# Efficient Energy Utilization in Plug-in Hybrid Electric Vehicles using Fuzzy Logic Controllers

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**Abstract:** Plug-in hybrid electric vehicles (PHEV) provide an appealing choice over conventional vehicles by reducing emissions and fuel consumption. This work provides an efficient methodology to improve the energy utilization efficiency of PHEV power train using fuzzy logic. The design of fuzzy logic controllers is responsible for the power split control between IC engine and electric motor in hybrid mode and gear shifting control of the IC engine. The effectiveness of the proposed methodology is further illustrated using the result comparison with fuel consumption and emission levels with and without the fuzzy controllers with the help of the ADVISOR tool of MATLAB software, which is utilised in benchmark studies to evaluate fuel consumption and emissions. Parameters such as torque required, state of charge, effective engine speed, and engine temperature are considered for efficient energy utilization. The efficacy of the proposed method clearly shows considerable reduction in fuel consumption and unburned hydrocarbons, nitrogen oxide (NOx) emissions under the Urban Dynamic Driving Schedule (UDDS).

Keywords: Efficient Energy Utilization, Hybrid Electric Vehicles, Fuzzy Logic Controllers

## 1. INTRODUCTION

Eco friendly vehicles are the only option in this era where strict emission restrictions are in place. To this end, vehicles have been manufactured with various new technologies, different fuels, and sophisticated controls [1]. Efforts have also been made in the direction of bringing up control strategies for gear shifting of the conventional IC engines so that the fuel consumption is drastically reduced and so are the emissions. Hybrid electric technologies prove to be a great step in this effort. Of all these, plug-in hybrid electric vehicles (PHEV) are the most desirable options that help in reducing overall fuel consumption and keeping the emissions at a very low value [2,3].

An attempt has been made by Eckert et al. [1] to develop an optimum fuzzy control designed for conventional vehicles gear shifting mechanism. It was aimed at reducing fuel consumption and decreasing the emissions of greenhouse gases like hydrocarbons (HC), carbon monoxide (CO) and nitrogen oxides (NOx). When PHEV is combined with alternative gear shifting control resulted in fuel economy and reduction in CO, NOx, and HC considerably, in comparison to a vehicle with IC engine [2]. Various strategies involving minimizing fuel usage for PHEVs that employed dynamic programming are aimed at finding optimal charge of battery that is based on path traffic and driving cycles [3,4].

Strategies for optimal utilization of energy in hybrid electric vehicles are addressed in [5]. Particle swarm optimization algorithm has been used by Zeng et al. [6] to optimize the energy that is consumed by IC engine and electric motor for better power management in PHEVs. A proportional-integral feedback controller has been used in [7] that aims at improving gear shifting mechanism of various PHEV configurations. Similarly, the effect of greenhouse gases that are emitted because of IC engine are also researched extensively in PHEVs [8-10]. Various methods have opted for model predictive control approach for PHEVs considering driving patterns to reduce emissions and fuel usage [11].

All these works concentrate in the improvement of energy efficiency of the PHEV, but not all factors are considered together. This work aims at providing a simple and efficient strategy in terms of efficient utilisation of the resources present in a PHEV, aiming at reduced fuel consumption and decreased emissions. Fuzzy logic controllers are designed separately for engine/electric motor power split control strategy and Gear shift control strategy of the IC engine. Moreover, the effectiveness of the proposed methodology is further illustrated using the result comparison with fuel consumption and emission levels with and without the Fuzzy controllers with the help of ADVISOR tool of MATLAB software, that serves as basis for various benchmark studies to evaluate fuel usage and emissions. This is used in proving the reduced fuel consumption and decreased emissions, for different configurations of PHEVs.

The paper is organized as follows. The following section provides the description of the dynamics of PHEVs considered in this work. Section 3 explains the design of the developed fuzzy logic controller with rules framed. The next section gives an idea of NREL's ADVISOR tool and its usage on this work. The last section provides the simulation results and discussion.

## 2. PHEV DYNAMICS

A PHEV is an aggregation of IC engine and electric motor powered by a battery that is rechargeable. The battery in PHEV can support fully for small range of distance and for long distances, it is necessarily hybrid. On the whole, PHEVs have an extended range capability compared to hybrid vehicles. Despite so many advantages, its behaviour is nonlinear and not predictable. So, efficient energy utilization strategy is required to decide the share of power contribution by both electric motor and IC engine, simultaneously aim at reducing fuel usage and reducing harmful emissions.

This work considers a parallel PHEV configuration, where the front wheels are propelled by the IC engine and rear wheels by the in-wheel electric motors. The wheels' traction torque is responsible for deciding the sharing of power between electric motor and the IC engine.

