A comparative study of hybrid electric vehicle fuel consumption over diverse driving cycles

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Abstract Environmental pollution and declining resources of fossil fuels in recent years, have increased demand for better fuel economy and less pollution for ground transportation. Among the alternative solutions provided by researchers in recent decades, hybrid electric vehicles consisted of an internal combustion engine and an electric motor have been considered as a promising solution in the short-term. In the present study, fuel economy characteristics of a parallel hybrid electric vehicle are investigated by using numerical simulation. The simulation methodology is based on a fast forward facing simulation model of a parallel hybrid and an internal combustion engine powertrains. The objective of this study is to present the main parameters which result in an optimum combination of hybrid powertrain components in order to obtain a better fuel economy of hybrid powertrains regarding different driven cycles and hybridization factors. Then, the fuel consumption of the parallel hybrid electric vehicles are compared considering various driven cycles and hybridization factors. The results showed that the better fuel economy of hybrid powertrains increases by decreasing average load of the test cycle and the point of the best fuel economy for a particular average load of the cycle moves towards higher hybridization factors when the average load of the test cycle is reduced.
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Global issues on the rise in oil prices, shortcomings in energy resources and reduction of the CO_2 emission force researchers to develop more fuel-efficient, low-emissions powertrain technologies. Among the alternative powertrains being investigated, hybrid electric vehicles (HEVs) consisting of an internal combustion engine (ICE) and an electric motor (EM) appear to be of significant importance, combining improved fuel economy with very low pollutant emissions levels[1,2] due to the use of smaller battery pack and their similarities with the conventional vehicles.[3] The HEVs appeared at the Paris Salon exhibition of 1899 for the first time.[4] The HEVs may be categorized to either parallel hybrid, series hybrid, or their combination.[1] This division is made regarding the level of electric power integration in the powertrain system and the engine-electric motor coupling strategy. In a series HEV, the driven system is solely powered by the electric motor that draws its power from the on-board battery unit which is charged by the vehicle engine. Parallel HEVs may be simultaneously powered by the engine and electric motor.[5] Figure 1 shows the block diagrams for a series and parallel HEVs, respectively. The electric motor can be used as a generator to charge the battery by regenerative braking energy or absorbing power from the engine when its output is greater than that required to drive the wheels. Compared to the series HEV, the parallel hybrid needs only two propulsion devices. Another advantage over the series HEV is that a smaller engine and a smaller electric motor can be used to obtain the same performance until the battery is depleted.[6] Therefore, all commercially available HEVs are the type of parallel vehicles.[3] The diesel engine is still the most efficient energy converter of fossil fuels for vehicle propulsion.[7] The current available hybrid electric vehicles runs on gasoline engines,[8,9] and the majority of the investigations relating to a reduction of fuel consumption due to hybridization are also made with gasoline engines as the ICE power source.[3,10,11] However, it is well-known that the diesel engine is more efficient than a gasoline engine, whereas the gasoline engines suffer from decreased part load efficiency due to higher throttling losses.[7,12] Hence, it is reasonable to select a diesel engine as the ICE power source of the hybrid powertrain to improve its fuel economy.

Numerous papers related to simulation based analysis of fuel consumption and exhaust emissions by powertrain hybridization have been published in recent years.[3,9,13,14] The majority of the simulation models rely on a map based or lookup tables based approach.[10,12,14] The software ADVISOR is used as a simulation tool in many papers.[3,15–17] It uses a hybrid backward/forward approach which is closely related to the strictly backward facing approach. It is confirmed that the backward facing approach has some defects. Dynamic effects are not considered in the maps or in the backward facing models, because efficiency maps are generally produced by steady state testing. On the other hand, many authors[16] consent that dynamic model can be included in a forward facing simulation model. It is also possible to model the vehicle and its

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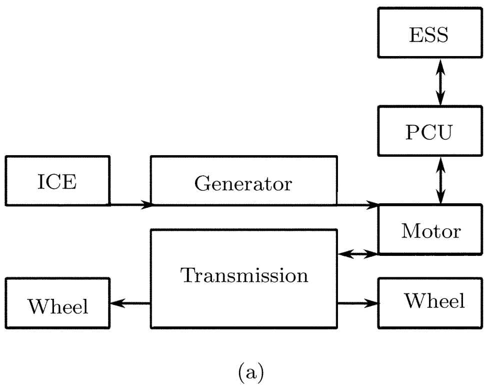
components in forward facing approach.[6,18,19] The main issue over the use of a forward facing approach is its large time consumption; however, it is possible to simulate a hybrid powertrain during the entire cycle with a forward facing model adequate for simulating dynamic operation of hybrid powertrains in real time.



