but sudden braking occasionally needs to operate the conventional braking system[68, 69]. Power electronic components: In addition to energy storage devices, electric motors, and transmission, DC-DC converters and DC–AC inverters are essential components in HEVs. The function of a DC-DC converter in HEVs is to convert the high voltage supplied by the battery kit to a lower voltage, which usually supplies 12 V to different accessories such as headlamps and wipers[70]. The inverter in HEVs is used to convert the DC voltage of the battery kit to a high AC voltage to supply the electric propulsion motor. During regenerative braking, this process is reversed; the AC motor operates as an AC generator, and output power is converted to DC power to charge the battery. The efficiencies of these power electronic components affect the overall efficiency of the vehicle[71].

K. *Hybrid Electric Vehicle System Analysis*

Energy flow analysis is a useful way to refine the improvement of vehicles' energy efficiency. The most popular forms of vehicle energy in the recent commercial market are fossil fuels and electricity, which can be converted into mechanical energy through the power machinery (engine, motor). Then, after a series of conversions, the mechanical energy is moved to the driving wheel, forcing the vehicle to overcome different resistances according to the driver's needs.

L. *Power Flow of Conventional and Hybrid Electric Vehicles*

Hao Dong, Jianqin Fu, et al,[72] measured the various paths of producing energy and the gradual dissipation of energy and calculated the efficiency of the energy passed through the various components. The obtained data described the energy flow distribution and path for the two vehicles, as can be shown in Fig.15, and Fig.16. [72].