The expression for the required torque $T_{req}$ is given by Eq. 1

$$T_{req} = \left(R_x + D_A + Ma_{req}\right)r \tag{1}$$

Where, r is dynamic radius
$R_x$ is rolling resistance
$D_A$ is vehicle aerodynamic drag
M is Mass displacement inertia
$a_{req}$ is required acceleration

and,

$$D_A = \frac{1}{2}\rho V^2 C_D A_f \tag{2}$$

$$R_x = 0.0981\left(1 + \frac{2.24V}{100}\right)M \tag{3}$$

V is vehicle speed
ρ is air density
$A_f$ is vehicle frontal area
$C_D$ is drag coefficient

The value of r is given by Eq. 4, it depends mostly on its geometric radius $r_g$, also corrected by the $k_v$ factor, which varies according to the vehicle speed.

$$r = 0.98r_g\left(1 + 0.01kv\right) \tag{4}$$

The total torque required would be the aggregate of frontal and rear wheels torques given by Eq. 5.

$$T_{req} = T_{req}^{Front} + T_{req}^{Rear} \tag{5}$$

## 3. DESIGN OF FUZZY LOGIC CONTROLLERS

Fuzzy logic controllers are more popularly used for nonlinear systems lacking parametric expressions. Different fields in engineering have vast usage of fuzzy systems [15-19]. The objectives of the current work are to have intelligent control of power split mechanism between IC engine and electric motor, also to have an efficient gear shifting strategy whenever IC engine is in use. The Mamdani method of inferencing is chosen in this study as it can handle non-linear systems like PHEV. Power split control technique aims at splitting the power to be drawn by the drive train from the IC engine and electric motor to reduce fuel usage and emissions in PHEVs. Gear shift control technique aims at the usage of appropriate gears to reduce emissions while the IC engine is in use. The trapezoidal linear membership functions are utilized to design the controllers as they have controlled linear characteristics.

### 3.1 Power split control

The power-split control helps in sharing the power between IC engine and Electric motor. As the power to be split depends on the charge available in the battery and other factors like output torque required and the temperature of the IC engine, these three are considered as input variables (Treq – Torque required, SoC – Battery state of charge, $Temp^{ICE}$ – Engine temperature) for the power split fuzzy logic controller. The first input variable, value of Treq is chosen in the range of 0 to 100 Nm. The second input to the controller is SoC, that is necessary to determine if the electric motor will be to drive the vehicle. A minimum charge of 40% is considered for battery SoC, beyond which electric motor cannot power the PHEV drive train and the IC engine take over. At this point, IC engine takes over and its temperature serves as the final input to the controller, as the emissions of a cold start vehicle are more prominent in the considered driving cycle.

The output of the designed fuzzy controller is the value of Pc, that varies between 0 and 1, indicating the share of torque or power required from electric motor, as indicated by equation (6). The rest of the torque or power is contributed by the IC engine, given by equation (7) .

$$T_{req}^{Rear} = T_{req} \times P_C \tag{6}$$

$$T_{req}^{Front} = T_{req} - T_{req}^{Rear} \tag{7}$$

The fuzzy logic controller for the power split control strategy is designed to have a rule base with 27 rules, as shown in Table. All the three input variables are divided into three membership functions each, which are divided into small medium and large. Based on the combination of input variables condition, and from the knowledge base driven by domain experience, the rules are designed. For example, Rule number 27can be explained as follows, if the state of charge is high, the temperature of the IC engine is high, and the torque required is also high, then to reduce fuel consumption and emissions, the electric motor should supply more torque. So, the PC value should be high. That is the contribution from electric motor should be high.

**Table 1.** Fuzzy rules for power split control strategy

| **Power Split Control ($P_C$) (Output)** | | **Torque Required (Input)** | | |
|---|---|---|---|---|
| **Battery State of charge (Input)** | **IC Engine Temperature (Input)** | $T_{req\ (L)}$ | $T_{req\ (M)}$ | $T_{req\ (H)}$ |
| **$SoC_{(L)}$** | **$Temp^{ICE}_{(L)}$** | $P_{C\ (L)}$ | $P_{C\ (L)}$ | $P_{C\ (L)}$ |
| | **$Temp^{ICE}_{(M)}$** | $P_{C\ (L)}$ | $P_{C\ (L)}$ | $P_{C\ (M)}$ |
| | **$Temp^{ICE}_{(H)}$** | $P_{C\ (M)}$ | $P_{C\ (M)}$ | $P_{C\ (H)}$ |
| **$SoC_{(M)}$** | **$Temp^{ICE}_{(L)}$** | $P_{C\ (M)}$ | $P_{C\ (M)}$ | $P_{C\ (H)}$ |
| | **$Temp^{ICE}_{(M)}$** | $P_{C\ (M)}$ | $P_{C\ (H)}$ | $P_{C\ (H)}$ |
| | **$Temp^{ICE}_{(H)}$** | $P_{C\ (H)}$ | $P_{C\ (H)}$ | $P_{C\ (H)}$ |
| **$SoC_{(H)}$** | **$Temp^{ICE}_{(L)}$** | $P_{C\ (M)}$ | $P_{C\ (H)}$ | $P_{C\ (H)}$ |
| | **$Temp^{ICE}_{(M)}$** | $P_{C\ (H)}$ | $P_{C\ (H)}$ | $P_{C\ (H)}$ |
| | **$Temp^{ICE}_{(H)}$** | $P_{C\ (H)}$ | $P_{C\ (H)}$ | $P_{C\ (H)}$ |

