Energy Management of Parallel-Mild HEVs: Optimization through Supervisory Control

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Abstract—**At times when humans are trying to mitigate environmental pollution and reduce the usage of natural energy resources, there is an urgent need to reconsider and re-imagine the transportation system around the globe. The advantage of using multiple energy sources for propulsion of vehicles makes hybrid vehicles a strong contender in this regard. Although, the primary propulsion source for such vehicles can be the traditional internal-combustion engines, the working capability of such primary source can be optimized by using a secondary energy source such as an electric component (electric motor or generator). Such hybrid vehicles are commonly referred to as hybrid-electric vehicles (HEVs) which are the current hot-topics in the domain of vehicle technology. With the realization of hybrid vehicle concept, the power distribution among different vehicle drives becomes an important factor of consideration. To understand the power distribution for the vehicle, different control algorithms can be designed to optimize the fuel efficiency of the combined vehicle drive. This paper presents an overview of the available control strategies and primarily focuses on the rule-based strategy for the development of control algorithm for a parallel mild hybrid electric vehicle. The experimental model is based on the quasi-static modelling of Mercedes-Benz A 170 CDI. Algorithm is designed in MATLAB/Simulink software using the QSS-toolbox.**

$Keywords$ - Energy management, Hybrid electric vehicle, Rule based, fuzzy logic

I. Introduction

In modern times, where increasing population is posing a challenge to every individual or rather, every family to own a personal means of transportation is boosting up the sales and manufacturing of the vehicles. This overpopulation further means the rising consumption of natural energy resources, as well as the increasing environmental pollution [1]. A solution to this postulated problem, can be realized by HEVs up-to certain extent, which means, utilization of a vehicle that uses energy from two energy sources available in the propulsion system of the vehicle i.e. conventional fuel (i.e. the chemical energy) or electric storage units/electric components (i.e. electrical energy). HEVs have an upper-hand when compared to a conventional vehicle, as different operation modes can be effectively realized and since, controlling of these operation modes is possible, which ultimately leads to a better fuel efficiency [2]. These operation modes significantly reduces the consumption of gasoline fuel (as the efficiency of the combustion engine is optimized) and environmental pollution due to the possibility of lower emission of the pollutants [2]. Along with this, reduction in noise pollution due to electric driving and variability in energy sources can be realized, especially with the variants of HEVs such as plug-in hybrid electric vehicle in which vehicle batteries can be charged from the external electric grid sources [1]. HEVs can be categorized on the basis of architecture of the propulsion system. In general, three architectures of the HEVs can be realized i.e. Series Hybrid Electric, Parallel Hybrid Electric and Combined Hybrid Electric.

In addition to these, HEVs can also be classified on the basis of degree of hybridization (i.e. the possible operation modes along-with their effectiveness). Based on the power delivered by the motor, vehicles can be divided in 'Micro-Hybrid, 'Mild-Hybrid' or 'Full-Hybrid'. Degree of hybridization can be understood as the ratio of the power rating of the motor to the power rating of the IC-engine [3]. Thus, size of the motor plays an important role in deciding the hybridization of the vehicle. Along-with this, there are few more variants available in Hybrid vehicles category, where electric driving dominates the other operating modes, such as Plug-in HEVs and Range extender HEVs.

Architecture of hybrid vehicles paves the way for control strategies, which structures the functioning of propulsion system of the vehicle and based on the power requirement of the vehicle, decides the mode in which the vehicle should be operated. These control strategies can effectively be understood as algorithms which are used to control the pollutants emission and minimize the fuel consumption of the vehicle, by splitting the overall power requirement of the vehicle between conventional thermal sources and electrical components [4]. A reliable control algorithm can be developed on the basis of three input factors i.e. Power-split ratio, status of the clutch and status of the engine. Power-split ratio (u) can be understood as the ratio of power delivered by the electric motor to the overall power requirement. Status of the clutch indicates whether the engine is engaged or disengaged with the transmission drive. Status of the engine depicts the state of the engine i.e. whether the engine is ON or OFF. These control parameters are of Boolean type (i.e. they can either acquire value 1 (representing ON) or 0 (representing OFF) and can be used in combinations to realize different vehicle modes [3]. Table 1. enlists some common control strategies along with their advantages and disadvantages. These strategies can be further explored mathematically to derive algorithms for supervisory control.

