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School of Industrial and Information Engineering
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Optimal Energy Management Control Strategies for Series Hybrid Powertrain with diesel range extender

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ABSTRACT

This thesis analyses the energy management problem of a special purpose series hybrid electric vehicle (SHEV) with diesel range extender which is to be used for railway track inspection. The primary objective of the problem is to minimize the fuel consumption for specified driving cycles which are very different from the ones specified for road vehicles. The work involves building a system level series hybrid powertrain model which is capable of portraying the behavior of various sub-systems with adequate accuracy while also having acceptable computational effort.

The vehicle model is then used to design, implement and analyze two of the most conventional heuristic (rule-based) control strategies that have been in existence for decades, namely Thermostat Control Strategy (TCS) and Power Follower Control Strategy (PFCS). After an extensive literature review of various types of advanced control strategies that are in different phases of research and development, a relatively new heuristic control strategy, called the Exclusive Operation Strategy (XOS), has been chosen to be implemented. Its performance is compared with the conventional strategies. The XOS, whose operation principle is inspired by an optimization-based control strategy is found to be significantly more effective than the conventional TCS and PFCS when it comes to fuel efficiency. With simple implementation and straight forward rules, the XOS is found to be operationally superior to the conventional benchmarks.

REPORT OUTLINE

Chapter 1 outlines the reasoning of the research and the basis of the problem intended to tackle.

Chapter 2: Elaborates on all essential background, specifications, equations, and concepts used in building up the Simulink model of the series hybrid powertrain with diesel engine range extender and lithium ion battery pack. A brief description of the special vehicle whose powertrain is being simulated has been included as well. It also discusses the rationale behind choosing the level of model fidelity, potential limitations, compromises and advantages of the choices made.

Chapter 3: A brief overview of the Thermostat Control Strategy, its basic operation principle, equations involved, parameters that play key roles in implementation as well as the tuning aspects to achieve optimal performance. It also discusses the results in terms of power split curves and fuel efficiency figures as per the two given driving cycles.

Chapter 4: The Power Follower Control Strategy is discussed with brief overview, its fundamental difference between load levelling strategies like TCS, basic operation principle, its advantages, turning parameters and so on. Like in the previous chapter, the simulation results of PFCS in terms of power split during the two given driving cycles and the corresponding fuel efficiency figures are presented.

Chapter 5: The Exclusive Operation Strategy is introduced along with a look into the how it relates as well as differs from the PFCS and GECMS. The operation principle is presented along with the equations involved, the logic behind the power split decisions made by the strategy and its influence on vehicle's performance parameters like SOC. Of course, the parameter tuning, and its influence of fuel consumption is discussed. The chapter concludes by discussing the simulation results for the two driving cycles along with fuel economy data.

Chapter 6: Summarizes the results and highlights the advantages of XOS over the aging TCS and PFCS with numerical evidence.

CHAPTER 1

INTRODUCTION

1 INTRODUCTION

1.1 PROJECT BACKGROUND

With the world facing alarming climate change crisis, it is imperative for every industry to work diligently to minimize, and if possible, eliminate their carbon footprint and improve sustainability. Climate change is undoubtedly the single largest challenge for the humankind to tackle in the present scenario and every improvement counts no matter how small they are.

The transportation industry, with its heavy consumption of oil, has been a significant contributor to CO2 emissions world-wide but in the recent years, the industry has been witnessing a paradigm shift towards more sustainable sources of power. As shown in Figure 1-1 the transportation industry covered 29% of the CO2 emissions in the United States alone. In an attempt to reduce the percentage, hybrid and battery electric vehicles were introduced, and currently are at the verge of becoming the new norm globally.

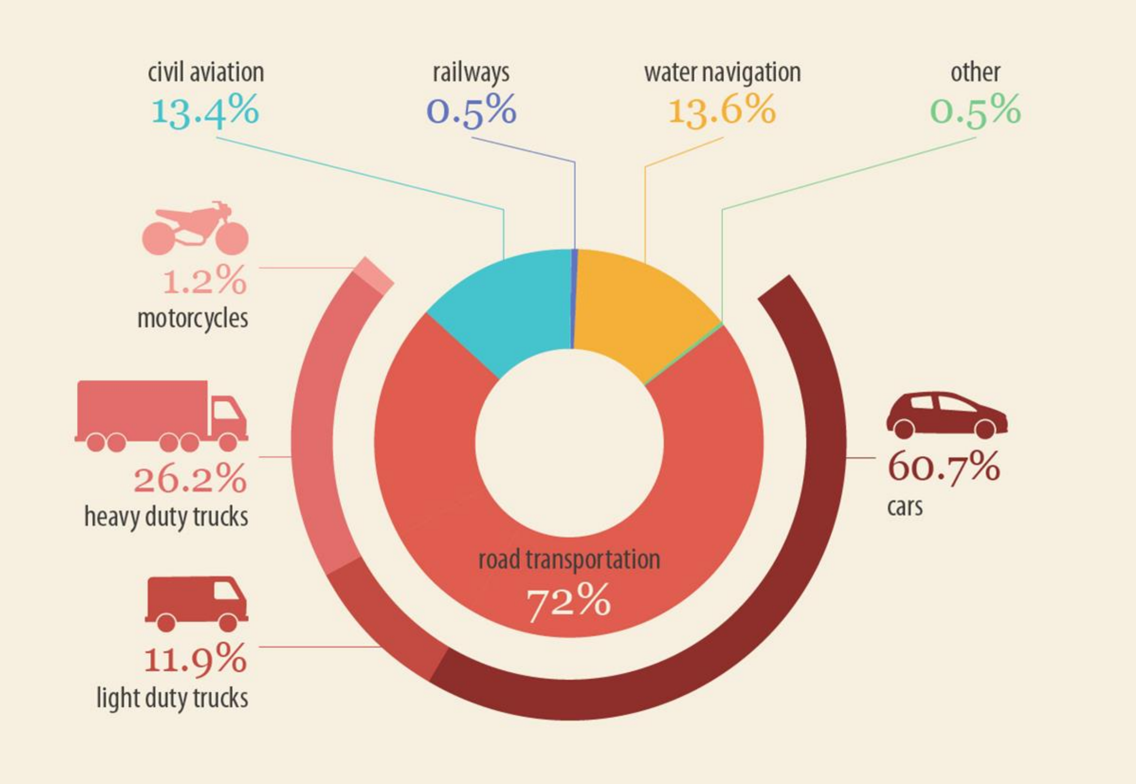


Figure 1-1: Carbon Emissions breakdown by transport mode in the EU in 2016 (Source: European Environment Agency)

Arguably, the railway sector has achieved the largest reduction in carbon footprint among all forms of transportation, thanks to large scale adoption of electrification. Developed nations and most developing nations have replaced their old diesel locomotives completely with electric ones even as the road transport is slowly and steadily working towards a similar goal. This is shown in Figure 1-1, where the percentage of road vehicles covers 72% of the emissions, while railways are taking up a mere 0.5%.

The climate change issue is being tackled not by merely reducing the CO2 emission but also continuously working on reducing the usage of non-renewable resources like crude oil. This means, wherever the internal combustion engines are used, there is strong need to optimize their efficiency to reduce energy consumption.

