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THE EFFECT OF DIFFERENT GEAR RATIO SELECTION ALGORITHMS ON THE EFFICIENCY OF CONVENTIONAL AND PARALLEL HYBRID DRIVETRAINS

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ABSTRACT

Road vehicles using electric power sources have become increasingly popular in the last decade. Meanwhile, battery technology is still not mature enough to meet expected vehicle range; thus the transition from ICE vehicle to fully electric vehicle is not imminent. Therefore the concept of hybrid drivetrain technology was introduced. The hybrid powertrain configuration includes at least two different energy converters together with an energy storage medium. In this article, different gear shifting algorithms were introduced to increase ICE efficiency in conventional vehicle. Besides, a parallel hybrid configuration was also introduced to enhance drivetrain efficiency. The Equivalent Energy Minimization Method (ECMS) and Dynamic Programming (DP) algorithms were selected as online and offline implementable optimal control methods for hybrid power sharing management. Totally six different case studies were planned to compare the efficiency of each configuration. Finally, the effect of the gear ratio selection and power split algorithms were compared on conventional and parallel hybrid drivetrains regarding overall efficiency.

Keywords: Parallel hybrid vehicle, Optimal gear shifting, Consumed energy minimization, Fuel consumption

1. INTRODUCTION

Petroleum based fuels obtained from crude oil and natural gas processing include gasoline, diesel fuel, jet fuel and liquid petroleum gas, all of which are used nowadays in transportation systems. In 2014, petroleum based fuels accounted for about 92% of the total energy used by the transportation sector in the US. Biofuels, such as ethanol and biodiesel, contributed approximately to 5% of the total energy demand while natural gas to only about 3%. Meanwhile, the share of electric energy usage in road vehicles still constitutes less than 1% of the total energy demand [1].

Alternative power sources have lately gained increased significance for enhancing fuel economy, reducing fuel costs and most importantly emissions. In that context, the ideal solution would be the exclusive usage of electric energy in automotive drive systems. The efficiency of electric motors (EM) is close to 95% making them much more efficient than internal combustion engines (ICE). However, due to the limitations of today’s battery technology and the fact that 78% of electricity production in Turkey is based on fossil fuels, it is not expected that pure electric vehicles will become popular in this country in the near future. An alternative approach is to increase energy efficiency by combining available energy sources. The most prominent approach is the use of hybrid drive systems operating a combination of ICE and EM [2].

According to the definition made by the United Nations in 2003, a hybrid vehicle configuration consists of at least two energy converters and an energy storage system. Today, most hybrid vehicles have an ICE, one or more EMs as energy converters on board, besides a battery and a fuel tank as energy sources [3]. Hybrid electric vehicle control strategies work based on the principle of satisfying driver’s demanded power, while, in the meantime, making the most efficient use of the two power sources. Fuel

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economy, emissions and vehicle performance are generally contradictory targets and optimization algorithms are more than often utilized while designing hybrid energy management systems [4]. The Maximum State of Charge (SoC) strategy, the Thermostat control strategy, the constrained thermostat Control strategy, the Equivalent Energy Minimization Method (ECMS) and Dynamic Programming (DP) are among the various control methods proposed for the energy management of hybrid drive systems [5].

The objective of the maximum SoC control strategy is to meet driver's demanded power while maintaining the SoC of the electric power source at a high level. Here, the ICE is considered as the primary power source. This control strategy is considered to be the proper design method for vehicles in which performance is the primary concern, such as vehicles with frequent stop-and-go driving patterns. The Thermostat Control Stategy is based on shutting down the ICE when the SoC is above a predetermined level and running it again to reload the battery when the SoC is below another predetermined level. The Constrained Thermostat Control strategy is a tradeoff between Maximum SoC and Thermostat Control strategies. The simplicity of the algorithm makes it a popular choice among various hybrid control algorithms. However, this concept bears several negative aspects. Firstly, the operation of the ICE is completely independent from driving conditions and the noise generated inside the cabin affects driving comfort. Secondly, the duty cycle of the ICE needs to be adjusted by also considering the vehicle emissions, which decreases fuel economy [6].

Dynamic programming is a numerical method that solves complex optimal problems by breaking them down into smaller subcomponents. This algorithm has been used in hybrid energy management systems as well to optimize vehicle fuel economy based on the knowledge of the driving cycle. This strategy is not suitable for real-time application because of the vehicle speed profile and road load is unknown in practice. Nevertheless, the method gives the global optimal solution and has been traditionally used to determine the efficiency of other hybrid management algorithms [6].

ECMS is an instantaneous online implementable optimization algorithm for hybrid energy management systems. ECMS operates by satisfying a number of constraints such as driver's power demand, actuator torque limitations, high voltage battery power and energy capacity limitations. In this method, the energy consumption of the battery is converted to an equivalent ICE fuel consumption. Then, the equivalent total fuel consumption is calculated and set as an objective function. Power split is determined so as to minimize equivalent fuel consumption at each time step [5-7].