Control strategy	Model	Information required	Constraints	Optimization	Online Implementation
Rule based strategies	None	Current state	No	No	Yes
ECMS	Analytical	Current state	No	Yes (No global optimum)	Yes
Pontryagins Minimum Principle (PMP)	Analytical	Current state	Yes	Yes (No global optimum)	Yes
Dynamic Programming (DP)	Arbitrary	Driving cycle	Yes	Yes (global optimum)	No
Stochastic Dynamic Programming (SDP)	Arbitrary	Current state	Yes	Yes (No global optimum)	Yes
Model Predictive Control (MPC)	Arbitrary (Linear)	Predicted state	Yes	Yes (No global optimum)	Yes

TABLE I: Different control strategies with varying parameters.

A. Rule Based strategy - a literature review

The Rule-based EMS is optimized by focusing on low efciency zones of the engine. Operation points can be found in certain distinct driving states or modes. The achievable improvement in fuel economy strongly depends on the vehicle and on its driving cycle. This potential can be realized only with a sophisticated control system that optimizes the energy flow within the vehicle. Earlier energy management control strategies were based on heuristic considerations inspired by the expected behaviour of the propulsion systems. For instance, the maximum torque of an IC Engine is low at low speeds, while electric motors are capable of producing high low-speed torque. Thus, a common control strategy is required to run the power-train in a pure electric mode from a standstill to a targeted vehicle speed. At this speed, the electric motor reaches its torque limit, and the engine is turned ”ON” [3].

The main aspect in rule-based energy management technique is its effectiveness in real time supervisory control of the power flow in a Hybrid drive-train. The rules are designed based on heuristics, intuition, human expertise and mathematical models and usually, without an inherent knowledge of driving cycle [5]. Rule based control strategies are intended to achieve best fuel economy, efficiency, performance and emission for a specific driving cycle [6]. The main idea of rule-based strategy is based on the concept of load levelling. The load levelling strategy means a shift in the actual IC Engine's operating point as close as possible to the optimal point of efficiency, fuel economy or emission at particular speed. Generally, the best fuel economy for this system is found at lower torque and lower engine speed as compared to best point of efficiency.

The Rule Based is set up based on the following heuristics:

- Below a certain minimum vehicle speed, only the electric motor is used.
- If the demanded power is greater than maximum engine power at its operating speed, the motor is used to produce excess power.
- The motor charges the battery by regenerative braking.
- The engine shut off when the power demanded falls below a limit at the operating speed to prevent inefficient operation of the engine.
- If the battery State Of Charge is lower than its minimum allowable value, the engine should provide additional power to replenish the battery via the electric motor or generator.

B. Parallel mild hybrid electric vehicle model

The Vehicle model considered for this project is a simple mild-hybrid vehicle (Mercedes-Benz A 170 CDI) with parallel architecture i.e. a vehicle in which both combustion engine and electric motor are coupled with the vehicle transmission links. In addition to these, the electric motor is coupled with the gearbox. Additionally, friction clutch is linked between combustion engine and electric motor, so that the engine can be engaged or disengaged with the electric motor as per requirements. The architecture considered here also supports electric boost, however, it is not possible to consider this in the approach of quasi-static modelling and simulation, which makes it impossible while designing the supervisory control algorithm. The modelling of the vehicle follows the approach of quasi-static modelling and simulation. Operating points are obtained from the driving cycle, for e.g. instantaneous vehicle speed or instantaneous gear number for discreet time instances t_k, such that the interval,

$$h = t_{(k+1)} - t_{(k)} = constant. \quad (1)$$

From these operating points, the component operating points, e.g. instantaneous engine angular velocity $\omega_{CE}(t_k)$ and instantaneous engine torque $t_{CE}(t_k)$ are obtained, which forms the basis for the control algorithm [2]. The MATLAB/Simulink model for the aforementioned vehicle can be further studied with Fig. 1. Quasi-static modelling of the vehicle can be clearly determined from the figure. The essential characteristics of the vehicle are further illustrated by Table 2.