### 3.2 Gear shift control

In order to have efficient fuel usage and to reduce exhaust emissions during IC engine's turn to drive the PHEV, the gear shift control helps in deciding the gear shifting towards upward or downward directions. This is essential to run the vehicle efficiently with IC engine, when the battery SoC is minimum. The input variables that decide the control of the gear shift are Treq – Torque required, $\omega^{ICE}_{eff}$ – Effective engine speed and $Temp^{ICE}$ – Engine temperature. Thus, the fuzzy logic controller can decide upon shifting of gear during cold start and heat run periods. During cold start, emissions are crucial in deciding the gear shifts, and when the engine is hot, it is the fuel usage that is optimized. The range of the engine speed is considered from 94 rad/s to 681 rad/s. The fuzzy output Gc is defuzzified as follows. The fuzzy output is compared to the lower limit Li and the upper limit Ls, and the upward or downward shift of gear is decided based on equation (8). The fuzzy rule base for the gear shift control is designed with 27 rules which are shown in Table 2.

$$Gear = \begin{cases} G_c < L_i \text{and} G_n > 1 \therefore Gear = G_n - 1 \\ L_i \leqslant G_c \leqslant L_s \therefore Gear = G_n \\ G_c > L_S \text{and} G_n < 5 \therefore Gear = G_n + 1 \\ \omega_{eff}^{ICE} \leqslant 94 \text{and} G_n > 0 \therefore Gear = G_n - 1 \\ \omega_{eff}^{ICE} \geqslant 681 \text{and} G_n \leqslant 4 \therefore Gear = G_n + 1 \\ V = 0 \text{and} T_{req}^{Front} \leqslant 0 \therefore Gear = 0 \\ E_{st} = 0 \therefore Gear = 0 \end{cases} \quad (8)$$

**Table 2.** Fuzzy rules for gear shift control strategy

| **Gear Shift Control (Gc) (Output)** | | **IC Engine Temperature (Input)** | | |
|---|---|---|---|---|
| **Torque Required (Input)** | **Vehicle Speed (Input)** | **$Temp^{ICE}_{(L)}$** | **$Temp^{ICE}_{(M)}$** | **$Temp^{ICE}_{(H)}$** |
| **$T_{req\ (L)}$** | **$\omega^{ICE}_{eff\ (L)}$** | $G_{C\ (L)}$ | $G_{C\ (L)}$ | $G_{C\ (M)}$ |
| | **$\omega^{ICE}_{eff\ (M)}$** | $G_{C\ (M)}$ | $G_{C\ (M)}$ | $G_{C\ (H)}$ |
| | **$\omega^{ICE}_{eff\ (H)}$** | $G_{C\ (M)}$ | $G_{C\ (H)}$ | $G_{C\ (H)}$ |
| **$T_{req\ (M)}$** | **$\omega^{ICE}_{eff\ (L)}$** | $G_{C\ (L)}$ | $G_{C\ (M)}$ | $G_{C\ (H)}$ |
| | **$\omega^{ICE}_{eff\ (M)}$** | $G_{C\ (L)}$ | $G_{C\ (L)}$ | $G_{C\ (M)}$ |
| | **$\omega^{ICE}_{eff\ (H)}$** | $G_{C\ (L)}$ | $G_{C\ (M)}$ | $G_{C\ (H)}$ |
| **$T_{req\ (H)}$** | **$\omega^{ICE}_{eff\ (L)}$** | $G_{C\ (M)}$ | $G_{C\ (M)}$ | $G_{C\ (H)}$ |
| | **$\omega^{ICE}_{eff\ (M)}$** | $G_{C\ (L)}$ | $G_{C\ (M)}$ | $G_{C\ (H)}$ |
| | **$\omega^{ICE}_{eff\ (H)}$** | $G_{C\ (L)}$ | $G_{C\ (M)}$ | $G_{C\ (M)}$ |

## 4. ADVISOR TOOL

### 4.1 Driving cycles

A driving cycle is a series of data points representing the speed of a vehicle versus time. Drive cycles are used to simulate through software, the road conditions like torque requirements, speed requirement in a given time period to reduce the cost of expensive physical run tests. In this study the UDDS (Urban Dynamometer Driving Schedule) driving cycle is considered for the simulation. This test is generally used for light weight vehicles testing. The following figure depicts the time v/s speed graph for UDDS driving cycle.