Boyalı et al. [8] proposed control rules extracted from offline DP calculations. Fleuren et al. [9] determined the equivalence factor of the ECMS algorithm with a systematic method. where they used the DP algorithm offline to design a feedback controller regulating the parameters of the ECMS algorithm. Several researchers proposed predictive and adaptive methods to enhance ECMS capability in different driving conditions. Musardo *et al.* [10] introduced an adaptive ECMS algorithm where algorithm parameters are updated during vehicle travel using real time information. By taking real time road power request into account, the control parameter of interest (the "equivalence factor") was updated periodically and battery SoC was maintained within specified limits while fuel consumption was minimized. It was shown that an adaptive ECMS algorithm could give results that are close to the optimal solution obtained from dynamic programming. In a study by Fu *et al.* [11] the model predictive control framework was blended with information obtained from the Intelligent Transportation Systems (ITS). A real-time vehicle energy management system was established and the sensitivity of the proposed system to noise and error in the velocity profile prediction under different control approaches were investigated.

The present study proposes a combination of gear shifting methods with hybrid management algorithms. Totally six different scenarios were planned. First four cases include a conventional ICE operating with transmission systems arranged in different configurations. The next two cases analyze the implementation of ECMS and DP algorithms on a parallel hybrid vehicle. Finally, fuel consumption values were evaluated and compared in all cases to determine the effect of gear shifting policies and hybrid control algorithms on overall drivetrain efficiency.

2. DESCRIPTION OF THE HYBRID ENERGY MANAGEMENT ALGORITHMS

2.1. ECMS Algorithm

The logic behind the ECMS algorithm is based on the assumption that, if minimum fuel consumption is achieved instantaneously, then minimum fuel will be consumed throughout the entire journey, as shown in equation (1).

$$\int Min[\dot{m}_{ice}(t)]dt \approx Min\int \dot{m}_{ice}(t)dt \tag{1}$$

Here, $\dot{m}_{ice}$, is the instantaneous fuel consumption of the ICE. The ECMS method strives to reduce the total energy consumption of both electric and thermal paths. The instantaneous cost function (J_t) based on equivalent fuel consumption is given below:

$$J_t = \dot{m}_{ice}(P_{ice}) + \zeta(P_{em}) \tag{2}$$

ζ is a key parameter named as equivalence factor. The description of the energy requirement in terms of fuel consumption is the reason for employing such a factor. $P_{ice}(t)$ and $P_{em}(t)$ are power value that are provided by ICE and EM. The optimum operating point of each power source must be calculated so as to keep the cost function at the lowest level:

$$\begin{gathered} \left\{P_{em}^{opt}(t), P_{ice}^{opt}(t)\right\} = \arg\min(J_t) \\ P_{req}(t) = P_{ice}(t) + P_{em}(t) \end{gathered} \tag{3}$$

where $P_{req}(t)$ is demanded power by the driver. This parameter is a constraint that must be satisfied when the cost function is minimized. Other constraints that must be satisfied are related to the rotational speeds of ICE (w_{ice}) and rotational speeds of EM (w_{em}) which must lie in their respective operating ranges. Also, the torque generated by ICE must be positive and smaller than its maximum value. EM torque must also lie in a predefined operating range. The minimum constraint for electric motor torque can be negative because of regenerative braking:

$$\begin{gathered} w_{ice,min} \leq w_{ice} \leq w_{ice,max} \\ 0 \leq T_{ice}(t) \leq T_{ice,max}(t) \\ w_{em,min} \leq w_{em} \leq w_{em,max} \\ 0 \leq T_{em}(t) \leq T_{em,max}(t) \end{gathered} \tag{4}$$

The amount of power split is controlled by the value of the control parameter $u(t)$. This control parameter must be in the range$[-u_l, u_r]$. Also, the SoC value must be limited

$$u(t) = \frac{P_{em}(t)}{P_{ice}(t)+P_{em}(t)} \tag{5}$$

$$SOC_{min} \leq SOC \leq SOC_{max} \tag{6}$$

The value of $u(t)$ is zero when the power of the hybrid system is provided by ICE alone in the pure thermal state. When the control variable is close to the u_r limit, a portion of the power generation task is undertaken by EM and the SoC begins to fall. Otherwise, when the control variable approaches the u_l limit, some of the power generated by ICE is stored in the battery via EM. Therefore, the battery SoC increases. For battery discharging and charging processes, two equivalence factors are defined, s_{dis} and s_{chg}. These factors are equivalent to the use of positive and negative (regenerative) electrical energy at the end of a driving cycle. Use of electric energy on the whole cycle can be converted to equivalent fuel energy by s_{chg} if it is negative, and by s_{dis} if it is positive. In order to calculate the mentioned equivalence coefficients, the hybrid system is run for a certain driving cycle, with permissible constant u values [12]. Equivalent fuel consumption of the EM ($\dot{m}_{elec,eqv}$), given in Equation 7, depends on the efficiency of EM (η_{em}) and the consumed power (P_{em}), the efficiency of the battery (η_{batt}) and the equivalence factors. Fuel lower heating value (H_{lhv}) was used to convert EM power to equivalent fuel consumption.

$$\dot{m}_{elec,eqv} = \gamma s_{dis} \frac{P_{em}(t)}{\eta_{batt}(P_{em})\eta_{em}(P_{em})H_{lhv}} + \tag{7}$$

$$(1-\gamma)s_{chg}\eta_{batt}(P_{em})\eta_{em}(P_{em})\frac{P_{em}(t)}{H_{lhv}}$$

$$\gamma = \frac{1+sgn(P_{em})}{2}$$

The following penalty function has been added to the optimization problem in order to ensure that the the battery SoC remains the same at the beginning and at the end of the cycle [4].