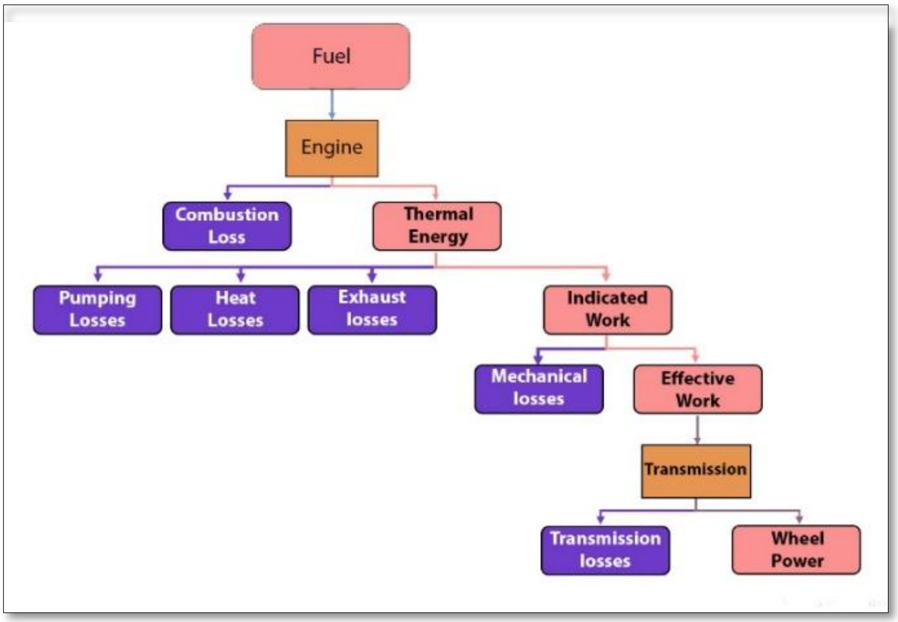

Figure 15. The energy flow distribution and path for conventional vehicles

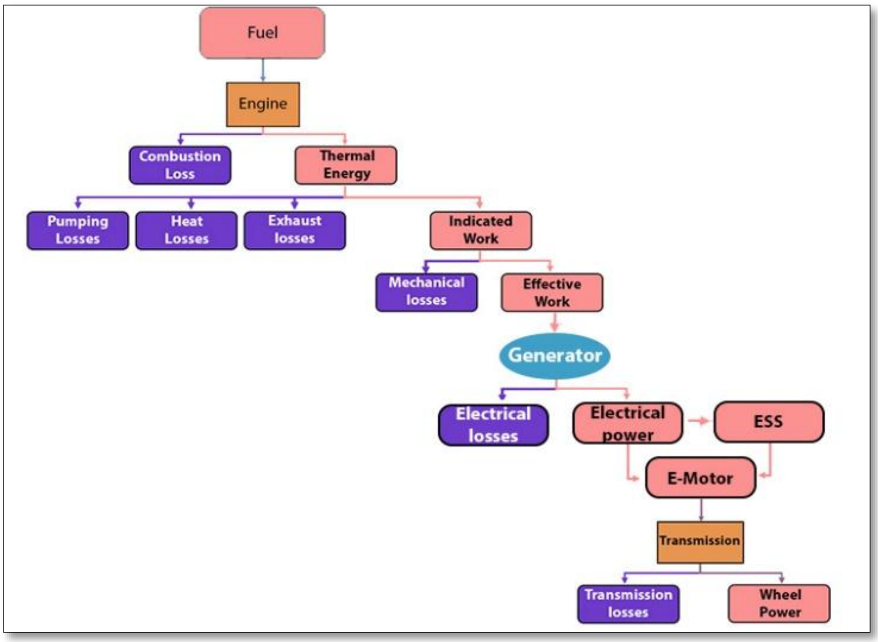

Figure 16. The energy flow distribution and path for PHEV

To expose the energy-saving principles of a hybrid vehicle, a conventional vehicle and a plug-in hybrid electric vehicle (PHEV) with the same internal combustion engine (ICE) is chosen to achieve energy flow test under the New European Driving Cycle (NEDC) of warm start and cold start. Many energy distributions are computed, the variations are compared, and the influencing factors are analyzed. Hao Dong, Jianqin Fu, et al,[72] described test results that showed that the conventional vehicle with turbocharged engine overcharges in conditions that don't need supercharging, and hybrid vehicles could alleviate this phenomenon.

Tested PHEV could reduce the engine working range to a specific limit through powertrain electrification and increase the tank-to-wheel efficiency. This proves that the benefits of improved engine thermal efficiency outweigh the losses caused by longer energy transmission paths. Regenerative braking energy could reduce the claim of effective engine power, which causes better energy saving, so regenerative braking should be used as much as possible on the principle of safety and driving comfort. The use of exhaust waste heat recovery technology can further improve its energy efficiency due to the high amount of exhaust gas enthalpy for the tested PHEV. The energy-saving contribution rates of tested PHEV Compared with tested conventional vehicles under NEDC are -5% for driving conditions, 5% for idling conditions, and 20% for braking conditions respectively. These guides further tap the potential of hybrid vehicles.

Wei Liu [19] discussed different power flow paths for different types of HEV configurations. As shown in Fig.17, the propulsion power comes from the electric motor that converts electrical energy into the mechanical energy needed to move the vehicle in a series hybrid power flow, while the motor can be powered by either the EES or the Genset.

The Genset can either supply the power needed for the electric motor or charge the ESS. In parallel hybrid power flow, the vehicle can be driven by either the engine or the electric motor, or both of them, due to the system state and the control strategy. During regenerative braking for both types, the motor acts as a generator converting mechanical energy into electrical energy to charge the ESS. The battery will provide electrical energy to the generator while cranking the engine.

M. Fuel Economy Benefits of Hybrid Electric Vehicles

Explanation of fuel economy enhancement of a P2-type hybrid electric vehicle to an ICE-only conventional vehicle in typical urban cycles has been shown in Fig. 18. To propel the vehicle in a typical urban cycle, shown by the dotted lines, 4.6 units of fossil energy are required to transfer one unit of energy to the wheels [19], when assuming that the conversion efficiency of fossil fuel energy to mechanical energy is about 28% for an ICE, the transmission efficiency is 85%, and the final drive efficiency is 92% in the conventional powertrain. 60% of the energy at the wheels is depleted by drag force and rolling resistance and only 40% is converted into kinetic energy and finally exhausted by braking in urban cycles [73]. Although the increase in the overall mass of a hybrid vehicle has the same performance as a conventional vehicle, the hybrid vehicle needs 1.05 units of energy at the wheels. But regenerative braking in a hybrid electric vehicle can recover most of the kinetic energy consumed by brakes in a conventional vehicle. Fig. 18 shows by the dashed line there is 0.3 of a unit of energy reaches the motor/generator shaft by regenerative braking and about 0.26 of a unit of energy stored in the battery if the efficiencies of the motor/inverter and the battery are assumed to be 92% and 96% respectively.

