Drive Cycle Analysis of the Performance of Hybrid Electric Vehicles

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Abstract. This paper presents a drive cycle analysis of hybrid electric vehicle power train configurations. Based on fuel economy and emissions factors, a tradeoff between conventional, series hybrid, parallel hybrid, and a parallel-series hybrid is drawn. The operational characteristics of conventional and hybrid electric vehicles are evaluated from the standpoint of fuel economy and emissions. First, models are formed for conventional, series hybrid, parallel hybrid, and series-parallel hybrid vehicles. Then, the models are simulated for fuel consumption, powertrain average efficiency, and emissions using drive cycles containing target speeds in predefined patterns. The simulation results signify that hybrid electric vehicles achieve lower fuel consumption and emissions. Finally, the powertrain configurations that are suitable for city and highway driving are determined.

Keywords: Hybrid electric vehicles, modeling and simulation, fuel consumption, emissions.

1 Introduction

With the population now growing, the demand for petroleum continues to increase whilst oil supplies remain finite. At some future date, conventional oil supplies will no longer be able to satisfy the global demands. The oil production will peak and then commence to decline. There is no certainty when the peaking will occur, but it has been forecasted that it could happen soon [1]. According to a report in 2006, 80 million barrel petrol is used per day. The transportation section consumes 66% of this petrol and the portion of the land transportation is 56% of this quantity [2]. Consuming this amount of fuel continues to aggravate the environmental issues.

Consequently, when it comes to energy security and climate change concerns, cars and trucks are considered one of the principal problems. They consume relatively a big portion of the oil in the world and emit a large amount of greenhouse gas (GHG). To overcome these problems, policymakers try to find solutions so that energy efficiency and emissions could be brought into focus at the United Nations Climate Change Conference in Copenhagen [3].

In response to the increase in the impacts of the vehicles on the environment and energy security, improving fuel efficiency can play a massive role. There are many techniques to improve the efficiency in vehicles. Over the past few decades, there has

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been significant development in automobile engine and body technology. Thus, there are little gains achievable in fuel economy through vehicle engine and body. This has resulted in the emergence of innovative technologies for automotive industry. Since pure electric vehicles do not have adequate source of energy for propulsion in relatively long distance ranges, and because their recharging process requires several hours, hybrid electric vehicles (HEVs) can be considered as alternative means of transportation. In comparison with conventional vehicles, fuel economy and reduced emissions have improved in HEVs [4-6]. As the HEV technology is considered as a successful solution to address some energy efficiency and emissions concerns about vehicles, by 2035 almost 80% of all vehicles introduced to the market will be hybrids, diesels, or turbocharged gasoline engines [3, 7-9]. An HEV enjoys a combination of at least two power sources whilst a conventional car employs only one source of propulsion. Although HEVs have made it possible to improve fuel efficiency and reduce emissions, considerable energy effectiveness can be achieved also with driving profile, environmental effects, driving behavior, control strategy as well as drive train configuration.

The energy efficiency in vehicles can be investigated in two parts: (i) efficiency of fuel making process and fuel distribution system (well-to-tank efficiency-WTTE), and (ii) efficiency of the vehicle itself (tank-to-wheel efficiency-TTWE). Without considering the plug-in HEV option, improvements in "tank-to-wheels efficiency directly correspond to improvements in well-to-wheels efficiency" [10]. Table 1 shows the efficiencies in two categories of vehicles. It reveals the importance of TTWE and its impact on total efficiency.

