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Control and optimization of pre-transmission parallel hybrid vehicle with fuzzy logic method and comparison with conventional rule based control strategy

Ön iletimli paralel hibrit aracın bulanık mantık yöntemi ile kontrolünün ve optimizasyonunun yapılması ve geleneksel kural tabanlı kontrol stratejisi ile karşılaştırılması

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Control and Optimization of Pre-Transmission Parallel Hybrid Vehicle with Fuzzy Logic Method and Comparison with Conventional Rule Based Control Strategy

Highlights

- *The parallel hybrid vehicle torque splite control with conventional rule-based and fuzzy logic method.*
- *Determination of optimum internal combustion and electric engine operating points*
- *Fuel savings between 2.277% and 12.878% were achieved with the fuzzy logic control strategy.*

Graphical Abstract

A pre-transmission parallel hybrid vehicle is modeled in Matlab/SIMULINK environment,and its control and optimization is carried out with fuzzy logic method. The power transmission system diagram and fuzzy logic membership functions of the vehicle are shown in the Figure.

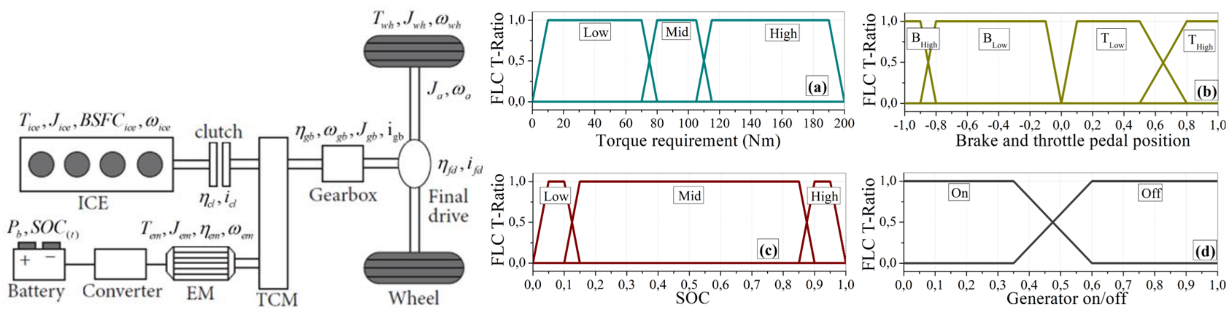

Figure. Pre-transmission hybrid vehicle powertrain and Fuzzy logic control strategy membership functions

Aim

The aim of the study is to determine the fuel savings achieved according to the conventional rule-based control strategy by controlling and optimizing a parallel hybrid vehicle with pre-transmission using fuzzy logic method.

Design & Methodology

Mathematical modeling and fuzzy logic control method used in the study were carried out in Matlab / SIMULINK environment.

Originality

Optimum torque split has been achieved with the fuzzy logic method control strategy of the parallel hybrid vehicle. A comparison of energy consumption values with conventional rule-based control strategy has been made. Fuel consumption values are also evaluated under conditions where the vehicle is cruising under different driving cycle conditions.

Findings

In the control of the vehicle with fuzzy logic control strategy, it has been obtained that it saves 12.878%, 6.62%, 2.277% and 6.239% respectively under the conditions of the driving cycles of FTP-75, NEDC, ECE-15 and EUDC.

Conclusion

With the developed fuzzy logic control strategy, the control of the parallel hybrid vehicle has been successfully performed, and it has been observed that significant fuel savings have been achieved compared to the conventional rule-based control strategy.

Declaration of Ethical Standards

The author(s) of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

Control and Optimization of Pre-Transmission Parallel Hybrid Vehicle with Fuzzy Logic Method and Comparison with Conventional Rule Based Control Strategy

Araştırma Makalesi / Research Article

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Abstract

In this study, a model of a pre-transmission parallel hybrid vehicle was created in MATLAB/Simulink environment. A torque control strategy has been developed for the hybrid vehicle on the created model. The hybrid vehicle's torque control is provided by fuzzy logic and conventional rule-based control strategies. The control strategies of the hybrid vehicle have been developed based on four input parameters: accelerator and brake pedal position, battery state of charge and the operating mode of the electric motor. The regenerative braking system of the pre-transmission parallel hybrid vehicle has been provided with a fuzzy logic control strategy in both vehicle structures. In the fuzzy logic torque split controller, a control algorithm has been created in which the safety, performance and fuel consumption values of the vehicle meet at the optimum point. Under different driving cycle conditions, the effects of control strategies on engine operating points have been examined and average fuel consumption values have been obtained. In the control of the parallel hybrid vehicle with fuzzy logic method, it has been obtained that it provides 12.87%, 6.62%, 2.27% and 6.23% fuel savings under FTP-75, NEDC, EUDC and ECE-15 driving cycle conditions, respectively. It has been observed that the vehicle cannot provide sufficient performance in US06 driving cycle conditions with the use of conventional rule-based control strategy.

Keywords: Fuzzy logic, energy saving, rule-based control strategy, modeling, parallel hybrid.

Ön İletimli Paralel Hibrit Aracın Bulanık Mantık Yöntemi ile Kontrolünün ve Optimizasyonunun Yapılması ve Geleneksel Kural Tabanlı Kontrol Stratejisi ile Karşılaştırılması

ÖZ

Bu çalışmada, MATLAB/Simulink ortamında çn iletimli paralel hibrit araç modeli oluşturulmuştur. Oluşturulan model üzerinde hibrit araç için tork kontrol stratejisi geliştirilmiştir. Hibrit aracın tork kontrolü, bulanık mantık ve geleneksel kural tabanlı kontrol stratejileri ile sağlanmıştır. Hibrit aracın kontrol stratejileri, gaz ve fren pedalı konumu, batarya şarj durumu ve elektrik motorunun çalışma modu olmak üzere dört girdi parametresine dayalı olarak geliştirilmiştir. Ön iletimli paralel hibrit aracın rejeneratif fren sistemi, her iki araç yapısında da bulanık mantık kontrol stratejisi ile sağlanmıştır. Bulanık mantık tork dağıtıcı denetleyicide aracın güvenlik, performans ve yakıt tüketim değerlerinin optimum noktada buluştuğu bir kontrol algoritması oluşturulmuştur. Farklı sürüş çevrimi koşulları altında, kontrol stratejilerinin motor çalışma noktaları üzerindeki etkileri incelenmiş ve ortalama yakıt tüketim değerleri elde edilmiştir. Bulanık mantık yöntemi ile paralel hibrit aracın kontrolünde, FTP-75, NEDC, EUDC ve ECE-15 sürüş çevrimi koşullarında sırasıyla %12.87, %6.62, %2.27 ve %6.23 yakıt tasarrufu sağlandığı sonucu elde edilmiştir. Konvansiyonel kural tabanlı kontrol stratejisinin kullanılması ile aracın US06 sürüş çevrimi koşullarında yeterli performansı sağlayamadığı gözlemlenmiştir.

Anahtar Kelimeler: Bulanık mantık, enerji tasarrufu, kural tabanlı kontrol stratejisi, modelleme, paralel hibrit.

