# Energy Management System for Parallel Hybrid Electric Vehicle

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***Abstract*—In recent years, Hybrid Electric vehicles (HEV) are contributed to a reduced amount of fuel consumption. Parallel Hybrid electric vehicle is one of the three types of electric vehicles, which has vast applicability for commuting. It has a combination of conventional power source, an internal combustion engine, an electric motor powered by a battery. This electric motor and the internal combustion engine are connected in parallel combination, which can drive the vehicle both individually. This paper is concentrated on achieving the minimum fuel consumption with a sustained battery charge. The implementation of the energy management system (EMS) would increase Mercedes-Benz A 170 CDI's fuel economy and can be implemented in a real-time environment for different driving cycles. The application of dynamic programming provides minimum fuel consumption compared to rule-based strategy. Moreover, a rule-based strategy is also used to compare the results of fuel consumption. It maintained a state of charge (SOC) by shifting between various operating modes like load point shifting, electric driving, regeneration, and engine start-stop. This paper addresses these strategies on a mild parallel hybrid electric vehicle model using MATLAB/ SIMULINK. The strategies are implemented on two drive cycles: The New European Driving Cycle (NEDC) and the Federal Test Procedure-75 (FTP-75). The HEV battery is recharged either by the engine or from regenerative braking to increase the vehicle's drive range, thus improving fuel economy.**

**Index Terms—charge sustainment, dynamic programming, electric drive, energy management strategies, fuel economy, hybridization, hybrid electric vehicles, load point shifting, regenerative braking, rule-based strategy.**

## I. INTRODUCTION

Automotive industry is a prominent name in the developmental sector. Petrol and diesel are the liquids elixirs that stage the functionality of this vast industry unless an alternative is discovered. While the production capacities of automotive plants have seen remarkable growth in past few decades, the fossils fuel derivates that bring the metal structures to life are depleting. With the increase in population, the resource that power drive train is decreasing and the consumption increasing. Various aspects of a vehicle are constantly being engineered to mitigate the fuel consumption, for example, quiet and efficient axles, exhaust gas treatment, recirculation of residual heat for air conditioning purposes, etc. Emission standards for vehicles are formulating strict rules that are posing challenges to the automation sector. Reduction in consumption of fuels is the need of the hour now since it positively correlates to the emission of toxic gases in the air humans inhale. These reasons led to the concept of Hybrid Electric Vehicles.

Hybrid Electric Vehicles (HEVs) differ from convention vehicles fundamentally in the mode of operation. An additional electric motor aids the propulsion of hybrids besides the internal combustion engine. HEV configure into two distinct architectures, the Series Hybrid and the Parallel Hybrid, on the basis of the form in which the motor is powered. In series architecture, a power generator working on an engine backs the motor to power the vehicle throughout operation. In parallel hybrid vehicle designs, the motor is charged on a battery as long as the vehicle requires to attain a speed level supported by the engine. HEVs do identify themselves classified on the basis of degree of hybridization as well. The relative power distribution between the engine and the motor defines the parameter called degree of hybridization [1]. Micro-Hybrid, Mild-Hybrid, and Full-Hybrid are the subdivisions. The internal combustion engine is not the fixed component to overpower a vehicle drivetrain dynamic, the electric drive leads the power distribution in other modes of operation, Plug-in HEV being one to name.

Economics of fuel is widely influenced in these configurations, accounting reduction in fuel consumption. They also have many other advantages like low engine noise, high flexibility and low carbon dioxide emissions. However, the energy buffers required in such vehicles increase the production costs and overall weight of the vehicle. The battery is rather sparingly used, but a possible replacement for lithium to facilitate more batteries in future is another problem not within the scope of this paper. Power supplied to the engine and electric motor must hence be managed specific to driving cycles despite the intricacies of the system.

## II. TYPES OF HYBRID ELECTRIC VEHICLES

Hybrid electric vehicles can be classified based on architecture:

1) Series hybrid electric vehicle
2) Parallel hybrid electric vehicle
3) Combined hybrid electrical vehicle

### 1. Series Hybrid Electric Vehicle

A series hybrid vehicle constitutes of an electric motor and a generator to serve the electric driving and regenerative breaking respectively. The battery charges via the electric motor that draws power from the engine and the generator. The power supplying phenomenon forms electric coupling between the internal combustion engine and the electric motor [2].