Table 1. Fuel efficiency of different vehicle configurations [11]

	WTTE%	TTWE%	Total Efficiency
Conventional car	88	16	14
HEV	88	37	32

Simulation and computer modeling can be implemented to decrease the expense of a product from design to prototype and mass production. The interest in HEVs has generated a number of simulation software programs such as simple electric vehicle simulation (SIMPLEV) [12] from the DOE's Idaho National Laboratory, MARVEL and PSAT from Argonne National Laboratory, CarSim from AeroVironment Inc., JANUS from Durham University, ADVISOR from the DOE's National Renewable Energy Laboratory, Vehicle Mission Simulator [13], and others [14]. Among these software tools, PSAT and ADVISOR are more popular than the others. PSAT is a look forward simulator. It allows the user to model more than 200 predefined powertrains including conventional, pure electric, fuel cell and all the types of hybrid. The features such as control strategies including the propelling, breaking, and shifting strategies make it more accurate to predict the fuel economy and vehicles performance. In this study, PSAT is used to model and simulate the devised configurations. The contribution of this paper is the determination of the configuration of HEVs that is more appropriate for city driving and the configuration of HEVs that is more suitable for highway driving.

2 Hybrid Electric Vehicles

An HEV is a complex system consists of many components. The necessary propulsion energy is generated and converted in some of these components which are known as powertrain or propulsion system. The ways of arrangement of these components determines the configuration of a powertrain. There are a vast range of feasible configurations for an HEV. However, based on the configuration of powertrain it can be classified by series hybrid, parallel and series parallel hybrid.

2.1 Series Hybrid

In this type, which has the simplest topology, the vehicle acts like an electric car with an on-board generator as a battery charger. When driving at slow speeds, the controller draws power from the batteries to drive EM. In this case, the vehicle acts like a pure electric car. During acceleration, the internal combustion engine (ICE) drives the generator to compensate the power being drawn from the batteries. The generator provides power to run EM, and if necessary, additional power may be drawn from the generator to recharge the batteries. The energy from regenerative braking is converted into electricity and stored in the batteries. Since ICE is not coupled to the wheels, it operates in a narrow region at near optimum efficiency [15]. In this type, clutch and multi-speed transmission is omitted, so in comparison with a conventional vehicle, the fuel economy is increased and the emissions are decreased. Fuel economy of the series hybrid is dependent on road load and is investigated in this study.

There are two stages of energy conversion during power flow to wheels, ICE/generator and battery/motor. These conversions cause a loss of energy. This issue is considered as a drawback for the series hybrid in comparison with parallel hybrid, thus making it more suitable for city driving.

2.2 Parallel Hybrid

Depending on how the electric motor contributes in the vehicle propulsion, parallel hybrid can be divided to three groups: micro hybrid, mild hybrid and full hybrid.

In micro hybrid, the vehicle has an electric motor but it does not supply additional torque when ICE runs. In other words, the electric motor does not contribute to propulsion. The electric motor provides functions such as starter/alternator, managing engine on/off, auxiliary loads, and the use of regenerative braking in order to charge the battery. Fuel economy of the micro hybrid is reported in the range of 5% to 15% [16].

In mild hybrid, EM contributes to providing supplementary torque to ICE, but it is not the only source of propulsion. This system also supports features such as starter/alternator, managing engine on/off, auxiliary loads, and the use of regenerative braking in order to charge the battery. Fuel economy of the mild hybrid is reported in the range of 15% to 25% [16].

In full hybrid, which is also called parallel hybrid, both ICE and EM are capable of producing the force that is need for the propulsion system. This approach eliminates the generator that is used in the series HEVs. In parallel HEVs, there are different ways to configure the transmission system. When ICE is on, the controller distributes the energy between the propulsion and the energy storage system. The split of energy between the two is determined by the speed and the driving pattern. For example, under acceleration, more power is allocated to the drivetrain than to the energy storage system. During the periods of idle or low speed, more power is allocated to the batteries than the propulsion. When ICE is off, the parallel hybrid can run like a pure electric vehicle. The batteries provide additional power to the transmission when ICE is unable to produce enough energy to run auxiliary systems such as the air conditioner and heater.

Similar to other types of HEVs, energy can be saved during regenerating breaking. The significant advantage of the hybrid is that less energy is wasted during conversion stages. It has been shown that fuel economy in the parallel hybrid is 4% better than that of the series hybrid [4]. However, fuel economy is dependent on road loads. Fuel economy of the parallel hybrid is reported around 40% [16].