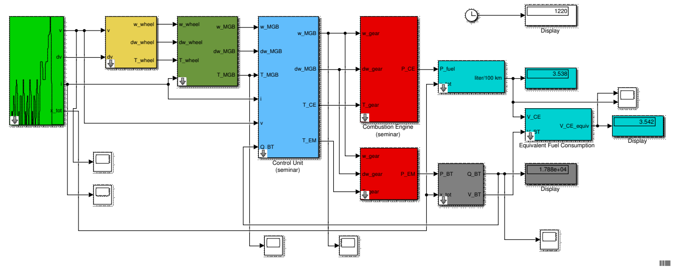

Fig. 1: Vehicle Model (Simulink)

C. Driving Cycles

To compare the performance of different vehicles in terms of emission and fuel economy, vehicle is evaluated through standardized profiles of speed and elevation. In reality, the driving patterns are much different than these driving cycles, but such patterns provides us with a common ground to test different supervisory control algorithms for hybrid vehicles [3]. Two driving cycles have been considered during the project to analyze the performance of developed algorithm

Vehicle	Mercedes-Benz A 170 CDI (W168, 1115 kg)
Engine	Diesel Engine (OM 622, 60 kW, 187 Nm, 4200 rpm, 1698 cm)
Motor	Permanent magnet synchronous motor (12 kW, 60 Nm, 7639 rpm, rescaled)
Battery	Lithium-ion battery (16.38 kW, 0.468 kWh, 46.8 V, 13 m)
Gearbox	Manual (5-Speed)

TABLE II: Vehicle Specifications.

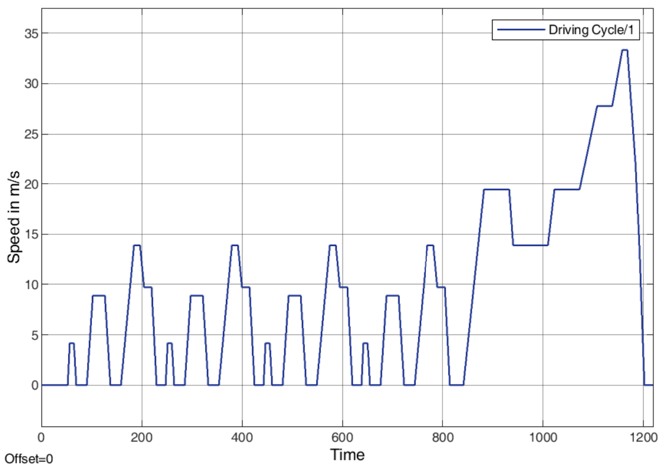

Fig. 2: Speed Profile (NEDC)

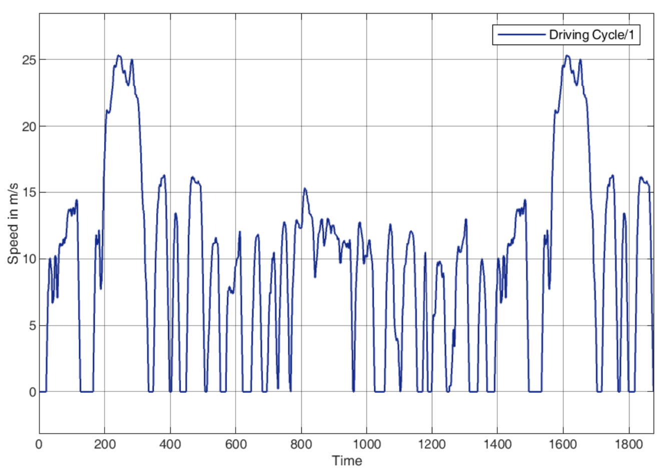

Fig. 3: Speed Profile (FTP-75)

i.e. New European Driving Cycle (NEDC) and Federal Test Procedure (FTP-75). The corresponding speed profile for each driving cycle is presented in Fig. 2 and Fig. 3 respectively while a general overview of both the test cycles is presented in table 3.