### 2. Parallel Hybrid Electric Vehicle

In a parallel hybrid electric vehicle both, the combustion engine and the electric motor are appointed to deliver traction power to wheel as per the amount of power deficit. The collective toque of the driving components is provided by the torque coupler since it couples both the components together preventing mutual exclusive fluctuations in speed [2].

3. Combined Hybrid Electric Vehicle

As the name suggests, combined hybrid electric vehicle is a fusion of both the series hybrid and the parallel hybrid vehicles. This configuration focuses on the differentiating the power demand and supply attribute imbalances between engine and driver [2].

This report would elaborate the design of an Energy Management Strategy implemented on a Parallel Mild Hybrid architecture vehicle. Various operating modes discussed at length further in the report, were used as testing conditions for programming a controller using MATLAB SIMULINK, subjected to both, the rule-based strategy and the dynamic programming strategy. Though both the rule-based strategy worked satisfactorily, we went ahead and tried implementing the dynamic programming strategy despite heavy computational requirements. The process revealed potential advantages and disadvantages over the rule-based strategy which shall be discussed in the concluding sections ahead. Abating the consumption of fuel and fulfilling the torque perquisites of the drivetrain by assisting distribution of power between the mechanical drive and the electric drive through the coded controller is the key objective of our work.

The driving cycles simulated on software to gauge the improvements in fuel consumption and the state of charge (SoC) of the battery were:

• The EU New European driving cycle (NEDC)
• EPA federal test procedure (FTP-75)

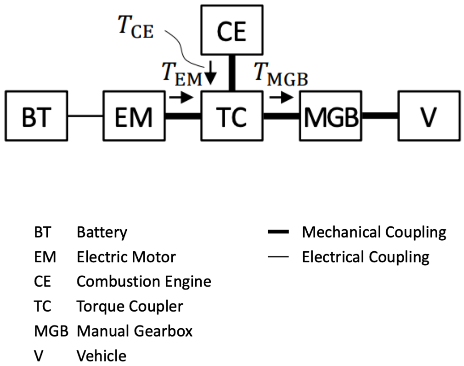


Fig. 1. Architecture of parallel mild hybrid electric vehicle

## III. REVIEW OF TERMS

### *A. Driving cycles*

A driving cycle represents the velocity profiling which upon mathematical differentiation denotes the speed of the vehicle at different instances of time. This profiling is primarily done to determine emission and fuel economy variations of vehicles. It is only a representation and does not evocatively speak of real-world framework, but rather provides a basis for control algorithms simulating the motor and its correlations with other components of the vehicle [2].

The vehicle is mounted on a test bench and the carbon-di-oxide emissions are measured, this gathers the fuel consumption. The tests are conducted in laboratory driving conditions under ideal conditions. In real world harsh conditions, the data varies to a considerable extent.

### *B. Torque Split Ratio*

Torque Split Ratio is defined the ratio of the torque supplied by the electric motor and the torque requested at the manual gear box.

$$u = \frac{T_{EM}}{T_{MGB}} \tag{1}$$

Where,
$u$ = torque split ratio
$T_{MGB}$ = torque of electric motor in Nm
$T_{EM}$ = torque of manual gearbox in Nm

Efficient distribution of torque between the engine and motor is the basic criteria to enhance fuel economy and to pushing the efficiency limitations higher. A torque coupler creates a confusion of power inputs to engine and motor and advocates power balance utilising the torque split ratio (u).

The torque coupler (TC) of the parallel hybrid vehicle is characterized by,

$$\omega_{CE} = \omega_{EM} = \omega_{MGB} \tag{2}$$
$$T_{CE} + T_{EM} = T_{MGB} \tag{3}$$

### *C. QSS Tool Box*

The Quasi-Static Simulation Toolbox (QSS TB) is known for giving a fast and direct estimation of the fuel usage for powertrain bodies. It also serves as the basis of comprehending models in MATLAB. The QSS TB favours the designing of powertrains in a plausible approach, and also to interpret their fuel consumption. The most proficient utilization of the QSS TB can be made once clients completely comprehend the strategies required (i.e., the optimization routines) to incorporate the tool compartment with different projects. This permits a smooth coordination with the usefulness of MATLAB and all its different tool kits. Because of the very short CPU time it requires (i.e., on an ordinary PC, a speedup factor of 100 to 1000 for a traditional powertrain), a QSS model is obviously appropriate for the improvement of the fuel utilization under different control procedures. However, the quasi-static approach clearly isn't reasonable for the catch of dynamic phenomena, for example those satisfactorily depicted by differential conditions. There are numerical methodologies more qualified for the proficient arrangement of those issues.