The main drawback of the parallel hybrid is the complexity of its transmission and control system.

2.3 Series-Parallel Hybrid

In this type, the advantages and complications of both series and parallel hybrids are combined. The engine can both drive the transmission directly (as in the parallel HEV) and be effectively disconnected from it (as in the series HEV).

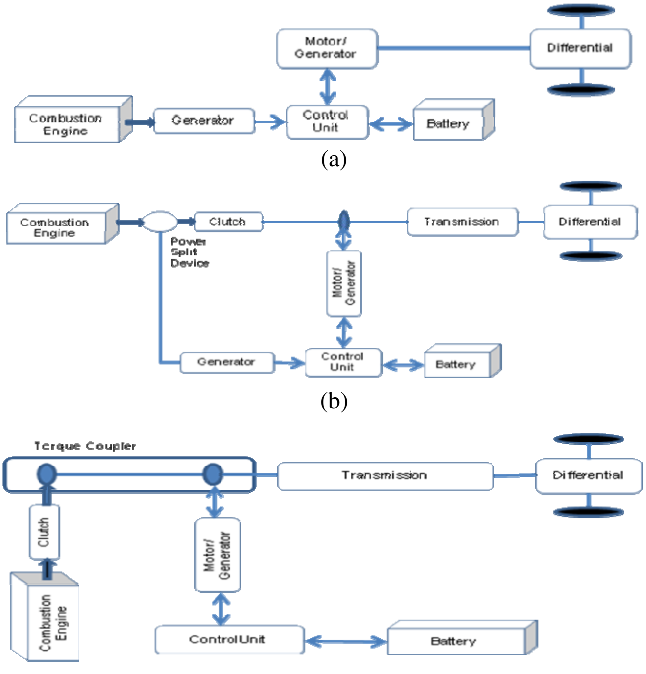
In this configuration, the engine can often operate at near optimum efficiency. At low speeds, the vehicle operates as a series vehicle, while at high speeds, where the series hybrid is less efficient, the vehicle acts like a parallel one. Since the system needs a generator, a larger storage system, and a complicated power flow control system, it has a higher cost than the other two hybrid types. However, the series-parallel HEV has the potential to perform better than each of the two other systems alone. Fuel economy of the series-parallel hybrid is investigated in this study.

In summary, considering the stated review of the popular hybrid types and their associated attributes, an outline of different power train configuration and the classification of hybrid vehicles is graphically presented in Fig. 1 and Fig. 2.

3 Modeling of Conventional and Hybrid Electric Vehicles

In a car, it is difficult to predict the relations among its internal components and systems because of dynamic interactions among the components and also the components' complex nature. Usually, prototyping and testing each design combination is expensive and time intense. Therefore, modeling and simulation are crucial for concept assessment, prototyping, and analyzing conventional and hybrid vehicles.

Simulation and modeling tools model vehicle components in different level of details [14, 17]. Modeling based on time scale can be divided into static, quasi-static, low-frequency dynamic, high-frequency dynamic and detailed physics. PSAT, which is used in this study, is considered as a low frequency dynamic vehicle modeling software. It can be used to evaluate fuel economy, performance and emissions of conventional, pure electric, hybrid electric, and hybrid electric FC. Furthermore, PSAT is designed to connect to other simulation tools with the aid of PSAT-PRO [18] in order to be used as a hardware-in-the-loop/software-in-the-loop testing program.



(a)

(b)

(c)

Fig. 1. Power train configuration. **(a)** Series HEV. **(b)** Parallel HEV. **(c)** Series-Parallel HEV.

