IOSR Journal of Electrical and Electronics Engineering (IOSR-JEEE)
e-ISSN: 2278-1676,p-ISSN: 2320-3331, Volume 14, Issue 4 Ser. I (Jul. – Aug. 2019), PP 61-69
www.iosrjournals.org

Implementation of an estimation approach to calculate energy consumption of HEV on different drive cycles

W. S. Zidan[1], M. A. Ibrahim[1], W. A. Oraby[1] and M. B. Abdelhady[1]
[1]*(Automotive and Tractors Engineering Department, Helwan University, Egypt)*

Abstract: *Hybrid electric vehicle (HEV) is gaining the world attention due to their ability to reduce fuel consumption while decreasing emissions. There is a progressively interest in the automotive industry to use HEVs; because they merge the advantages of internal combustion engine vehicles (ICEVs) and electric vehicles (EVs). However, this merge generates a problem in calculating the energy consumption which results from using two different energy sources including an electric energy source. Consequently, there is a need to find an accurate suitable solution to this challenge as much as possible. This paper introduces an estimating approach in order to calculate both fuel consumption, fuel economy, and energy consumption of a series HEV which has been proposed by the same authors in a previous published paper. The series HEV model has been developed by adding the proposed estimating approach which has been implemented on different standard drive cycles to compare driving patterns. The simulation has been done under the MATLAB/SIMULINK environment; in order to validate the proposed estimating approach under different driving conditions. Finally, the simulation results are analyzed and compared to check the approach validity and show the main factors affect the energy consumption.*

Keywords: -*estimation approach, hybrid electric vehicles, energy consumption, drive cycles*

Date of Submission: 28-07-2019 Date of acceptance: 13-08-2019

I. Introduction

The reserves of fossil fuel are limited, they will be gone by 2052 as mentioned in CIA World Factbook [1] at the rate of 4 billion tonnes a year. Since vehicles have a significant factor in fuel consumption and air pollution, it is necessary to monitor the energy consumption precisely; in order to concern the economic and environmental effects.

Hybrid electric vehicle (HEV) is considered one of the most promising alternative solutions which can be used to reduce the dependency on fossil fuel while decreasing emissions caused by automobiles [2].

HEVs use two different energy sources, the first is the internal combustion engine (ICE) which uses the released energy form fuel combustion to operate, and the other is the electric motor (EM) which needs electrical energy. It is easy to calculate the fuel consumption for the ICE, but the main challenge is to calculate the equivalent fuel consumption, and electric energy consumption for the EM accurately as much as possible.

Several papers have been tried to address this challenge includes the theory of life cycle assessment (LCA) as presented in [3] which uses a calculation model for comparing the life cycle energy consumption and emissions of BEV and HEV, but the authors didn’t mention any clear details for calculating the energy consumption except a complicated flowchart.

The utility factor (UF) method as presented in [4] to estimate the average energy consumption for a plug-in hybrid electric vehicle (PHEV) based on the travel characteristics of passenger vehicles in Harbin, China. The main disadvantage of this method is using several complicated formulas which contain a lot of integrations and curve fittings.

A hybrid approach (“grey-box”) as presented in [5] which was used to develop models for estimating the energy consumption rate based on driving data collected experimentally for a test EV using GPS data logger to get the latitude and longitude of the vehicle and a diagnostic tool to get data from CAN bus, such as speed, current and voltage for each cell, accessory power, and state of charge (SOC). This approach is based on battery power equations and characteristics of the regenerative brake system.

The study presented in [6] developed models using detailed values of kinematic parameters to increase the link with the vehicle dynamics; in order to determine the relationship between the electric vehicle (EV) kinematic parameters and its energy consumption using real-world data.

The study presented in [7] used two microscopic models: car-following (linear) model for longitudinal moving, and lane-changing model for lateral displacement; in order to investigate the effect of the hybridization on energy consumption. The investigation was done by comparing between the energy consumption of HEV Toyota Prius model realized in the Matlab/Simulink and a classical ICEV model in a real driving cycle.