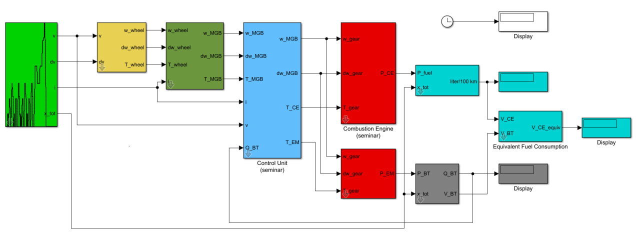

Fig. 2. Hybrid Electric vehicle model of QSS Toolbox for fuel consumption

Control Unit:
The control unit encompasses the following physical quantities as input:

1. Angular velocity of the guide gear box
2. Angular acceleration of the manual gear box
3. Torque of the manual gear box
4. Charge on the battery

The set of codes that bring about the power allocation between the combustion engine and the electric motor is inserted in the functional blocks analysed in MATLAB.

## IV. VEHICLE OPERATION MODES

### *A. Conventional Driving*

In conventional driving mode the torque feed of the vehicle is handled solely by the combustion engine.

### *B. Load Point Shifting*

To encourage the Internal Combustion Engine (ICE) to operate at its maximum efficiency, the load on ICE should be varied proportional to the electric motor. This act is termed as Load point shifting. When the load upon the engine is required to be increased the motor operates in generator configuration assisting charging of the battery, and when load is to be decreased motor switches to the motor mode. Since the ICE has a reputation of being less efficient at low and high loads, it is made to operate generally at intermediate loads. The energy conserved in the charged battery could be used for electric driving.

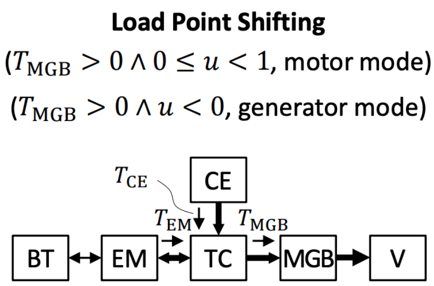


Fig. 3. Load Point Shifting

### *C. Electric Drive*

This operating mode is employed at very low loads because of the high torque offered at lower rpms. Electric driving can be thought of an alternate arrangement to load point shifting mode. Resorting to electric drive when the requirements are not much not only recharges the battery but also effects the efficiency positively.

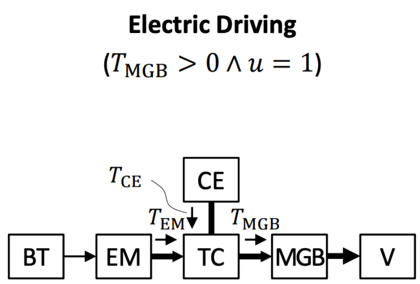


Fig. 4. Electric drive

### *D. Regeneration*

The kinetic energy of the wheels in conventional vehicle is succumbed to heat as waste after frictional braking. However, in hybrid electric vehicles the kinetic energy dissipated can be of utility in charging the battery converting it into electric energy by the motor in generator mode in regenerative braking. This is the concept of regeneration in vehicle driving mode. Parameters such as maximum motor torque, battery energy, and the battery capacity impose restrictions on the regenerative break power. Regeneration is at prime on the off chance that the engine could be decoupled due to drag force, and could not be conceived when the battery is charged to its utmost limits. Better mileage could be achieved operating the vehicle in drifting stage decoupling the engine.

