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# Optimization of power train and control strategy of hybrid electric vehicles

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Fuel consumption;
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Optimization.

**Abstract.** This paper aims to optimize the transmission and control strategy of a parallel hybrid electric vehicle in order to minimize Fuel Consumption (FC) and emissions, simultaneously. Vehicle transmission is a Power Split Continuously Variable Transmission (PS-CVT), while the employed Torque Coupler (TC) is a two-speed TC. Using this type of TC increases designer ability to create a more efficient transmission. In this vehicle, the electric assist control strategy is used as the control strategy. In this strategy, the engine operates at optimal operation points, obtained using the Global Criterion method (GC). A multi-objective optimization is implemented using GC to minimize vehicle FC and emissions without sacrificing dynamic performance. Finally, results of the conventional method of hybrid vehicle optimization and the results of using the Dynamic Programming method are compared.



## 1. Introduction

Among all solutions for decreasing vehicle Fuel Consumption (FC) and emissions, hybrid vehicles are one of the most advantageous. These vehicles use two or more distinct power sources to propel the vehicle. A Hybrid Electric Vehicle (HEV) is a type of vehicle that uses an electric system besides a conventional Internal Combustion Engine (ICE) to provide propulsion energy. It may not be as advantageous as an Electric Vehicle (EV) in terms of air-pollution, but it offers significant FC and emission benefits over conventional vehicles without sacrificing vehicle performance. There are significant factors which affect HEV performance indices. One of these parameters is vehicle transmission. Proper design of the transmission can decrease vehicle FC and emissions and satisfy the desired dynamic performance. One of the most promising transmissions used in the HEV is the Continuously Variable Transmission (CVT), which offers a continuous speed ratio between ICE and the wheels, and, therefore, allows the ICE to work efficiently in terms of FC or emissions. Furthermore, through application of this transmission, vehicle jerking associated with conventional transmissions is eliminated. The control strategy is another important parameter of an HEV which determines the power split between the power sources. As the control strategy has many effects on the performance of an HEV, its proper design could result in better fuel economy, lower emissions, and better dynamic performance of the vehicle. There are different strategies for controlling HEV and a well-known one is the Electric Assist Control Strategy (EACS). It is the most popular strategy among rule-based strategies, and, at present, is still the most practicable method [1].

For the purpose of improving the control strategy, many studies have been implemented. Montazeri et al. [2] conducted an optimization on EACS parameters in order to reduce the FC and emissions of the consid-

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ered vehicle. Van et al. [3] performed a multi-objective optimization on a PHEV equipped with a CVT drive train in order to optimize the distribution of power in the vehicle. Dorriet et al. [4] defined a novel control algorithm for a PHEV equipped with a CVT and then optimized it with the aim of minimizing vehicle FC and emissions. They used a weighted sum method to minimize the objectives, simultaneously. Wu et al. [5] used a Particle Swarm Optimization Algorithm (PSO) to optimize the EACS strategy and the size of the HEV elements in order to reduce FC, emissions and the total production cost of the vehicle, at the same time. In this study, for the purpose of simultaneous optimization of these functions, the Goal Attainment method was used.

In some studies, an optimization procedure has been accomplished in order to optimize the size of power sources and the number of batteries, while vehicle transmission has remained unchanged during the optimization process [6-9]. Furthermore, some research has tried to optimize the size of the power sources and the control strategy [10-13].

In the mentioned studies, HEV transmission is considered fixed and is not optimized. There are a few studies on optimization of the HEV power train. Roy et al. [14] optimized the power train of a HEV in order to reduce the vehicle FC in different drive cycles. A similar study was implemented by Jianping et al. [15].

Some studies have been implemented on optimization of the CVT transmission in a non-hybrid vehicle. Akbarzadeh et al. [16] optimized a half-toroidal CVT in order to increase its efficiency and reduce its weight under fixed operating conditions. Delkhosh et al. [17,18] optimized the geometry of a half and full toroidal CVT with the aim of increasing efficiency and decreasing weight. Also, the authors of [19] embedded a fixed ratio mechanism between the full-toroidal CVT and the final drive, and optimized the proposed transmission in the NEDC drive cycle in order to minimize vehicle FC. Furthermore, Delkhosh et al. [20] implemented the same study on a power-split CVT.

It is notable that there is no research into the simultaneous optimization of continuous transmission and the control strategy of a HEV, so far. As demonstrated in [16-19], due to the high dependence of the continuous transmission performance on its geometry, its performance and, therefore, vehicle performance, can be improved by its proper design. On the other hand, the proper selection of control strategy parameters in the HEV will improve vehicle performance. Consequently, optimization of continuous transmission besides the control strategy may result in a more efficient vehicle. This study aims to optimize the transmission and control strategy of a PHEV to minimize vehicle FC and emissions, simultaneously. Vehicle transmission is a Power Split Continuously Variable Transmission (PS-CVT) added to a two-speed Torque Coupler (TC). The proposed TC creates two gear ratios between the Electric Motor (EM) and the wheels. In this paper, firstly, the considered PS-CVT and TC, as well as the rules of the EACS strategy, are introduced. Afterwards, the method of obtaining ICE optimum operation points is explained. Then, the design parameters of the proposed transmission, besides the control strategy parameters, are considered as optimization variables, and a multi-objective optimization problem is formulated and solved using the Global Criterion (GC) method and the Backtracking Search optimization Algorithm (BSA). Finally, the effectiveness of the simultaneous optimization is evaluated by comparing it with the conventional method in which the transmission is optimized after finding the optimal control strategy [1]. Furthermore, in order to evaluate the effectiveness of the obtained control strategy, it is compared with the Dynamic Programming (DP) strategy, for the case of using optimized transmission.

## 2. Method

In this section, first, the PHEV model is presented. Then, the rules of EACS are explained and the "Partnership for a New Generation of Vehicles (PNGV)" criteria are introduced.

### 2.1. PHEV model

In this section, the models of PHEV main elements are presented. The considered vehicle is a post transmission parallel hybrid vehicle. Figure 1 shows the configuration of this vehicle.

It mainly consists of an ICE, a PS-CVT transmission, an electric motor, two automated dry clutches and a TC. In Table 1, the detailed specification of the vehicle is listed. In this section, a brief description for each element is presented.