Fully electrifying the ground transportation sector would be the straightforward way to approach the climate change but there are some practical issues with such a solution. While complete electrification makes sense to cars and vehicles that are restricted to urban setting, vehicles that are meant to travel longer distances and haul heavy goods still have to rely on IC engine as a primary source of power. This situation is expected to stay unchanged as long as the battery technology becomes advanced enough to have an energy density that is comparable to that of a full tank of fossil fuel. So, until that time, hybridization is the obvious solution.

This necessity has led to several ongoing research projects related to energy management control strategies of different types of hybrid electric powertrains. A hybrid powertrain strikes a balance between range as well as overall energy consumption. It is more fuel efficient than a conventional IC engine powered vehicle which directly translates into less CO2 emissions. A properly configured hybrid powertrain can achieve better overall performance, thanks to instantly available torque from the electric motor.

The complex amalgamation of various sub-systems and their highly dynamic nature warrants robust as well as efficient energy management control strategies. With the hybrid powertrains still yet to achieve their completely potential, there is a lot of room for improvement when it comes to sub-systems, materials used, aerodynamics and Supervisory Control System (SCS).

The primary function of the SCS is to decide on the best possible way to split the load power between the available sources of energy on board (IC engine and battery). The choice of energy management control strategies heavily influences the overall system's fuel consumption as we will see in the subsequent chapter. This makes selecting the appropriate strategy specific to the hardware configuration, type of hybrid powertrain and the driving cycle very important for optimal performance of the hybrid powertrain system.

Academic research in the field of Hybrid Electric Vehicle (HEV) controls strategies picked up pace in mid-1990s and has achieved significant developments. The ongoing research deals with advanced concepts that are derived from modern control theory such as dynamic programming, neural networks, genetic programming genetic algorithms and so on. However, these concepts are mostly applied on low-fidelity models due to high computational efforts required. So, there are still some time away from make their way to commercially available HEVs on a larger scale.

As far as commercial viability is concerned, simpler and more robust heuristic control strategies (also called as rule-based control strategies) still emerge as the top choice. They are time-proven, easy to implement and can point the engineers in right direction even if the models used for their implementation is not very detailed. Heuristic control strategies also demand less expensive on-board hardware for implementation and the software code required for implementation is not as complex as it would be for more sophisticated techniques like dynamic programming, MPC, genetic algorithm, neural network, etc. For this reason, the cycle time for the development, simulation and validation of heuristic strategies are significantly much shorter, making them superior when it comes to commercial implementation as things stand now.

1.2 OBJECTIVE

This project involves building a suitable sub-system level model of series hybrid powertrain with diesel engine range extender with a level of fidelity that is adequate for studying the effectiveness of various heuristic control strategies with acceptable computational effort and quick simulation time. With this model, sufficient knowledge regarding various heuristic as well as advanced control strategies can be achieved, thereby helping us to choose an appropriate strategy for our particular application.

The series hybrid powertrain with diesel range extender will be propelling a special purpose autonomous railway bogie for executing fast and efficient track inspections. The special construction and payload mean that the conventional electric pantograph cannot be used for fully electric propulsion and hence we resort to a hybrid architecture.

While there are numerous commercial and academic tools to design, test and simulate hybrid powertrain control strategies for road vehicles, attempting to adapt them for our special vehicle would be a futile process since road-tire and rail wheel-track interactions are significantly different (and so are the driving cycles).

Fortunately, once the vehicle model is ready, the same control strategies that have proven useful on road vehicles can be implemented on our special vehicle since, on a sub-system level, the hardware components are similar. At the end of the day, once the longitudinal vehicle dynamics part of the overall system model is configurated as per the rail vehicle, and specific driving cycle is determined, we can approach the problem just like it is done for a regular road vehicle.

1.3 LITERATURE REVIEW

Literature review for this project involves two parts. The first one deals with various modelling techniques and approaches to simulate the behaviours of the series hybrid sub-systems individually as well as their combined effect on a system level. Several technical papers dealing with different levels of series hybrid powertrain modelling have studied as a part of the literature review exercise and finally, the modelling techniques proposed in the paper by Davide Tarsitano, Fernandino Luigi Mapelli and Marco Mauri in their paper [1] have been adopted as far as IC engine and lithium-ion battery pack are concerned.

The energy loss modelling of the electric motor, linear vehicle dynamics of the railway bogie, driver, driveline etc. are derived from the modelling approach proposed by Ed Marquez and Christoph Hahn in their Simulink Racing Lounge Tutorial [2]. Even though the technique was primarily proposed for road vehicle, required adjustments in driving cycle and longitudinal dynamics have been made to make it suitable for simulating the railway bogie system.

The second part of the literature review deals with numerous Supervisory Control System (SCS) and control strategies for optimal power-split between IC engine and lithium-ion battery to maximize fuel efficiency of hybrid electric powertrain. The Thermostat Control Strategy (TCS), a long standing, time-proven control strategy has been discussed widely in several papers including the one by C.G. Hochgraf, et al [3]. In existence since the 90’s, this time-tested control strategy is robust and has found application in several commercially available HEVs of different configurations.

The Power Follower Control Strategy (PFCS) is also a long-standing and widely used heuristic control strategy which has been widely discussed in several papers including the one by N. Jalil, et al [4]. In addition to these most popular rule-based strategies, recent academic research has broken new grounds with the help of modern concepts. As a result, more advanced and sophisticated control strategies based on optimization such as Global Equivalent Consumption Minimisation Strategy (GECMS) [5], Model Predictive Control [6] etc. have been developed.

While these are predominantly in research stage now, a few have the potential to make it into production-spec HEVs in the foreseeable future. However, given the complexities and heavy computational effort (not to mention expensive hardware requirement for real-world implementation and validation) involved in optimizing these strategies, decision has been taken to explore an easy to implement heuristic strategy that is closest to one of these optimization-based strategies in terms of fuel efficiency performance. The search lead us to Exclusive Operation Strategy (XOS) which is discussed by Wassif Shabbir in his paper [7]. As demonstrated by his research, this strategy which derives its inspiration from PFMS as well as GECMS emerges as a simple yet effective approach for series hybrid powertrain as we will see in the further chapters.

CHAPTER 2 – SERIES HYBRID POWERTRAIN

2 MODELLING OF SERIES HYBRID POWERTRAIN WITH DIESEL ENGINE RANGE EXTENDER

The vehicle model used in this work is based on a general-purpose road vehicle, but the parameters and specifications of every sub-system has been set as per the hardware components that make up the series hybrid system of the special railway bogie under investigation.

The railway bogie which consists of two wheelsets, both powered by an AC induction motor each, a pair of lithium-ion battery packs as source of electricity. The battery packs are charged by means of an AC generator is powered by a diesel engine range extender. The special railway vehicle, along with its payload of track inspection equipment and autonomous driving hardware is estimated to weight approximately 10.5 tons.

The main components that are to be modelled to enable control strategy simulations are the IC engine along with generator, electric motor, battery, the longitudinal vehicle dynamics of the railway bogie (vehicle model), and a pilot (driver model) which executes the control action to match the given velocity profile.

2.1 HARDWARE LAYOUT OF SERIES HYBRID POWERTRAIN

As the name suggests, a series hybrid powertrain which is sometimes referred to as range-extended electric vehicle has its IC engine and battery pack connected in series. This means, the tractive force for the wheels are fully taken care of by the electric motor which derives power from the battery. The IC engine is not mechanically connected to the wheels and its primary function is to generate electricity by driving a generator which then charges the battery pack or supplies the required electricity directly to the electric motor.