II. Methodology

In the presented study, a control algorithm for supervisory control has been developed following rule-based strategy (heuristic approach). The selected approach follows Boolean logic and is based on 6 different parameters i.e. Angular velocity of gear box (ω_{MGB}), Torque of gear box (T_{MGB}), change in angular velocity of gearbox ($d\omega_{MGB}$), vehicle velocity (v), gear number (i) and battery charge (Q_{BT}). Specific parameters such as vehicle velocity (v) and gear

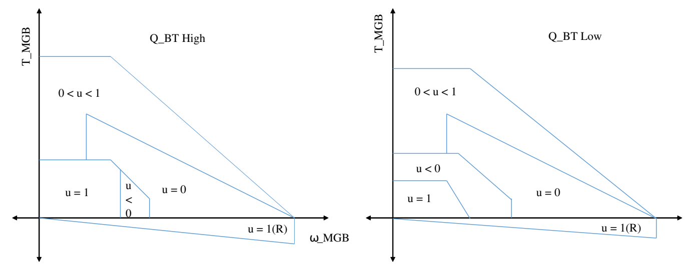

Fig. 4: Torque vs Angular velocity profile

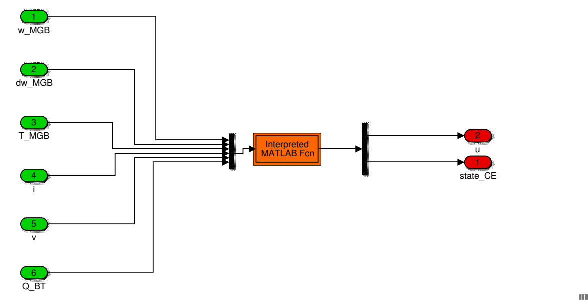

Fig. 5: Controller block (Simulink)

number (i) can be extracted from driving cycle while the remaining parameters can be obtained through quasi-static modelling approach. These parameters acts as input for the controller block in the Simulink model (Fig. 1) and can be used in different combinations to control the selection of operation mode.

To decide the operation mode of the vehicle, two parameters have been further considered i.e. Torque split ratio and Engine state. As depicted in Fig. 5, both of these parameters have been integrated in a single MATLAB function block. Additionally, Table 4 outlines the different operation modes for the vehicle along with the attained parameter value to shift the vehicle propulsion system into the desired operation mode. Control algorithm for the supervisory control has been developed by exploring different execution combinations of these operation modes. Based on the efficiency map of the combustion engine, T_{MGB} vs ω_{MGB} (i.e. Torque of the mechanical gearbox and angular velocity of the motor gearbox) graph can be divided into multiple sections to optimize efficiency of the vehicle propulsion system. This can be understood from Fig. 4, in which a general distribution is shown. Here, Torque and angular velocity acts as conditioning parameters that aids in selecting the correct operating mode. Along with the Torque and angular velocity, the proposed algorithm is also conditioned on the basis of battery charge and vehicle velocity to enhance the performance and efficiency of the propulsion system.

New European Driving cycle		Federal test procedure - 75	
Length (Km)	11 Km	Length (Km)	17.77 Km
Duration (s)	1180 s	Duration (s)	1874 s
Maximum Speed (km/hr)	120 km/hr	Maximum Speed (km/hr)	91.2 km/hr
Average Speed (km/hr)	33.6 km/hr	Average Speed (km/hr)	34.1 km/hr

TABLE III: General specifications of both the test cycles.