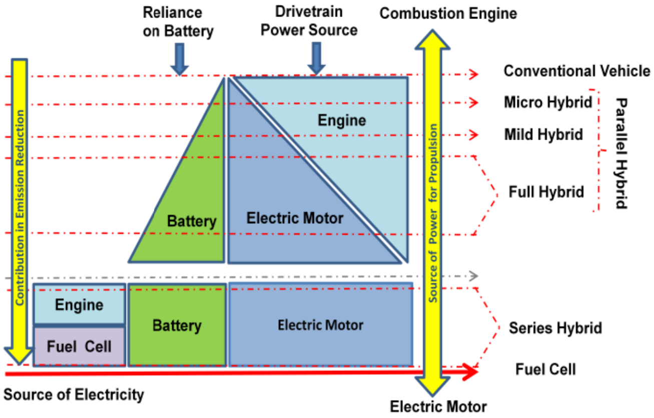


Fig. 2. Vehicle classification and hybridization concept

We have created models in PSAT for the following vehicles: conventional, series hybrid, parallel hybrid, and series-parallel hybrid. Each component corresponds to an actual vehicle. The initial values and other assumptions for the modeled conventional and hybrid vehicles are listed in Table 2. As an example, the block diagram description of the model for the parallel hybrid is shown in Fig. 3. The only traction power source in the conventional vehicle is ICE, but the electric motor provides an extra source of power. This feature makes HEVs more flexible and hence more efficient. In conventional vehicles based on the driver demand, ICE provides the necessary torque from chemical energy. It then flows through the powertrain in a forward direction to provide the traction power. Similarly in HEVs, the two sources of energy, chemical and electrical are used to supply traction demand. The traction force in the all models (Conventional and HEVs) is derived from the equation of solid body motion in the following form.

$$F = c_{rr}mgCos\alpha + mgSin\alpha + ma + \frac{1}{2}c_D AV^2 \tag{1}$$

The modularity in the model is to facilitate the consequence between the vehicle components. There is a common format for the components. Each component has the same input and output parameters. For each module, there is an input from the controller, for instance, engine on/off command or gear shift number in transmission block. There is an output from each module. This output is used in powertrain controller as well as for post-processing. The second port (input and output) carry the effort such as voltage in electrical parts and torque in mechanical ones. The last port carries the flow for instance current or speed.

Table 2. The initial values and assumptions

Description	Conventional	Series	Parallel	Series-Parallel
Engine type	Si	Si	Si	Si
IC Engine Power – kW	100.52	100.52	85.72	100.5
Electric Motor #1 Peak Power-kW	-	170	32.26	52.35
Electric Motor#1Cont Power – kW	-	81.32	16.13	26
Electric Motor #2 Peak Power-kW	-	-	-	15.39
Electric Motor#2Cont Power – kW	-	-	-	7.695
Engine Torque Max – Nm	173.2	173.2	140.5	173.2
Transmission type	Ct	No Trns.	dm	dm
Final Drive Ratio	4.07	3.55	4.44	3.77
Vehicle Mass (m)	1553.59	1844.5312	1678	1500
Fuel Heating Value	43000000	43000000	43000000	43000000
Fuel Density	0.749	0.749	0.749	0.749
Vehicle Frontal area (A)-m^2	2.18	2.18	2.25	2.06
Vehicle Drag Coeff. (C_D)	0.3	0.3	0.3	0.31
Tire Rolling Res. (C_{rr})	0.008	0.009	0.008	0.007
Wheel Radius (m)	0.292	0.348	0.365	0.290
Engine Max Eff.	0.359	0.365	0.365	0.365

The driver block is used to model the accelerator and brake pedals. Through the driver block, power traction demand is imposed to the model. The desired vehicle speed is compared with the actual speed, and a PI controller is used to request more or less torque to the vehicle. The control block supervises the components such that the demand can be guaranteed by the entire powertrain. The driver demand in vehicle simulation tools is determined by "drive cycle". Drive cycle specifies the speed in a predefined pattern. Before prototyping, it is important to simulate the vehicle under different driving environments [19]. In recent years, several standard driving cycles have been developed. They are used to describe various driving modes in different regions. Some of them were developed to evaluate the statistical flow of traffic in urban areas. In contrast, there exist some which consider rural or cross-country driving. In order to investigate the fuel economy and emissions factors among the conventional powertrain and HEV configurations, two frequent drive cycles are used in this work - a highway (HWFET) and an urban drive cycle (UDDS). These drive cycles are shown in Fig. 4.