The considered PS-CVT is equipped with a full-toroidal CVT. In Figure 2, the arrangement of this transmission is presented. As shown in the figure, this transmission consists of a CVT, a Planetary Gear (PG), and a Fixed Ratio mechanism (FR). The reason behind selecting a PS-CVT as the vehicle transmission is because the torque capacity of the toroidal CVT and its speed ratio range are limited, and connecting

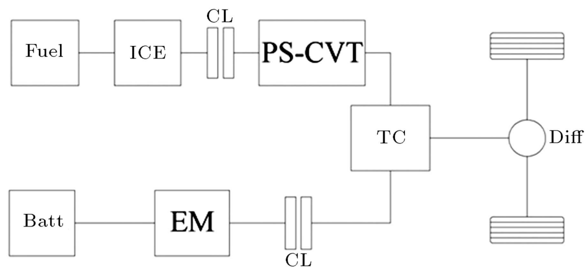


**Figure 1.** Configuration of the considered vehicle.

**Table 1.** Characteristics of the vehicle's elements.

| Element | Characteristics |
|---|---|
| **Internal combustion engine [21]** | |
| Volume | 1.3 L |
| Maximum power | 53.2 kW at 5200 rpm |
| Maximum torque | 113 Nm at 288 rpm |
| Peak efficiency | 0.34 |
| **Electric motor [22]** | Asynchronous induction motor/generator |
| Maximum power | 30 kW |
| Maximum torque | 305 Nm |
| Maximum speed | 6000 rpm |
| Peak efficiency | 0.9 |
| Minimum voltage | 60 V |
| **Battery [23]** | Lithium-ion polymer rechargeable |
| Number of modules | 96 |
| Nominal capacity | 10.05 Ah |
| Nominal voltage | 14.8 V |
| Internal impedance | 15 mΩ |
| Maximum allowable current | 10.05 A (charge), 120 A (discharge) |
| **Vehicle [24]** | Light passenger car |
| Frontal area | 1.94 m$^2$ |
| Rolling resistance | 0.014 |
| Drag coefficient | 0.46 |
| Wheel radius | 0.264 m |
| Cargo mass | 136 kg |
| Total mass | 1224 kg |
| **Transmission** | Power split continuously variable transmission |
| Efficiency | Variable with respect to input torque, speed and speed ratio |
| Differential speed ratio and efficiency | 3.778,97% |
| Torque coupler | Two-speed gear mate |

$$\eta_{\text{PS-CVT}} = \frac{\eta_{\text{FR}}\tau_{\text{PS-CVT}}\left(\frac{1}{\tau_{\text{FR}}} - \frac{\eta_{\text{PG}}}{\tau_{\text{CVT}}}\right)}{1 - \eta_{\text{FR}}\eta_{\text{PG}}\eta_{\text{CVT}}(T,\omega,\tau) + \tau_{\text{PS-CVT}}\left(\frac{\eta_{\text{FR}}\eta_{\text{CVT}}(T,\omega,\tau)}{\tau_{\text{FR}}} - \frac{1}{\tau_{\text{CVT}}}\right)}, \tag{1}$$

Box I

the PG and FR mechanisms to CVT could increase its speed ratio range and torque capacity [25,26]. Unlike conventional transmissions, PS-CVT efficiency is severely dependent on the speed ratio and efficiency of its elements, and also its operating condition, which includes the input torque, speed and speed ratio [20]. In this paper, to simulate the PS-CVT, the model introduced in [20] is employed. Using this model, the efficiency of PS-CVT as a function of its elements' efficiency and speed ratio, which is expressed in Box I, can be achieved where $\eta$ and $\tau$ denote the efficiency and speed ratio of each component of PS-CVT, respectively. Furthermore, $T$ and $\omega$ show the input torque and rotational speed of CVT, respectively. The speed ratio of each element is defined as its output speed divided by input speed. For the given geometry of CVT, its speed ratio range is definite. In this study, the speed ratio range of CVT is [0.77-3.44]. If the speed ratio ranges of CVT and PS-CVT are defined, the speed ratios of PG and FR can be calculated [20]. Therefore, the speed

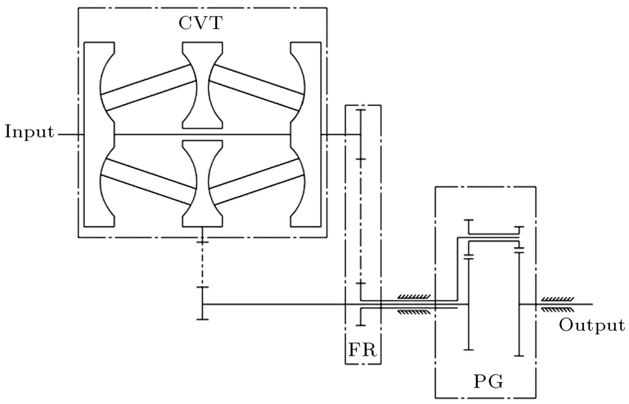


**Figure 2.** Arrangement of PS-CVT elements.

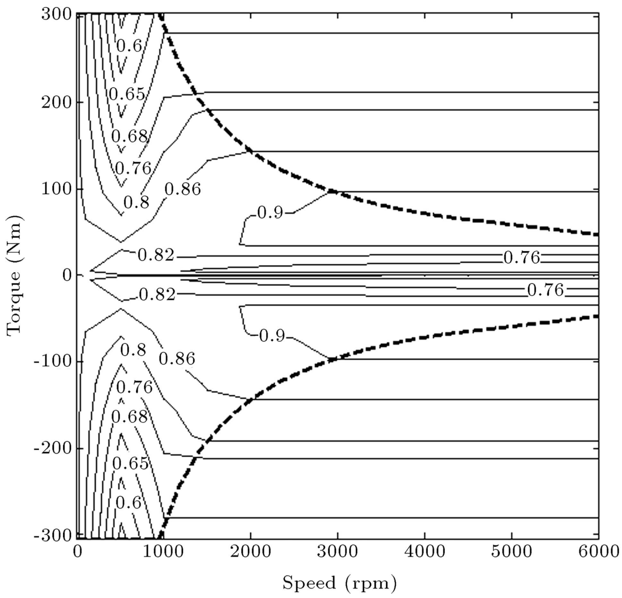


**Figure 3.** Efficiency contours of the selected EM.

ratios of PG and FR are definite values if the speed ratio range of PS-CVT is determined.