The primary advantage of such an arrangement is that, since the IC engine is not tasked at propulsion, it can be operated flexibility at its most efficient point and can be packaged without having too many constraints regarding rigid mechanical connections.

Furthermore, since motor handles the drive, transmission and control systems can be simpler. With sufficient charge in the battery pack, the series hybrid powertrain can be operated as a Battery Electric Vehicle (BEV) for a limited duration of time, thus achieving zero emission and zero fuel consumption.

The overall bulkiness of the series hybrid powertrain makes it suitable for heavy and large vehicles such as the railway bogie under investigation. The basic powertrain layout is represented in the block diagram below.

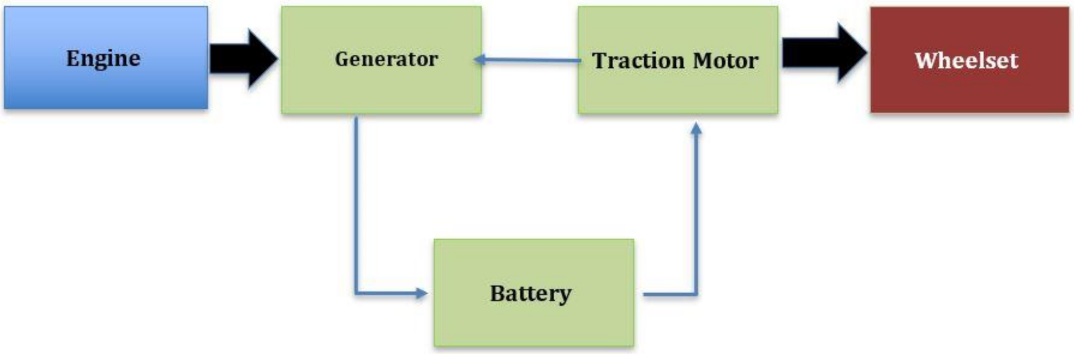


Figure 2-1: Layout of a series hybrid powertrain

2.2 INTERNAL COMBUSTION ENGINE

The internal combustion (IC) engine to be used for the railway bogie is a Deutz TCD 3.6-liter L4-HP four-cylinder turbocharged diesel engine. In this configuration, the engine is tuned to develop: 105 kW at 2,300 rpm, and 550 Nm of torque at 1,600 rpm.

A highly accurate IC engine model would require knowledge of various critical parameters like geometries of intake, exhaust, combustion chamber and cylinder in addition to spark plug position, valve timing and so on. However, for the purpose of control strategy simulation, a simpler 3D map-based engine model will be sufficient to derive instantaneous fuel consumption.

The torque vs speed (rpm) curve of the engine has been obtained from the manufacturer along with the fuel consumption map. These data are used to build a 3D torque and fuel-consumption maps as discussed in [1]. The data from 3D maps are then fed into Simulink Compression Ignition engine model from the powertrain block set.

The model receives throttle pedal position (which is calculated based on the torque demand required to execute the driving cycle) and engine speed from the longitudinal dynamic model of the vehicle as inputs and deliver effective torque output and instantaneous fuel consumption as outputs as shown in this simple block diagram in Figure 2-3.