1. INTRODUCTION

Vehicles used on highways comprise 27% of the total energy consumed in the world and 33% of the greenhouse gas emissions released to the atmosphere. Most of the vehicles that cause high energy consumption and the release of high pollutant gas emissions are conventional vehicles with low efficiency values, powered only by the internal combustion engine[1]. The issue of increasing energy efficiency and emission standards does not fall from the agenda due to the expectation that the harmful gases emitted by

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conventional vehicles with fossil fuels to the environment and the expectation that most of the fossil fuels will come to an exhaustion in the near future [2-5]. Hybrid electric vehicle structure was introduced by combining the advantages of electric vehicles and conventional vehicles and minimizing the disadvantages [6,7]. The biggest advantage of hybrid vehicles compared to the electric vehicle is that there is no range problem. There are mostly parallel and serial hybrid vehicle structures on the market. In the series hybrid vehicle structure, the vehicle drive is provided only with EM, while in the parallel hybrid vehicle structure, the vehicle drive is provided with EM and ICE. Energy production on parallel hybrid vehicle is provided by synchronous operation of ICE and EM, which provide the vehicle's drive [8-11]. Different control strategies are available to minimize the energy consumption values of parallel hybrid vehicles and continue to be developed. One of the most important points of increasing the energy efficiency of the parallel hybrid vehicle is the best creation and optimization of the torque distribution algorithm [12]. The control strategies of parallel hybrid vehicles are basically divided into two basic parts: optimization and rule-based. Two types of optimization based control strategies, ECMS (equivalent consumption minimization strategy) and DP (dynamic programming), are widely used. Conventional and fuzzy logic (FL) methods are used in the common use of rule-based control strategy in hybrid vehicle structures [13].

The ECMS control algorithm is a real time optimization based method [14]. Using the instant optimization method in the ECMS control strategy, optimum energy consumption is achieved at every moment of driving. Thus, it is aimed to keep the total energy consumption at the optimum level during the entire ride [15]. In this method, the equivalent of the energy consumed by the electric motor (EM) in terms of fuel is determined, and by combining it with the fuel consumed by the internal combustion engine (ICE), it is combined in one fuel type and real-time optimization is performed [16]. Although the ECMS control method is frequently used in the literature, there are calibration processes based on iterations to obtain equivalent fuel coefficients. Dynamic programming control algorithm is a global optimization based method [14]. The dynamic programming method ensures optimum energy consumption for a given cycle, driving and road condition, while not achieving optimum energy consumption values in real time and in different driving conditions. Although DP control algorithm currently has such a problem, its efficiency can be increased by taking it within the framework of certain rules [16]. The biggest disadvantage of the dynamic programming control algorithm is that the system load increases exponentially with the increase in unknown number and the inputs provided to the control algorithm. For the availability of DP and ECMS algorithms, the entire driving procedure needs to be known in advance and is unlikely to be used in real-time controls [17].

Rule-based control strategies are used effectively in the torque distribution control of hybrid vehicles. The basis of the rule-based control strategy is based on the evaluation of the input parameters within the framework of the established rules and the production of the outputs. Due to the rule-based control strategy, it is not necessary to know the driving cycle in advance, so optimum values can be obtained under flexible working conditions [18]. Fuzzy logic and conventional rule-based control strategies are widely used on hybrid vehicles. The biggest reason for the conventional rule-based control strategy to be implemented on the parallel hybrid vehicle is that it is easy to implement, the system is simply controlled and does not cause errors. The biggest disadvantage is that the vehicle has insufficient processing power to ensure optimum fuel consumption and performance. In this context, improvement of vehicle performance and fuel consumption, hybrid vehicle control and optimization can be achieved with fuzzy logic control strategy.

FL theory, which is the basis of FL control algorithm, was introduced by Lotfi Zadeh in 1965 as an extension of the convantional set theory. FL, one of the sub-branches of artificial intelligence, which emerges as a result of the simulation studies of the human brain working system, is a mathematical system based on fuzzy set theory. Logical expressions and the relationships between these logical expressions are used at the basis of control systems using FL. FL can perform the control process by using verbal variables without having to extract the mathematical model of the system. Today, FL has found use in many areas such as electronic control systems, automotive industry, process planning and home electronics [19].

FL control strategy has many advantages. The mathematical model of the FL system is simple and easy to apply for system control. It provides a flexible structure by allowing the closest result to be obtained despite the missing and inadequate data. It allows control of complex and nonlinear structures. In line with the rules written in the FL controller, it provides the most appropriate results for the entered parameters. Due to all these advantages and flexible structure, it is frequently preferred in the control of electric and hybrid electric vehicles [20].

FL has two basic methods, Mamdani and Sugeno. Mamdani FL method forms the basis of other methods. Mamdani fuzzy logic method graphics are shown in Figure 1. Due to the fact that the model can be created easily in Mamdani method, it has a very common usage. Also, Mamdani method is suitable for human behavior and senses. If the first rule of the Mamdani type FL method is “If $x = A_1$ and $y = B_1$ is $z = C_1$” and the second rule is “If $x = A_2$ and $y = B_2$ if $z = C_2$”, it is compared to the x and y input applied. The z value seen in is obtained. [21].

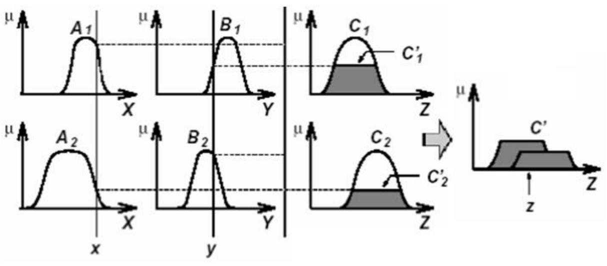


Figure 1. Mamdani type FL control

Sugeno FL method is an adaptation of Mamdani method. Fuzzy input and FL operations are exactly the same as Mamdani method. The only difference is in output membership functions. The output values obtained in Sugeno FL method consist of fixed or linear values. The Sugeno fuzzy model has advantages such as suitability for mathematical analysis, controlling nonlinear systems, and clarity of output data. In addition to these advantages, there are disadvantages such as not being suitable for human intuition and taking a complex structure in high-grade fuzzy models [21]. A Sugeno fuzzy model is expressed by the equation "If x = A and y = B, if z = f (x, y) = px + qy + r (c)". The x and y variables, which are provided in the input, result in z expression in accordance with the written rules and fuzzy sets. The parameters r, p, q and r defined in the equation mean logical operations and vary depending on the rule written [22].

Fuzzy logic control system has 5 basic elements. The fuzzy logic control system block diagram of these elements is shown in Figure 2. The turbidizer transforms the net values entered into the control system into fuzzy values and makes them suitable for use in fuzzy sets in the rule base. The fuzzy inference motor unit determines the output value of the control system for the input parameters by evaluating all the rules created between the fuzzy sets of input and output in the rule diagnosis. The defuzzification is the section that converts the fuzzy results obtained from all processes into definite usable numerical output values [23].