In this power transmission, the efficiency of the PG and the FR are almost fixed, compared to the efficiency of CVT which is a function of its operating condition [18,27,28]. In order to calculate CVT efficiency, the model presented in [18] is employed.

In order to simulate the EM, it is necessary to use the efficiency contours of the EM, with respect to its rpm and torque. It is notable that the employed EM can be used as a generator in the charge moments. Figure 3 shows these data for the selected EM in both motor and generator modes. These data are achieved from the ADVISOR library [29].

In order to simulate ICE, the data of its FC and emissions are needed. Figure 4(a) shows a schematic of the ICE optimal operating points in terms of FC and emissions. As seen in this figure, the fuel-optimal and emission-optimal points are not the same. ICE

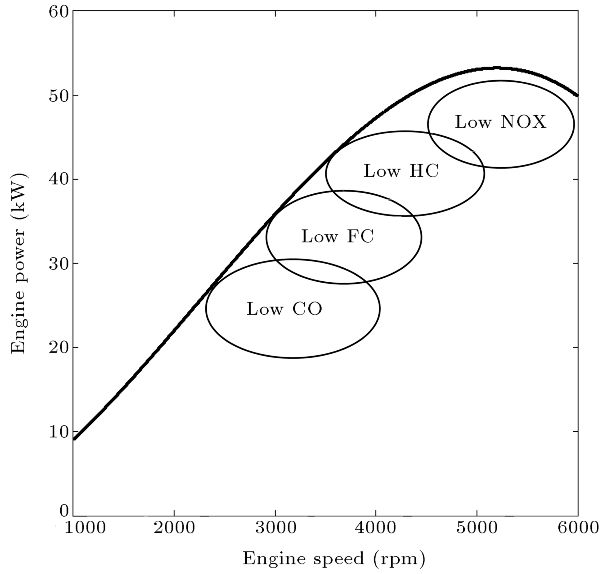


**Figure 4a.** Optimal operating points of the ICE in terms of FC and emissions.

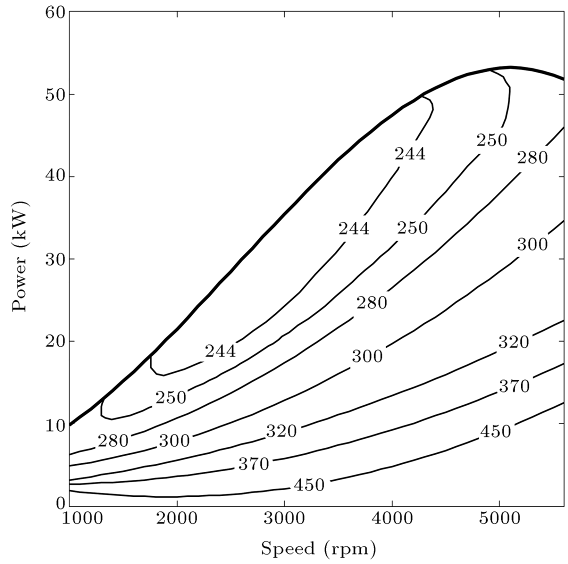


**Figure 4b.** BSFC data of the ICE (in gr/kWh).

operation in the fuel-optimal area does not guarantee low emissions, and vice versa.

The experimental data of the ICE emissions and FC are available for simulation. For example, the Brake Specific Fuel Consumption (BSFC) and CO data (in gr/kWh) of the selected ICE, with respect to its power and rpm, are shown in Figure 4(b) and (c), respectively.

In the ICE model, its dynamics are ignored due to quasi-static assumption [30]. Furthermore, it is assumed that the engine is fully warmed-up. Therefore, the effect of engine temperature on the FC and emissions is not considered.

The battery module is simulated using the model presented in [31]. The equivalent circuit diagram of the battery is shown in Figure 5.

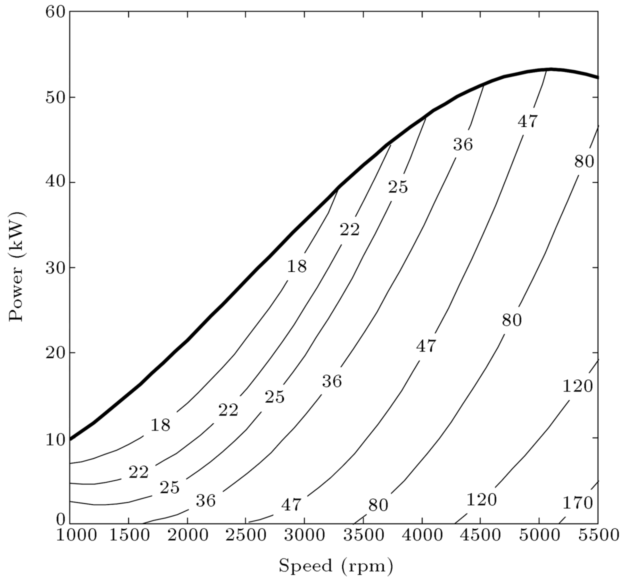


**Figure 4c.** CO data of the ICE (in gr/kWh).

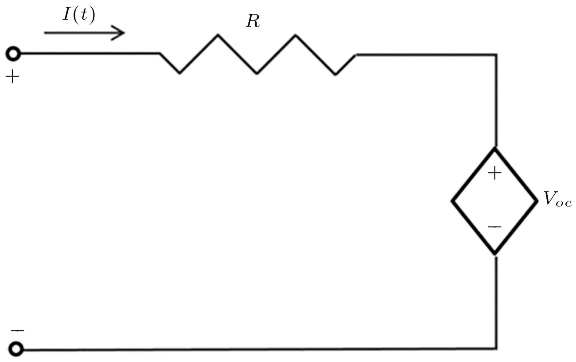


**Figure 5.** Equivalent circuit diagram of the battery.

According to this model, the efficiency of the battery during charge and discharge can be expressed as:

$$\eta_{\text{batt}} = \frac{V_{oc}I(t)}{V_{oc}I(t) + I^2(t)R}, \tag{2}$$

where $V_{oc}$ is the absolute of the open circuit voltage; $I(t)$ is the absolute of the battery current; and $R$ is its internal impedance. During the battery charge and discharge, its current is calculated by:

$$I_{\text{charge}} = \frac{-V_{oc} + \sqrt{V_{oc}^2 + 4.R.P(t)}}{2R}, \tag{3}$$

$$I_{\text{discharge}} = \frac{V_{oc} - \sqrt{V_{oc}^2 - 4.R.P(t)}}{2R}. \tag{4}$$

In this equation, $P(t)$ means the absolute of the transferred power to/from the battery. The current of the battery and also its efficiency are obtained easily, by knowing the power of the EM. Regarding these relations, the maximum transmitted power of the battery during charge and discharge stages is limited by its maximum current. The limitations of the electric power transfer, due to the limitations of battery charge and discharge and motorpower, should be considered in the hybrid vehicle model.