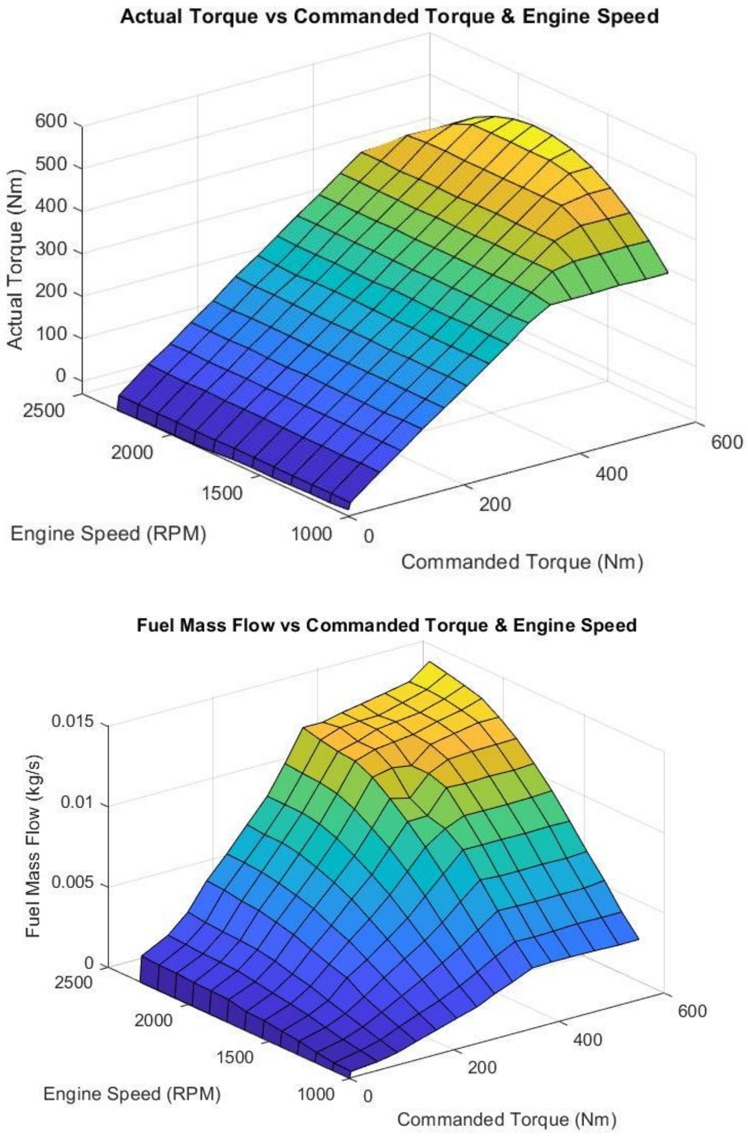


Figure 2-2: Torque (top) and Fuel Consumption (bottom) Maps

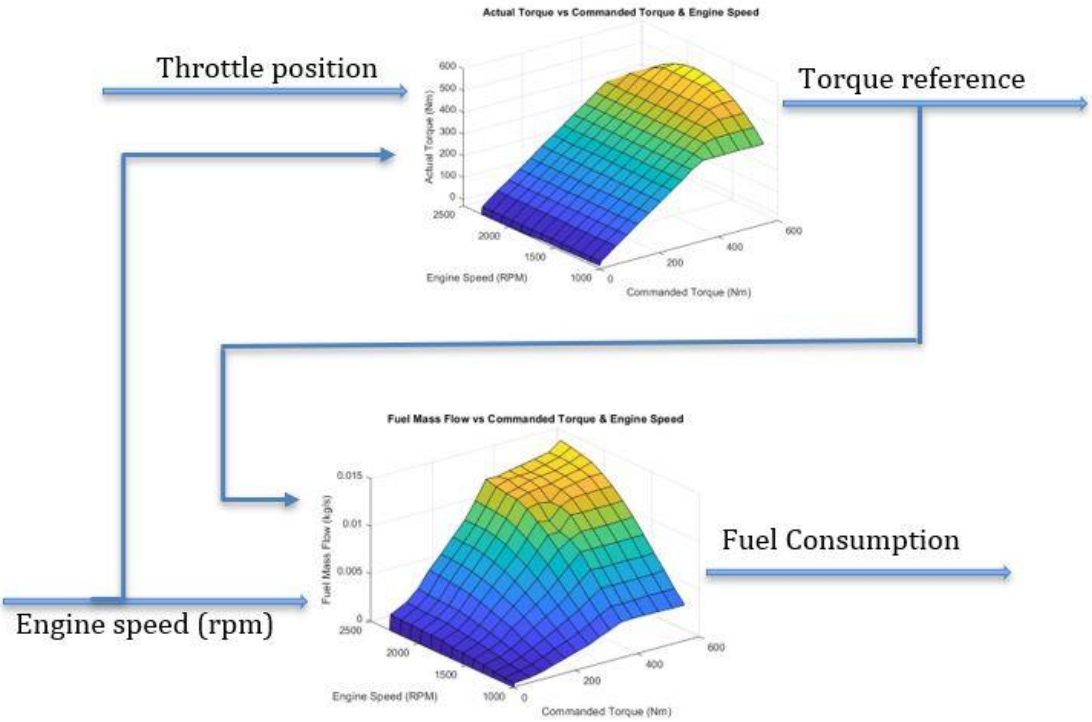
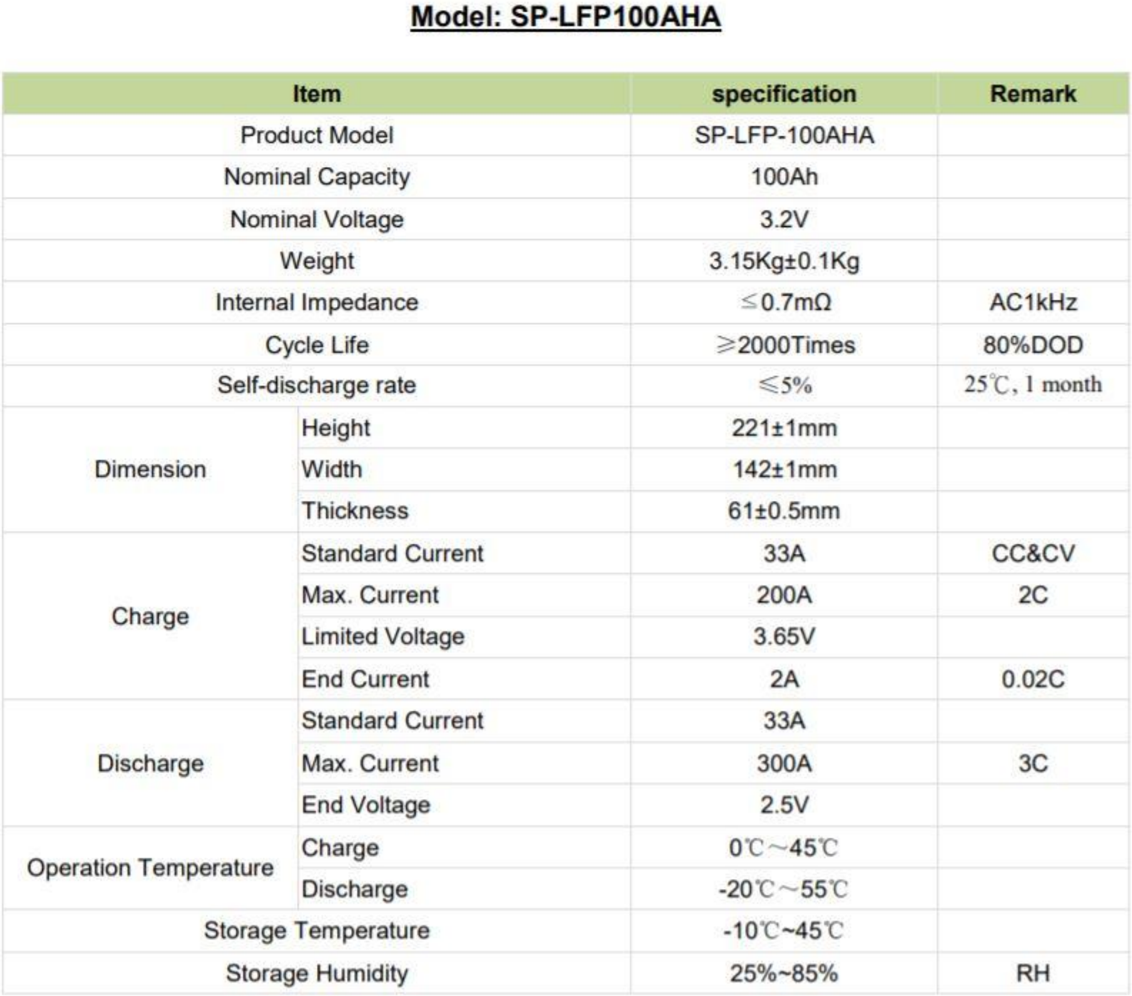


Figure 2-3: Map-based Engine Model

2.3 LITHIUM ION BATTERY

The battery packs used in this application is a pair of SinoPoly SP-LFP100AHA lithium ion units. Each 100 Ah battery pack consists of 360 3.2 V cells. The detailed specifications can be found in the table below.

Table 2-1: Lithium Ion Battery Specifications



Model: SP-LFP100AHA

Item		specification	Remark
Product Model		SP-LFP-100AHA	
Nominal Capacity		100Ah	
Nominal Voltage		3.2V	
Weight		3.15Kg±0.1Kg	
Internal Impedance		≤0.7mΩ	AC1kHz
Cycle Life		≥2000Times	80%DOD
Self-discharge rate		≤5%	25℃, 1 month
Dimension	Height	221±1mm	
	Width	142±1mm	
	Thickness	61±0.5mm	
Charge	Standard Current	33A	CC&CV
	Max. Current	200A	2C
	Limited Voltage	3.65V	
	End Current	2A	0.02C
Discharge	Standard Current	33A	
	Max. Current	300A	3C
	End Voltage	2.5V	
Operation Temperature	Charge	0℃~45℃	
	Discharge	-20℃~55℃	
Storage Temperature		-10℃~45℃	
Storage Humidity		25%~85%	RH

In order to simulate the behavior of a series HEV, it is important for the battery model to evaluate the output voltage considering the State of Charge (SOC) of the battery. Since the battery pack is made of series connection of 360 cells, as per standard procedure discussed in [1], a numerical model is constructed considering a single cell and the total battery voltage is calculated by simply multiplying it with the number of cells. It is reasonable to assume that every cell has uniform behavior.

Equation 2-1

$$V_{batt} = n_{cell}V_{cell}$$

The battery SOC is calculated using the equation (2.2) where Cn represents the battery capacity in Ah. The ibatt required is calculated from the electric drive model.

Equation 2-2

$$SOC(t) = SOC_0 - \int_0^t \frac{i_{batt}(t)}{3600 \cdot C_n} dt$$

While the battery's temperature dependency is a very important parameter when one builds a model with a purpose of designing battery management system, for our application, it is reasonable to simplify the model by assuming constant temperature. So, the battery model gives us battery voltage V_{batt} as a function of SOC and battery current i_{batt}.

2.4 POWER LOSS MODEL FOR ELECTRIC MOTOR AND GENERATOR

Considering that the focus of the work is to evaluate different energy management control strategies, the power flow through various components are of interest. So, from this point of view, a power loss models for the electric motor and generator are adequate to receive the reasonably accurate system response for the control strategy implemented. A detailed equation-based or map-based model of the electric motor will no doubt make the overall model more accurate and closer to reality, but this enhancement could be brought on board during further stages of development and design process.