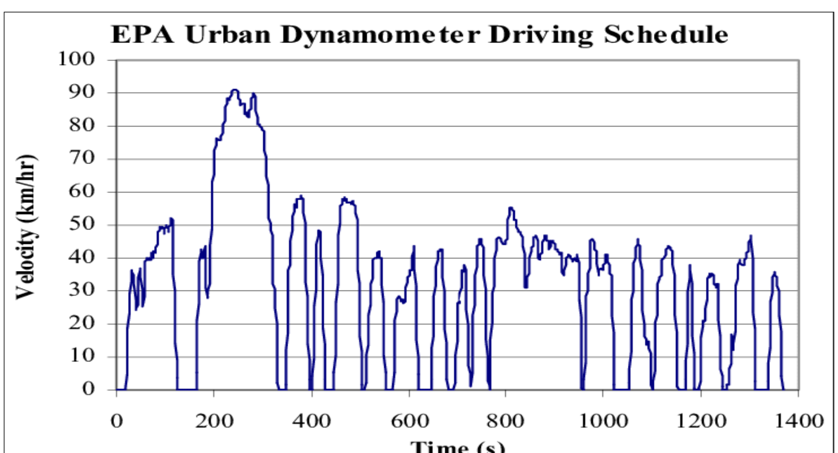

**Figure 1.** UDDS driving cycle

ADVISOR (Advanced Vehicle Simulator) is an application of NREL (National Renewable Energy Laboratory) [20], it is a set of model, data, and script text files, that can be used in conjunction with MATLAB and Simulink. This application is used for fast investigation of the working of different types of vehicles like conventional, electric, and hybrid vehicles. Certain drive train profiles created by the user also can be simulated easily in this software. The specifications of the PHEV and its components are listed in Table 3 and Table 4.

**Table 3.** Hybrid Vehicle base component values

| Parameter | Advisor file name | Specifications |
|---|---|---|
| Engine power | FC_SI41_emis | 41kW |
| Motor power | MC_AC75 | 75kW AC induction motor |
| Energy storage | ESS_PB25 | 12V, 26Ah, 10EP VRLA battery |
| Transmission | TX_5SPD | 5-speed transmission |

**Table 4.** Hybrid Vehicle parameters

| Parameter | Value |
|---|---|
| Aerodynamic drag coefficient | 0.335 |
| Wheel radius | 0.282m |
| Initial state of charge | 0.8 |
| Vehicle mass (calculated) | 1659kg |
| Cargo mass | 445 kg |

## 5. SIMULATION RESULTS AND DISCUSSION

The PHEVs are simulated using ADVISOR for different power train approaches like Conventional, Parallel Hybrid Electric Vehicle without Power split and Parallel Hybrid Electric Vehicle with Power split.

### 5.1 Conventional Vehicle

From the ADVISOR Vehicle input GUI select the Powertrain configuration as Conventional and the appropriate component values are selected. The corresponding results are illustrated in Figure 2. The Fuel consumptions for a distance of 12.2 km has come out to 7.5 Litres for 100km and emissions in grams per kilometre are 0.39, 2.501 and 0.335 of HC, CO and NOx respectively.

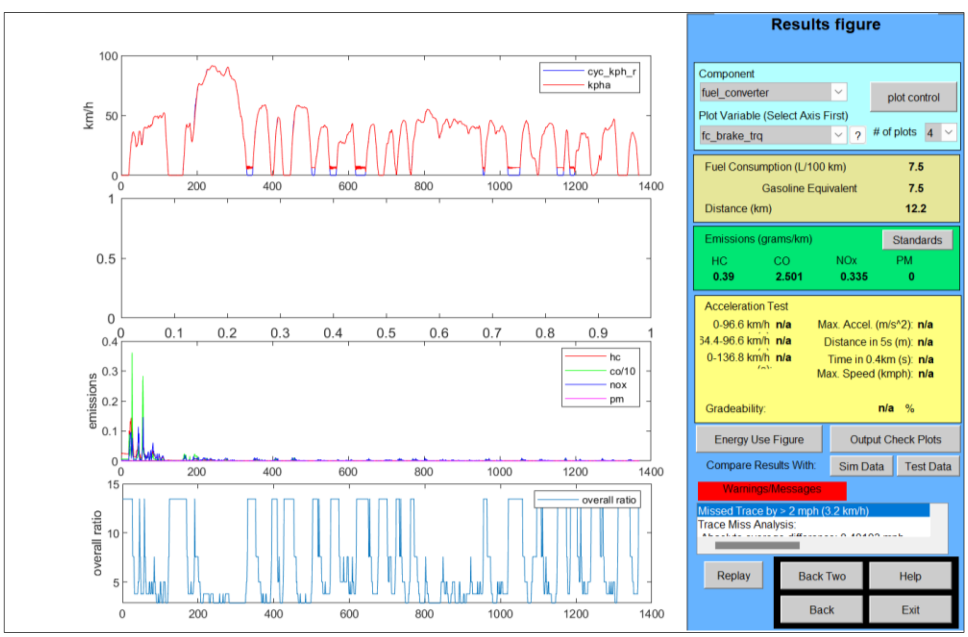


**Figure 2.** Results of Conventional Vehicle

Torque curve for the given driving cycle as shown in figure 3.