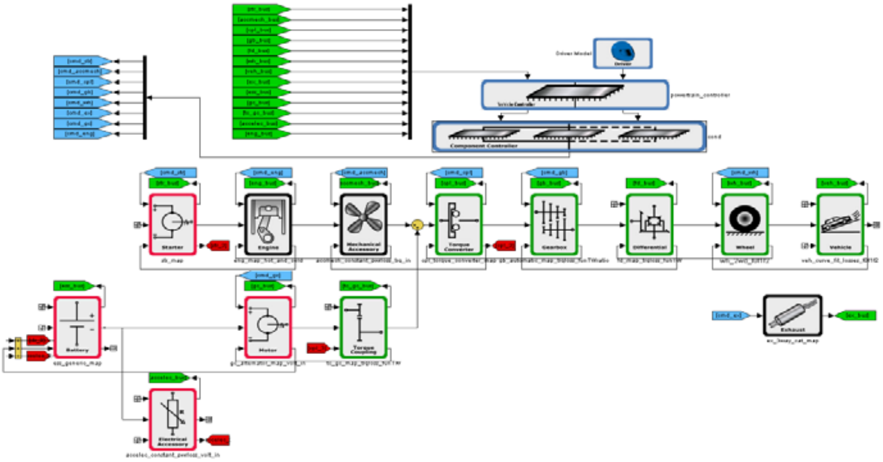


Fig. 3. The modeled parallel hybrid powertrain configuration

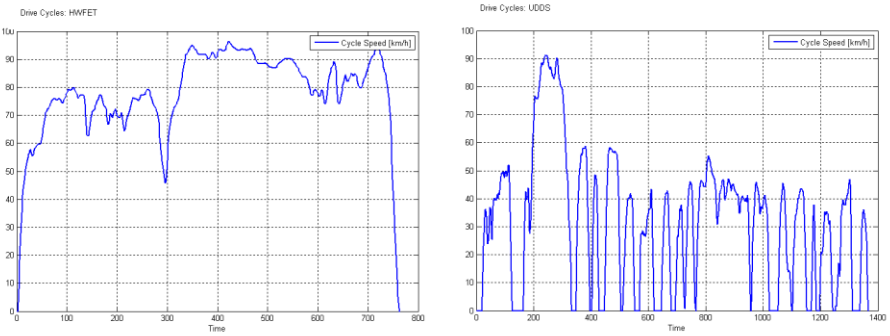


Fig. 4. Drive cycles used in our simulations. (left) Highway fuel economy driving schedule (HWFET). (right) Urban dynamometer driving cycle (UDDS).