$$x_{SOC}(t) = \frac{SOC(t) - \frac{SOC_{min}+SOC_{min}}{2}}{\frac{SOC_{min}+SOC_{min}}{2}} \tag{8}$$

$$-1 \leq x_{SOC}(t) \leq 1$$

$$\Omega(SOC) = 1 - x_{SOC}(t) + \mu \sum_{1}^{t_f} x_{SOC}(t)$$

Here, μ is a coefficient used to control the cumulative charge variation. For each step in the driving cycle, the parameters above are calculated and the cost function given in equation 2 is calculated as below.

$$J_t = \dot{m}_{ice}(P_{ice}) + \Omega(SOC)\dot{m}_{elec,eqv}(P_{em}) \tag{9}$$

For every time step, the appropriate value of u that holds J_t value at the lowest level is calculated and sent to the next time step as the control value. By knowing the instantaneous values of vehicle speed and selected gear ratio, the rotational speeds of ICE and EM are calculated. By keeping the cost function at the minimum possible value, these two energy sources are used in the most efficient manner by the ECMS method.

2.2. Dynamic Programming (DP) Algorithm

Dynamic programming (DP) is a powerful numerical method for solving optimal control problems. In this method, global optimality of solution is guaranteed. However, if the number of state variables and inputs of the underlying dynamic system is increased, computational effort grows exponentially [15]. In this paper, a special class of optimal control problems is studied. These problems have fixed final time and a partially constrained final state. Also, the considered problems are assumed to include state constraints and input constraints. It is assumed that the system in this study include only one state variable, the battery SoC. In summary, this problem can be written as an optimal control problem [16, 17].

$$\min_{u(t)} J\big(u(t)\big) \tag{10}$$

$$\dot{x}(t) = F(x(t), u(t), t) \tag{11}$$

$$x(0) = x_0 \tag{12}$$

$$x(t_f) \epsilon \left[x_{f,min}, x_{f,max}\right] \tag{13}$$

$$x(t) \epsilon X(t) \tag{14}$$

$$u(t) \epsilon U(t) \tag{15}$$

The Cost function is defined as follows:

$$J(u(t)) = G\left(x(t_f)\right) + \int_0^{t_f} H(x(t), u(t), t))dt \tag{16}$$

In a hybrid application energy management system, battery SoC may be defined as a state variable and ICE fuel consumption may be used to form the cost function. For implementing the DP method, the continuous time control problem must be converted to discrete time. Discrete-time model is given as below,

$$x_{k+1} = F_k(x_k, u_k),\ k = 0,1, \dots, N-1 \tag{17}$$

where the state variable is $x_k \epsilon X_k$ and control signal $u_k \epsilon U_k$. If $\pi = \{\mu_0, \mu_1, \dots, \mu_{N-1}\}$ is considered as a state-dependent control policy, the expression of Equation 16 can be defined as follows

$$J_\pi(x_0) = g_N(x_N) + \varphi_\pi(x_N) \dots + \sum_{k=0}^{N-1} h_k(x_k, \mu(x_k)) + \varphi_k(x_k) \tag{18}$$

where $g_N(x_N) + \varphi_\pi(x_N)$ is the final cost function. The first term $g_N(x_N)$ corresponds to the final cost of the Equation 16. The second term $\varphi_\pi(x_N)$ is the additional penalty function forcing a partially constrained final state (13). The function $H(x(t), u(t), t))$ is the cost of applying $\mu(x_k)$ at x_k, according to *H(x(t), u(t), t)* in Equation (16). The state constraints (14) are enforced by the penalty function $\varphi_k(x_k)$ for $k = 0,1, \dots, N-1$. The optimal control policy π^0 is the policy that minimizes J_π

$$J^0(x_0) = \min_{x \in \Pi} J_\pi(x_0) \tag{19}$$

where Π is the set of all admissible policies. Based on the principle of optimality, dynamic programming is the algorithm which assesses the ideal cost function $\mathcal{J}_k(x^i)$ at each time loop in the discretized state-time space by progressing backwards in time. Detailed information about DP algorithm for parallel hybrid vehicle can be found in Guzzella et al. [15,16,17]

2.2. Driving Cycle Specific Gear Ratio Selection Algorithm

In this section, a generic algorithm has been developed to determine the most appropriate gear ratio for a vehicle equipped with ICE for a given driving cycle. For a given specific driving cycle, it is possible to establish different criteria for gear ratio selection. These criteria may focus on achieving highest possible torque or least fuel consumption; methods can be performance-oriented or fuel economy-oriented. In an algorithm developed by Başlamışlı et al., the least fuel consumption was targeted [13]. A vehicle may use various gear ratios when traveling at a certain speed. As the present work is based on a selected driving cycle, instantaneous vehicle speed information and the demanded traction force values are assumed to be known. With the algorithm developed in this study, it is possible to calculate the optimum gear ratio and throttle positions by using instantaneous resistance forces, vehicle speed and acceleration information. The schematic of the optimal gear selection algorithm is given in Figure 1. According to the driving cycle data and resistance force calculations requested velocity (V) and torque (T) is evaluated. Then, the ICE speed (w_{ice}) demanded from the driving cycle for each gear number (i) is calculated. Some gear ratios will not satisfy the engine speed range ($w_{ice,min}$ and $w_{ice,max}$) and will not be taken into account for the given calculation step. Then, the amount of engine torque (T_{ice}) is calculated for each feasible gear ratio. Some gear ratios that do not satisfy the engine torque range (0 and $T_{ice,max}$) are eliminated. Also, the gear ratios that cause engine to operate non-smoothly in terms of torque are instantly eliminated from the analysis and the remaining gear ratios are taken into consideration. According to the required engine rotational speed and torque values, the throttle positions are calculated for the candidate gear ratios in the ICE Speed-Torque map Block. Finally, knowing throttle and speed data, fuel consumption values can be calculated from the engine map. Hence, one is able to calculate instantaneous fuel consumption for each valid gear ratio. All these feasible values are stored in memory to select the minimum one. This way, the optimal gear ratio providing the lowest fuel consumption can be chosen.