The number of battery modules to be connected in series is determined knowing the minimum voltage of the motor ($V_{M\,\min}$) and the battery ($V_{B\,\min}$), as below [9]:

$$N_{B\text{series}} = \text{round}\left(\frac{V_{M\,\min}}{V_{B\,\min}}\right). \tag{5}$$

In this equation, the *round* function provides the greater integer of the argument. The number of battery packs to be connected in parallel is determined according to the fact that the battery pack should not limit the power which can be transmitted through the EM. This value is achieved by:

$$N_{B\text{parallel}} = round\left(\frac{P_{M\,\max}}{V_{oc}N_{B\text{series}}I_{\max}}\right), \tag{6}$$

where $I_{\max}$ is the maximum current of the battery. As shown in Table 1, the values of $I_{\max}$ for charge and discharge modes are different. Therefore, the minimum value between these values is considered as $I_{\max}$.

The required torque (which is determined considering vehicle speed and acceleration) is split between the power sources by the vehicle TC. Another task of TC is that, while the output torque of the ICE is more than the required value, the additional torque will be transmitted to the EM via the TC to replenish the battery. Moreover, during braking, the absorbed power is transferred to the battery by the TC and the EM. In the conventional TC, an equal speed ratio is used between the motor and wheels in all modes of vehicle motion, i.e. charge and discharge modes. In this study, in order to increase the efficiency of the electro-mechanical energy conversion, two different speed ratios between the motor and the wheels can be used. One is used during transmitting power from/to EM to/from wheels, and the other is used through battery charging via the ICE. Using two different gear ratios gives the designer more latitude to design a more efficient TC. The structure of the proposed TC is shown in Figure 6. In this figure, the power flow direction in different modes is exposed. According to this figure, the speed ratio between the wheels and EM is $Z_5/Z_3$ during the battery charge/discharge by wheels, while it will be $Z_6/Z_4$ for the case of battery charging by ICE. The parameter, $Z_i$, denotes the number of gear teeth.

For this mechanism, the relations between its elements' speed and torque are as below:

$$\omega_{\text{in1}} = \frac{Z_2}{Z_1}\omega_{\text{out}}, \qquad \omega_{\text{in2}} = \frac{Z_3}{Z_5}\left(\text{or}\frac{Z_4}{Z_6}\right)\omega_{\text{out}}, \tag{7}$$

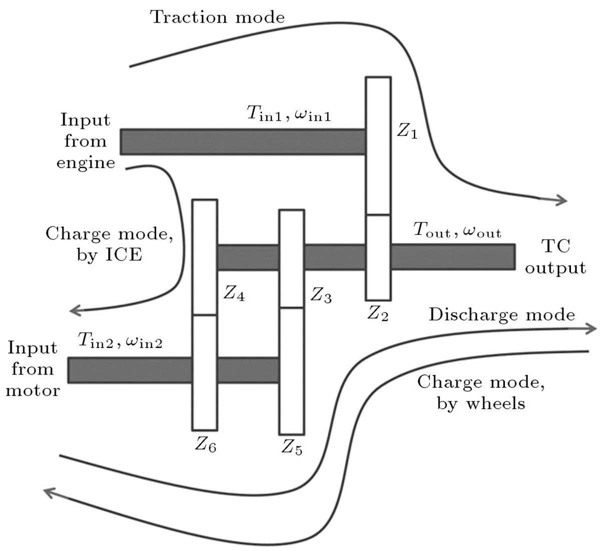


**Figure 6.** Structure of two-speed TC mechanism.

$$T_{out} = T_{in1}\frac{Z_2}{Z_1}\eta + T_{in2}\frac{Z_3}{Z_5}\left(\text{or}\frac{Z_4}{Z_6}\right)\eta^{\alpha}, \quad (8)$$

where $\omega$ and $T$ mean the rotational speed and torque of each shaft, while $\alpha$ denotes the power flow direction of the EM. During the battery charge (negative motor torque) $\alpha = -1$, while it is equal to 1 through discharging (positive motor torque). In this equation, $\eta$ is the efficiency of the gear mate in TC.

As shown in Table 1, the final drive efficiency is considered fixed because of the low variation of gear mate efficiency in the differential.

The clutch used in this vehicle is a dry clutch which acts as a Boolean switch. It connects and disconnects the engine to the wheels immediately, and its power losses during connecting and disconnecting are ignored.

As presented in this section, the main components of the introduced PHEV are simulated.

### *2.2. Control strategy*

The control strategy defines the power split between the power sources, regarding the operating condition of the hybrid vehicle. The proper design of the control strategy will result in better fuel economy and lower levels of emission. Among different methods, the rule-based strategies are the most feasible patterns. EACS is a well-known strategy among different rule-based methods. According to this strategy, while the vehicle requires small amounts of power at low speeds, the ICE would be off and the required power is supplied by the EM. The rules of this strategy are described briefly as follows:

1. If SOC $> L_{SOC}$ and $\begin{cases} V < V_L \\ \text{or} \\ P_{req} < t_{off}P_{E\max} \end{cases}$, then ICE off, MG on;
2. If SOC $> L_{SOC}$ and $P_{req} > t_{off}P_{E\max}$, then ICE on, MG off;
3. If SOC $< L_{SOC}$ and $P_{req} < t_{min}P_{E\max}$, then $P_E = t_{min}P_{E\max}$. Battery is charged by additional power;
4. If SOC $< L_{SOC}$ and $P_{req} \geq t_{min}P_{E\max}$, then $P_E = P_{req} + t_{chg}P_{E\max}$. Battery is charged by additional power;
5. If SOC $< L_{SOC}$ and $P_{req} > P_{E\max}$, then vehicle cannot provide required power;
6. If SOC $> L_{SOC}$ and $P_{req} > P_{E\max}$, then $P_E = P_{req} - t_{dischg}P_{E\max}$. Motor supplies rest of required power
7. SOC $> H_{SOC}$, then ICE off, MG on;
8. If vehicle is at standstill, then ICE off, MG off;
9. If vehicle brakes, then braking energy is stored in the battery.