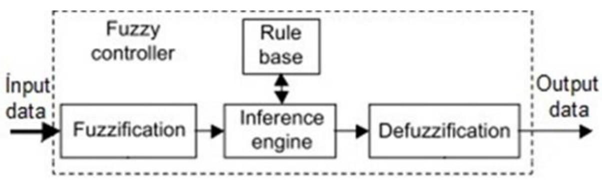


Figure 2. Fuzzy logic control system block diagram

He et al. used the fuzzy logic control strategy to optimize the energy storage system of a hybrid vehicle. They observed significant improvements in the performance and efficiency of the energy system [24]. Xu et al. have developed regenerative braking system control strategy with fuzzy logic method to use on an electric vehicle. In the developed brake control method, they aimed to keep the vehicle balance at the optimum level and distribute the mechanical and regenerative brake force in the most appropriate way. They observed that with the developed fuzzy logic brake control strategy, a 25.7% range increase was achieved [25]. Guo et al. in their study, they controlled the regenerative braking system using electric vehicles with fuzzy logic and examined its effect on energy consumption. They concluded that with the development of the regenerative braking system control strategy, it is possible to recover 23.33% more of the total brake energy [26]. Chanden et al. have developed the model of a hybrid electric vehicle powered by a fuel cell in MATLAB / Simulink environment and made torque distribution optimization with fuzzy logic method. As a result of the study, UDDS driving cycle conditions, the average fuel consumption of the vehicle, HC, CO, NO_x values respectively %6.81, %4.72, %1.07, %19.2 there has been improvement in the rate [27]. Gujarathi et al. controlled the parallel hybrid vehicle with the fuzzy logic control strategy and observed that there was a significant reduction in fuel consumption with HC, CO, NO_x and PM emissions but it was concluded that not all parameters could be reduced together [28]. Ming et al. have created a double-axis plug-in PHEA model and developed fuzzy logic method and conventional rule-based control algorithm. They obtained the result that fuzzy logic control method improved 5.99%, 5.56% and 5.63% respectively in US06, HL07, EUDC driving cycle conditions compared to conventional rule based control method [29]. Dawei, M et al. found that there were serious improvements in NO, HC and CO emission values in the control strategy it developed. They developed a control algorithm using fuzzy logic method on a single shaft parallel hybrid vehicle. In this algorithm, they saw that the operating points of the internal combustion engine were reduced to the points where BSCF values were lower than the traditional rule-based control method, and the fuel consumption was significantly reduced [30]. Kunqi et al. Controlled the effect of a parallel hybrid vehicle with the fuzzy logic method depending on the battery state of charge (SOC) and vehicle torque requirement, and investigated the effect of energy consumption in NEDC and WLTC driving cycle conditions. With the two-parameter input fuzzy logic strategy, they observed 13% and 4.5% improvement in the fuel consumption of the hybrid vehicle, the NEDC and WLTC driving cycle, respectively [31]. Parallel hybrid vehicle structure can be classified as pre-transmission and post-transmission. In the pre-transmission architecture, EM and ICE power is exposed to the gearbox reduction ratio. In the post-transmission architecture, on the other hand, only the ICE power is exposed to the transmission reduction ratio [32]. Kocakulak et al., investigated fuel consumption values under different driving cycle conditions by modeling pre-transmission parallel hybrid, post-transmission parallel hybrid, serial hybrid and conventional vehicle structures in Matlab/SIMULINK environment. In the study, they obtained the lowest fuel consumption value in the pre-transmission hybrid structure [5]. Chen et al., series, pre-transmission parallel and post-transmission parallel hybrid vehicle structures were compared under different driving cycle conditions. They concluded that parallel hybrid vehicle structures are more efficient than serial hybrid vehicle structures. They found that the pre-transmission hybrid vehicle structure is more efficient than other structures in some driving conditions [33].

In this study, a model of a parallel hybrid vehicle was created in MATLAB / Simulink environment. As a parallel hybrid vehicle structure, pre-transmission power transmission system is used. Transfer function equations representing the power transmission system are derived. Aerodynamic, acceleration and rolling resistance forces are included in the vehicle model. 7-speed DCT gearbox is used as a gearbox and a lithium-ion battery pack model is used as a battery pack.

In the literature, it is concluded that fuzzy logic method is applied in many areas and has positive effects on energy consumption values. In the literature, a study examining the control with the fuzzy logic method and the conventional rule-based control method on the parallel hybrid vehicle has not been encountered, and this issue has been clarified on this study. In addition, in this study, in addition to the studies in the literature, the parameters used in the fuzzy logic vehicle torque distribution method were enriched and regenerative brake control was realized by the fuzzy logic method. The input of the parameters of the vehicle's torque requirement, throttle and brake pedal position, battery state of charge and generator operation status are provided to the fuzzy logic algorithm in vehicle torque distribution control. In regenerative brake control with fuzzy logic method, the input of battery charge current, brake pedal position, battery state of charge and vehicle speed parameters are provided. The cases of controlling the pre-transmission parallel hybrid vehicle with the conventional rule-based control method and the fuzzy logic method developed were examined. On the model created, ICE and EM working points used in the vehicle were determined and evaluated. On the model, the fuel consumption values of the vehicle in different driving conditions were determined and evaluated. FTP75 and ECE-15 driving cycles used in the model represent urban, EUDC driving cycles for intercity and NEDC driving cycles represent mixed use conditions. In this study, different driving cycles are used to simulate urban, intercity and mixed driving [34,35].

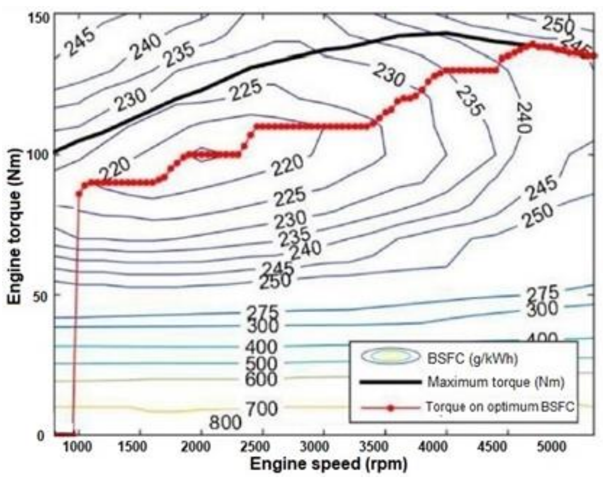
2. MATERIAL and METHOD

In this study, the model of the pre-transmission parallel hybrid vehicle in MATLAB / Simulink environment was created. Parallel hybrid vehicle model consists of system and subsystems. The mathematical equations of the systems are used throughout the vehicle model. The ICE model used the brake spesific fuel consumption (BSFC) map of the 1.8 L petrol engine. DC Motor efficiency map which can produce maximum 160 Nm torque is used in EM Motor model. In the vehicle model, "Hyundai Transys" brand, "D022S7" model 7-speed dual clutch transmission (DCT) is used. Transmission reduction ratios are taken from the catalog as 3.813, 2.261, 1.957, 1.073, 0.902, 0.837 and 0.756, respectively. A lithium-ion battery pack modeling with the equivalent circuit Rint method is used on the vehicle with an energy capacity of 5 kWh.