The main target of this paper is to propose an approach in order to address the issue of estimating the energy consumption and calculating the total equivalent fuel consumption of a HEV that driving in real world traffic.

The proposed estimation approach, which is considered a calculation technique, has been implemented in a series HEV which has been proposed by the same authors in a previous published paper in [8]; to calculate the fuel consumption, fuel economy, and energy consumption using MATLAB/SIMULINK during different standard drive cycles in order to evaluate the proposed approach on the selected vehicle.

The remainder of this paper is organized as follows: section II introduces description for the technique calculations, followed by the description of the selected driving cycles in section III. The analyses of the simulation results and the discussion are presented in section IV. Finally, the conclusion is presented in section V.

II. Calculations

In electric-drive mode, HEV will not consume any amount of fuel directly; because the vehicle depends only on the electric motor to move the vehicle. Since the vehicle consumes energy, it has a fuel economy (miles per gallon or mpg) which will not be infinite.So, the main target of the following section is to calculate the total consumed energy, and the fuel economy.

Firstly, the total energy consumed during any drive cycle (E_t) can be calculated using equation (1):

$$E_t = E_{eq\_e} + E_{ch} \tag{1}$$

where E_{eq_e} is the equivalent electric energy removed from the traction battery, and E_{ch} represents the fuel energy consumed to charge the battery. All terms in this equation are in British Thermal Unit (BTU).

The equivalent electric energy can be calculated using equation (2):

$$E_{eq\_e} = E_e * \eta_c * f \tag{2}$$

where η_c is the conversion efficiency (assumed to be 25%), and f is an energy unit conversion factor (from W.h to BTU) =3.41214 [9].

While E_e represents the electrical energy consumed to move the vehicle in watt-hour (W.h), and can be calculated using equation (3):

$$E_e = V_{oc} * A.h_{cons} \tag{3}$$

where V_{oc} is the open-circuit voltage in volts (V), and $A.h_{cons}$ represents the consumed ampere.hour (A.h) which can be calculated as shown in equation (4):

$$A.h_{cons} = \left(SOC_i - SOC_f\right) * A.h \tag{4}$$

where SOC_i is the initial battery state of charge, while SOC_f represent is the final battery state of charge, and $A.h$ is the battery ampere.hour capacity.

Secondly, a conversion method using equivalence measures will be used in order to calculate the value of fuel economy. This method is called miles per gallon gasoline equivalent (MPG_e) which represents the number of milesthe vehicle can travel using a quantity of fuel with the same energy content as a gallon of gasoline. This method allows to compare between vehicles using different fuels [10].

Fuel economy (miles per gallon gasoline equivalent) can be calculated using equation (5) in mpg:

$$MPG_e = \frac{S}{V_{RF}} \tag{5}$$

where S is the distance traveled by the vehicle in miles, and V_{RF} is the amount of consumed reformulated fuel to produce the same amount of consumed energy in gallons which can be calculated using equation (6):

$$V_{RF} = \frac{E_t}{H_{RF}} \tag{6}$$

where H_{RF} is the fuel heating value of the reformulated fuel in BTU/gallon.

The fuel heating value depends on the fuel density and the lower heating value of the fuel which is selected to be diesel B20. The lower heating value of a fuel defined as the amount of heat released by combusting a specified quantity of fuel (initially at 25°C) in oxygen with all of the products being gaseous and in which the latent heat of vaporization of water in the reaction products is not recovered (water remains as vapor) [11].

The selected fuel will be diesel B20 as listed in the Standard ASTM (American Society for Testing and Materials) D7467 and means 20% biodiesel and 80% ultra-low sulfur diesel in volume percent [12]. The average density for the diesel B20 will be used as in equation (7):

$$\rho_{B20} = 0.85\ kg/l \tag{7}$$

While the lower heating value (LHV) of the selected fuel will be used as in equation (8):

$$LHV = 43\ MJ/kg \tag{8}$$

This value was selected as an average value for the lower heating value of the fuel standardized by ASTM as D3338, "Standard Test Method for Estimation of Net Heat of Combustion of Aviation Fuels" [13].