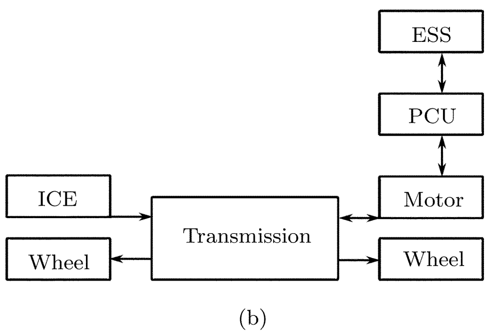


Fig. 1. Block diagram of (a) series HEV configuration and (b) parallel HEV configuration.[13]

This paper presents a comparative analysis of fuel consumption of parallel hybrid electric vehicle of different hybridization levels over diverse driving cycles. A forward facing simulation model of an ICE and models of other hybrid powertrain components are implemented. The optimum hybridization ratio is determined. The conducted simulations aimed at providing fuel consumption characteristics in comparison with that of conventional vehicles.

The powertrain architecture of the parallel HEV studied in this paper is shown in Fig. 2. The advantages of parallel HEVs are analyzed with the emphasis on fuel consumption. The analysis is based on the energy balance and efficiencies of components.[20] The HEVs can improve fuel economy in three following ways compared to conventional powertrains:[14] First, they allow engine to stop under vehicle stop status; second, they make it possible to reduce engine size which results in higher engine efficiency for a specific condition and third, they provide regenerative braking energy. Analysis of the fuel consumption is generally conducted over a specific test cycle. All subsequently defined quantities are averaged values over the applied test cycle.

The energy consumed to propel the vehicle based

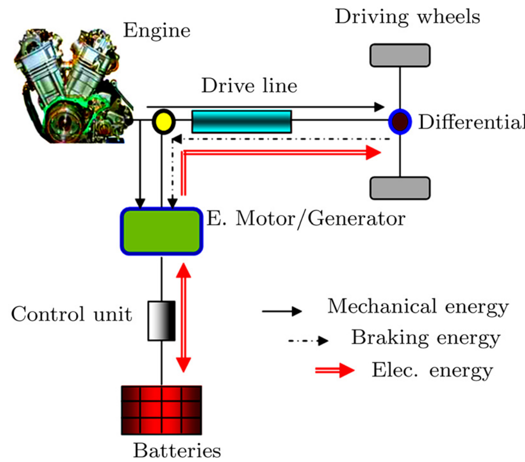


Fig. 2. Powertrain configuration of parallel HEV.[21]

on the test cycle is equal to the energy produced by the ICE and decreased by the energy consumed by the brakes.

$$W_{\mathrm{tc}} = \int_0^{t_{\mathrm{tc}}} P_{\mathrm{tc}} \mathrm{d}t = W_{\mathrm{ICE}} - W_{\mathrm{br}} = \int_0^{t_{\mathrm{tc}}} P_{\mathrm{ICE}} \mathrm{d}t - \int_0^{t_{\mathrm{tc}}} P_{\mathrm{br}} \mathrm{d}t, \tag{1}$$

where

$$P_{\mathrm{br}}(t) = P_{\mathrm{ICE\,min}}(t) - P_{\mathrm{tc}}(t) \tag{2}$$

is the difference between the negative power required to the engine at a particular speed and the negative torque imposed by the test cycle.[6]

In parallel hybrid powertrain, electric energy is never produced and consumed simultaneously. According to Fig. 3, the energy balance of the parallel hybrid powertrain is written as follows

$$W_{\mathrm{tc}} = W_{\mathrm{ICE}} + W_{\mathrm{EM}} - W_{\mathrm{EG}} - W_{\mathrm{br}}, \tag{3}$$

$$W_{\mathrm{EM}} = \eta_{\mathrm{EL}} W_{\mathrm{EG}}. \tag{4}$$

At the beginning of the test cycle, the state of charge (SOC) of all electric storage devices is equal to the SOC at the end of the test cycle, thus

$$\eta_{\mathrm{EL}} = \eta_{\mathrm{EG}} \eta_{\mathrm{EM}} \eta_{\mathrm{ES}}. \tag{5}$$