Parallel hybrid vehicle power system control, brake/throttle pedal position control and rule-based control strategy and torque distribution control are provided in two stages. In the first stage, the brake / accelerator pedals were controlled by PID controls.Torque in parallel hybrid vehicle is produced by EM and ICE, EM can provide a drive to the vehicle as well as a generator. It is aimed to operate EM and ICE, which drive the vehicle, at the most efficient working points. In this context, the use of parallel hybrid vehicle in five different modes is controlled. Torque distribution control of hybrid vehicle is provided with fuzzy logic and conventional rule-based control strategy. Simulink blocks are used in the conventional rule-based control strategy model. In the fuzzy logic control strategy model, sugeno type fuzzy logic controls within MATLAB / Simulink are used.

2.1. Engine and Electric Motor Model

The driving force and electrical energy generation of the parallel hybrid vehicle are carried out by ICE and EM. The torque, speed and map of the engine with a volume of 1.8 liters were used as the model of ICE. The internal combustion engine has a cylinder diameter x stroke of 86x86 mm, number of cylinders 4, compression ratio 13, a maximum torque/power of 142 Nm/73 kW. On the vehicle model, the speed, efficiency and torque characteristic graph of the Ashwoods/Elmo-D576 brand/model direct current EM was used. The electric motor can produce maximum 155 Nm torque, 5000 rpm speed and 50 kW power. Maps giving the characteristics of ICE and EM are shown in Figure 3. The red line on the graph gives the torque values that ensure optimum fuel consumption depending on the transfer of ICE.



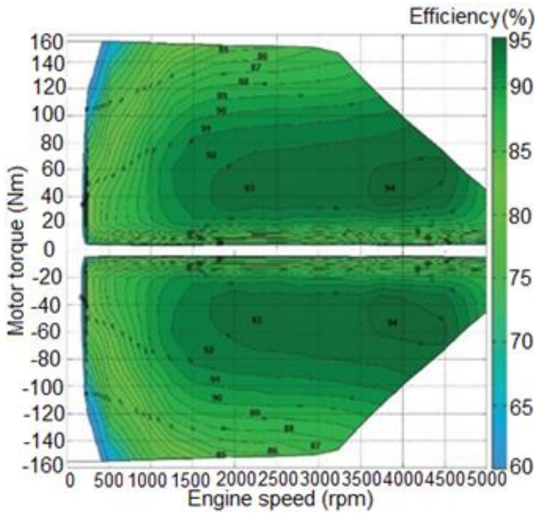


Figure 3. ICE torque, speed, BSFC and EM torque, speed, efficiency maps

2.2. Pre-Transmission Parallel Hybrid Vehicle Power System Model

The torque produced by EM and ICE combine directly on the mechanical coupler. The connection between EM and ICE can be cut and combined with the help of clutch. The torque combined in the mechanical torque coupler is reduced by the gearbox and transmits it to the differential, and then to the axles and wheels. The power system schema of the parallel hybrid vehicle is shown in Figure 4.

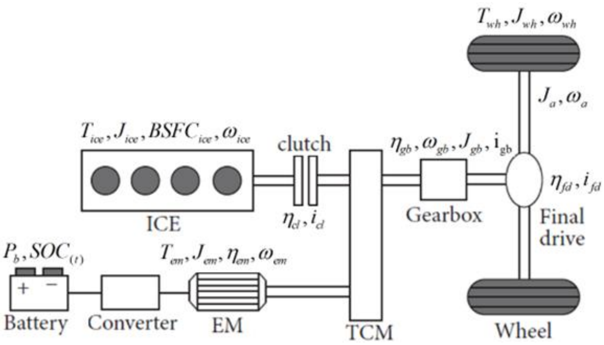


Figure 4. Schematic representation of the powertrain

The derivation of the power transfer function is based on the equation that the net torque is divided by a moment of inertia which gives the angular acceleration. In Equation 1, T_{net} represents the net torque on the shaft, J_{toplam} represents the total moment of inertia of the shaft, and ω represents the angular velocity of the shaft.

$$\frac{d\omega}{dt} = \frac{T_{net}}{J_{total}} \tag{1}$$

The powertrain system transfer function of the parallel hybrid vehicle is given in equation 2, the vehicle wheel speed,

$$\omega_w = \int_t \frac{\begin{pmatrix} T_e i_{gb} \eta_{gb} i_{fd} \eta_{fd} \eta_{cl} + \\ T_m i_{rg} \eta_{rg} i_{gb} \eta_{gb} i_{fd} \eta_{fd} - T_w \end{pmatrix}}{\begin{bmatrix} \eta_{fd} i_{fd}^2 \begin{pmatrix} J_e i_{gb}^2 \eta_{gb} \eta_{cl} + J_{rg} i_{gb}^2 i_{rg} \eta_{rg} \eta_{gb} \\ + J_m i_{rg}^2 i_{gb}^2 \eta_{rg} \eta_{gb} + J_{gb} i_{gb} \eta_{gb} \end{pmatrix} \\ + (4J_w + 2J_a) \end{bmatrix}} dt \tag{2}$$

is calculated with equality. Defines the expressions, T torque, J moment of inertia, ω angular velocity, i reduction ratio, η efficiency. Among the indices in the equations, e refers to the internal combustion engine, gb gearbox, fd final drive, cl clutch, m vehicle weight, rg gearbox, w wheel and a axle.Providing the calculation of the output speed of ICE by multiplying the equation (2) by the differential and gearbox reduction ratio,

$$\omega_e = \omega_w i_{gb} i_{fd} \tag{3}$$

Provides the calculation of the EM output speed by multiplying the equation (2) by the gearbox, gearbox and differential reduction ratio,

$$\omega_m = \omega_w i_{rg} i_{gb} i_{fd} \tag{4}$$

is derived from equality. All equations are input on the MATLAB / Simulation simulation program representing the powertrain system of the parallel hybrid vehicle. The rolling resistance that creates a force against the movement of the vehicle [36],

$$F_r = mgC_r \tag{5}$$

It is defined by equality. Here, rolling refers to the coefficient of resistance. Aerodynamic resistance acting on the vehicle,

$$F_a = 0.5\rho C_d A_f V^2 \tag{6}$$

It is expressed with equality. Acceleration resistance,

$$F_i = ma \tag{7}$$

It can be determined by the expression. In this study, the total resistance force affecting the vehicle,

$$F_{load} = F_i + F_a + F_r \tag{8}$$

It is expressed by the formula. The torque value affecting the wheels,

$$T_r = F_T \cdot r_w \tag{9}$$

is calculated with equality.

2.3. Parallel Hybrid Vehicle Operating Modes

Torques produced by ICE and EM in parallel hybrid vehicle structures are combined in the mechanical torque coupler and directed to different roads. In the first steering, ICE torque is transmission directly to the wheels, in the second steering, the torque produced by EM is transmission to the wheels, and in the third steering, the torque produced by ICE is transmission to the electric motor and the electric motor operates as a generator. Figure 5 shows the torque movements between ICE, EM and wheels [37-39].