There is a need to use some conversions that will be mentioned in equations (7-9) in order to use them in calculating the fuel heating value using equation (12):

$$1\ BTU = 1055\ J\ (Joules) \tag{7}$$

$$1\ MJ = \frac{1}{1055} * 10^6 = 947.8672986\ BTU \tag{8}$$

$$1\ litre = 0.264172\ gallon \tag{9}$$

Therefore

$$H_{RF} = \frac{LHV * 947.8672986 * \rho_{B20}}{0.264172} = 131143.9129 BTU/gallon \tag{10}$$

Substituting the fuel heating value which has been obtained from equation (10) in equation (6) in order to get the amount of consumed reformulated fuel which will be used to calculate the fuel economy in equation (5).

III. Implementation the approach on driving cycles

Energy consumption of vehicles depend on many parameters, including parameters related to the vehicle such as size, fuel type, and parameters related to the road such as road gradient, and operational parameters such as speed, acceleration.

To compare performance, fuel consumption of vehicles from different manufacturers, there is a need to use driving cycles which are considered fixed schedule of vehicle operation allow to evaluate vehicles under reproducible conditions according to standard driving conditions which is defined in terms of vehicle speed and as a function of time [14].

The proposed estimation approach has been implemented on a series HEV model using MATLAB/SIMULINK during different standard drive cycles. The proposed model has been taken into account the various factors affecting energy consumption.

Therefore, different standard driving cycles have been selected to measure the fuel consumption and energy consumption for a series HEV. Each cycle represents a specific type of driving pattern in both urban areas and on highway, as well as long and short distance travels.

The selected driving cycles are New European Driving Cycle (NEDC), Federal Test Procedure (FTP-75), US06 Supplemental FTP, Highway Fuel Economy Test (HWFET), Urban Dynamometer Driving Schedule (UDDS), and Worldwide Harmonised Light Vehicle Test Procedure (WLTP).

New European Driving Cycle (NEDC):

This driving cycle is a standard cycle in Europe recognized as one of the EU legislative cycles which has been used since 1990 to determine emission certification and fuel sampling of passenger vehicles. It can be divided into two main sections, the first section with low speed, and the other with high speed with several start and stops to simulate driving in downtown crowded areas, as shown in figure 1 [15].

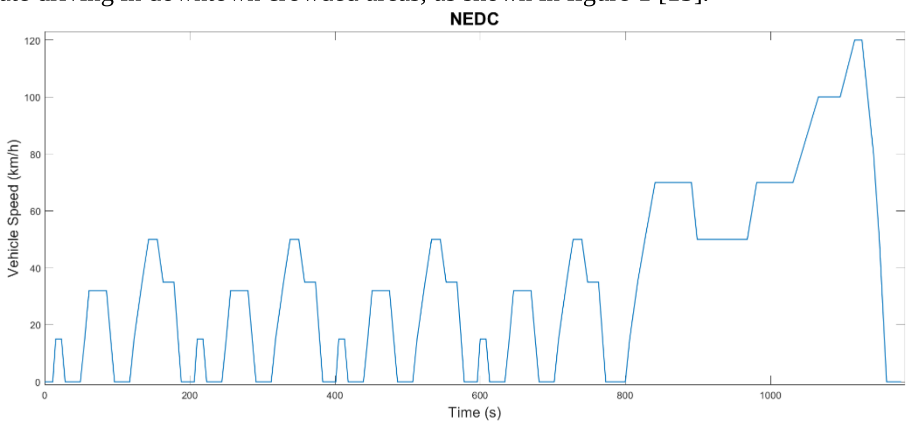

Figure 1: New European Driving Cycle (NEDC)

Although this cycle combines both urban and extra-urban sections to better represent the on-road driving, it has a main disadvantage of the ability to represent the actual normal driving pattern.

Firstly, simulation has been done under the NEDC which has a total travelling distance of 10.9522 km. Simulation results shows that the selected series HEV consumes amount of fuel about 629.9207 grams of B20. Therefore, the fuel consumption will be 0.1089 L/km, the fuel economy will be 29.2017 miles/gallon, and the total energy consumed is 28244.4681 kJ. All results will be discussed and compared later with results from other drive cycles.