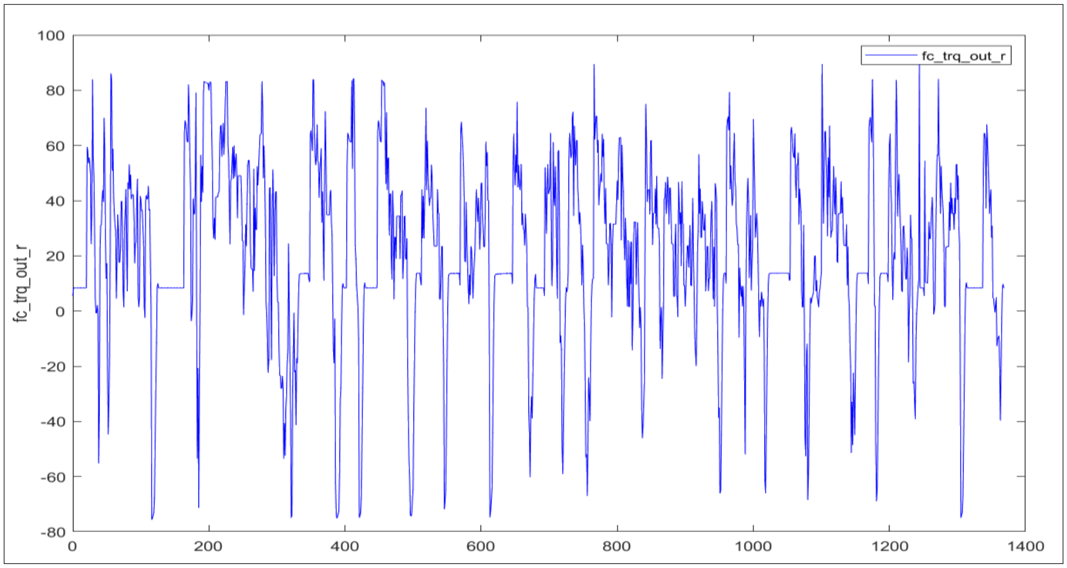


**Figure 3.** Torque vs Time graph for one driving cycle

The range of parameters considered for simulation are, the range of torque is 0–100 Nm, the range of temperature is 20–100 °C, and the range of the state of charge is 0.4–0.8.

One driving cycle is divided into 14 sections and simulated for every section, with the corresponding values of various parameters are calculated and tabulated as shown.

**Table 5.** Results of Conventional vehicle

| TIME (sec) | TORQUE (N-m) | NET FUEL (lit) | CURRENT FUEL (lit) | EMMISIONS (gms) | | |
|---|---|---|---|---|---|---|
| | | | | HC | CO | Nox |
| **0-100** | 38.635 | 0.0696 | 0.0696 | 3.2656 | 21.1008 | 2.1224 |
| **100-200** | 32.82 | 0.1316 | 0.062 | 0.2694 | 2.3282 | 0.2982 |
| **200-300** | 48.835 | 0.2808 | 0.1492 | 0.1226 | 1.5694 | 0.3226 |
| **300-400** | 14.505 | 0.3456 | 0.0648 | 0.1248 | 0.672 | 0.1512 |
| **400-500** | 29.67 | 0.4256 | 0.08 | 0.1208 | 1.12 | 0.18 |
| **500-600** | 24.5 | 0.4712 | 0.0456 | 0.1162 | 0.5012 | 0.1071 |
| **600-700** | 24 | 0.5236 | 0.0524 | 0.0792 | 0.2463 | 0.096 |
| **700-800** | 33 | 0.592 | 0.0684 | 0.1498 | 0.7341 | 0.1881 |
| **800-900** | 25 | 0.6525 | 0.0605 | 0.0812 | 0.1432 | 0.1248 |
| **900-1000** | 14 | 0.704 | 0.0579 | 0.0902 | 0.4262 | 0.114 |
| **1000-1100** | 21 | 0.7519 | 0.0415 | 0.0847 | 0.2541 | 0.0966 |
| **1100-1200** | 26 | 0.8066 | 0.0547 | 0.0798 | 0.3195 | 0.0729 |
| **1200-1300** | 34 | 0.855 | 0.0484 | 0.0905 | 0.4318 | 0.1049 |
| **1300-1400** | 20 | 0.9 | 0.045 | 0.071 | 0.275 | 0.096 |
| **TOTAL** | | | | **4.7458** | **30.1218** | **4.0748** |

Net Fuel = fuel consumption from starting to corresponding section.