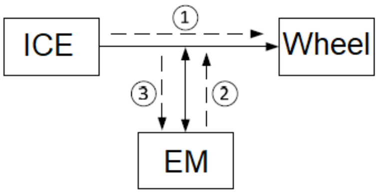


Figure 5. Torque distribution diagram

Power and energy control in parallel hybrid vehicle is carried out in 5 different modes. In the graph in Figure 6, A-B range refers to EM drive only, B-C range is driven by ICE only, C-D range refers to generator drive with ICE, D-E range is hybrid drive, E-F range is regenerative braking mode [18]. In ICE driven mode alone, ICE generates the total power required for the movement of the vehicle alone while the electric motor is disabled. This mode is used when ICE operates near optimum operating conditions while the vehicle is in motion. It is only when the vehicle is driven by the electric motor in electric drive mode, when the ICE is off and the battery is full. This mode is used in situations where the efficiency of the IAT is low, such as when the vehicle is running new, driving at low speeds in urban use and use in reverse gear. In hybrid mode, the wheels are driven by both motors. This mode is used in situations such as sudden acceleration of the vehicle or traveling at high speeds, that is, when the vehicle should operate at high powers.

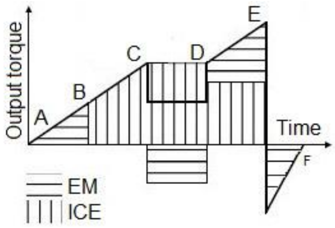


Figure 6. Parallel hybrid vehicle driving modes [17]

In the mode where ICE drive and battery are charged, ICE produces more of the power required for the vehicle to move. In this case, the electric motor is powered by an excessive power and the electric motor supplies energy to the battery by using it as a generator. In regenerative braking mode, the kinetic energy spent in the vehicle during braking or downhill movement is recovered with the regenerative braking system. Parallel hybrid structure provides efficiency and performance increase in use at high speeds, long road trips and travels. This increase in this structure is realized by the simultaneous operation of electrical and mechanical power sources while giving them the flexibility of transition.

2.4. Throttle / Brake Pedal Control

The gas and brake pedal position control is carried out by the PID controller in order to maintain the course of the parallel hybrid vehicle at reference speed lines. The PID controller determines the throttle and brake pedal position to equalize the vehicle speed to the reference speed. Parallel hybrid vehicle accelerator and brake pedal control, Simulink model can be seen in Figure 7.

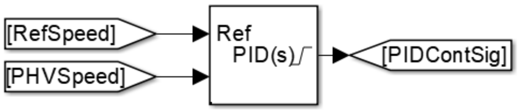


Figure 7. Parallel hybrid vehicle throttle and brake pedal control model

2.5. Rule-Based Control Strategy Models

Power and energy control strategy in parallel hybrid vehicles is one of the most important factors for energy efficiency and vehicle performance. In this study, the hybrid vehicle torque distribution has been checked and compared with the fuzzy logic created and conventional rule-based control strategies.

2.5.1. Conventional rule-based control strategy model

In this study, the torque control of the parallel hybrid vehicle, the EM and the ICE was provided by the conventional rule-based control strategy. As control parameters, input of vehicle torque requirement, generator mode on / off status, gas brake pedal position and maximum electrical engine torque information are provided. With this control strategy, rules have been determined in order to reduce the average fuel consumption values of the vehicle to the lowest level. Input parameters are evaluated within the framework of determined rules and ICE, EM and mechanical brake torque ratios are determined at the controller's output. Parallel hybrid vehicle can switch to 5 different operating modes.

The conventional rule-based control algorithm model in which the parallel hybrid vehicle is controlled and it is shown in Figure 8. In the control algorithm shown in Figure 8, outputs of ICE torque ratio (a), EM torque ratio (b) and mechanical brake torque ratio (c) are obtained. The hybrid vehicle is driven by EM when the generator is off and at low torque needs. In areas where ICE specific fuel consumption is low, it is driven only by ICE. In high torque requirements, it is driven together with ICE and EM. While the generator is on, ICE is operated at maximum torque and it is operated as an EM generator with increasing torque from the vehicle drive. The mechanical brake is activated when it operates as an EM generator and in situations exceeding the EM maximum brake torque.

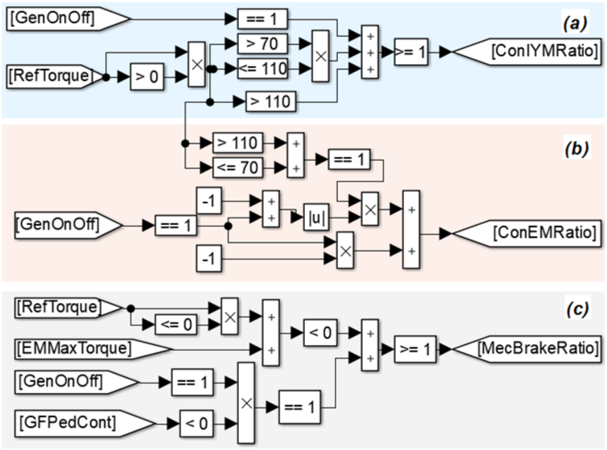


Figure 8. Parallel hybrid vehicle conventional rule-based control model

2.5.2. Fuzzy logic control method model

In this study, the torque distribution control of the hybrid vehicle was carried out by fuzzy logic method. Fuzzy logic controller is provided with the torque requirement of the vehicle, accelerator / brake pedal position, generator mode on / off position and input of SOC values. These input values are calculated instantly in vehicle subsystem models and vary. The most suitable rules have been determined in order to maintain the vehicle in the targeted driving conditions and to ensure minimum fuel consumption. Fuzzy logic controller is aimed to analyze these parameters which are input in accordance with the entered rules and to perform EM, ICE and mechanical brake control in an optimum way.

The first of the fuzzy logic method membership functions was created as vehicle torque requirement (a). Parallel hybrid vehicle is driven by EM only in low torque requirements, only by ICE in medium torque needs and by both electric and ICE in high torque needs. Thus, ICE tries to keep the cycle of work at the lowest levels of BSFC values.

The second of the fuzzy logic method membership functions is formed as the accelerator and brake pedal position (b). When the brake pedal position reaches high levels, the fuzzy logic controller begins to engage the mechanical brake regardless of other parameters. If the vehicle brake pedal position is low, the vehicle is slowed down by regenerative braking. When the brake pedal position reaches high levels, regenerative braking is supported by mechanical braking. If the accelerator pedal position is at a low level, the controller continues with which motor the vehicle is driven at that moment. If the accelerator pedal position is at a high level, EM and ICE provide the vehicle drive together.

The third of the fuzzy logic method membership functions was created as battery state of charge (c). When the SOC level is nominal, the internal combustion engine is operated at the most efficient points during charging. When the SOC level reaches a low level, ICE is operated at the maximum torque level. When the battery charge level reaches 90%, the electric motor exits the generator mode and generates torque for the vehicle's drive through the algorithm that provides the vehicle control.