The schematic of this control strategy is shown in Figure 7.

At each moment of the driving cycle, after determining the ICE power, its rpm should be decided, and the speed ratio of the transmission should be determined with regard to vehicle speed and ICE rpm. It is clear that proper determination of ICE rpm has a significant impact on the level of the FC and emissions. The optimum operation point of the ICE is the point at which its BSFC and emissions are as low as possible. In many studies implemented on hybrid vehicles equipped with CVT, the fuel-optimal operation line of the ICE is considered as the operation line [32,33]. However,

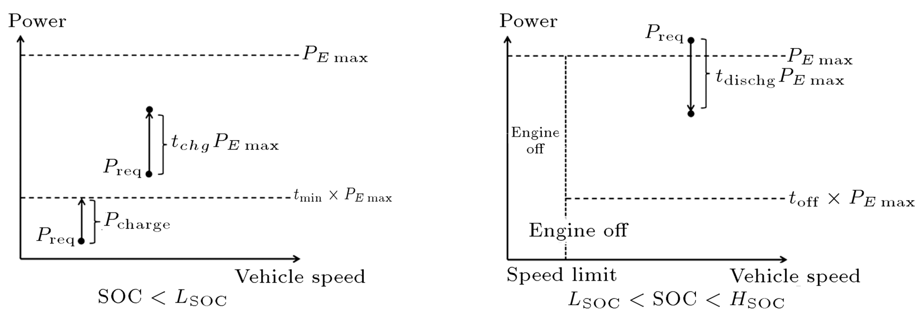


**Figure 7.** The schematic of the EACS pattern.

this method is not appropriate for a control strategy that aims to minimize emissions as well as vehicle FC.

The other method is on the basis of defining a cost function, as below [3]:

$$F = \frac{1}{w_1 + w_2 + w_3 + w_4} \left( w_1 \frac{\mathrm{FC}}{\overline{\mathrm{FC}}} + w_2 \frac{\mathrm{HC}}{\overline{\mathrm{HC}}} + w_3 \frac{\mathrm{CO}}{\overline{\mathrm{CO}}} + w_4 \frac{\mathrm{NOX}}{\overline{\mathrm{NOX}}} \right). \quad (9)$$

In this function, HC, CO and NOX are functions describing pollutants, while FC denotes vehicle fuel consumption. The methods of calculating these functions are similar. For instance, the method of FC calculation is presented in [19]. $\overline{\mathrm{FC}}$, $\overline{\mathrm{HC}}$, $\overline{\mathrm{CO}}$ and $\overline{\mathrm{NOX}}$ are mean values of these functions in the ICE map, while $w_i$ denotes the relative importance of the $i$th function. This function is calculated for all operating points of the ICE and its contours are plotted. According to this method, at any specific power, the rpm at which the cost function is minimal is selected, and the speed ratio of the continuous transmission is determined to create the desired speed. Obviously, this method uses a 'sum of weighted function' approach to determine the optimum operation point of the ICE. However, it has been demonstrated in relevant literature [34-36] that this method is not successful in reaching satisfactory results, especially in non-convex spaces, and the result is highly sensitive to the importance of weight.

The method of determining the optimal operation points of the ICE employed in the present study is on the basis of minimizing FC and emissions using the GC method. This method has more advantages over the sum of weighted function approach [35]. This method will be described in the "Optimization" section. In this way, for a definite value of ICE power, the lowest values of BSFC and emissions are determined. Then, using the GC method, the rpm, where BSFC and emissions are as close to their minimal values as possible, is determined. This process is accomplished for different values of ICE power and the optimum points of the ICE rpm versus its power are attained. These points are shown in Figure 8. In the control strategy, for each value of the ICE power, its rpm is determined using these data.

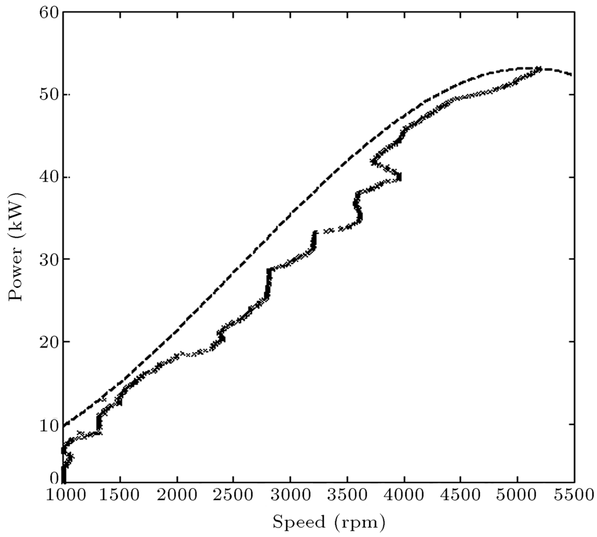

**Figure 8.** Optimum operation points of the ICE.

A model of the introduced vehicle is created in MATLAB containing very detailed component maps, which yield realistic FC and emission results for a non-hybrid vehicle. A conventional way to simulate the hybrid vehicle is to use ADVISOR software. However, since the model of vehicle components, e.g. PS-CVT transmission and TC, includes lots of details, in this study a model created in MATLAB was used.

### *2.3. PNGV criteria*

One of the main concerns in the hybridization of vehicles is degradation of their dynamic performance. Therefore, in order to prevent a decline in vehicle performance, some constraints on dynamic performance must be defined during the optimization process. These constraints are called "Partnership for a New Generation of Vehicles (PNGV)" and are summarized in Table 2.