Federal Test Procedure (FTP-75):

The Federal Test Procedure (FTP-75), shown in figure 2, is one of the US cycles and has been created by EPA (Environmental Protection Agency). This cycle represents a travelling cycle, consists of a combination of an urban section including frequent stops and a highway section.

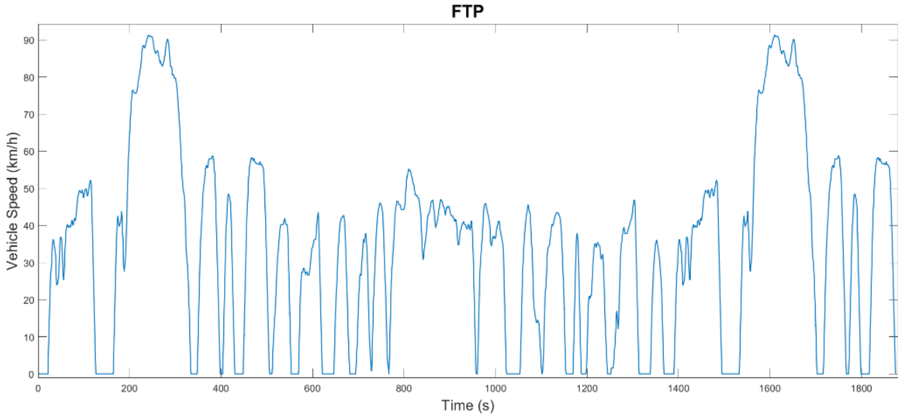

Figure 2: Federal Test Procedure (FTP-75)

Secondly, simulation has been done under the Federal Test Procedure (FTP-75) which has a total travelling distance of 17.6209 km. Simulation results shows that the selected series HEV consumes amount of fuel about 943.9524 grams of B20. Therefore, the fuel consumption will be 0.10143 L/km, the fuel economy will be 30.5981 miles/gallon, and the total energy consumed is 43368.4107 kJ.

US06 Supplemental FTP:

The standard driving cycle US06, shown in figure 3, is one of the US cycles. This cycle is a supplemental to the FTP-75 driving cycle and developed to overcome the shortcomings which are founded in the FTP-75 such as representing the high speed. So, it has a higher top speed of 130 km/h instead of 90 km/h.

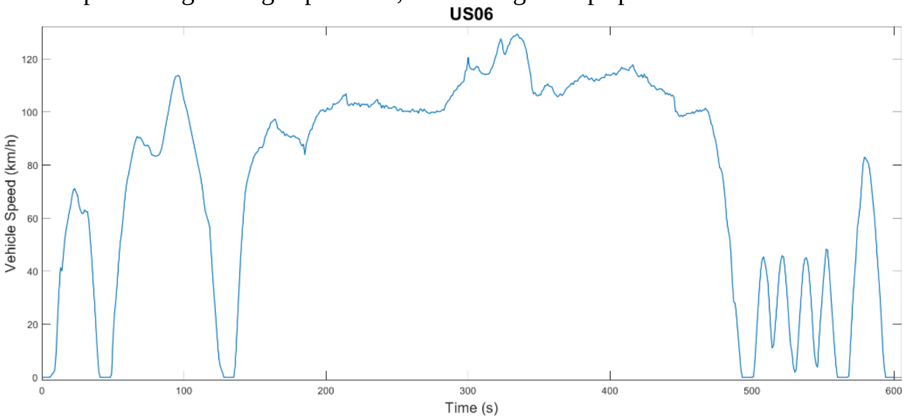

Figure 3: US06 Supplemental FTP

Thirdly, simulation has been done under the US06 which has a total travelling distance of 12.3694 km. Simulation results shows that the selected series HEV consumes amount of fuel about 1455.471 grams of B20. Therefore, the fuel consumption will be 0.22278 L/km, the fuel economy will be 14.2848 miles/gallon, and the total energy consumed is 65210.3017 kJ.