Combining Eqs. (1), (4) and (5), we obtain

$$W_{\mathrm{tc}} = W_{\mathrm{ICE}} - W_{\mathrm{br}}, \tag{6}$$

For further analysis, the following correlations are defined

$$\eta_{\mathrm{f}} = \frac{W_{\mathrm{c}} \eta_{\mathrm{c}}}{m_{\mathrm{f}} Q_{\mathrm{LHV}}}, \tag{7}$$

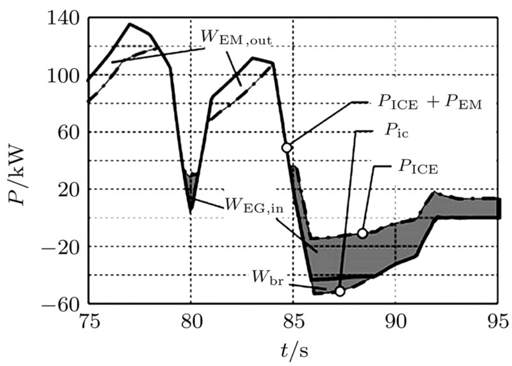


Fig. 3. Power outputs/inputs of the constituting components of the parallel hybrid powertrain.[6]

The effective efficiency is defined as the ratio of energy delivered by the ICE to the energy supplied by the fuel

$$\eta_{\rm eff}=\frac{W_{\rm ICE}}{m_{\rm f}Q_{\rm LHV}}. \tag{8}$$

The mechanical efficiency of the ICE is defined as the ratio of the energy delivered by the ICE to the indicated work performed during the test cycle

$$\eta_{\rm mech}=\frac{\eta_{\rm eff}}{\eta_{\rm f}}. \tag{9}$$

Combining the above equations, we have

$$\frac{m_{\rm f,tc,h}}{m_{\rm f,tc}} = \frac{\eta_{\rm mech}\eta_{\rm f}}{\eta_{\rm mech,h}\eta_{\rm f,h}}\left[\frac{W_{\rm tc}+(1-\eta_{\rm EL})W_{\rm EG}+W_{\rm br}}{W_{\rm ICE}}\right]. \tag{10}$$

It is obvious that if $m_{\rm f,tc,h}/m_{\rm f,tc}<1$, the fuel energy utilization by the hybrid powertrain during the test cycle is more efficient than the conventional powertrain. It should be noted that $W_{\rm br}$ is typically larger than $W_{\rm br,h}$, since hybrid powertrains enable regenerative braking energy, which further improves the fuel consumption of hybrid powertrains.[1]

The forward-facing approach model is used to analyze the hybrid powertrain configurations. The simulation code is capable of simulating various types of loads; including engine dynamometer and chassis dynamometer test cycles as well as vehicle dynamics. For the purpose of this analysis, the FORTRAN code was developed with models of electric machines, electric storage systems and controlling devices. The simulation model is very fast compared to other forward facing dynamic simulation models.

The 1.6 L HDi 16 V diesel engine is used as the baseline internal combustion engine. General specifications of the ICE are given in Table 1. For the purpose of higher computational speed a zero dimensional (0-D) model is used. The accuracy and applicability of the 0-D code depend strongly on the amount of experimentally determined inputted data available. The important parameters such as mechanical efficiencies and combustion parameters are applied in the simulation code.

Table 1. General specifications of the ICE engine.

Engine	1.6 L HDi 16 V
Number of cylinders	4
Bore/mm	75
Stroke/mm	88.3
Compression ratio	16
Maximum torque/(N · m)	240@1750 rpm
Maximum power/kW	81@4000 rpm
Idle speed/rpm	950

The Hawker Genesis12 V 25 Ah VRLA battery is considered as the module of the storage system. Battery charging and discharging are done based on the model presented by Kutluay et al.[22] The battery discharge model takes into account the change of actual capacity with discharge current and temperature. The coefficient for the discharge current rate is calculated from the manufacturer's data proposed by Kutluay et al.[22] They are sized adequately in order to avoid limiting the performance of the electric motor. Although, the charge–discharge efficiency increases with the number of battery modules, increasing the number of battery modules increases costs and imposes a weight and storage place penalty. The simulations are performed with the characteristics of new batteries.