PNGV criteria satisfaction depends heavily on the characteristics of the power sources and vehicle

**Table 2.** PNGV criteria [37].

| Performance requirement | Value |
|---|---|
| Gradeability | $\geq$ 88.5 km/h at 6.5% grade in 5th gear |
| | $\geq$ 30% grade |
| Acceleration time for | 0-97 km/h: $\leq$ 12 sec |
| | 0-137 km/h: $\leq$ 23.4 sec |
| | 64-97 km/h in 5th gear: $\leq$ 5.3 sec |
| Maximum speed | $\geq$ 161 km/h |
| Distance in 5 sec | $\geq$ 42.7 m |

transmission. In this study, specifications of ICE and the EM are pre-defined and their effects on mass distribution of the vehicle are taken into account. Therefore, the transmission must be designed in order to satisfy all PNGV constraints. The most important parameters of the transmission that could affect vehicle dynamic performance is the PS-CVT speed ratio range ($\tau_{\min}-\tau_{\max}$) and the speed ratios of TC ($Z_1/Z_2$, $Z_6/Z_4$, $Z_5/Z_3$). Therefore, these parameters should be considered design variables to satisfy PNGV constraints. As is clear, these parameters affect the transmission performance and, therefore, impact vehicle FC and emissions.

## 3. Optimization

As stated above, vehicle FC and emissions are strongly influenced by the control strategy and the transmission. In addition, dynamic performance depends on transmission design. Therefore, by varying the parameters of the control strategy and transmission, it is possible to decrease vehicle FC and emissions without sacrificing dynamic performance. This goal can be achieved by optimization. The optimization problem is summarized below:

Minimize $f_i$(X)

where:

$f_1(X)$ = vehicle FC (L/100 km),

$f_2(X)$ = NOX emission (gr/km),

$f_3(X)$ = CO emission (gr/km),

$f_4(X)$ = HC emission (gr/km),

$$X = \begin{bmatrix} Z_1/Z_2, Z_5/Z_3, Z_6/Z_4, \tau_{\max}, \tau_{\min}, \cdots \\ L_{\text{SOC}}, H_{\text{SOC}}, t_{\text{off}}, t_{\min}, V_L, t_{\text{chg}}, t_{\text{dischg}} \end{bmatrix}^T.$$

Subject to:

- PNGV criteria (listed in Table 2),
- $\omega_{E\min} \leq \omega_E \leq \omega_{E\max}$,
- $\omega_M \leq \omega_{M\max}$,
- $T_E \leq \min(T_{E\max}(\omega_E), T_{\text{PS-CVT}\max}(\tau_{\text{PS-CVT}}))$,
- $T_M \leq T_{M\max}(\omega_M)$,
- $L_{\text{SOC}} \leq \text{SOC} \leq H_{\text{SOC}}$,
- $P_{\text{Elec}} \leq \min(P_{M\max}(\omega_M), P_{\text{Batt}\max})$,
- $P_E \leq P_{E\max}$,
- $\tau_{\min} \leq \tau_{\text{PS-CVT}} \leq \tau_{\max}$,

where $\omega_E$ and $\omega_M$ are rotational speeds of ICE and EM, respectively, while $\omega_{E\max}$ and $\omega_{M\max}$ are their maximum allowable values, and $\omega_{E\min}$ is the ICE minimum allowable speed. Furthermore, $P_{\text{Elec}}$ is the electric power transferred through the battery and EM. In the optimization process, the optimization parameter set which violates PNGV criteria is eliminated and an infinite value is assigned to the objective function.

In order to optimize the objectives simultaneously, the GC method is used. This method is a scalarization method. In the scalarization methods group, the objectives are converted to a scalar function and this objective is optimized similar to single-objective optimization. This method has some advantages, e.g. its simplicity, and the ability to reach Pareto optimal solutions, etc. [38]. In the GC method, first, the optimal value of each objective is obtained by optimization without considering other objectives. These values are called utopia points. Afterwards, employing the function, $F(X) = \left\{ \sum_{i=1}^{k} \left[ \frac{f_i^o - f_i(X)}{f_i^o} \right]^2 \right\}^{\frac{1}{2}}$, the multi-objective problem is converted to a single-objective one. In this function, $f_i$ denotes the $i$th objective, $f_i^o$ means its utopia point, and $X$ is the vector of optimization parameters. In fact, this function shows the sum of the normalized Euclidean distances between each objective and its utopia point. Minimizing this function leads to a reduction in the mentioned distances, and, therefore, leads the objectives to their optimal value.

The optimization parameters and their variation ranges in the optimization process are listed in Table 3. As discussed above, these parameters are the design parameters of the introduced transmission ($Z_1/Z_2$, $Z_5/Z_3$, $Z_6/Z_4$, $\tau_{\max}$, $\tau_{\min}$) and the control strategy ($L_{\text{SOC}}$, $H_{\text{SOC}}$, $t_{\text{off}}$, $t_{\min}$, $V_L$, $t_{\text{chg}}$, $t_{\text{dischg}}$). The ranges of speed variators in TC are determined considering production limitations. In addition, variation ranges of $\tau_{\min}$ and $\tau_{\max}$ are decided, regarding conventional transmissions. Ranges of $L_{\text{SOC}}$ and $H_{\text{SOC}}$ are defined, with regard to the recommendations of the battery manufacturer. The upper bounds of $t_{\text{chg}}$ and $t_{\text{dischg}}$ are determined considering the maximum charge and discharge rates of the battery. Finally, the variation ranges of other control parameters in the optimization

**Table 3.** The optimization parameters and their variation range in the optimization process.

| Parameter | Range | Parameter | Range |
|---|---|---|---|
| $Z_1/Z_2$ | [0.25-4] | $Z_5/Z_3$ | [0.25-4] |
| $Z_6/Z_4$ | [0.25-4] | $\tau_{\min}$ | [0-2] |
| $\tau_{\max}$ | [1-4] | $L_{\text{SOC}}$ | [0.2-0.5] |
| $H_{\text{SOC}}$ | [0.55-0.8] | $t_{\text{off}}$ | [0.01-0.6] |
| $t_{\min}$ | [0.01-1] | $V_L$ (m/s) | [2-12] |
| $t_{\text{chg}}$ | [0.01-0.035] | $t_{\text{dischg}}$ | [0.01-0.35] |

process are determined considering conventional values.