The power loss equations have been modelled based on the work done by Zhang and Mi [8]. Thus, both motor and regeneration efficiency are obtained to derive both drive and regeneration torque.

Equation set 2-3

$$P_{mot} = T_{mot}\omega_{mot}$$

$$P_{Loss} = k_c T^2 + k_i\omega + k_\omega \omega^3 + C$$

$$P_{In} = \tau \cdot \omega + P_{Loss}$$

$$\eta_{\mathrm{motor}} = \frac{T_{mot}\omega_{mot}}{T_{mot}\omega_{mot} + P_{Loss}}$$

$$\eta_{gen} = \frac{T_{mot}\omega_{mot} + P_{Loss}}{T_{mot}\omega_{mot}}$$

2.5 VEHICLE MODEL

To evaluate the longitudinal vehicle dynamics, the railway bogie is modelled as a point mass moving on an incline. Popularly known as the glider model, the equations take into account the resistance exerted against the tractive force of the bogie by aerodynamic forces, inclination of the surface, rolling resistance at the rail wheel-track interaction, inertial force due to the bogies own weight. This simple lower order modelling has been widely used in the automotive industry to calculate the overall resistance power with acceptable accuracy and hence, it is adequate for our application as well. For unknown parameters like surface area of the front fascia and aerodynamic coefficients, reasonably assumptions were made.

Equation set 2-4

$$F_{tr} = F_{aero} + F_i + F_{grade} + F_{rr}$$

$$F_{aero} = \frac{1}{2}\rho C_d A_f V^2$$

$$m_i = 1.04\, m$$

$$F_i = a\, m_i$$

$$a = \frac{F_{tr} - (F_{aero} + F_{grade} + F_{rr})}{m_i}$$

$$F_{grade} = m\, g\, \sin(\theta)$$

$$F_{rr} = m\, g\, C_{rr}$$

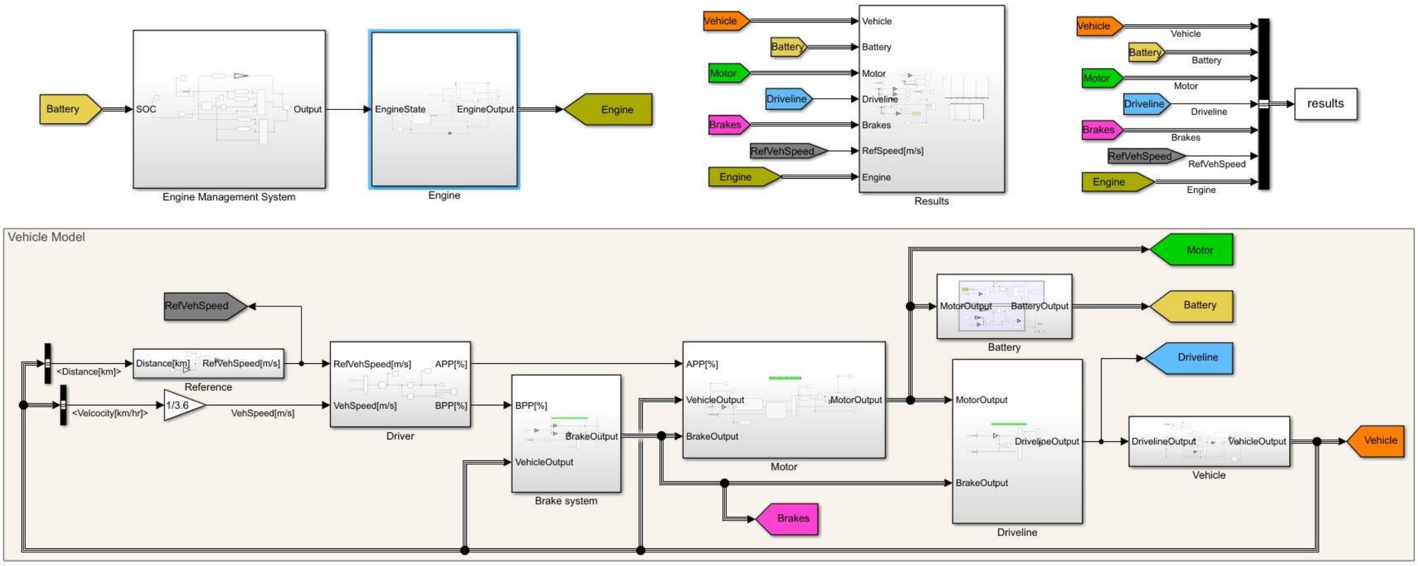
The model receives the drive cycle as input and calculates the power required by the motor to execute it.

2.6 DRIVER MODEL

The driver model is essentially a simple PID controller which receives the vehicle's reference velocity (drive cycle) as input, compares it with the vehicle velocity output from the longitudinal dynamics model and applies the control action to eliminate the error. The model is capable of accelerating or decelerating the electric motor to match the drive cycle.

2.7 OVERALL SYSTEM MODEL

Once the sub-systems are modelled and linked properly, the overall series hybrid powertrain model is ready for implementation of energy management control strategy. Macroscopically, the system receives driving cycle as the input, executes the power split between the IC engine and battery as per the energy management control strategy implemented, and delivers the overall fuel consumption as the final output.



2.8 DRIVING CYCLES

In order to execute the simulation, we need the driving cycle as an input for the system. The driving cycle is essentially the speed profile of the vehicle operation on a particular route. From the distance vs track inclination data between Milan and Turin, and Rome and Naples, we obtain two driving cycles with the help of simple velocity profiles.

Unlike the driving cycle data for ground vehicles like WLTP and NEDC which are merely approximation of real world driving conditions, the driving cycle we have for the railway bogie is complete and hence, one can expect the fuel economy calculations to be fairly representative of the real world scenario.

2.9 FUEL ECONOMY CALCULATIONS

Given that the vehicle has multiple sources of energy, the concept of fuel economy is not as straightforward as it is in case of conventional fossil fuel vehicle. There are two basic approaches to evaluate the fuel economy performance of the control strategies.

The first approach is to consider the absolute fuel consumed by the IC engine without focusing on the usage pattern of the secondary power source, i.e. the battery pack. The logic behind this approach is, all the energy of the battery pack ultimately is sourced from the IC engine and hence, the diesel fuel is the only true source of energy. One potential disadvantage of this method is, during shorter cycles, depending on the control strategy implemented, the IC engine may not be put into action. Thus, the theoretical fuel efficiency would be approaching infinity which is not true. However, given that all the two of our driving cycles are long enough to employ IC engine even if the battery pack starts with an initial SOC of 100%, this approach makes for an easier and direct comparison of effectiveness of various control strategies.

The second approach follows the first one albeit with an additional constraint on SOC such that $SOC_{final} = SOC_{initial}$. With this method, one can obtain fuel consumed as the only relevant factor since the control strategy will be forced to finish the cycle with zero net effective battery charge spent. This is a popular approach in the academic circle, especially to evaluate optimization-based control strategies. However, this approach requires prior knowledge of complete driving cycle and enforcement of artificially strict SOC constraint.

In this work, the first approach discussed above will be used to calculate the fuel economy performance of the series hybrid powertrain and the results will be obtained in liters.