Operating Modes	Torque requirement	Torque split ratio, u	State of the engine, State_CE
Regeneration	<0	$0 \leq u<1$	off
Electric Driving	>0	1	off
Load point shifting (Motor mode)	>0	$0 \leq u<1$	on
Load point shifting (Generator mode)	>0	$u<0$	on
Combustion Driving	>0	0	on

TABLE IV: Different operation modes.

Vehicle Type	Driving Cycle	Equivalent Fuel Consumption (litres/100 kms)	Charge at the end of driving cycle (*10^4)	Average fuel consumption
Conventional Vehicle	NEDC	4.897	-	4.786
	FTP-75	4.675	-	
Parallel Hybrid Mild Electric Vehicle	NEDC	3.542	1.788	3.4065
	FTP-75	3.271	1.786	

Fig. 6: Results (Charge Sustainment)

The Torque split ratio

$$u = T_{EM}/T_{MGB} \tag{2}$$

denotes the ratio of torque delivered by the motor (T_{EM}) to the overall torque requirement (T_{MGB}), in which, the torque coupler constraint must also be regarded.

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

III. Results

The study presented here aims at optimizing the overall performance of the hybrid electric vehicle propulsion system in comparison with conventional vehicle. As discussed earlier, the modelling of the vehicle follows quasi-static approach and the efficiency for both type of vehicles can be calculated using MATLAB/Simulink models. The equivalent efficiency achieved using the developed algorithm and its comparison with the fuel efficiency of conventional vehicle is further illustrated by Fig. 6.

The fuel efficiency and the equivalent fuel efficiency for both the driving cycles are shown in the Fig. 11 and Fig. 12.

Another aim of the study is to sustain the battery charge, as charging from external grid is not available in the configuration of parallel mild hybrid electric vehicle. Provision for penalizing the battery use is formulated in the Simulink model of the vehicle. The overall summary of battery charge for both the driving cycles are further illustrated by the Fig. 13 and Fig. 14.

For the overall assessment of the developed algorithm, average of equivalent fuel efficiencies from both the driving cycles (NEDC and FTP-75) is considered as shown in eq. 4.

$$V_{CE,equiv} = 1/2(V_{CE,equiv,NEDC} + V_{CE,equiv,FTP-75}) \tag{4}$$

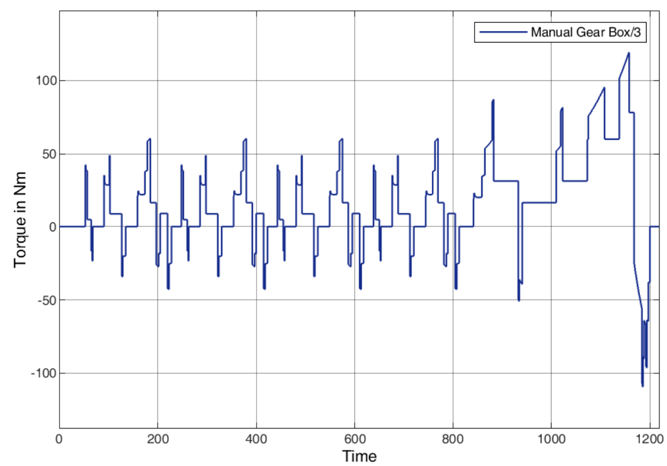

Fig. 7: Torque (NEDC)

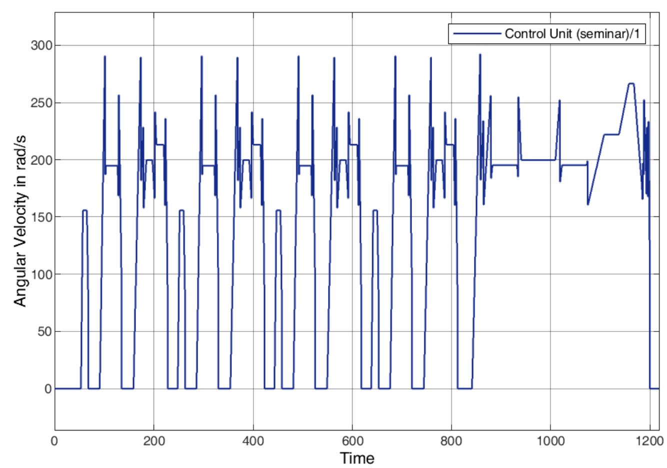

Fig. 8: Angular Velocity (NEDC)