A prototype electric motor-generator was produced by ISKRA Avtoelektrika d.d. The torque characteristic of the electric motor-generator was scaled linearly in order to represent electric machines in the analyzed power output range, whereas the efficiency characteristics were also modified simultaneously in accordance with the instructions provided by ISKRA Avtoelektrika d.d.[6]

For parallel hybrid powertrain, the hybridization factor (HF)[3] can be considered and equals

$$HF=\frac{P_{\rm EM}}{P_{\rm EM}+P_{\rm ICE}}=0.45, \tag{11}$$

where $P_{\rm EM}$ and $P_{\rm ICE}$ are the maximum power output of the electric motor and ICE, respectively. It is more suitable to define the alternative HF proposed in Ref. 6 as

$$HF'=\left(\frac{M_{\rm EM}}{M_{\rm EM}+M_{\rm ICE}}\right)_{\rm MaxICE}=0.55, \tag{12}$$

where HF' is implemented at the engine speed corresponding to the peak torque of the baseline ICE.

The engine parameters are evaluated according to the European transient cycle (ETC) engine dynamometer transient cycle.[23] An engine dynamometer version of the ETC was chosen rather than a vehicle one since it enables adequate evaluation of the changes solely in the powertrain configuration, excluding the influences of gearshift strategy, vehicle parameters, and control strategies during vehicle stops. The average torque of the ETC is relatively high as shown in Ref. 24. Additionally, it was found in Refs. 6 and 15 that the driven cycle has a considerable effect on the optimum combination of component sizes and on the fuel economy of the hybrid powertrain. The original ETC was chosen to get test cycles with lower average torque to enable systematic comparison and analysis of the powertrain parameters when operating according to test cycles with different average loads and the same engine speed. This scaling might be considered as the operation of vehicles carrying different loads when real driving conditions are concerned.[1] Positive torque values of the ETC were therefore multiplied by the torque factors (TF) 0.6 and 0.8 to determine new test cycles.

Control strategy (CS) has a significant influence on the performance and fuel consumption of a vehicle. Therefore, the CS should be flexible enough to provide equivalence at all hybridization factors. A simple CS was used to guarantee reasonable comparisons of various hybrid powertrain configurations running under different operating conditions. The ICE was considered as the primary source of traction that was supported by the electric motor, thus keeping the battery SOC above a certain minimum value. Batteries are recharged by regenerative braking energy or by working the ICE at higher torques to replenish the batteries. The CS of the parallel hybrid powertrain allows the following: (1) electric assistance of the ICE; (2) replenishing the batteries by operating the ICE at higher torque output; (3) regenerative braking energy; (4) simultaneous operation of the ICE and EM to prevent charging the batteries above the specified limit; (5) normal operation of the ICE.[1,6]

The mean effective pressure was applied as the parameter determining engine load, since it is a universal parameter for all engines and is also easily evaluated by the ECU of the ICE. The following values were applied in the CS: $\mathrm{SOC_{min}} = 0.45$, $\mathrm{SOC_{ch1}} = 0.75$, $\mathrm{SOC_{ch2}} = 0.6$, $\mathrm{SOC_{dch}} = 0.7$, for the battery, $\mathrm{SOC_{min}} = 0.2$, $\mathrm{SOC_{ch1}} = 0.9$, $\mathrm{SOC_{ch2}} = 0.8$, $\mathrm{SOC_{dch}} = 0.95$. It should be kept in mind that it is possible to reduce the fuel consumption of hybrid powertrains with more complicated control strategies.

The results of the ETC test cycle are analyzed to highlight the differences in powertrain hybridizations. Equation (10) could be rewritten as

$$\frac{m_{\mathrm{f,tc,h}}}{m_{\mathrm{f,tc}}} - 1 = \left\{ \frac{\eta_{\mathrm{mech}}\eta_{\mathrm{f}}}{\eta_{\mathrm{mech,h}}\eta_{\mathrm{f,h}}} \left[1 + \frac{(1-\eta_{\mathrm{EL}})W_{\mathrm{EG}}}{W_{\mathrm{ICE}}} \right] - 1 \right\} + \left[\frac{\eta_{\mathrm{mech}}\eta_{\mathrm{f}}}{\eta_{\mathrm{mech,h}}\eta_{\mathrm{f,h}}} \frac{W_{\mathrm{br,h}} - W_{\mathrm{br}}}{W_{\mathrm{ICE}}} \right], \tag{13}$$

where the left hand side of the equation represents the relative change in the fuel consumption of the hybrid powertrain in comparison with that of the baseline one. The first term on the right hand side represents the influences of powertrain efficiencies (mechanical and fuel conversion efficiency of the ICE and electric conversion efficiency), generator input work and work produced by the baseline ICE and the second term of the right hand side represents the influences of the powertrain efficiencies, energy consumed by the brakes and work produced by the baseline ICE.[6]