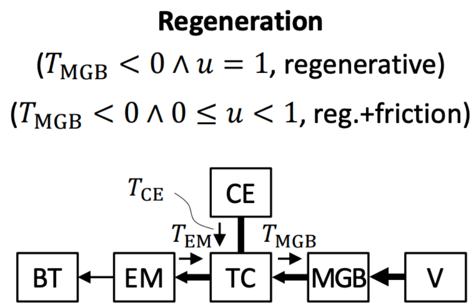


Fig. 5. Regeneration

### *E. Engine Start-Stop*

The engine of a hybrid electric vehicles consumes fuel in the idle phase, this contributes to the increase in overall fuel consumption of the vehicle. An operating mode where the engine sleeps in the idle phase, for example in heavy traffic, would save the consumption of fuel baselessly [3]. In the engine start-stop mode the vehicle performs Electric Driving or the Regenerative configuration, promoting the engine to shut down and restart when required, thereby improving fuel consumption and emission. It should be noted that relying on start-stop frequently may decrease the output of the engine.

## V. POWER MANAGEMENT STRATEGIES

### *A. Rule Based strategy - a literature review*

Nowadays, most of the hybrid electric vehicles use rule-based power management strategies/ algorithms. The parallel EHV uses five feasible modes of operations, such as Engine mode, motor mode, engine plus motor(power assist mode), regenerative braking and, recharging (engine charges the battery). The rule-based strategy can be effectively used with real-time supervisory control over the flow of power into the engine drive train. The rule-based control strategy is based on a set of predetermined rules. The rules are designed based on heuristics, intuition, human expertise, and mathematical models, usually without inherent driving cycle knowledge. Furthermore, the parameters such as the torque required at the gearbox, battery state of charge, the flywheel's angular velocity, etc. are considered while determining these rules. The rule-based EMS works on switching between different operating modes, as mentioned above.

The rule-based strategy is based on the concept of load levelling. That is shifting the actual IC engine's operating point as close as possible to the optimal point of efficiency, fuel economy, and emission at a particular speed. In a rule-based EMS, a controller is programmed to choose an optimal operating mode and split the torque between two power sources, namely the internal IC engine (ICE) and the electric motor (EM), while meeting the driver's demand and maintaining battery state of charge, Also, for this system the fuel economy is found at lower torque and engine speed as compared to best port of efficiency.

The rule based is set up based on the following heuristics:

1. Below a certain minimum torque/vehicle speed, only the Electric motor is used.
2. If the demanded power is greater than the maximum engine power at its operating speed, the motor is used to produce excess power.
3. The motor charges the batteries by regenerative braking.
4. The engine shuts off when the power demand falls below a limit at the operating speed to prevent inefficient operation of the engine.
5. If the battery SOC is lower than its minimum allowable value, the engine should provide additional power to replenish the battery via the EM/G [4].

The rule-based strategy for the two driving cycles (NEDC and FTP-75) is different and differentiated based on the stop time of the current driving cycle, but the operation modes are identical. The different operation modes and control logic is explained below.

*1. Regenerative braking*

In regenerative braking, the more torque is available at manual gearbox than demand, that means ($T_{MGB} < 0$). The example of where this condition or mode of operation is considered when vehicle is moving downhill. While down hilling, the battery is charged through regenerative braking. Further, the torque split ratio can be calculated by following formula:

$$u = \min\left(\frac{-T_{EM,\,max}(\omega_{EM}) + \left|\theta_{EM} d\omega_{EM}\right| + \varepsilon}{T_{MGB}},\ 1\right) \quad (4)$$

where,

$T_{EM,\,max}$ = maximum torque of electric motor
$T_{MGB}$ = manual gearbox torque
$\omega EM$ = angular velocity of electric motor
$\theta EM$ = engine inertia,
$d\omega EM$ = angular velocity of electric motor
$\varepsilon$ = epsilon

*2. Load Point Shifting (LPS)*

In this phenomenon, or in load point shifting, the power split ratio ‘u’ can be expressed as:

$$u = \min\left(\frac{T_{EM,\,max}(\omega_{EM}) - \left|\theta_{EM} d\omega_{EM}\right| - \varepsilon}{T_{MGB}},\ u_{LPS,\,max}\right) \quad (5)$$

Here, the denominations for all the parameter in equation 3 are same as per above equation 2, except. The parameter $u_{LPS,\,max}$ is defined as maximum torque ratio in load point shifting [2].