Highway Fuel Economy Test (HWFET):

The Highway Fuel Economy Test (HWFET), shown in figure 4, is one of the US cycles developed by the EPA as a chassis dynamometer driving schedule; in order to represent a highway driving cycle.

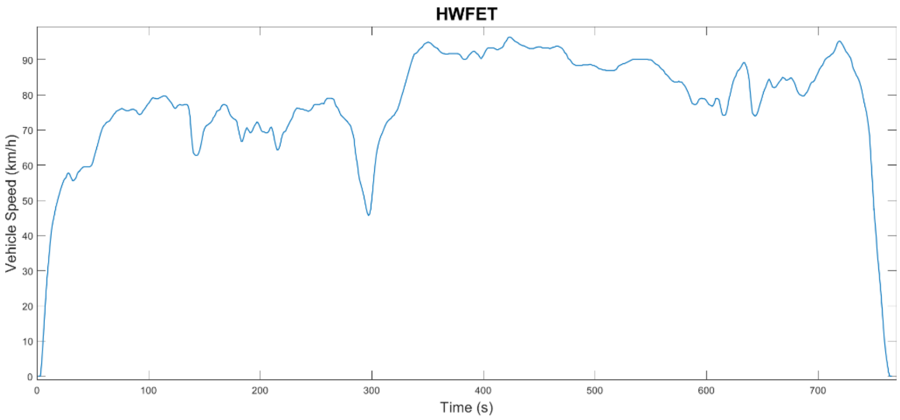

Figure 4: EPA Highway Fuel Economy Test (HWFET)

Fourthly, simulation has been done under the HWFET which has a total travelling distance of 16.443km. Simulation results shows that the selected series HEV consumes amount of fuel about 1218.944 grams of B20. Therefore, the fuel consumption will be 0.14036 L/km, the fuel economy will be 23.5657 miles/gallon, and the total energy consumed is 52545.9695 kJ.

Urban Dynamometer Driving Schedule (UDDS):

The Urban Dynamometer Driving Schedule (UDDS), shown in figure 5, is one of the US cycles. This cycle has been used to simulate an urban route with frequent stops.

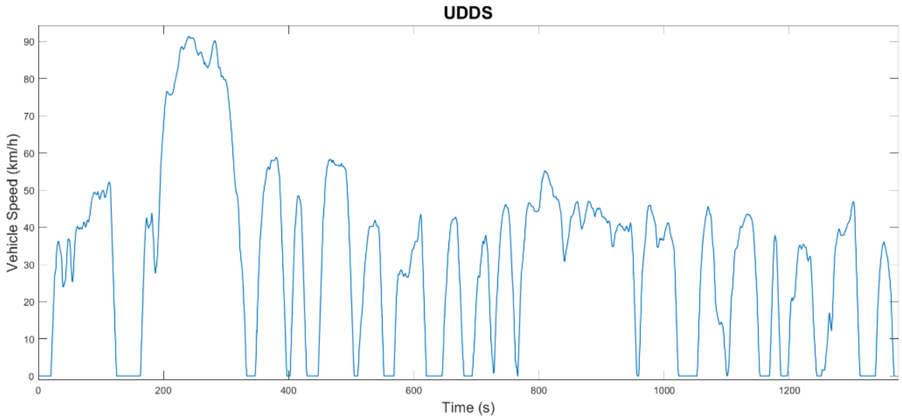

Figure 5: Urban Dynamometer Driving Schedule (UDDS)

Fifthly, simulation has been done under the UDDS which has a total travelling distance of 11.8908 km. Simulation results shows that the selected series HEV consumes amount of fuel about 502.9559 grams of B20. Therefore, the fuel consumption will be 0.080084 L/km, the fuel economy will be 35.4207 miles/gallon, and the total energy consumed is 25281.0636 kJ.

Worldwide Harmonised Light Vehicle Test Procedure (WLTP)

The Worldwide Harmonised Light Vehicle Test Procedure (WLTP) / WLTC cycle for Class 3b vehicles, shown in figure 6, is an international chassis dynamometer test. This cycle represents actual different speed conditions; because it combines urban, suburban, extra-urban, and highway driving sections respectively.