CHAPTER 3 – THERMOSTAT CONTROL STRATEGY

3 THERMOSTAT CONTROL STRATEGY

3.1 OVERVIEW

When it comes to rule-based control strategies, Thermostat Control Strategy (TCS) is by far the most conventional of all of them. The birth of TCS can be traced back to 1995 when Anderson et al [9] put forward numerous concepts for the design of HEV control strategies. In 1996, the research work done by Hochgraf et al [3] performed a deeper analysis of TCS. Soon after, TCS has been widely adopted as the conventional control strategy for HEVs (both parallel and series architectures). It has also emerged as an important benchmark to evaluate newer control strategies and is being used even till date. TCS is simple and very robust supervisory control strategy which is known to deliver good fuel economy.

3.2 PRINCIPLE

TCS operates the series hybrid powertrain systems between two modes. The first mode is the battery-only operation with the IC engine off and the second mode is hybrid operation with the IC engine running at a constant operating point (usually its most efficient point) while the battery levelling of the load. The power to be supplied by the battery is obtained as follows:

Equation 3-1

$$P_{\mathrm{batt}} = P_{\mathrm{load}} - P_{\mathrm{IC,Const}}$$

Where, $P_{\mathrm{IC,const}}$ is the chosen constant operating point for the IC engine. As mentioned earlier, this point usually the most fuel-efficient operating point of the engine. This IC engine + battery operation mode will be carried on until the SOC of the battery pack reaches a specified upper limit SOC_U. In our case, the upper limit we have set is 65% in an attempt to have a closer comparison between TCS and other strategies. Once the set SOC_U is achieved, the control system switches to battery-only mode, thus switching off the IC engine and depleting the charge quickly. Naturally, we need a lower SOC threshold (SOC_L) to switch the engine on and resume the charging of battery.

The TCS is implemented by the following logic where the state S(t) determines whether the IC engine is active (S(t) = 1) or not (S(t) = 0):

Equation 3-2

$$\mathrm{S(t)} = \begin{cases} 0 & \mathrm{SOC(t)} \geq \mathrm{SOC_U} \\ 1 & \mathrm{SOC(t)} \leq \mathrm{SOC_L} \\ \mathrm{S(t^-)} & \mathrm{SOC_L} < \mathrm{SOC(t)} < \mathrm{SOC_U} \end{cases}$$

Where, $S(t^-)$ is the state S in previous time sample. It is to be noted that the IC engine will be demanded to supplement the power ($P_{IC} = P_{IC,const}$) if the load power P_{load} exceeds the maximum capacity of the battery pack ($P_{batt} < P_{load}$), without changing the state S(t) to 1. An additional rule wherein the IC engine reduces its power supply to battery if it's about to be charged beyond its capacity. Such a scenario usually occurs during heavy regenerative braking. In our work, instead of implementing this additional rule, we have applied a limit on maximum regenerative brake torque the motor can use to recharge the battery.

3.3 IMPLEMENTATION

The TCS involves operation in two different states and hence, it is best implemented by means of a state machine. This can be designed easily by using the Stateflow tool in Simulink.

3.4 TUNING

Naturally, the most fuel efficient operating point of the engine would be the starting point for the $P_{IC,const}$. However, in our specific case, since the driving cycle demands high power during most time intervals, it is best to operate the IC engine at a slightly higher power level so as to reduce the load on battery pack. Moreover, such an approach will reduce the number of engine on-off cycles (more fuel consumed when the engine switches on frequently), thus compensating for loss due to slight shift in operation from most efficient point.

All the two driving cycles were run at both most fuel-efficient operating point (85 kW) as well as the point of peak power output (105 kW). Since both points are reasonably close to each other as per the given engine specific fuel consumption map, the latter point emerged as advantageous since it operates the IC engine for lesser duration throughout the driving cycles.

This can be explained by the contribution to battery pack efficiency in overall operation. If the load power is comparable to the optimum power supply of the IC engine, the battery pack efficiency does not have a noticeable impact on the overall fuel economy. However, as in our case, if the load power exceeds the optimal power supply of the IC engine ($P_{load} >> P_{IC,const}$), then the amount of power derived from the battery pack goes up, thus its efficiency significantly influences the overall fuel economy of the system.

3.5 OPERATION

Here are the power time histories corresponding to the two driving cycles. In all the cases, the vehicle started the driving cycle with initial battery SOC of 50% and continued to operate in battery-only mode until the SOC_L threshold of 35% is reached. The system then switches on the IC engine at its constant operating point while the battery achieves load levelling operation. The steep increase in SOC levels towards the end of the drive cycle can be attributed to the sudden and sustained deceleration in velocity profile which results in significant regeneration power.