Obviously, energy is consumed in the HEV by the ICE and the EM. Therefore, it is necessary to consider both energy consumptions in the vehicle. In this study, in order to eliminate the effect of energy usage by the battery, at each iteration of the optimization process, the simulation is accomplished with different initial SOC until the final SOC value (SOC at the end of the drive cycle) satisfies the inequality, $\frac{|SOC_{Initial} - SOC_{Final}|}{SOC_{Initial}} \leq 0.01$. This technique is called the "dichotomy method" [12,39].

Vehicle motion is considered in the SC03 drive cycle. The reason for selecting this driving cycle is because the vehicle experiences high accelerations and, therefore, needs high power values.

In the present study, the BSA is used to reach the minimum value of the considered objective function, at each step of the multi-objective optimization. This method is a new Evolutionary Algorithm (EA), which can be used to optimize non-differentiable, non-linear and complex functions. As discussed in [40], since this method uses only one control parameter, its sensitivity is lower than that of other EA methods. This method is thoroughly introduced in [40]. In this reference, this method has been compared with some EA methods using some benchmark problems, and the higher success rate of this method in solving optimization problems has been demonstrated.

### 3.1. Optimization results

As stated above, in order to optimize the objective functions using the GC method, it is necessary to find the utopia point of each objective. The utopia point of each objective is obtained by optimizing it, while ignoring other objectives. The achieved values are shown in Table 4. At each row of this table, the optimization results for each objective are shown. At this row, besides the optimal value of the considered objective function, the values of other objectives for this case are presented.

Obviously, in case of optimizing one of the objectives, other objectives are away from their utopia points. It is because the optimal regions of the ICE in terms of FC and emissions are different. This fact can be drawn from Figure 4(a). According to this figure, the NOX and CO-optimal regions are completely distinct. Thus, in case of optimizing CO emission, the NOX value is not minimized and the results shown in Table 4 confirm this fact. As shown in the third row of this table, through minimization of the CO value, NOX emission reaches the maximum value among all single-objective optimization cases. Similarly, through minimization of NOX emission, the CO value reaches its maximum value among all optimization cases. Due to this fact, in order to reach the optimum point in terms of vehicle FC and emissions, multi-objective optimization seems to be essential.

Once the utopia points are obtained, the optimal value of the defined objective function presented in the previous section can be found using the GC method. This optimization was implemented several times and the optimization results were achieved using BSA methodology. Furthermore, the optimization was run again, using PSO. Objective function variations during both optimization processes are shown in Figure 9. According to this figure, BSA gives better results and the objective function converges at a lower number of iterations, compared to the PSO method. Therefore, it can be concluded that the BSA method is more efficient than PSO, in this case.

The optimal values of optimization parameters added to optimal values of the considered objectives are shown in Table 5.

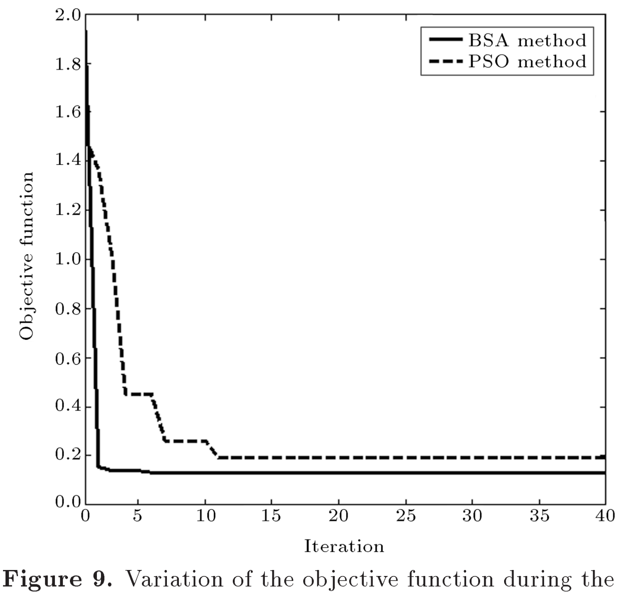


**Figure 9.** Variation of the objective function during the optimization process.

**Table 4.** Optimization results for single-objective optimizations.

| Objective function | FC (L/100 km) | HC (gr/km) | CO (gr/km) | NOX (gr/km) |
|---|---|---|---|---|
| FC (L/100 km) | 2.08 | 0.31 | 2.95 | 0.41 |
| HC (gr/km) | 2.17 | 0.18 | 3.3 | 0.29 |
| CO (gr/km) | 4.1 | 0.42 | 1.40 | 0.56 |
| NOX (gr/km) | 5.77 | 0.49 | 6.54 | 0.09 |

**Table 5.** The results of multi-objective optimization.

| Parameter or function | Value | Parameter or function | Value |
|---|---|---|---|
| $Z_1/Z_2$ | 2.16 | $Z_5/Z_3$ | 2.21 |
| $Z_6/Z_4$ | 0.87 | $\tau_{\min}$ | 1.37 |
| $\tau_{\max}$ | 3.67 | $L_{\text{SOC}}$ | 0.45 |
| $H_{\text{SOC}}$ | 0.66 | $t_{\text{off}}$ | 0.40 |
| $t_{\min}$ | 0.65 | $V_L$ (m/s) | 5.78 |
| $t_{\text{chg}}$ | 0.01 | $t_{\text{dischg}}$ | 0.24 |
| NOX (gr/km) | 3.47 | FC (L/100 km) | 0.37 |
| CO (gr/km) | 2.21 | HC (gr/km) | 0.40 |
| Objective function | 3.47 | | |

Comparison of the objective values shown in Tables 4 and 5 reveals that the objective function values achieved from the multi-objective optimization are not minimal (the values shown in Table 4), but are acceptable. According to Tables 3 and 5, the optimized $L_{\text{SOC}}$ and $t_{\min}$ are high values. This condition increases the possibility of ICE operation at higher power (according to the third to fifth laws of EACS).

As stated above, the transmission parameters should satisfy optimization constraints, e.g. PNGV criteria. PNGV criteria and the dynamic performance resulted from the optimized transmission are shown in Table 6.

Figure 10 shows variations of the vehicle speed, ICE power, EM power and the battery SOC during the first 100 seconds of SC03. As can be seen, while the vehicle is at standstill, both the ICE and EM are turned off and the battery SOC is unchanged. Through braking, braking energy is saved in the battery and its SOC increases. During a large part of the considered time, EM propels the vehicle and ICE is turned off. This is because the ICE is inefficient at low power. At these moments, the battery SOC decreases.