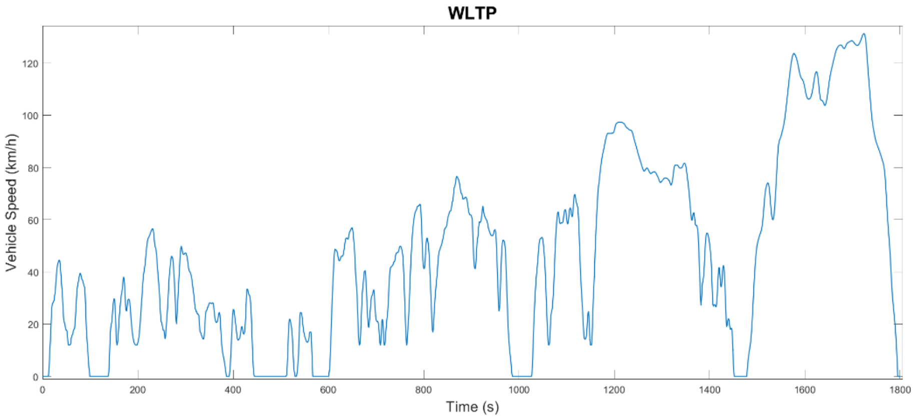

Figure 6: Worldwide Harmonised Light Vehicle Test Procedure (WLTP)

Finally, simulation has been done under the WLTP which has a total travelling distance of 22.9226 km. Simulation results shows that the selected series HEV consumes amount of fuel about 1651.3407 grams of B20. Therefore, the fuel consumption will be 0.1364 L/km, the fuel economy will be 22.5511 miles/gallon, and the total energy consumed is 76548.254 kJ.

IV. V. Results and Discussion

Simulation results will be summarized in table 1 under all selected driving cycles; in order to compare between them according to the distance and the average and maximum vehicle speed. The table shows the fuel consumption in terms of grams of fuel and average fuel consumption per in liter per unit distance. It also shows the fuel economy in miles per gallon, and energy consumption in mega joule and kilo joule per unit distance which represents the average value of the vehicle total consumed energy over the driving cycle, divided by the cycle length.

Table 1: Summarized simulation results

Programme	Cycle Name	Distance	Average Speed	Max. speed	Fuel Consumption		MPGe	Energy Consumption	
		km	*km/h*	*km/h*	*grams of B20*	*L/100km*	*miles/ gallon*	*MJ*	*kJ/100km*
EU legislative cycles	New European Driving Cycle (NEDC)	10.95	33.6	120.09	629.92	10.89	29.2	28.24	25.79
US cycles	Federal Test Procedure (FTP-75)	17.62	34.2	91.09	943.95	10.14	30.6	43.37	24.61
	US06 Supplemental FTP	12.37	77.9	128.91	1455.47	22.28	14.29	65.21	52.72
	EPA Highway Fuel Economy Test (HWFET)	16.44	77.7	96.32	1218.94	14.04	23.57	52.55	31.96
	Urban Dynamometer Driving Schedule (UDDS)	11.89	31.6	91.15	502.96	8.01	35.42	25.28	21.26
International	Worldwide Harmonised Light Vehicle Test Procedure (WLTP) / WLTC cycle for Class 3b vehicles	22.92	46.5	131.3	1651.34	13.64	22.55	76.55	33.39

Bar-charts can be extracted from the table; in order to enable easy comparisons between results under the selected driving cycles.

A comparison between the fuel consumption per unit distance of the selected vehicle under all the selected driving cycles is shown in figure 7. The figure shows that the vehicle has the highest fuel consumption under the US06, and has the lowest value under the UDDS.