A. Lowest fuel consumption

During the study, it was also observed that the lowest equivalent efficiency for FTP-75 driving cycle was obtained by draining the battery above the initial limit (i.e. when charge sustainment is not completely achieved). The lowest equivalent fuel consumption along-with its comparison with conventional vehicle is further depicted by Fig. 15 and Fig. 16 respectively.

Along-with this, the plots of equivalent fuel consumption

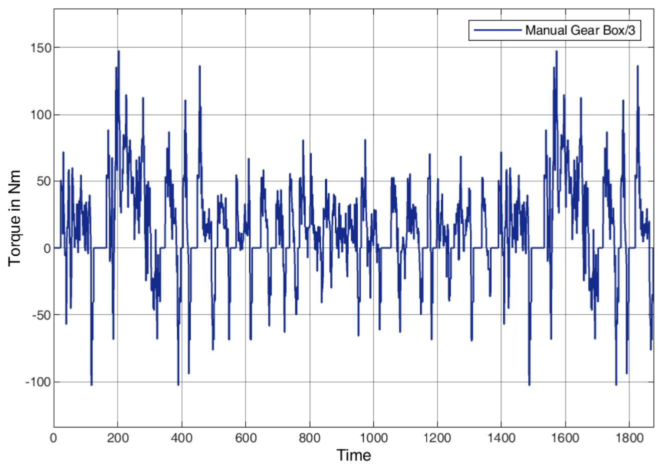

Fig. 9: Torque (FTP-75)

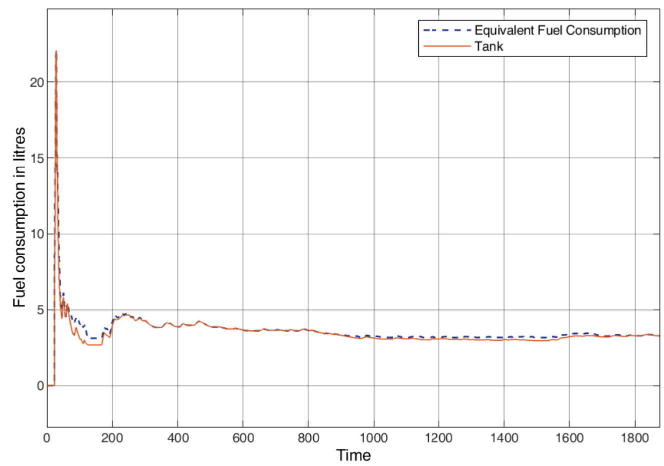

Fig. 12: Fuel efficiency (FTP-75)

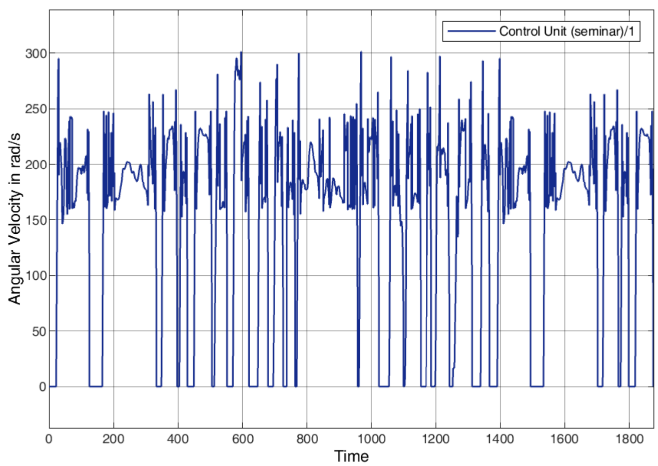

Fig. 10: Angular Velocity (FTP-75)