Current Fuel= fuel consumption in that corresponding section.

From above case Total fuel consumption and emissions for 12km distance are:

Total fuel consumption = 0.9 lit
Total hydrocarbon (HC) emissions = 4.7458 grams
Total carbon monoxide (CO) emissions =30.1218 grams

Total nitrogen oxide (NOx) emissions =4.0748 grams

### 5.2 Parallel Hybrid Vehicle (without fuzzy controller)

Select the parallel powertrain configuration from the ADVISOR vehicle input GUI and the appropriate component values are selected. The number of driving cycles and the initial conditions are selected, and initial state of charge as 0.8 is considered. The corresponding results are illustrated in Figure 3. The Fuel consumptions for a distance of 12 km has come out to 5.2 Litres for 100km and emissions in grams per kilometre are 0.284, 1.34 and 0.197 of HC, CO and NOx respectively. The values of all other parameters in one driving cycle are listed in Table 6.

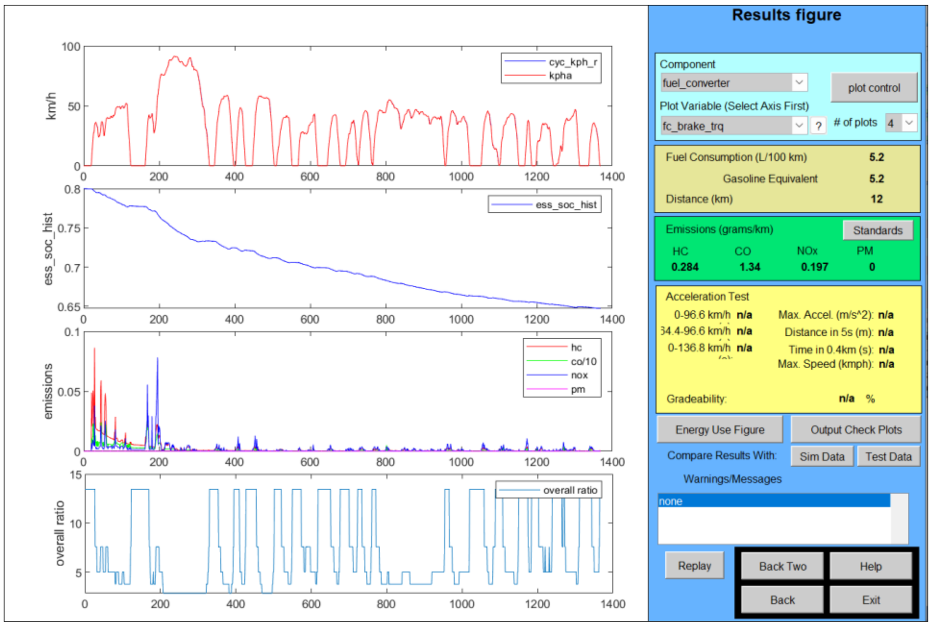


**Figure 4.** Results window of Parallel Hybrid Electric Vehicle

**Table 6.** Parallel Hybrid Electric vehicle (without fuzzy controller)

| TIME (sec) | TORQUE (N-M) | SOC | Temp($^0$c) | NET FUEL (lit) | CURRENT FUEL(lit) | EMMISIONS (gms) | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | HC | CO | Nox |
| 0-100 | 38.635 | 0.8 | 20 | 0.0296 | 0.0296 | 1.5768 | 6.8632 | 0.4376 |
| 100-200 | 32.82 | 0.788 | 32.2 | 0.0644 | 0.0348 | 0.7108 | 4.9514 | 0.5872 |
| 200-300 | 48.835 | 0.78 | 45 | 0.148 | 0.0836 | 0.3505 | 1.7089 | 0.4367 |
| 300-400 | 14.505 | 0.76 | 75 | 0.1872 | 0.0392 | 0.0547 | 0.1661 | 0.0553 |
| 400-500 | 29.67 | 0.755 | 85 | 0.2408 | 0.0536 | 0.096 | 0.3328 | 0.1296 |
| 500-600 | 24.5 | 0.748 | 96 | 0.2728 | 0.032 | 0.0446 | 0.1306 | 0.0338 |
| 600-700 | 24 | 0.74 | 96.1 | 0.306 | 0.0332 | 0.0702 | 0.2546 | 0.0674 |
| 700-800 | 33 | 0.734 | 96.1 | 0.3552 | 0.0492 | 0.0638 | 0.154 | 0.0876 |
| 800-900 | 25 | 0.724 | 96 | 0.4089 | 0.0537 | 0.1037 | 0.366 | 0.0962 |
| 900-1000 | 14 | 0.714 | 96.2 | 0.4512 | 0.0423 | 0.0393 | 0.0948 | 0.075 |
| 1000-1100 | 21 | 0.703 | 96 | 0.4841 | 0.0329 | 0.0723 | 0.2303 | 0.0845 |
| 1100-1200 | 26 | 0.698 | 96 | 0.5341 | 0.05 | 0.0764 | 0.3 | 0.0891 |
| 1200-1300 | 34 | 0.692 | 96.3 | 0.57 | 0.0359 | 0.0811 | 0.2917 | 0.1 |
| 1300-1400 | 20 | 0.68 | 96.2 | 0.624 | 0.054 | 0.0678 | 0.234 | 0.084 |
| | | | | | | | | |
| TOTAL | | | | | 0.624 | 3.408 | 16.08 | 2.364 |