2.3. CVT Algorithm

A typical petrol engine torque speed map with Specific Fuel Consumption (SFC) contours and constant power lines is shown in Figure 2. The minimum fuel consumption (min SFC) area was shown on torque-speed map. It consists of medium speed and high torque operation points. By moving away from this area, the value of SFC is increased. In order to get maximum output power in every engine speed, it is advised to operate ICE on the *economy line*. Hence, by equipping the thermal path with a CVT device, it is theoretically possible to follow the economy line which ensures correct matching between engine condition and vehicle output speed [18].

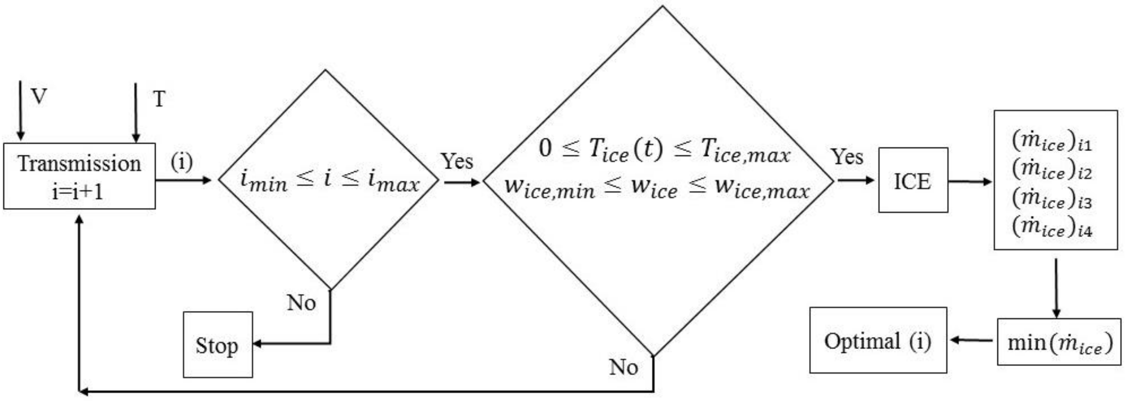

Figure 1. Optimal Gear Selection Algorithm Schematic

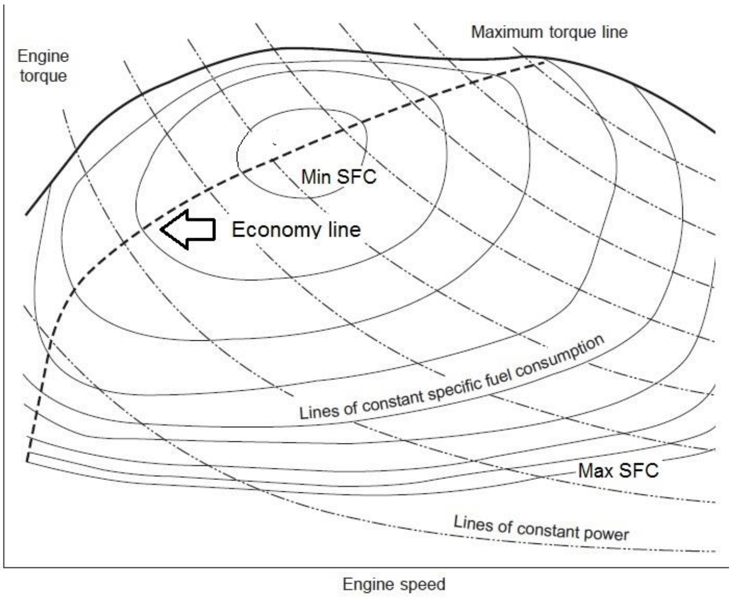

Figure 2. Economy line on ICE Torque-Speed map [18]

3. VEHICLE MODEL

A parallel hybrid vehicle model was constructed in MATLAB/Simulink environment. Figure 3 shows the parallel hybrid drivetrain configuration that makes use of a torque coupler to transfer the generated torque to the gearbox. The specifications of the vehicle model and power sources are given in Table 1. In order to compare the different control algorithms, urban 'ECE-R15' driving cycle was used in this study. Vehicle speed and acceleration profiles resulting from this driving cycle are shown in Figure 4,. The road resistances exerted on the vehicle can be seen in Figure 5. Tractive force, inertial, rolling and air resistance forces are calculated according to [14].

Specific fuel consumption and torque maps that depend on throttle angle and engine angular velocity are used for ICE. For the electric motor, an efficiency map depending on torque and motor angular speed is used. Battery modeling is also implemented by using an equivalent circuit diagram, where battery internal resistance is a function of SoC. The electrical current drawing from battery during charging and discharging situations are calculated with the equations below [14].