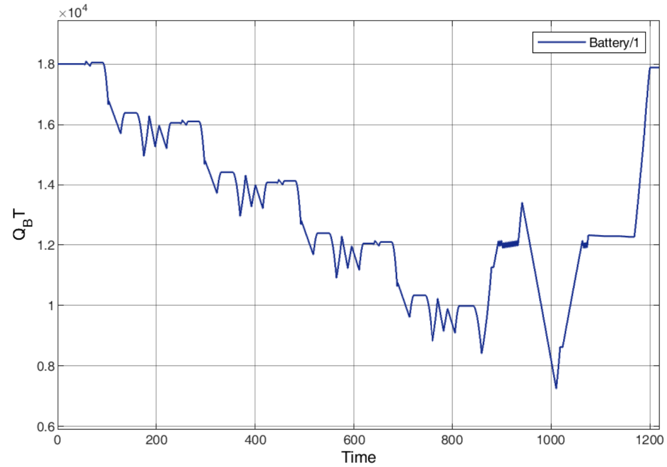

Fig. 13: Battery charge for NEDC

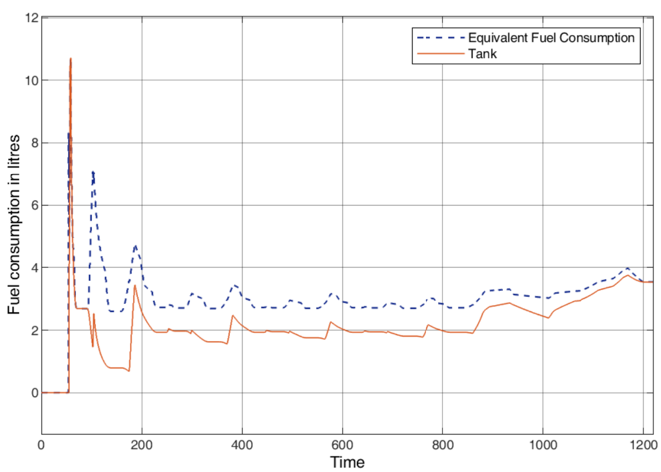

Fig. 11: Fuel efficiency (NEDC)

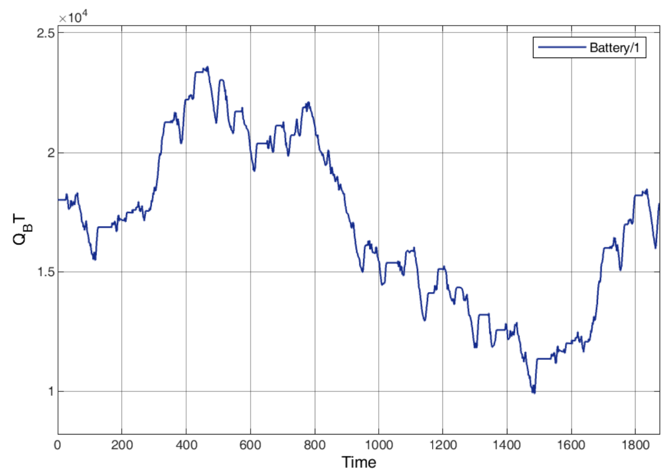

Fig. 14: Battery charge for FTP-75

Vehicle Type	Driving Cycle	Equivalent Fuel Consumption (litres/100 kms)	Charge at the end of driving cycle (*10^4)	Average fuel consumption
Conventional Vehicle	NEDC	4.897	-	4.786
	FTP-75	4.675	-	
Parallel Hybrid Mild Electric Vehicle	NEDC	3.542	1.788	3.4
	FTP-75	3.258	1.091	

Fig. 15: Results (Lowest fuel efficiency)

Driving Cycle	Efficiency Improvement		Overall Efficiency Improvement	
	Full Charge Sustainment	Partial Charge Sustainment	Full Charge Sustainment	Partial Charge Sustainment
NEDC	27.67%	27.67%	28.82%	28.95%
FTP-75	30.03%	30.31%		