The results of relative change of fuel consumption with different HFs are depicted in Fig. 4 for all the test cycles. It is evident that the fuel consumption of hybrid powertrains increases if the average torque of the test cycle is decreased and if the average torque of the test cycle is reduced, the minimum value of the fuel consumption for a particular average torque of the test cycle would move towards higher HFs.

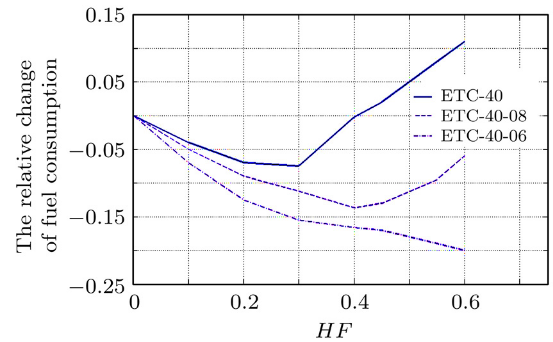


Fig. 4. Relative change of fuel consumption for different test cycles.

Figure 5 shows the effect of electric storage efficiency on relative change of fuel consumption for different HFs. According to the equations presented in the analytical section, it is obvious that the relative change of fuel consumption increases by reducing electric storage efficiency. It is affected by the change in electric storage efficiency more significantly at higher HFs.

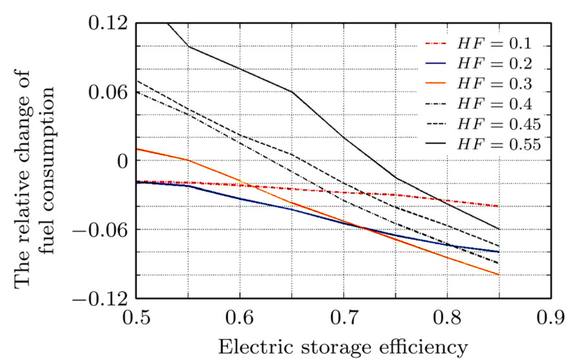


Fig. 5. Effect of electric storage efficiency on relative change of fuel consumption for various HFs.

In this paper, combined simulation and analytical analysis of the fuel consumption in parallel hybrid powertrains are investigated. It is shown that the evaluation of an optimum fuel consumption considering the various driven cycles and performance characteristics of the hybrid powertrain components would be possible. From the results obtained, it is evident that hybridization and downsizing would lead to improved fuel economy characteristics. It was found that the driven cycle has a considerable effect on the optimum combination of powertrain components. The results showed that the better fuel economy of hybrid powertrains increases by decreasing average load of the test cycle, the point of the best fuel economy for a particular average load of the cycle moves towards higher HFs when the average load of the test cycle is reduced. It was also mentioned that the electric storage efficiency has a significant impact on the fuel economy improvement of hybrid powertrains. Reducing HEVs weight and increasing the electric storage efficiency result in enhanced fuel economy of HEVs. It should be noted that this study implements Diesel engine as the ICE power source, whereas the fuel economy improvement would be much greater for gasoline engines, because of decreased part load efficiency of gasoline engines. It should also be taken into account that it is possible to improve the fuel economy of hybrid powertrains by using the stop and start strategy.

Nomenclature

m mass/kg
$Q_{\rm LHV}$ lower fuel heating value/J
W work/J
P power/J
t time/s
η efficiency

Subscripts

br braking
c engine cycle
ch charge
dch discharge
eff effective
EG electric generator
EL electric
EM electic motor
ES electric storage
f fuel
h hybrid
ICE Internal Combustion Engine
Max Maximum
mech mechanical
tc test cycle

Abbreviations

CS control strategy
HF hybridization factor
SOC state of charge
rpm round per minute
ECU electric control unit
ETC European test cycle

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