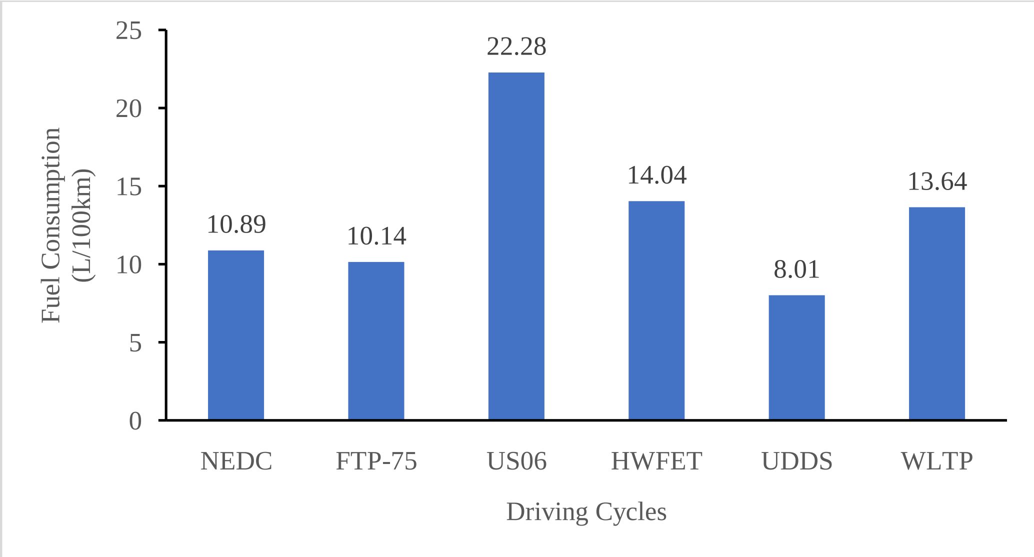

Figure 7: Fuel consumption per unit distance under all selected driving cycles

A comparison between the fuel economy of the selected vehicle under all the selected driving cycles is shown in figure 8. The figure shows that the vehicle has the best fuel economy under the UDDS, and has the lowest value under the US06.

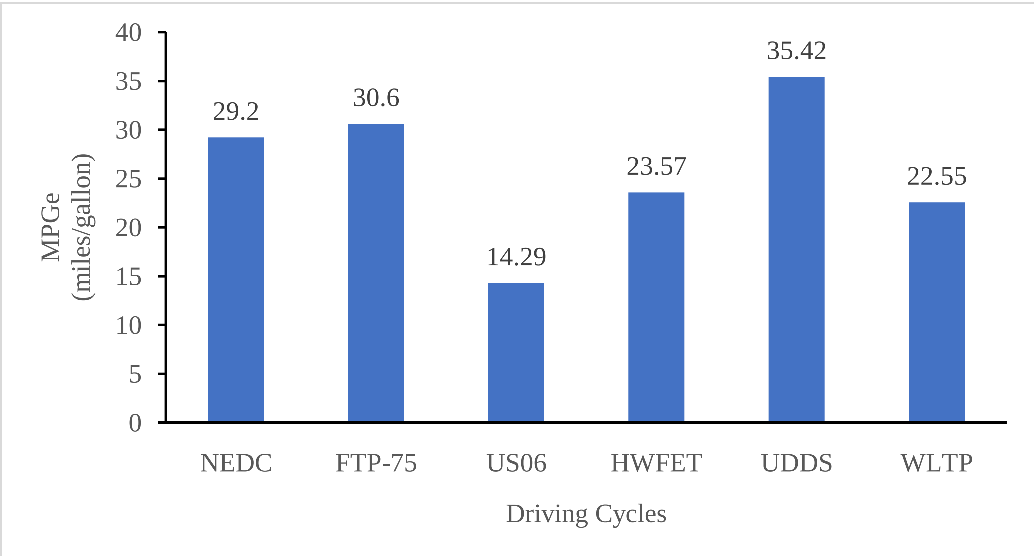

Figure 8: Fuel economy under all selected driving cycles

A comparison between the energy consumption per unit distance of the selected vehicle under all the selected driving cycles is shown in figure 9. The figure shows that the vehicle has the highest energy consumption under the US06, and has the lowest value under the UDDS.