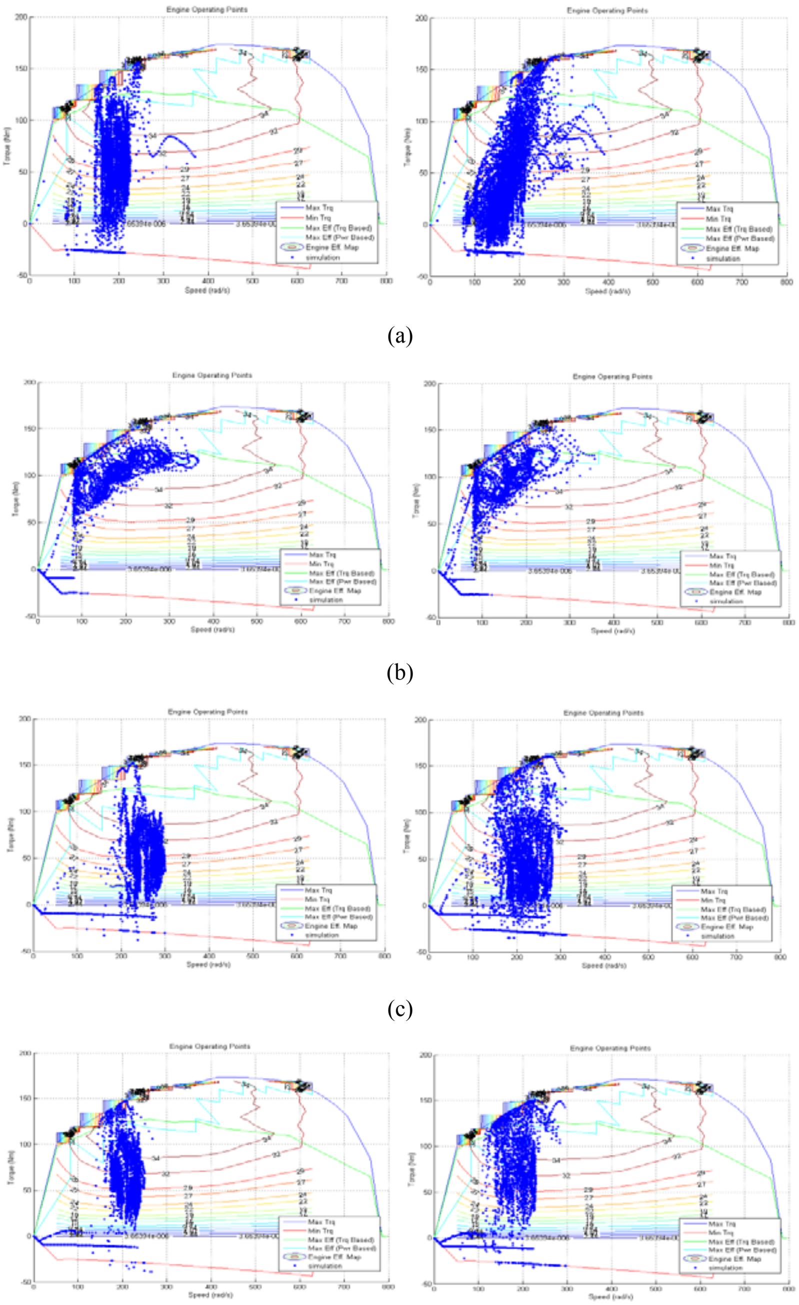
Table 3. Simulation results

		Conventional Vehicle		**Series HEV**		**Parallel HEV**		**Series-Parallel HEV**	
Description	Unit	HWFET	UDDS	HWFET	UDDS	HWFET	UDDS	HWFET	UDDS
Cycle distance	km	16.5	11.97	16.5	11.97	16.5	11.97	16.5	11.97
THERMAL INFORMATION									
Fuel economy	liter/100km	6.13	8.59	4.74	3.42	4.54	5.459	4.475	3.885
Fuel economy gasoline equivalent	liter/100km	6.18	8.67	4.79	3.45	4.61	5.601	4.619	3.925
Fuel mass	kg	0.73	0.78	0.59	0.31	0.56	0.601	0.565	0.347
HC emissions	g/km	0.06	0.17	0.07	0.11	0.035	0.118	0.062	0.162
CO emissions	g/km	1.06	3.67	0.98	1.85	0.435	2.360	1.058	3.210
NOx emissions	g/km	0.04	0.09	0.09	0.07	0.037	0.067	0.039	0.069
CO2 emissions	g/km	120.7	175.1	111.51	78.35	118.6	138.9	107.5	87.56
ELECTRICAL INFORMATION									
Initial ESS SOC	%	70	70	70	70	70	70	70	70
Final ESS SOC	%	69.6	69.55	60.68	59.62	63.91	61.12	70.12	68.59
COMPONENT AVERAGE EFFICIENCIES									
Engine Bidirectional Efficiency	%	28.77	25.83	33.35	31.34	34.23	28.29	32.59	30.97
Generator Bidirectional Eff.	%	85	85	91.17	90.45	-	-	89.64	89.10
Transmission Bidirectional Eff.	%	96.75	93.13	-	-	93.12	90.16	94.55	92.17
Motor Bidirectional Efficiency		-	-	83.89	87.08	86.11	84.96	87.58	92.77
Powertrain Bidirectional Eff.	%	25.39	18.97	28.15	38.13	30.41	27.02	31.02	35.22