*3. Conventional engine*

The maximum amount of torque is supplied by IC engine. At the time of acceleration, the torque of manual gearbox is $T_{MGB} > 0$, and below the threshold the value ($T_{MGB} < T_{MGBth}$). In this condition, the complete load shifts on conventional engine. That is mode of operation shifts to conventional engine mode(engine only mode). in this mode, value of torque split ratio, ‘u’ is zero [3].

$$u = 0 \quad (6)$$

*B. Dynamic optimization approach*

In contrast to the rule-based strategy, the dynamic optimization technique is based on a dynamic model and used to evaluate the best control strategy for power management for electric hybrid vehicles. With the dynamic optimization approach, the optimal operating strategy to reduce fuel consumption and to sustain battery charge can be obtained for a given driving cycle.

*1. Dynamic programming Principle*

The dynamic programming tool is used to solve the dynamic optimization problems. While obtaining a universally optimal solution, it can easily tackle the nonlinearity and constraints of the problem. It is based on the Bellman’s principle of optimality. That is, first solving the one subproblem consisting, only one last stage, then gradually moving to subproblems consisting last two stages, then three last stages, and so on until the whole problem is solved. Therefore, the dynamic optimization problems can be divided into the sequence of easier minimal problems [5]. It is represented as follows:

Step $N-1$:

$$J^*_{N-1}(x(N-1)) = \min_{u(N-1)} \left[L(x(N-1), u(N-1)) + G(x(N))\right] \quad (7)$$

Step $k$, for $0 \leq k < N-1$

$$J^*_k(x(k)) = \min_{u(k)} \left[L(x(k), u(k)) + J^*_{k+1}(x(k+1))\right] \quad (8)$$

Where, $J^*_k(x(k))$ is the optimal cost function at state $x(k)$ starting at state $k$

*2. Dynamic programming algorithm*

Here, the deterministic dynamic programming is used, and implemented in the $dpm$ function. Further, for solving a continuous time control problem, the continuous time model is discretized [6]. The discrete time model is given by,

$$x_{k+1} = F_k(x_k, u_k) \quad k = 0, 1, \ldots, N-1 \quad (9)$$

Our approach:

$$x_{k+1} = f(x_k, u_k, w_k, a_k, T_k) + x_k \quad (10)$$

where,
$x_k$ = battery state of charge (SOC)
$u_k$ = torque split ratio
$\omega_k$= manual gearbox angular velocity
$a_k$ = manual gearbox angular acceleration
$T_k$ = torque of manual gearbox

Here, the aim is to reduce the fuel consumption and also to sustain the battery charge at the end of the cycle. Furthermore, the $dpm$ function calculates the cost function and minimize it by applying given constraints.

The cost function is given by,

$$J = \sum_{k=0}^{N-1} \triangle\, m_f(u_k, k)\,.\,T_s \tag{11}$$

Where;
$\triangle\, m_f$= fuel consumed for $k^{th}$ time step
$T_s$ = time step
$k$ = cycle time from 0 to $N-1$

## VI. RESULTS AND DISCUSSION

The simulation is done in the QSS toolbox for a mild parallel of hybrid electric vehicle (EHV) in the Matlab/ Simulink using rule based strategy. here, the model used is Mercedes-Benz A 170 CDI. The specifications of the model is presented in table 1.

TABLE 1
VEHICLE SPECIFICATIONS

| Vehicle Parameter | Value |
|---|---|
| Vehicle Model | Mercedes - Benz A 170<br>Curb Weight: 1115 Kg |
| Engine | Diesel<br>Maximum Power: 60KW<br>Maximum Torque: 187 Nm @ 4200 rpm |
| Motor | Permanent Magnet<br>Maximum Power: 12 KW<br>Maximum Torque : 60 Nm @ 7639 rpm |
| Battery | Lithium -ion,<br>Capacity: 10 Ah<br>Maximum Voltage: 48 V<br>Maximum Power 16.38 KW |
| Transmission | Manual 5- speed |

After the simulation, the obtained values for equivalent fuel consumption and battery charge for rule based strategy and dynamic programming are shown in table 3 and the table 4 for NEDC and FTP-75 driving cycle respectively.

In case of rule based strategy, the fuel consumption for NEDC and FTP driving is approximately 3.56 and 3.283 repetitively.