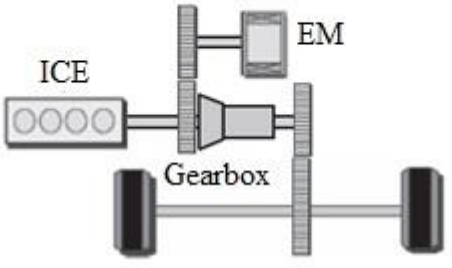

Figure 3. Hybrid Drivetrain Model

Table 1. Specifications of vehicle model and power sources

Element	Parameter	Value
Vehicle	Type	Parallel Hybrid
	Mass	3000 (kg)
	Air Resistance Coefficient	0.4
	Air Density	1.24 (kg/m^3)
	Frontal Area	3.5 (m^2)
	Wheel Radius	0.34 (m)
Transmission	Gear Ratios	[3.7 2.2 1.35 0.95]
	Final Drive Ratio	4.5
	Transmission Efficiency	0.9
Internal Combustion Engine	Fuel Type	Diesel
	Maximum Torque	141 (N.m)
	Maximum Power	35 (kW)
	Maximum Angular Velocity	3000 (RPM)
Electric Motor	Maximum Torque	140 (N.m)
	Maximum Power	23.4 (kW)
	Maximum Angular Velocity	5700 (RPM)
Battery	Capacity	1 kw.h
	Open circuit voltage	280 V
	Maximum current	50 A

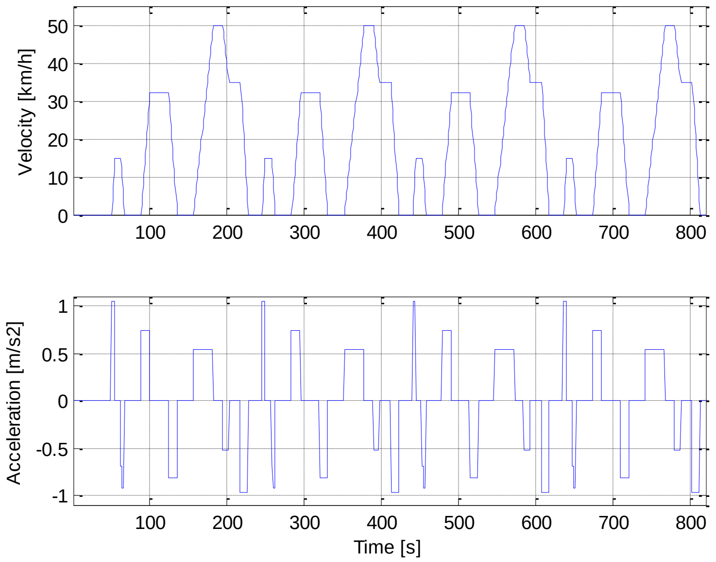

Figure 4. ECE_R15 driving cycle velocity and acceleration profile

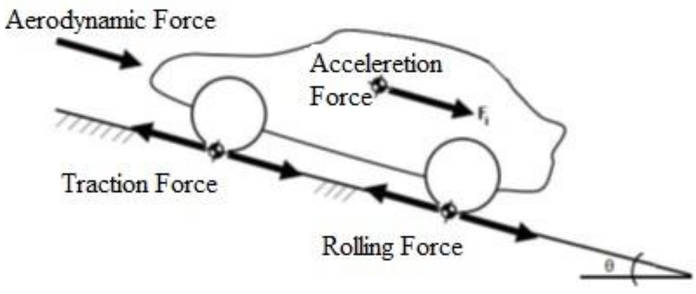

Figure 5. Resistance Forces Acting on the Vehicle Body

$$I_{chg} = \frac{-V_{oc}+\sqrt{{V_{oc}}^2+4R_iP_{chg}(t)}}{2R_i} \tag{10}$$

$$I_{dis} = \frac{V_{oc}-\sqrt{{V_{oc}}^2-4R_iP_{dis}(t)}}{2R_i}$$

Here, $P_{chg}(t)$, $P_{dis}(t)$ are the charge loads during charging and discharging at the battery terminal, V_{oc}, open circuit voltage and R_i are internal resistances of the battery.

4. SIMULATION RESULTS

Resistance forces acting on vehicle through the ECE_R15 driving cycle are shown in Figure 6.

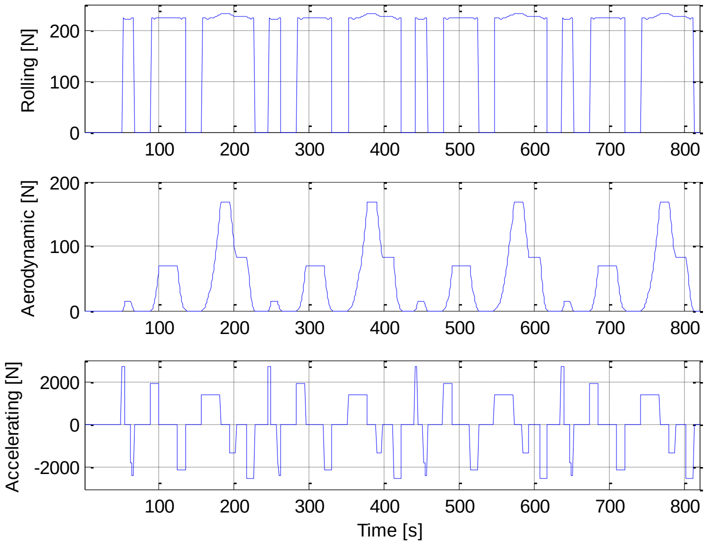

Figure 6. Resistance forces on vehicle in ECE_R15 driving cycle

As vehicle speed and resistance forces are known for the entire driving cycle, it is possible to calculate requested power. Figure 7 presents road requested power that should be supplied by energy sources to the vehicle.