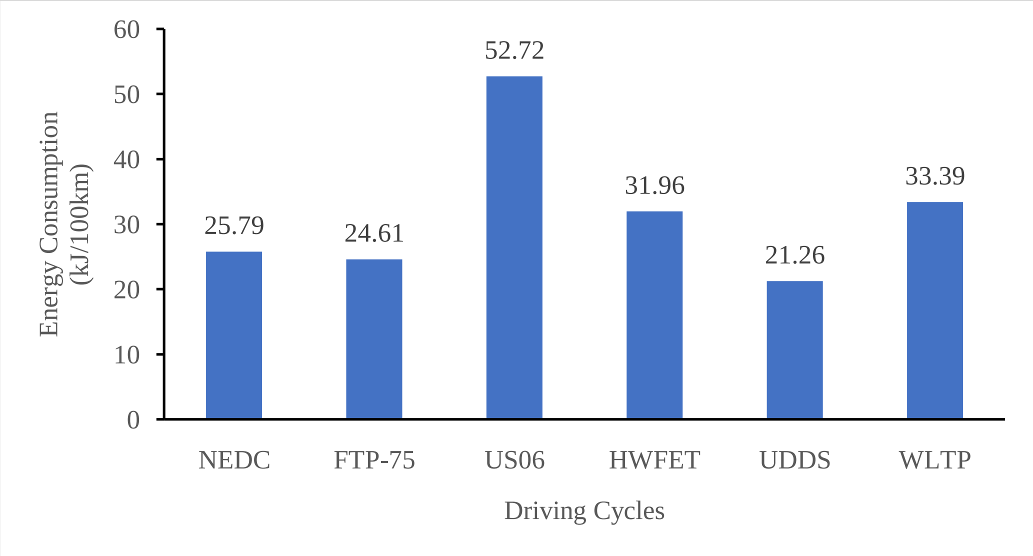

Figure 9: Energy consumption per unit distance under all selected driving cycles

It is obvious that the vehicle has the highest value of fuel consumption per unit distance during the US06. As a result, the energy consumption will be the highest value and the fuel economy will be the lowest value through this cycle. There are two main reasons which causes the higher consumption. The first reason is that the US06 cycle has a few stops with a limited stopping time. The second reason is the higher maximum speed of this cycle with respect to all other cycles.

In contrast, the vehicle consumes the lowest value of fuel consumption per unit distance during UDDS. Thus, the energy consumption will be the lowest value and the fuel economy will be the highest value through this cycle. There are two main reasons which causes the lower consumption. The first reason is that the UDDS cycle has a lot of stops with a long stopping time. The second reason is the lower average and maximum speed of this cycle with respect to other cycles.

Although the HWFET doesn't contain any stops, it has a relatively low maximum speed which doesn't reach 97km/h. So, the fuel and energy consumption per unit distance of the vehicle during the HWFET is higher than during the UDDS. While the vehicle during the HWFET is more fuel efficient compared to the US06 which means that the vehicle consumes lower fuel and energy per unit distance during HWFET than US06.

The results reveal that the repetitive stops and the maximum vehicle speed are the two main parameters which have the largest impact on energy consumption. In contrast, the travelling distance doesn't have a great effect on the average energy consumption.

V. Conclusion

This paper has been proposed an estimation approach to calculate energy consumption of a series HEV model which has been established based on previous published paper by the same authors. Then the proposed approach has been described in details and has been implemented using MATLAB/Simulink environment under different driving conditions using different standard driving cycles. Finally, simulation results have been shown, analyzed, and discussed which show that the proposed estimation approach is valid and can be implemented effectively on any HEV; because the calculation technique is very simple, clear, integral, and has no hidden steps or parameters which leads to disambiguate found in other calculation techniques. Simulation results show thatrepetitive stops during any drive cycle have a direct effect onenergy consumption. Also, the maximum vehicle speed is one of the main parameters which effects directly on energy consumptionregardless of the cycle length.

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W. S. Zidan" Implementation of an estimation approach to calculate energy consumption of HEV on different drive cycles" IOSR Journal of Electrical and Electronics Engineering (IOSR-JEEE) 14.4 (2019): 61-69.