The fourth of the fuzzy logic method membership functions is determined as generator on / off information

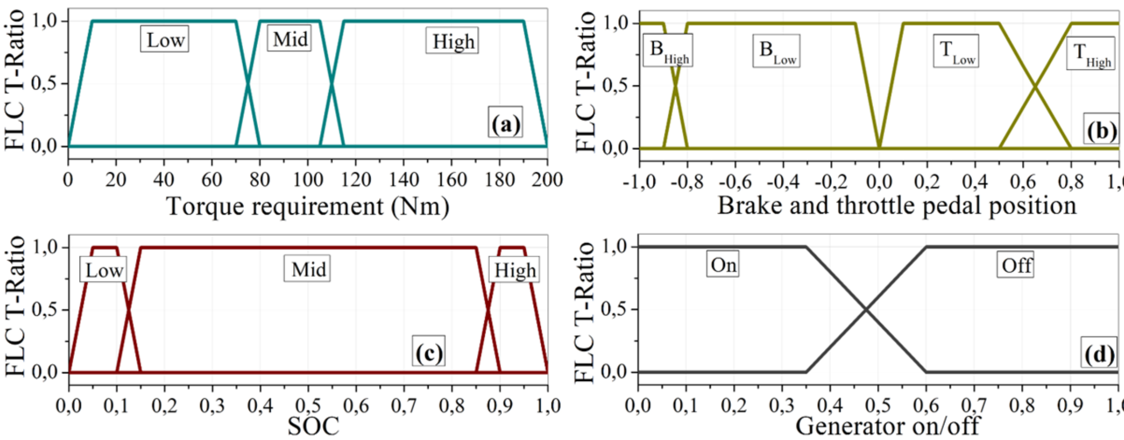


Figure 9. Fuzzy logic control strategy membership functions

Fuzzy logic control method has 4 membership functions: vehicle torque requirement, accelerator / brake pedal position, battery state of charge and generator on / off position information. Fuzzy logic control strategy vehicle torque requirement (a), accelerator and brake pedal position membership function (b), battery state of charge (c), generator's on / off information (d) membership functions are shown in Figure 9.

(d). Battery charge control is controlled by an on-off management strategy called a thermostat. When the battery charge level drops below 30%, it is ensured that the electric motor is operated as a generator by generating the electrical energy by providing the ICE to the EM with the other control membership functions. Vehicle input parameters, controls and output parameters of the fuzzy logic controller, developed for the torque control of the hybrid vehicle, are shown in Figure 10.

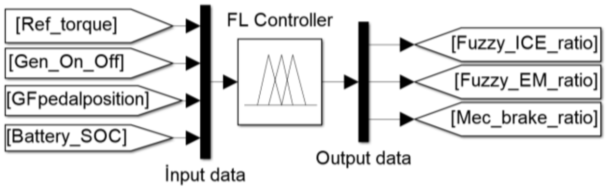


Figure 10. Parallel hybrid vehicle fuzzy logic control system model

The fuzzy logic method input and output parameters and rules of the hybrid vehicle are shown in Table 1. The fuzzy logic controller generates the most appropriate output parameters by interpreting the vehicle inputs on the created rule algorithms.

Table 1. Fuzzy logic strategy input / output parameters and rules

Rule no	Torque req.	Gen. status	Gas/Brake pedal position	ICE ratio	EM ratio	MB ratio
1	L	Closed	GaspedL	0	1	0
2	L	Closed	GaspedH	0	1	0
3	L	Closed	BrakepedL	0	1	0
4	L	Closed	BrakepedH	0	1	0.5
5	L	Open	GaspedL	1	-1	0
6	L	Open	GaspedH	1	0.5	0
7	L	Open	BrakepedL	0	1	0
8	L	Open	BrakepedH	0	1	0.5
9	M	Closed	GaspedL	1	0	0
10	M	Closed	GaspedH	1	0.5	0
11	M	Closed	BrakepedL	0	1	0
12	M	Closed	BrakepedH	0	1	0.5
13	M	Open	GaspedL	1	-1	0
14	M	Open	GaspedH	1	0,5	0
15	M	Open	BrakepedL	0	1	0
16	M	Open	BrakepedH	0	1	0.5
17	H	Closed	GaspedL	1	0.5	0
18	H	Closed	GaspedH	1	1	0
19	H	Closed	BrakepedL	0	1	0
20	H	Closed	BrakepedH	0	1	1
21	H	Open	GaspedL	1	-1	0
22	H	Open	GaspedH	1	1	0
23	H	Open	BrakepedL	0	1	0
24	H	Open	BrakepedH	0	-1	1

Technical characteristics of the hybrid vehicle and parameters provided for simulation are shown in table 2.

2.6. Regenerative Brake System Model

In order to provide energy recovery on hybrid and electric vehicles, regenerative brake system is used in addition to the mechanical brake system on the vehicle. Regenerative braking system is used more actively due to its high power electric motor and high energy capacity battery pack on fully electric vehicles and its control is simpler than the regenerative braking system used on the hybrid vehicle. Control of the regenerative braking system has an important share so that vehicle safety, comfort, battery pack life and energy recovery do not adversely affect [40-43].

In this study, fuzzy logic control method and control algorithm have been created in order to ensure optimum energy recovery, so as not to negatively affect the regenerative brake system control, vehicle safety, comfort and battery pack health. Input of battery charging status, vehicle speed, brake pedal position and charging current parameters are provided to the created control algorithm. In addition, the front axle load distribution ratio of the vehicle is included in the equation. The equation that gives the ratio of the total braking force to the current regenerative braking force is given in equation 10. The equal $\varphi_{Chargecurrent}$ represents the battery charge current, $\varphi_{BPPosition}$ the brake pedal position value, φ_{SOC} the battery charge and $\varphi_{VehSpeed}$ the vehicle speed.

$$RBR = \frac{F_f}{F_{total}} \cdot (\varphi_{Chargecurrent} \cdot \varphi_{BPPosition} \cdot \varphi_{SOC} \cdot \varphi_{VehSpeed}) \quad (10)$$

Regenerative brake system fuzzy logic method membership functions can be seen in Figure 11.

Technical characteristics of the hybrid vehicle and parameters provided for simulation are shown in Table 2.

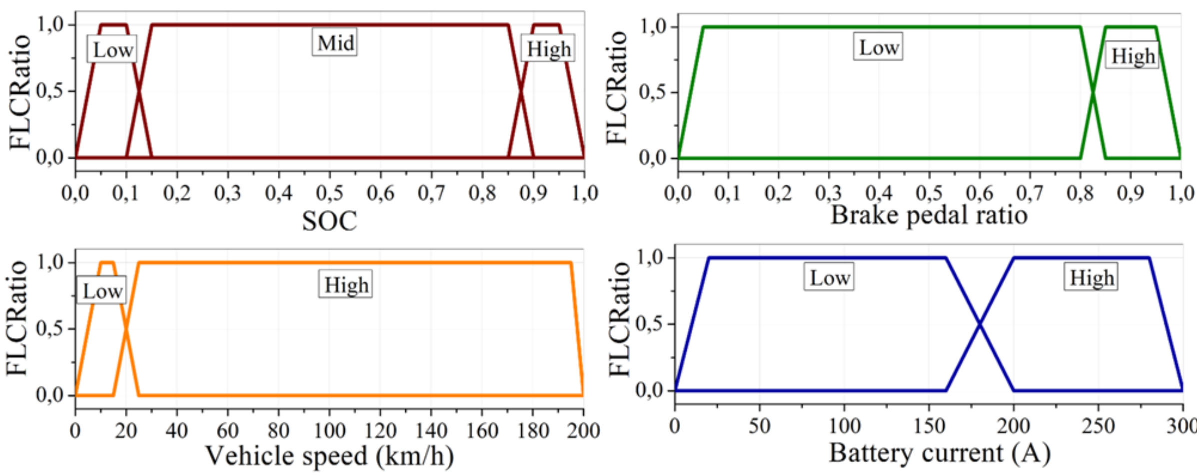


Figure 11. Regenerative brake fuzzy logic membership functions

Table 2. Parallel hybrid vehicle specifications and simulation parameters

Parameter	Value	Unite
Vehicle mass	1420	kg
Wheel radius	0.315	m
Battery pack energy	5	kWh
Accessory power	400	W
Final drive efficiency	0.96	-
Gearbox efficiency	0.95	-
EM gearbox efficiency	0.97	-
Fuel density	0.803	kg/l
Rolling. res. coefficient	0.01	-
Aero. res. coefficient	0.32	-
Vehicle front section area	2.55	m^2
Air density	1	Kg/m^3
EM/ICE moment of inertia	0.12	kg/m^2
Wheel/Gearbox moment of inertia	1/0.1	kg/m^2