From above case Total fuel consumption and emissions for 12km distance are:

Total fuel consumption = 0.624 lit
Total hydrocarbon (HC) emissions = 3.408 grams
Total carbon monoxide (CO) emissions = 16.08 grams
Total nitrogen oxide (NOx) emissions = 2.364 grams
Final state of charge (SOC) remained = 0.68

### 5.3 Parallel Hybrid Vehicle (with fuzzy controller):

Select the parallel powertrain configuration from the ADVISOR vehicle input GUI and the appropriate component values are selected. The number of driving cycles and the initial conditions are selected, and initial state of charge as 0.8 is considered.

The fuel converter torque scale and motor controller torque scale are modified to divide the torque split between the motor and engine. The torque supplied by the motor and engine can be regulated using these values. The current SOC, torque required, and engine temperature are all considered when determining the power split. The fuzzy controller's input parameters are converted into a crisp value. It will determine the power split for the motor (based on equations 9 and 10) and engine.

The fuzzy controller output is illustrated using an example. If the initial SOC is 0.8, the engine temperature is 20°C, and the required torque is 38.635 Nm, based on the designed fuzzy rules (Table 1), the controller produces the output as displayed in Figure 5. Here it gives the fuzzy output as 0.644. So, load the Electric motor to supply 64.4% torque and remaining by Engine.


**Figure 5.** Fuzzy outputs for Power split control

The corresponding results are illustrated in Figure 5. The Fuel consumptions for a distance of 12 km has come out to 3.7 Litres for 100km and emissions in grams per kilometre are 0.13, 1.999 and 0.127 of HC, CO and NOx respectively. The values of all other parameters in one driving cycle are listed in Table 7.