Fig. 16: Percentage efficiency comparison between Conventional and Hybrid Vehicle

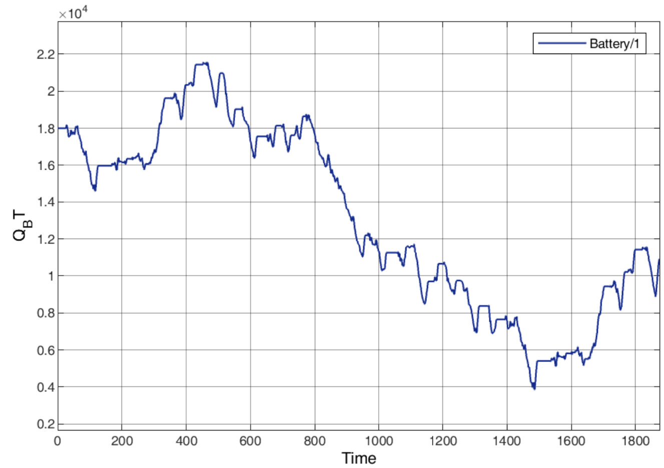

Fig. 18: Battery charge for FTP-75

and battery charge for FTP-75 (with lower charge sustainment) is separately presented in the Fig. 17 and Fig. 18 respectively. Differences between the equivalent fuel consumption values (with and without full charge sustainment) are not very significant and are a result of tuning of component parameters.

IV. Future Work

Hybrid electric vehicles have enticed a research trend with energy management of vehicles being a major topic of discussion. Energy management implies the most efficient utilization of the fuel (chemical energy), which can be attained by decreasing the losses in energy conversion during the vehicle propulsion. Comparing the pace with which the efficiency of conventional engines and electrical components are being improved, refinements in the control algorithms to improve overall efficiency of the propulsion system proves to be a better strategy. Additionally with the pioneering research being conducted in the field of vehicular communications, it seems more feasible to develop an algorithm that can easily predict the future driving profile of the vehicle. Using this, an optimum (global) solution can be attained along with the prospects of real time implementation. A thorough research in the field can thus be helpful to answer many challenges in enhancement of supervisory control which implies the optimum performance of the hybrid electric vehicle.

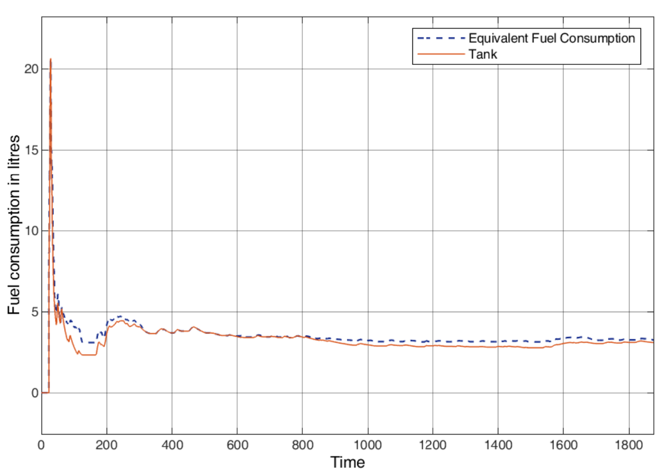

Fig. 17: Equivalent fuel consumption

V. Conclusions

The study aims at presenting an overview of heuristic approach to develop a supervisory control, which can be realized in the field of current hybrid electric vehicles. A simple algorithm is developed for a parallel mild hybrid electric vehicle, which can be mathematically manipulated to enhance the performance of other hybrid electric configurations. Heuristic approach helps us in understanding impact of different vehicular parameters on the overall efficiency of the propulsion system. However, globally optimum solution is not achievable, following this approach and different control strategies such as dynamic programming, can be mathematically explored to enhance the overall efficiency. For configurations of hybrid electric vehicles with higher degree of hybridization (Plug-in hybrid or Range-extender hybrid), separate control algorithm can be developed, considering the possibility of battery charging from external source grid.

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