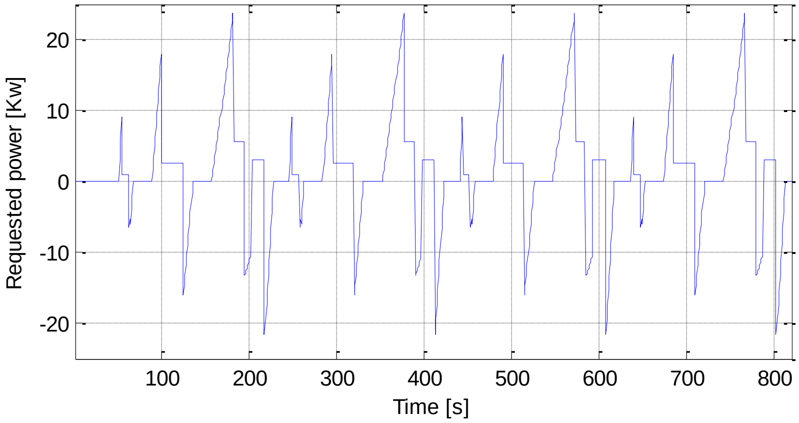

Figure 7. Road requested power in ECE_R15 driving cycle

Different arrangements of drivetrains have been studied in this paper. A brief description of the different case studies is shown in Table 3. Cases 1 to.4 represent conventional vehicles that use the ICE as the only energy source while employing different algorithms for gear shifting. The Manual gearbox method uses a predefined gear shifting schedule that is available in the literature for the specific driving cycle [19]. The Manual gear shifting profile for ECE_R15 driving cycle is presented in Figure 8(a). Automatic gearboxes use the gear shifting method that was described in Section 2.2 of this article. The version “Automatic gearbox with 4 gear ratios” uses the best ratios from the set [3.7 2.2 1.35 0.95] that minimize instantaneous ICE fuel consumption value. The version “Automatic gearbox with 3 gear ratios” works with the subset [3.7 2.2 1.35]. Calculated Automatic gear shifting profiles for ECE_R15 driving cycle are shown in Figure 8(b) and 8(c). The CVT gearbox is able to select any gear ratios between 3.7 and 0.95 values. Calculated CVT gear shifting profile for ECE_R15 driving cycle is presented in Figure 8(d).

Case.5 includes a hybrid vehicle configuration which makes use of ECMS control method for power splitting and the CVT gear shifting method. In Case.6 DP control method was used for power splitting of the same hybrid vehicle. This time, Manual Gearbox gear shifting method was used.

Table 2. Summary of Case Studies

Case No.	Powerline	Vehicle
Case.1	Only ICE + Manual Gearbox	Conventional ICE
Case.2	Only ICE + Automatic Gearbox with 3	Conventional ICE
Case.3	Only ICE + Automatic Gearbox with 4	Conventional ICE
Case.4	Only ICE + CVT Gearbox	Conventional ICE
Case.5	ECMS + CVT Gearbox	Hybrid
Case.6	DP + Manual Gearbox	Hybrid