4 Simulation

Two drive cycles are selected to study the behavior of different powertrain configurations in city and highway driving (see Fig. 4). From the point of view of efficiency and fuel economy, engine efficiency is usually less than 36% in all types. In the conventional vehicle, considering the overall losses in powertrain, total efficiency is less than 20% in cities. In this type, the produced torque and speed by ICE is dependent on the road load. Therefore, the engine cannot work in an efficient region at all times. However, in higher speeds and around highways speeds, the engine and powertrain run more efficiently. This matter is demonstrated in Fig. 5(a) by the density of operating points on the torque-speed map with the contours of efficiencies for the two tested drive cycles.

The average efficiency shows more than 6% improvement in highway driving. Although emissions in the conventional vehicle are controlled effectively by using a fuel-injection system and catalysts in exhaust system, still they are significant



(a)

(b)

(c)

(d)

Fig. 5. Engine operating points (left: HWFET, right: UDDS). (a) Conventional. (b) Series HEV. (c) Parallel HEV. (d) Series-Parallel HEV.

contributors to pollutant emissions. The simulation results reveal that the road load has an enormous effect on increasing emissions. Accordingly, HEVs can be considered as the appropriate alternative to conventional vehicles in order to reduce emissions and increase fuel economy.

Due to the existence of electric motor in HEVs, the load can be balanced and ICE can be commanded to work near its optimal operating region. The density of operating points on torque-speed map with the contours of efficiencies for two drive cycles are shown in Fig. 5(b-d). In all HEV configurations, engine runs near its maximum efficiency to some extent (graphs reveal the dense points around the efficient regions on the map), thus comparing to the conventional vehicle they are more efficient. The obtained results in Table 3 and Fig. 5 approve this observation.

However, selecting the appropriate powertrain configuration can influence the fuel economy and the amount of emissions. From the summarized results in Table 3, we can conclude that the series hybrid is more appropriate for city driving especially with a plug-in feature and for commuter drivers lower emissions can obtain [20]. In contrast, parallel HEV is less efficient than series type in stop-and-go driving. Therefore, this type is more suitable for highway driving; hence it can be a proper substitution for conventional vehicles in long distance and out of cities driving. With the expense of complexity, series-parallel brings together the advantages of both HEVs. From the obtained results this observation can be confirmed.

5 Conclusion

This paper presented an overview of vehicles from conventional to hybrid and classified them according to the use of electricity in the propulsion system. Using two sources of energy in the propulsion system allows very diverse set of powertrain configurations. A conventional vehicle and three types of HEVs were modeled in this study. The technical characteristics of the models are comparable providing the ability to compare the simulation results. Two frequent standard drive cycles, HWFED and UDDS, were employed to simulate the models under urban and highway driving conditions. The simulation results demonstrate better fuel economy and lower emissions for all types of hybrid vehicles.

The operating points of engines on efficiency maps for two drive cycles have been extracted. The graphs and calculated average efficiencies imply that the series hybrid performs better in city driving. In contrast, the parallel hybrid achieves lower emissions and fuel consumption in highway driving. This reveals that series HEVs are a proper substitution for conventional cars in city driving, and parallel HEVs for the speedy cars in highway driving.

In series-parallel HEVs, we can achieve the advantages of both series and parallel configurations. In this type, the simulation results from the two drive cycles showed lower emissions and better efficiencies. However, this configuration is more complex; hence, its complicated control system and additional equipments augment its cost.

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