TABLE 2
RESULTS FOR RULE BASED STRATEGY

| Rule based strategy | Equivalent Fuel consumption in l/100km | Charge sustainment (*10000) |
|---|---|---|
| NEDC | 3.56 | 18010 |
| FTP-75 | 3.283 | 18010 |

TABLE 3
RESULTS FOR DYNAMIC PROGRAMMING

| Dynamic Programming | Equivalent Fuel consumption in l/100km | Charge sustainment (*10000) |
|---|---|---|
| NEDC | 3.27 | 18010 |
| FTP-75 | — | — |

Seeing the results, it can be observed that dynamic programming is most reliable strategy for the fuel consumption of parallel hybrid electric vehicle. The drastic change in fuel consumption can be seen by dynamic programming because it is highly accurate strategy of optimization. Fuel consumption for NEDC cycle using the rule-based strategy is comparatively improved, but not as much as dynamic programming. The battery charge is sustained for all this strategy of optimization.

The graphs for torque, the state of charge of the battery and equivalent fuel consumption for NEDC and FTP driving cycles are shown below

*1. NEDC- Rule based strategy:*

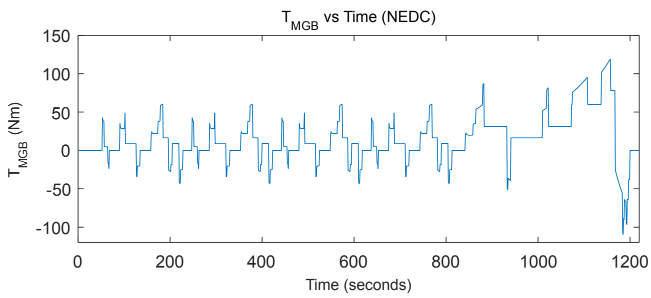


Fig. 6. Torque profile for NEDC

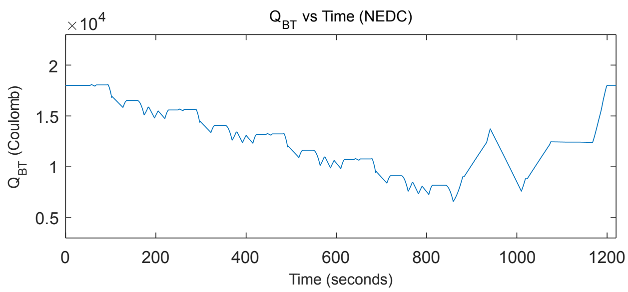


Fig. 7. The state of charge of the battery for NEDC

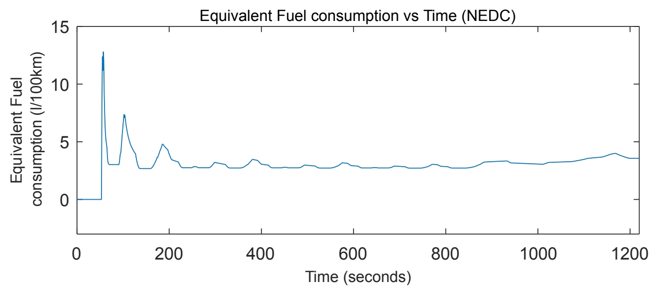


Fig. 8 . The fuel consumption of the vehicle for NEDC

*2. FTP-75- Rule based strategy*

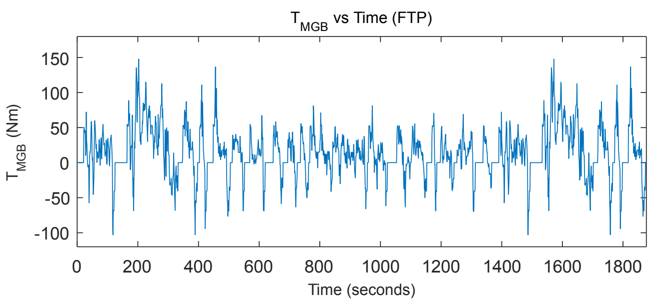


Fig. 9. Torque profile for FTP-75

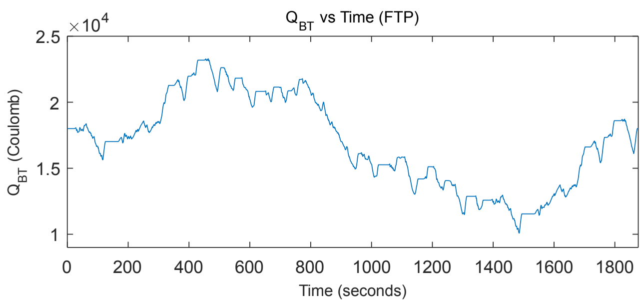


Fig. 10. The state of charge of the battery for FTP-75

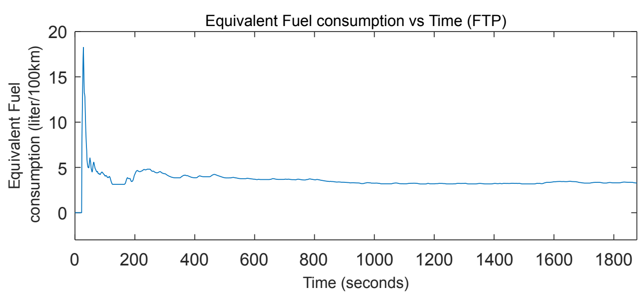


Fig. 11. The fuel consumption of the vehicle for FTP -75

*3. Dynamic programming:*

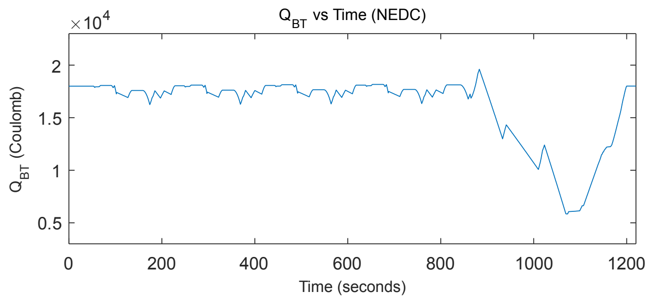


Fig. 12. The state of charge of the battery for NEDC using DPM function

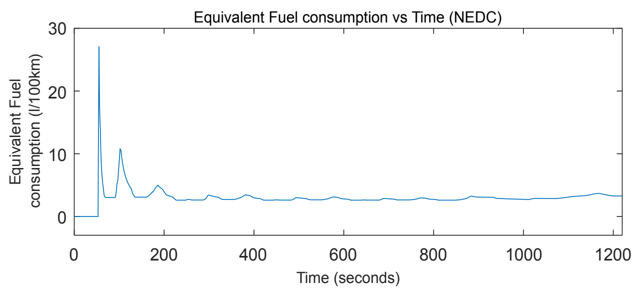


Fig. 13. The fuel consumption of the vehicle for NEDC using DPM function