5. RESULTS AND DISCUSSION

The model was created and controlled by FL method and conventional rule-based control strategy. Simulation results and average fuel consumption values were obtained when using the pre- transmission parallel hybrid vehicle under different driving cycles. ICE and EM torque distribution graphs of hybrid vehicle were obtained and working modes were examined. On the specific fuel consumption and EM efficiency map of ICE, working points were obtained under NEDC driving cycle conditions and evaluated.

generator mode. In the cases where EM works in a generator state, it is obtained that it fails to provide the required performance and fails. It is seen that the performance of the vehicle speed can be maintained under reference speed conditions by controlling the hybrid vehicle with FL control strategy.

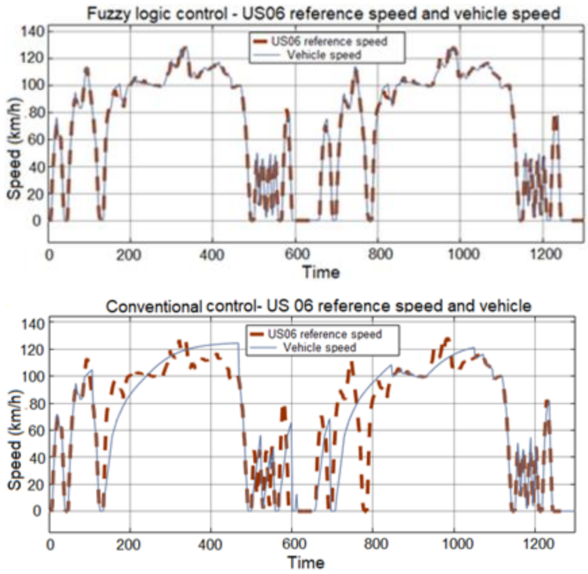


Figure 12. US06 (2 cycles) driving cycle with FL and conventional rule-based control strategy

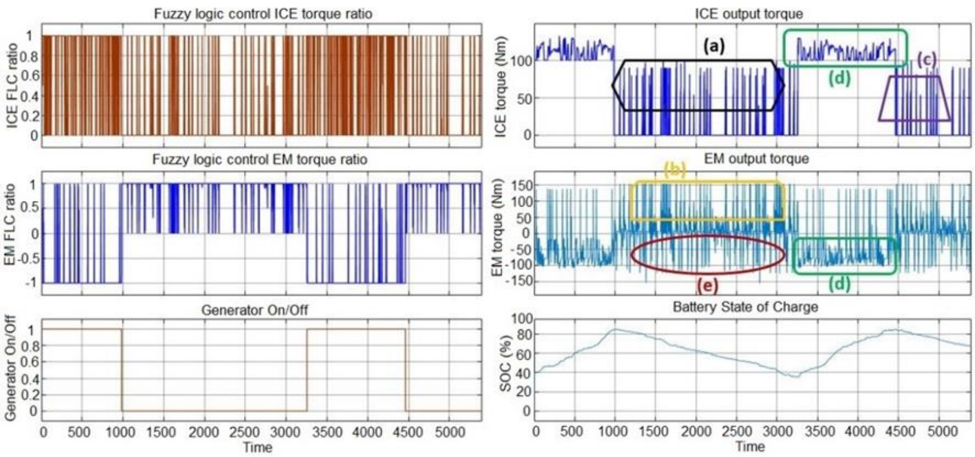


Figure 13. Torque control with the FL method of the hybrid structure

It has been observed that the hybrid vehicle, which is controlled by FL and conventional rule-based control strategy, can maintain its driving under the conditions of FTP-75, NEDC, EUDC and ECE-15 driving cycles. The parallel hybrid vehicle, controlled by the conventional rule-based control strategy, was found to be unable to maintain its course under the conditions of the US06 driving cycle. Comparison of hybrid vehicle speeds managed with FL and conventional rule-based control strategy with reference speed can be seen in Figure 12. In the US06 driving cycle conditions, hybrid vehicle controlled by conventional rule-based control strategy, deviations were observed when EM was not working in

In Figure 13, if the vehicle is controlled using FL method is used in 3 cycles under FTP-75 driving cycle conditions, battery state of charge, ICE and EM torque distribution rates and output torque values are shown. On this figure, only ICE (a), EM (b), ICE and EM together (c), generator (d) and regenerative brake (e) mode of the parallel hybrid vehicle can be seen.

In NEDC driving cycle conditions of the vehicle controlled by FL and traditional rule-based control strategy, ICE operating points were obtained and shown in Figure 14. With FL and control strategy, ICE operates at optimum torque level, and it is observed that it reaches maximum torque level in high torque needs. With the conventional rule-based control strategy, ICE has been found to work at points where the BSFC value is low, but it is not working in the optimum torque line. It is also seen that instead of the optimum torque line, it works more on the maximum torque line, where the BSFC value is higher.

The EM operating points of the vehicle, controlled by FL and traditional rule-based control strategy, have been obtained under NEDC drive cycle conditions and are shown in Figure 15. In FL control strategy, EM has been observed to operate at maximum torque values with low efficiency. But it appears to work more in the negative maximum torque region than in the conventional rule-based control strategy. Thus, it is understood that regenerative braking is used more effectively. In the conventional rule-based control strategy, it was obtained that EM positively and negatively worked in efficient regions in the torque torque zone.

The average fuel consumption values of the vehicle controlled by FL and conventional rule-based control strategy are used in different driving cycle conditions. The average fuel consumption results obtained as a result of simulation are shown in Figure 16. If the vehicle is controlled with FL method under US06, FTP-75, NEDC, ECE-15 and EUDC conditions, average fuel consumption values of 6.289, 4.262, 4.288, 4.591 and 3.817 L / 100 km were obtained. The fuel consumption values of 4.892, 4.592, 4.698 and 4.071 L / 100 Km were obtained in the case of using the vehicle controlled by the conventional rule-based control strategy under the conditions of the FTP-75, NEDC, ECE-15 and EUDC. The average fuel consumption value could not be calculated since the hybrid vehicle, controlled by the conventional rule-based control strategy, could not provide sufficient performance under the conditions of the US06 driving cycle.