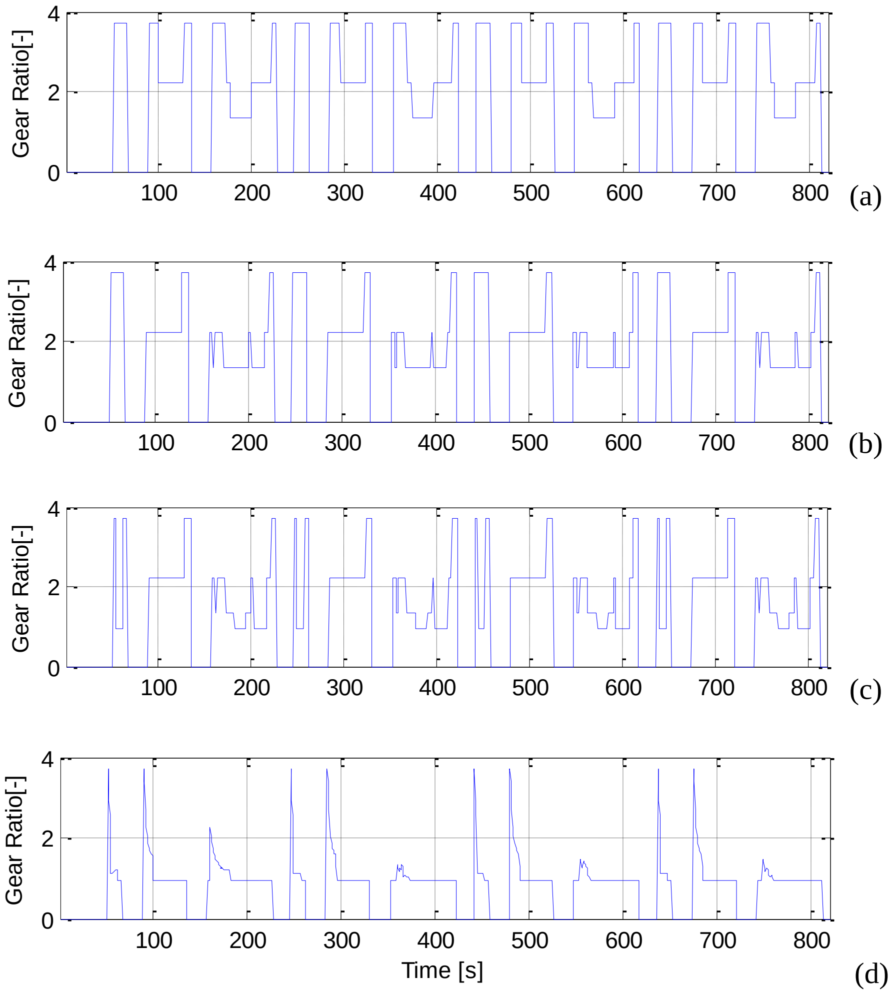

Figure 8. Gear shifting scenarios (a) Manual (b) Automatic with 3 gear ratios (c) Automatic with 4 gear ratios (d) CVT for ICE Vehicles

In order to compare the six different case studies, it is useful to investigate the operating points of the power sources on the ICE speed torque map. Depending on the gear shifting and power splitting control method, ICE operating points are differently arranged. Figure 9 shows the operating points of ICE on torque-speed map for all of case studies including conventional and hybrid configuration. Figure 9(a) is representing the operation points of ICE in a conventional vehicle equipped with manual gear box. It is evident that engine has been operated all over the speed-torque map without considering min SFC area. Employing automatic gearbox and CVT in powerline, make it possible to collect most of operation points close to min SFC area. This the key factor in reducing fuel consumption that can be distinguished in Figure 9(b)-(e).

For hybrid configurations (Case.5 and Case.6), the operating points of EM must also be considered. Figure 10 shows the operating points of EM for hybrid configurations. Figure 10(a) is representing operation point of EM in ECMS algorithm. Power generation and recovery was accrued in low speeds. However, extended range of EM speed was employed in DP power sharing (Figure 10(b)).

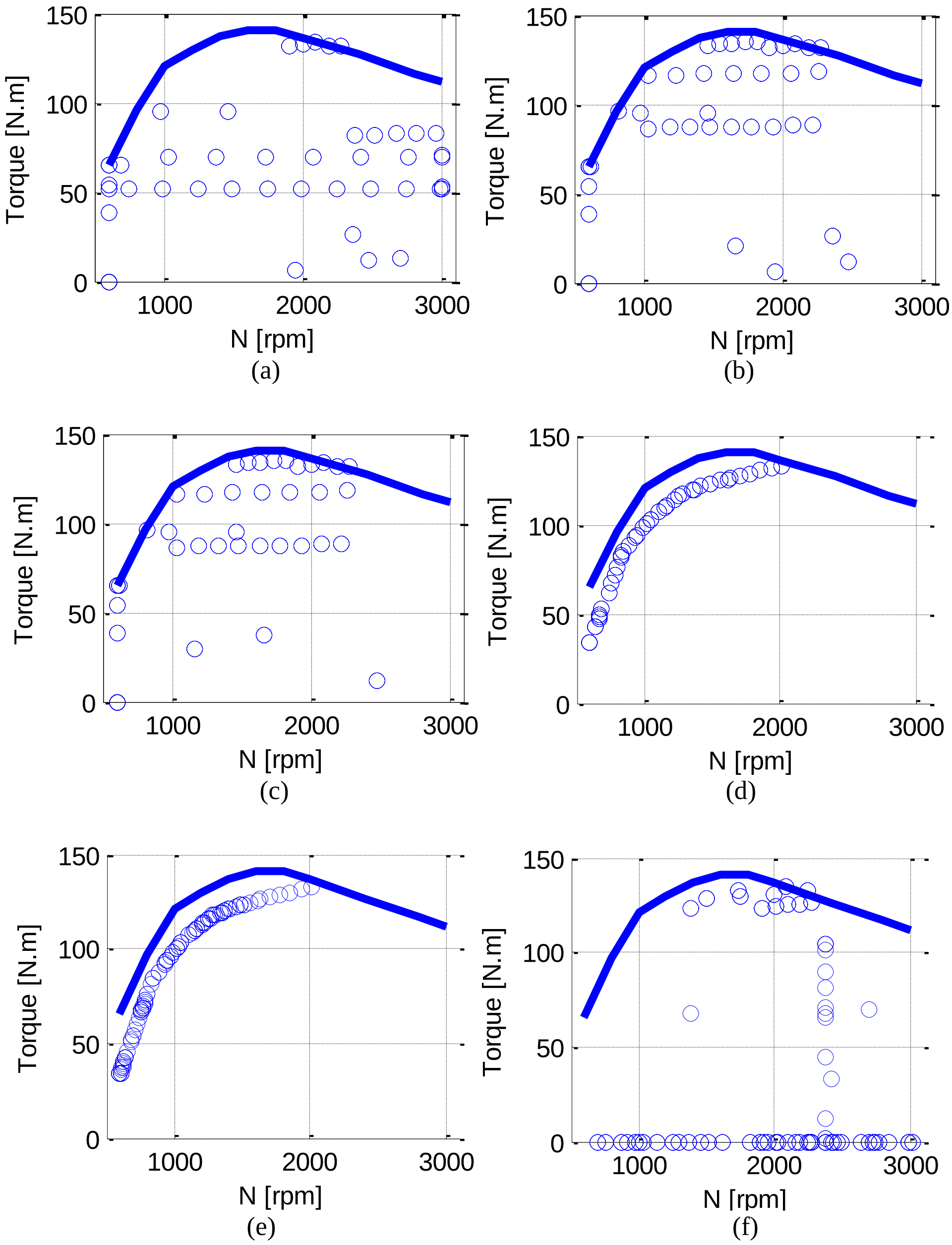

Figure 9. ICE operating points on Speed-Torque map (a) Case.1 (b) Case.2 (c) Case.3 (d) Case.4 (e) Case.5 (f) Case.6