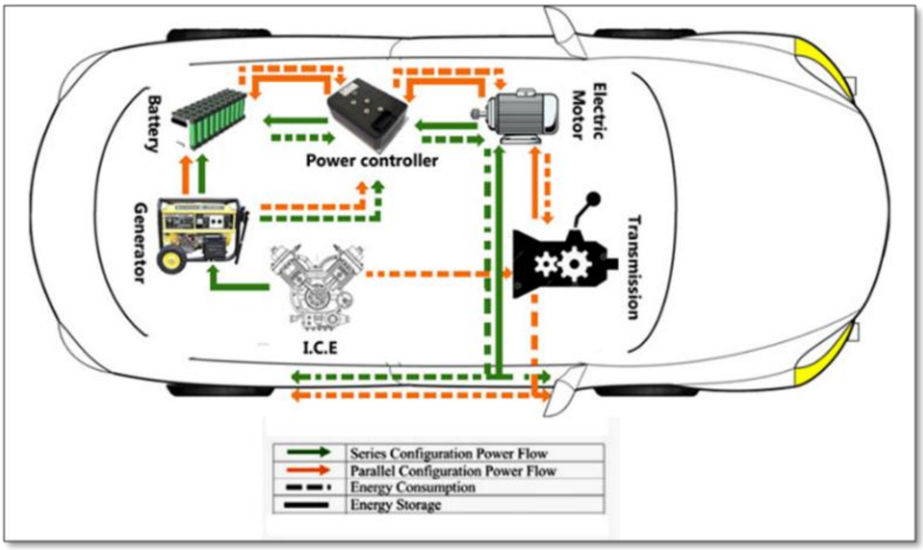

Figure 17. Power flow of a series and parallel hybrid electric vehicle

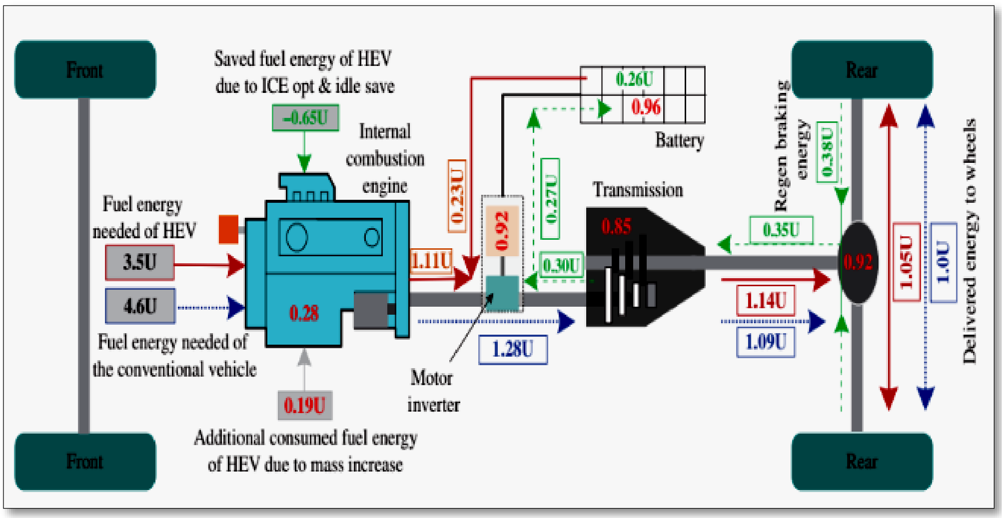

Figure 18. Typical urban cycle energy flows of a conventional powertrain and a hybrid electrified powertrain [19].

Further, the second source of electrical power offers the ability for the ICE to operate at optimal states and shut down the ICE when the vehicle is stopped, which saves about 0.68 of a unit of fossil fuel energy[74]. Generally, hybridization can improve fuel economy by about 24% in typical urban cycles, as shown by the pale grey line in Fig. 18 [19]. The actual fuel consumption of conventional vehicles and their emissions can be directly measured. Since HEVs, especially plug-in HEVs, can use an external electrical source (for example the public grid), the electrical energy extracted from that source must be individually accounted for to perform fuel consumption and emissions calculations.

N. Vehicle Drivability

Drivability can be defined as the ability of a vehicle to deliver the torque requested by the driver at the expected time. It is often evaluated individually but can also be calculated through accelerometers. Problems such as hesitation, powertrain irritation during acceleration, and deceleration are identified in this attribute. Hybrid vehicles have more operational modes compared with conventional vehicles [75]. The transferred torque is not only linked with the states of the internal combustion engine (ICE), the electric motor, and the battery but also with the energy management strategy governing how to divide needed power between the ICE and the electric motor.which makes it a challenge to evaluate an HEV’s drivability[76].