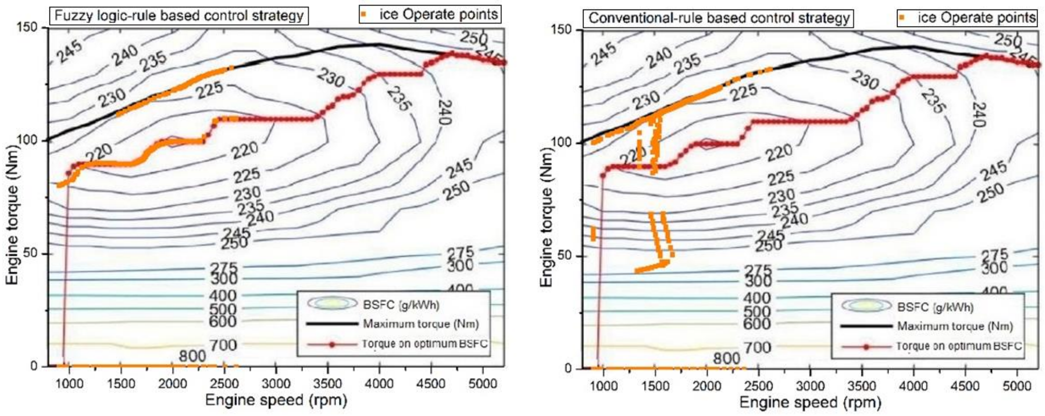


Figure 14. ICE operate points under the conditions of NEDC driving cycle with FL and conventional control method of hybrid vehicle

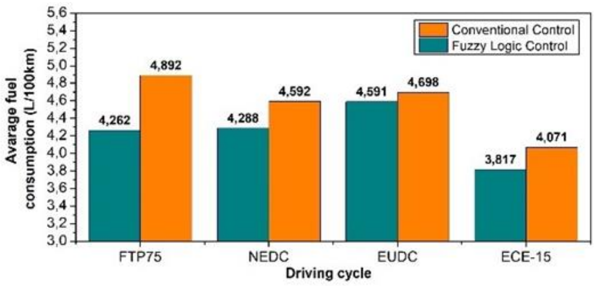


Figure 16. Average fuel consumption values (L / 100 Km) of different driving cycle conditions of FL and conventional rule based control strategy

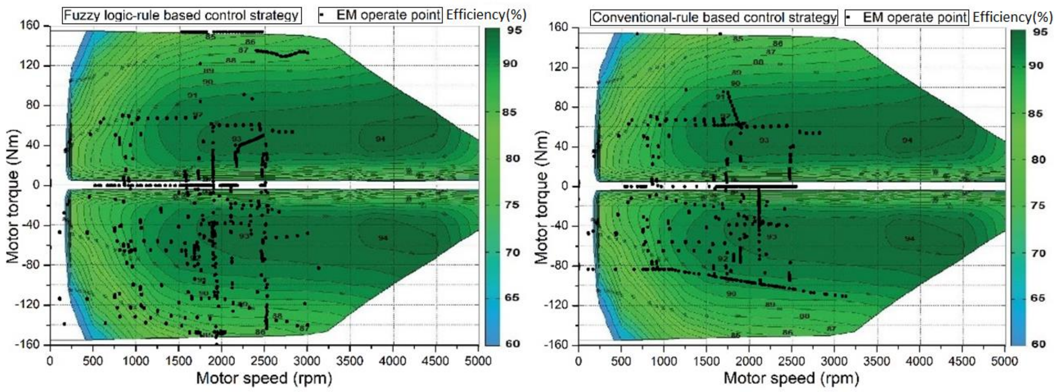


Figure 15. EM operate points under the conditions of FTP-75 driving cycle with FL and conventional control method of hybrid vehicle

The control of the hybrid vehicle with FL, according to the conventional rule-based control strategy, the saving rates provided in different driving cycle conditions are shown in Figure 17. If the vehicle controlled by FL method is used under the conditions of the FTP-75, NEDC, ECE-15 and EUDC driving cycles, it is obtained that the vehicle saves 12.878%, 6.62%, 2.277% and 6.239% compared to its control with the conventional rule-based control strategy.

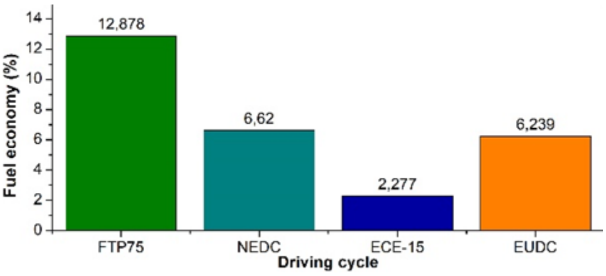


Figure 17. Average fuel saving rate under different driving cycle conditions according to FL and conventional rule based control strategy

6. CONCLUSION

In this study, the vehicle model of a pre-transmission parallel hybrid vehicle was created in MATLAB / Simulink. Torque control of the modeled hybrid vehicle was provided by fuzzy logic and conventional rule-based control strategy. The vehicle controlled by different strategies, ICE and EM working points under different driving cycle conditions were examined, and average fuel consumption values were obtained. It has been found that the hybrid vehicle US06 managed with the conventional rule-based control strategy does not provide sufficient performance under driving cycle conditions. Thus, the vehicle controlled by the fuzzy logic method obtained the result that it operates with higher performance and more stable. With fuzzy logic method, ICE has been provided to operate at optimum torque value. In the conventional rule-based control method, although EM operates at more efficient points in the positive and negative torque region, regenerative braking has been observed to be more ineffective. In the control of the vehicle with fuzzy logic control strategy, it has been obtained that it saves 12.878%, 6.62%, 2.277% and 6.239% respectively under the conditions of the driving cycles of FTP-75, NEDC, ECE-15 and EUDC.

NOMENCLATURE

a	: acceleration (m/s^2)
A_f	: front surface area (m^2)
BSFC	: brake spesific fuel consumption (g/kWh)
C_d	: aerodynamic resistance coefficient
CO	: carbonmonoxsit
C_r	: rolling resistance coefficient
DCT	: dual clutch transmission
DP	: dynamic programming
ECE-15	: Urban Driving Cycle
ECMS	: equivalent consumption minimization strategy
EM	: electric motor
EUDC	: Extra Urban Driving Cycle
FTP-75	: Federal Test Procedure
g	: gravity (m/s^2)
HC	: hydrocarbon
ICE	: internal combustions engine
i	: reduction ratio
J	: moment of inertia ($kg.m^2$)
m	: vehicle mass (kg)
ƞ	: efficiency
NEDC	: New European Driving Cycle
NO_x	: nitrogen oxide
PID	: proportional, integral, derivative
PM	: particulate matter
r_w	: wheel radius (m)
SOC	: state of charge
T	: torque (Nm)
US06	: Hight Speed Driving cycle
V	: speed (m/s)
$\dot{w}$	: angular acceleration (rad/s^2)
ω	: angular velocity (rad/s)
ρ	: air density (kg/m^3)

DECLARATION OF ETHICAL STANDARDS

The author(s) of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

AUTHORS' CONTRIBUTIONS

Tolga KOCAKULAK: Conceptualization, Methodology, Investigation, Data curation, Visualization, Writing - original draft, Writing - review & editing.

Hamit SOLMAZ: Conceptualization, Methodology, Investigation, Data curation, Visualization, Writing - original draft, Writing - review & editing.

Fatih ŞAHİN: Conceptualization, Methodology, Investigation, Data curation, Visualization, Writing - original draft, Writing - review & editing.

CONFLICT OF INTEREST

There is no conflict of interest in this study.

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