To examine the effectiveness of the simultaneous optimization of the transmission and the control strategy, the results can be compared with the results of the conventional method. As the conventional method, at first, the control strategy is optimized using the fixed transmission. After reaching the optimal control strategy, the transmission is optimized [1]. This method is considered conventional and its results are compared with simultaneous optimization results.

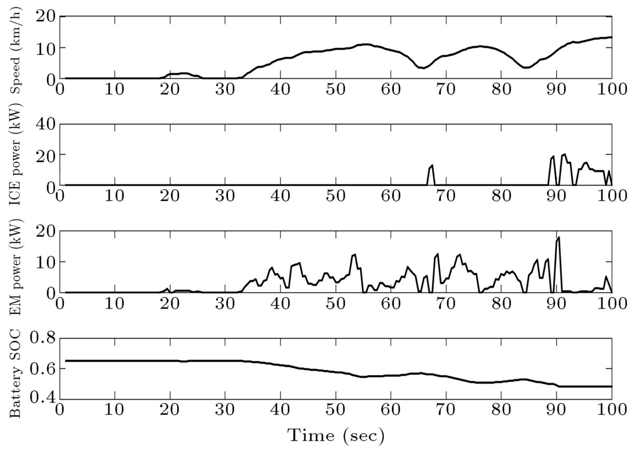


**Figure 10.** Variations of the vehicle speed, ICE power, EM power and the battery SOC during the first 100 seconds of SC03.

In order to more accurately investigate the optimization results, another way is to compare the results of the employed control strategy with another strategy, for certain values of design parameters. In much literature, the Dynamic Programming Method (DP) has been used as a benchmark to evaluate rule-based controllers [41,42]. In this section, vehicle FC and emissions for the case of employing DP and the optimal strategy are compared, while the design parameters are the values shown in Table 5. These two comparisons are shown in Table 7.

The comparison reveals that the presented method gives better fuel economy and low levels of emission compared to cases using conventional and DP methods.

## 4. Conclusion

The goal of this paper is to introduce a parallel hybrid vehicle equipped with a power split continuously

**Table 6.** The desired and achieved dynamic performances.

| Performance requirement | Required value | Achieved value |
|---|---|---|
| Gradeability | $\geq$ 88.5 km/h at 6.5% grade in 5th gear | 100 km/h at 6.5% grade in upper bound of transmission |
| | $\geq$ 30% grade | 32% grade |
| Acceleration time for | 0-97 km/h: $\leq$ 12 sec | 9 sec |
| | 0-137 km/h: $\leq$ 23.4 sec | 17.6 sec |
| | 64-97 km/h in 5th gear: $\leq$ 5.3 sec | 4.1 sec |
| Maximum speed | $\geq$ 161 km/h | 180 km/h |
| Distance in 5 sec | $\geq$ 42.7 m | 42.96 m |

**Table 7.** The comparison between the presented optimization method, the conventional one and DP strategy.

| | Presented method | Conventional method | DP method |
|---|---|---|---|
| FC (L/100km) | 3.47 | 5.78 | 4.82 |
| HC (gr/km) | 0.40 | 0.55 | 0.42 |
| NOX (gr/km) | 0.37 | 0.39 | 0.37 |
| CO (gr/km) | 2.21 | 5.31 | 3.45 |

variable transmission, and to optimize vehicle transmission and the parameters of the control strategy, with the aim of simultaneous minimizing vehicle FC and emissions. For this purpose, first, PS-CVT, as the vehicle power transmission, was introduced. In order to increase the degree of freedom of the employed TC and the ability to increase its performance, a new configuration for this component was proposed. In this mechanism, a two-speed gear ratio was used between the motor and the wheels. Since the considered transmission (PS-CVT and TC) has a significant effect on the dynamic performance of the vehicle and also its FC and emissions, their parameters were considered part of the optimization parameters.

Afterwards, the rules of the EACS were described. A map of the optimal operation points of the ICE, in terms of FC and emissions, was achieved using the GC method, and is used in the EACS for determining the ICE operation point at each moment of the driving cycle. Since the parameters of the EACS impact its performance and, therefore, vehicle FC and emissions, these parameters were considered the remaining part of the optimization parameters. The aim of optimization was to attain an acceptable value for vehicle FC and emissions without sacrificing dynamic performance. In order to optimize vehicle FC and emissions simultaneously, the GC method was employed. It can be concluded from the optimization results that the achieved values for the objectives are not the same utopia points, but are acceptable values. Then, it was demonstrated that the optimized parameters satisfy the PNGV criteria. Finally, the effectiveness of the simultaneous optimization was evaluated by comparison with conventional methods and it was demonstrated that simultaneous optimization gives better results. Also, the optimized EACS and the DP strategy were compared using optimal transmission and the superiority of the EACS over the DP was shown.

## Nomenclature

| | |
|---|---|
| $\eta$ | Efficiency |
| $I_{\max}$ | The maximum current of the battery |
| $\tau$ | Speed ratio |
| $Z_i$ | The number of gear teeth |
| $T$ | Torque |
| $V_L$ | Lunch speed |
| $\omega$ | Rotational speed |
| $P_E$ | ICE power |
| $V_{oc}$ | The absolute of the battery open circuit voltage |
| $P_{E\max}$ | ICE maximum power |
| $I(t)$ | The absolute of the battery current |
| $P_{\text{req}}$ | Required power |
| $R$ | Internal impedance of the battery |
| $L_{\text{SOC}}$ | Lower limit of battery state of charge |
| $P(t)$ | The absolute of the transferred power to/from the battery |
| $H_{\text{SOC}}$ | Higher limit of battery state of charge |
| $V_{M\min}$ | Minimum voltage of the motor |
| $w_i$ | Relative importance of $i$th function |
| $V_{B\min}$ | Minimum voltage of the battery |
| $\tau_{\min}$ | Minimum speed ratio of transmission |
| $\omega_E$ | Rotational speed of ICE |
| $\tau_{\max}$ | Maximum speed ratio of transmission |
| $\omega_M$ | Rotational speed of EM |
| $X$ | The vector of optimization parameters |
| $P_{\text{Elec}}$ | Electric power transferred through battery and EM |
| $f_i^o$ | Utopia point of $i$th function |

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