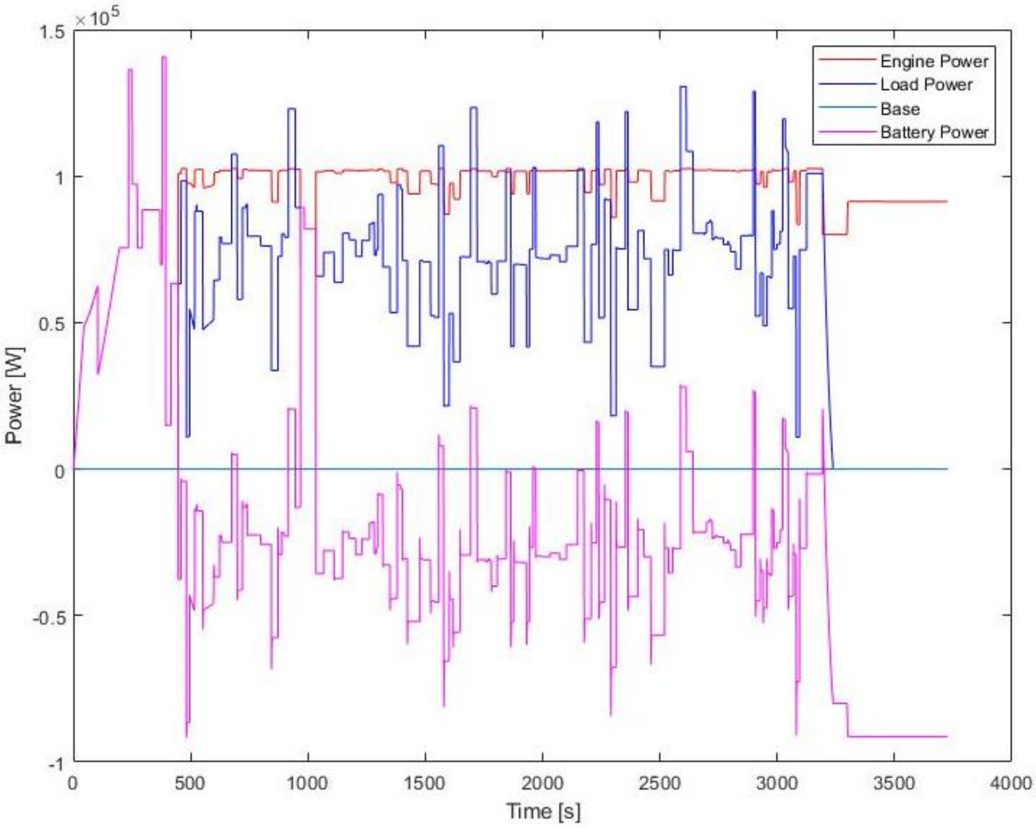


Figure 3-1: Power Cycle from Milan to Turin - $SOC_{Initial}$ at 50%

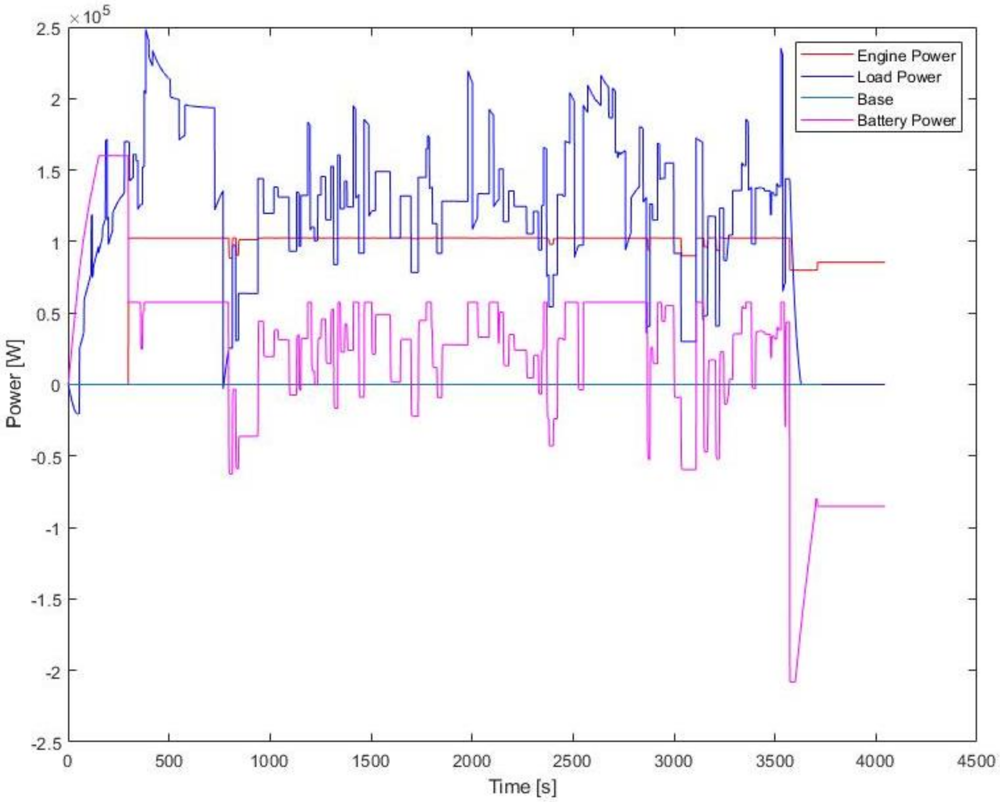


Figure 3-2: Power Time History from Rome to Naples - $SOC_{Initial}$ at 50%

Table 3-1: Fuel Economy Calculations

Driving Cycle	Fuel Consumption (liters)	SOC_{final}
Milan - Turin	41.73	63%
Rome - Naples	62.27	57%

3.6 SUMMARY

As we can observe, there are instances where the SOC continues to drop down even when the IC engine is on. This indicates then when the required power is much higher than the constant IC engine power for a long enough duration, the TCS will not be charge-sustainable. Also, it exposes the battery pack to heavy loads which could lead to accelerated battery degradation.

CHAPTER 4 – POWER FOLLOWER CONTROL STRATEGY

4 POWER FOLLOWER CONTROL STRATEGY

4.1 OVERVIEW

The Power Follower Control Strategy (PFCS) is the second most conventional strategy for HEVs and like TCS, it has been in existence for decades. The first implementations of PFCS for series hybrid powertrain can be traced back to 1997 when Cuddy and Wipke used it in their work [10]. Shortly after, Jalil et al. would also adopt the same in their work [4]. While the TCS is a load levelling strategy, the PFCS is a charge-sustaining strategy. As in, after a certain level of load power, the IC engine is responsible to deliver the required power.

4.2 PRINCIPLE

The PFCS operates in multiple modes of which the two primary ones are battery-only mode when the load power is very low and power following mode in which the IC engine follows the load power trend to complete the driving cycle. At any point, if the load power exceeds the IC engine power, the battery kicks in to remove the deficit.

In general, the IC engine follows the load power with some deviation to correct the varying SOC. When the P_{load} is low and SOC is high, the battery pack is employed as the source of power in which case, S(t) = 0. When the P_{load} is high or SOC is low, the IC engine comes into action in which case S(t) = 1. The operational states are defined by the following rules:

Equation 4-1

$$S(t) = \begin{cases} 0 & SOC(t) \geq SOC_U \text{ and } P_{load} < P_{min} \\ 1 & SOC(t) \leq SOC_L \text{ or } P_{load} > P_{batt\,max} \\ S(t^-) & SOC(t) \geq SOC_L \text{ and } P_{load} < P_{batt\,max} \end{cases}$$

When S(t) = 0, the P_{IC} = 0 always but when S(t) = 1, the operation of IC engine is not at a constant point like in the TCS. Instead, the IC engine operation is defined by the following rules:

Equation 4-2

$$P_{IC} = \begin{cases} P_{min} & SOC(t) \geq SOC_U \\ P_{PF}(t) & SOC_L < SOC(t) < SOC_U \\ P_{IC\,max} & SOC(t) \leq\ SOC_L \end{cases}$$

Where, $P_{PF}(t)$ is given by,

Equation 4-3

$$\mathrm{P_{PF}(t) = P_L + P_{ch}\left[\frac{SOC_U + SOC_L}{2} - SOC(t)\right]}$$

From the set of rules described above, it is easy to observe that, whenever the battery SOC is between the SOC_U and SOC_L thresholds, the IC engine essentially follows the P_{Load} but the operation is biased towards charging or discharging the battery when the SOC is low or high respectively. The PCH is the scaling factor which determines the extent of bias towards charging or discharging. This term helps the system maintain its SOC close to 50%, thus, PFCS is charge sustaining and will not run out of battery charge even during long operations. It is also permissible to have this $P_{CH} = 0$, provided the driving cycle is not too hard on the battery.

4.3 IMPLEMENTATION

Just like the TCS, PFCS involves operation of the IC engine in two different states and hence can be implemented using a state machine such as Stateflow.

4.4 TUNING

PFCS has two tunable parameters namely P_{CH} and P_{min}. The charging factor P_{CH} has to have a positive value in order to have a charge sustaining operation. Since the charging factor defines the amount of recharge, it should obey the constraint for the for the maximum power the battery can absorb. That is defined by

Equation 4-4

$$P_{ch}\frac{(SOC_L - SOC_U)}{2} \leq P_{batt\,max}$$

Similarly, the charging factor should also obey the maximum power threshold for the battery as defined by,

Equation 4-5

$$P_{ch}\frac{(SOC_U - SOC_L)}{2} \leq P_{batt\,max}$$

Based on trials, varying the P_{CH} between the range of [0,10] kW, we found that 0 kW offers best fuel without being a hindrance to charge sustaining operation.

The second and the most important tuning parameter of PFCS is P_{min}. In the literature, the magnitude of this parameter varies widely across depending on the works. Some describe it as the physical constraint of the powertrain, but we can explore the range between the power at engine idling speed of 1,000 rpm all the way up to the peak engine power, i.e [40 105] kW. Upon performing the simulation by varying the P_{min}, we found that the PFCS returns the best fuel economy at P_{min} = 95 kW. Of course, the optimal tuning value for each driving cycle is unique but, in each case, the difference is neglible and hence for the sake of simplicity and robustness, we have opted to use P_{min} = 95.