O. Controls of Hybrid Electric Vehicles

While a hybrid vehicle is a complex structure of electrical and mechanical components, which contains different technologies, modern control system methodologies and techniques are playing vital roles in hybrid technology. An HEV’s performance has been affected by many related aspects; therefore, advanced control strategies could drastically improve the performance and low down the cost[65]. The overall control purpose of a hybrid vehicle is to maximize fuel economy and enhance emissions. To achieve these objectives, some major system variables must be managed optimally, these variables mainly include the system energy flow, energy and power accessibility, temperature of subsystems, and finally engine and electric motor dynamics[76]. Some typical HEV control issues are as follows:

- Make sure the ICE works at the optimum operating points: Each ICE has the best operating points on its torque-speed plane in terms of fuel economy and emissions [27]. When the ICE operates at these points, maximum fuel economy and minimum emissions can be achieved. Verifying that the HEV’s ICE operates at these points under different operating requirements is a challenging control objective.
- Minimize ICE dynamics: Because an ICE has inertia, extra energy is consumed to produce the related kinetics when the operational speed changes. Thus, the operating speed of the ICE has to be steady as much as possible and any rapid variations should be prevented[76].
- Improve ICE operational speed: According to the working basis of an ICE, fuel efficiency is low when the ICE runs at a low speed. The ICE speed can be separately controlled with the vehicle speed and can even be shut down when its speed is lower than a certain value, to get maximum benefits[57].
- Minimize ICE operating duration: The ICE in an HEV can be frequently turned on and off as it has a secondary power source; besides, the times at which the ICE is turned on/ off can be controlled based on an optimal control method to reduce fuel consumption and emissions.
- Optimally manage battery state of charge (SOC): The SOC is in needs to be controlled to be able to provide sufficient energy to drive the vehicle and store the energy of regenerative power during braking or while moving downhill to maximize battery service life. The easiest control strategy is to stop the ICE while high SOC of the battery and turn the ICE on when the SOC is low. Another more advanced control strategy will be able to adjust the output power of the ICE based on the actual SOC level of the battery[68].
- Improve power distribution: an HEV has two power sources, that's why splitting the vehicle's power demand between the ICE and the electric motor based on the driving mode is the most challenging and important control task, to achieve the best fuel economy, and minimum emissions[73].
- Ability to achieve zero emissions policy: In some areas such as tunnels or workshops, HEVs may require to be operated in the fully electric mode[77].
- Optimal use of the HEV transmission system: The recent Hybrid Electric Vehicle systems have the features of the parallel hybrid and also incorporate unique advantages of the series hybrid. The key to this implementation is to use an advanced transmission system that provides more than a mechanical transmission channel across the clutch control. In midtown driving, the HEV system extremely uses the advantage of a series hybrid. The needed power is simultaneously produced by the ICE and the electric motor when full-throttle acceleration is needed, but the ICE is operated at a steady speed as much as possible. While the vehicle is normally driven, the power is collaboratively supplied by the ICE and electric motor to the wheels.
- This article describes how hybrid electric vehicles (HEVs) have evolved and how they may be used in the Egyptian market. The purpose of this study was to examine the various advantages and disadvantages of the HEV system. The HEV is a great way to increase the sustainability of transportation. However, the government's drive for electric cars (EVs) will dramatically rise as a result of its need to adhere to strict emissions regulations.

IV. Final Remarks

This paper described the transportation share of energy consumption and how this affects on fossil fuel energy crisis and described the share of global emissions. Hybrid electric vehicles are a good solution to reduce the use of fossil fuel due to their higher efficiency and it is recommended to be widely used.

- The purpose of this project is to introduce hybrid electric vehicle technology as a low-cost alternative to the Egyptian market.
- This research stresses the significance of taking into account the charging patterns and time-varying resolution of emissions from HEVs.
- The comparative fuel savings benefits of HEVs over regular ICE cars were comparable to those found in laboratory tests. Under urban driving circumstances, with low speeds and random traffic, the benefits of HEVs are more visible.
- The findings of this study demonstrate that incorporation of the HEV might improve urban air quality while meeting the CO2 reduction objective.

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Conflicts of Interest:

The authors do not have any conflict of interest.

V. ABBREVIATIONS AND SYMBOLS

ICE, internal combustion engine;
GHG, greenhouse gas;
EPA, Environmental Protection Agency;
HEVs, hybrid electric vehicles;
CO_2, Carbon dioxide;
CO, Carbon monoxide;
IPCC, Intergovernmental Panel on Climate Change;
FCV, fuel cell vehicles;
VRLAs, Valve-regulated lead–acid batteries;
PHEVs, Plug-in hybrid electric vehicles;
ESS, The energy storage system;
4WD, four-wheel drive;
NEDC, New European Driving Cycle;

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