Moreover, the battery charge graph indicates that the battery charge is also stabled at its initial charge position throughout the cycle. The rule-based strategy does not look upon its discrete points. There is only one on set controlled parameters for a cycle. As a result, the battery charge does not lie near to the defined value.

## VII. CONCLUSION

Our approach for fuel reduction is optimum using dynamic programming. We have discussed the types of HEV drive, different operating modes of HEV, and rule-based strategy. For rule-based strategy, we required much tuning of parameters, whereas the dynamic programming required only a range of torque split ratio and intended range of battery charge as a constraint. The results obtained from Dynamic programming are far better than the results of the rule-based strategy. However, dynamic programming takes too much time for computing. Our approach for dynamic programming performs the calculations from the Simulink model. Therefore, it takes too much time than a rule-based strategy and restricts applicability in a real-life environment. However, the battery charge sustainment of NEDC and FTP-75 is fulfilled by both strategies.

## VIII. FUTURE WORK

Dynamic programming is a better optimization strategy for fuel consumption of the hybrid electric vehicle. Dynamic programming using MATLAB and Simulink gives the optimum value of input parameters by reducing the cost function. However, dynamic programming has some limitations. It is not so convincing when input parameters are varying tremendously. Also, the FTP-75 cycle's optimization is not feasible right now, and it needs further development. Furthermore, We have found through the simulation that the battery charge cannot be sustained for the FTP-75 in the discrete range of torque split ratio. In detail specification, the cycle uses more battery to reduce fuel consumption, and in the battery charging situation, this system becomes infeasible. Moreover, the rule-based strategy can be further improved by making it more adaptive and improving rules based on existing rule-based strategy.

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