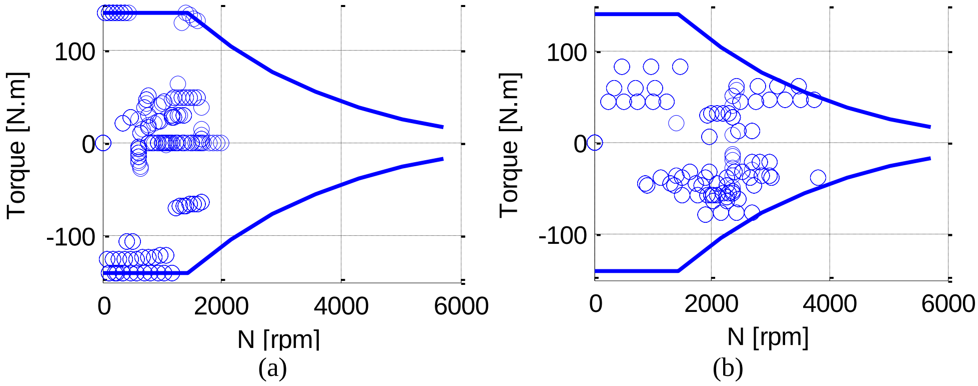

Figure 10. EM operating points on Torque-speed map (a) Case.5 (b) Case.6

Batteries SoC is another significant parameter to be considered during power splitting task. For the two hybrid cases, initial SoC of battery was selected as 0.65. Figure 11 shows that this parameter was here controlled between lower and upper limits of 0.60 and 0.7 successfully. In Case.5, ECMS algorithm had a tendency to recharge the battery in most of the driving period. Table 3 provides a comparison of achieved fuel consumption between the 6 case studies presented in this study.

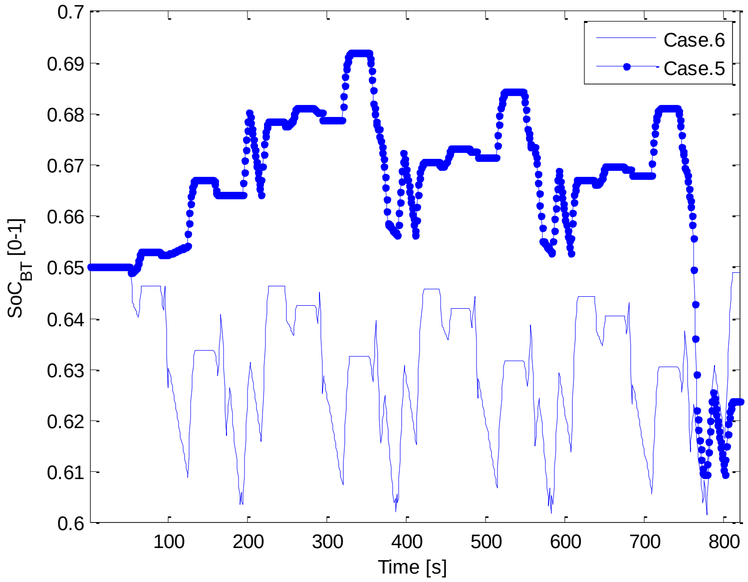

Figure 11. Battery SoC variation for hybrid configurations (a) Case.5 (b) Case.6

Table 3. Performance comparison of case studies

Case No.	Initial	Final SoC	Fuel Consumption	Fuel Consumption
Case.1	-	-	190	-
Case.2	-	-	162	14.7
Case.3	-	-	156	17.9
Case.4	-	-	149	21.6
Case.5	65	62.4	123	35.3
Case.6	65	65	119	37.4

5. DISCUSSION OF RESULTS AND CONCLUSION

In this paper, six different case studies were planned for investigating the effect of different gear shifting methods in conventional and hybrid vehicle drivelines. First of all, four different gear ratio selection algorithms were compared in a conventional ICE vehicle. Next, two parallel hybrid drivetrains were analyzed. All cases were simulated on the ECE_R15 driving cycle. Among the conventional ICE vehicle configurations, Case.4, where the vehicle is equipped with a CVT transmission, provided 21.6% improvement of fuel consumption over Case 1, where the vehicle is equipped with a manual gearbox and where a predetermined shifting schedule available in the literature is utilized. Case.5 presented a parallel hybrid configuration equipped with a CVT transmission and the ECMS control algorithm was used for power splitting. Here, 35.3% improvement in fuel consumption was realized over Case.1. Finally, Case.6 analyzed the parallel hybrid configuration where gear shifting was achieved as in Case 1 and where DP was selected as the power splitting algorithm. 37.4% of fuel saving over Case 1 was obtained for this last design. It is interesting to note that besides using a non-optimal gear shifting method, the highest fuel saving is achieved by the DP control method. The reason is that DP is a global optimization method that makes use of EM in the most efficient way without depleting the battery at the end of driving cycle. Meanwhile, the hybrid drivetrain configuration run by the ECMS algorithm is still the most efficient solution among the real time implementable solutions presented here.

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