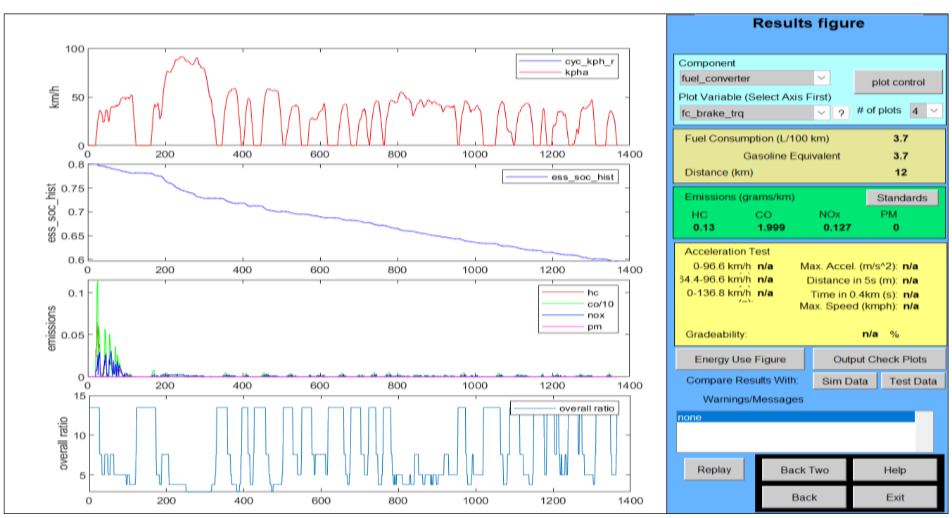

**Figure 5.** Result figure of HEV with power split

**Table 7.** Hybrid Electric vehicle (with fuzzy controller)

| TIME(sec) | TORQUE (N-m) | SOC | Temp($^0$c) | NET FUEL (lit) | CURRENT FUEL (lit) | Power split % | | EMMISIONS(gms) | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | M | E | HC | CO | NOx |
| **0-100** | 38.635 | 0.8 | 20 | 0.044 | 0.044 | 1.288 | 0.712 | 2.0672 | 17.1608 | 1.3872 |
| **100-200** | 32.82 | 0.788 | 35.25 | 0.049 | 0.005 | 1.754 | 0.246 | -1.265 | -2.024 | -0.718 |
| **200-300** | 48.835 | 0.7685 | 69 | 0.1036 | 0.0546 | 1.754 | 0.246 | 0.0451 | 0.2714 | 0.0782 |
| **300-400** | 14.505 | 0.7257 | 96 | 0.1296 | 0.026 | 1.754 | 0.246 | 0.0263 | 0.4476 | 0.0302 |
| **400-500** | 29.67 | 0.713 | 96.1 | 0.1624 | 0.0328 | 1.754 | 0.246 | 0.0448 | 0.7664 | 0.0456 |
| **500-600** | 24.5 | 0.693 | 96.2 | 0.186 | 0.0236 | 1.75 | 0.25 | 0.0426 | 0.6772 | 0.0448 |
| **600-700** | 24 | 0.684 | 96 | 0.2176 | 0.0316 | 1.748 | 0.252 | 0.0522 | 0.8036 | 0.05 |
| **700-800** | 33 | 0.674 | 96.1 | 0.2442 | 0.0266 | 1.752 | 0.248 | 0.0302 | 0.65 | 0.0366 |
| **800-900** | 25 | 0.657 | 96.1 | 0.304 | 0.0603 | 1.722 | 0.278 | 0.2007 | 0.4928 | 0.1677 |
| **900-1000** | 14 | 0.648 | 96.2 | 0.336 | 0.032 | 1.71 | 0.29 | 0.0807 | 0.5988 | 0.1065 |
| **1000-1100** | 21 | 0.635 | 96.1 | 0.3605 | 0.0245 | 1.718 | 0.282 | 0.0039 | 0.5611 | -0.0031 |
| **1100-1200** | 26 | 0.625 | 96 | 0.3597 | 0.0008 | 1.754 | 0.246 | -0.1297 | 0.7853 | -0.0812 |
| **1200-1300** | 34 | 0.6 | 96.1 | 0.3762 | 0.0165 | 1.754 | 0.246 | 0.0322 | 0.04932 | 0.0411 |
| **1300-1400** | 20 | 0.59 | 96.1 | 0.444 | 0.0678 | 1.706 | 0.294 | 0.2688 | 0.6012 | 0.2304 |
| **TOTAL** | | | | | **0.444** | | | **1.5** | **21.84152** | **1.416** |

From above case Total fuel consumption and emissions for 12km distance are:

Total fuel consumption = 0.444 lit
Total hydrocarbon (HC) emissions = 1.5 grams
Total carbon monoxide (CO) emissions = 21.84152 grams
Total nitrogen oxide (NOx) emissions = 1.416 grams
Final state of charge (SOC) remained = 0.59

The relative comparison of conventional, parallel hybrid vehicle (without fuzzy controller) and parallel hybrid vehicle (with fuzzy controller for power split) are illustrated in Table 8.

**Table 8.** Fuel consumption and Emission comparison

| Vehicle Type | Fuel Consumption (litres) | Emissions (grams) | | |
|---|---|---|---|---|
| | | **HC** | **CO** | **NOx** |
| **Conventional Vehicle**<br>(Only IC engine) | 0.9 | 4.7458 | 30.1218 | 1.0748 |
| **Parallel HEV**<br>(without Power split control) | 0.624 | 3.408 | 16.08 | 2.364 |
| **Parallel HEV**<br>(with Fuzzy Power split control) | 0.444 | 1.5 | 21.84152 | 1.416 |

It is clear from the above results that fuel consumption is 28.84% less in Parallel HEV (with power split) compared with Parallel HEV (without fuzzy controller). Fuel consumption of Parallel HEV (with fuzzy controller) is 50.66% less compared with Conventional Vehicle. It is clear from the above results that fuel consumption is 30.66% less in Parallel HEV (without fuzzy controller) compared with Conventional vehicle.

From the results emissions in Parallel HEV (without fuzzy controller) are 28.18% of HC, 46.61% of CO and 41.98% of NOx less compared with Conventional vehicle. From the results Emissions in Parallel HEV (with fuzzy controller) are 68.39% of HC, 27.48% of CO and 65.24% of NOx less compared with Conventional vehicle. From the results, emissions in Parallel HEV (with fuzzy controller) are 55.98% of HC, 65.24% of NOx less compared with Parallel HEV (without fuzzy controller).

## 6. CONCLUSION

A fuzzy logic-based torque control strategy using power split for the plug-in parallel hybrid electric vehicle has been designed. The simulation results show that the adaptive ability of the fuzzy logic torque control give better results in fuel consumption and emissions. In this work it concludes that fuzzy logic power split control decides the torque control between the electric motor and combustion engine, which predominantly saves the fuel and reduces the emissions. The threat to the environment and the burning of fossil fuels, which are harmful to the environment, can be reduced.

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