4.5 OPERATION

As can be seen from the power time histories, the operation is not very different from that of the TCS. Of course, the PFCS' P_{min} is lower than the TCS' $P_{IC,const}$ and when the IC engines become operational, it follows the load power curve.

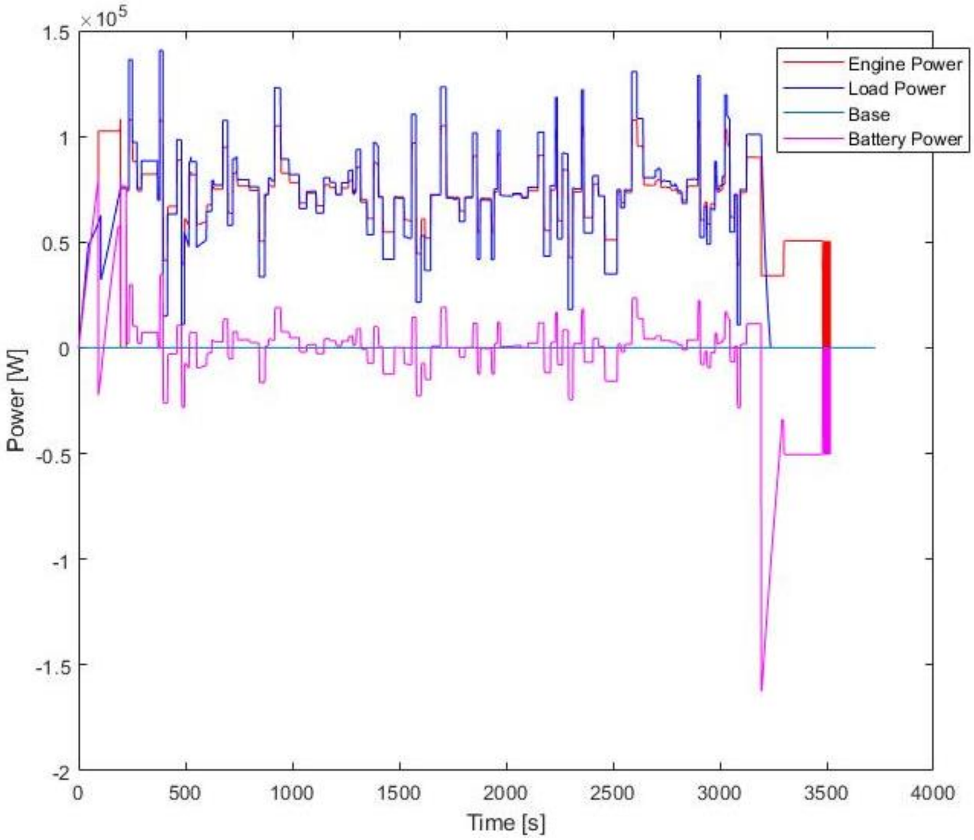


Figure 4-1: Power Time History for Milan to Turin - SOC$_{initial}$ at 50%

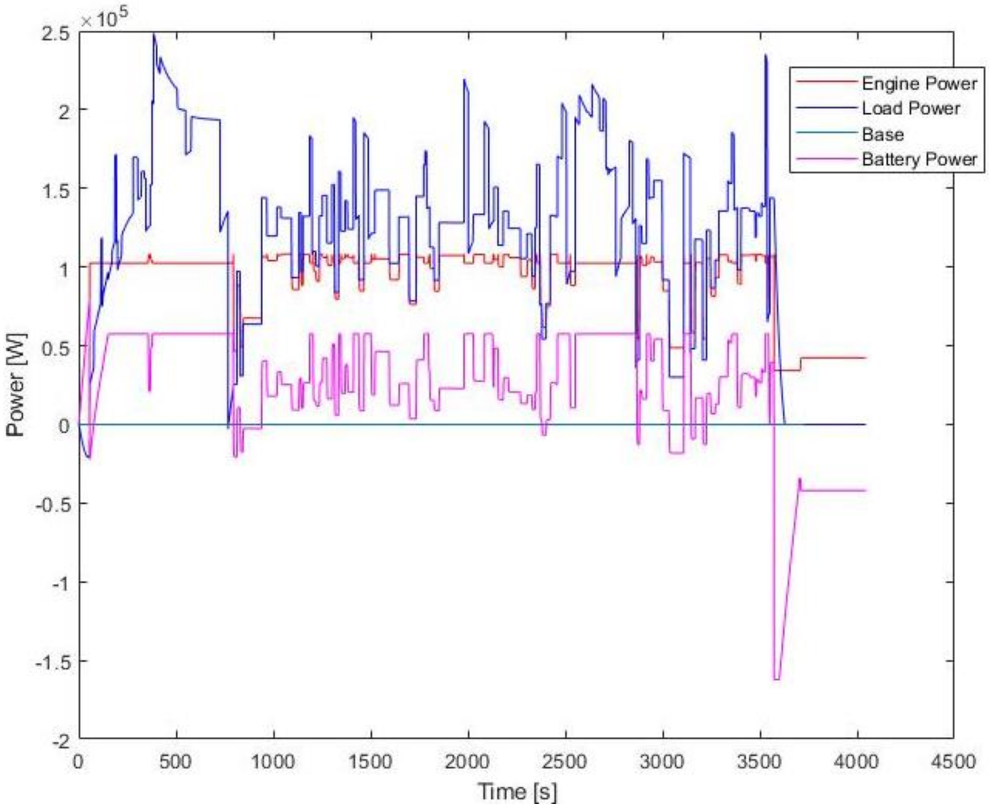


Figure 4-2: Power Time History for Rome to Naples

Table 4-1: Fuel Economy Calculations

Driving Cycle	Fuel Consumption (liters)	SOC_{final}
Milan - Turin	43.28	52%
Rome - Naples	53.85	41%

4.6 SUMMARY

Just like in the case of TCS, the final SOC values after the end of driving cycles varies considerably with PFCS as well. Since the difference between the P_{min} and $P_{IC,const}$ is very narrow, PFCS does tend to operate in a very similar manner to the TCS. The overall fuel economy figures are marginally better than those of TCS.

We can also notice that since the load power exceeds the peak power output of IC engines at most of the time intervals, the battery kicks in to plug the deficit.

CHAPTER 5 – EXCLUSIVE OPERATION STRATEGY

5 EXCLUSIVE OPERATION STRATEGY

5.1 OVERVIEW

The exclusive operation strategy (XOS) is a modern heuristic load following strategy which derives its inspiration from several other control strategies such as Power Follower Control Strategy (PFCS), Global Equivalent Consumption Minimization Strategy (GECMS) [see Appendix A] and Global Efficiency Maximization Map Strategy (GEMMS). In addition to adopting load following technique, XOS also employs threshold changing technique to facilitate charge sustaining operation. It was presented by Wassif Shabbir in his paper [7].

5.2 PRINCIPLE

Under most driving cycles, across different types of control strategies, a thorough analysis of power split between the IC engine and battery pack often revealed that optimum operation is achieved with battery during low load power demand and IC engines at high load power demand. This is because the IC engine is inherently efficient at higher loads while its quite the opposite in case of battery. This is basic principle behind the XOS which employs only the battery when the load power is below a certain level or if the SOC level is above the set upper limit. Under medium load power conditions, this control strategy derives all the required power from the IC engine. The hybrid mode comes into picture only when the instantaneous load power exceeds the maximum limit of the power source that is currently in operation or if the SOC level falls below the set lower limit.

The operational behavior of XOS is pretty similar to that of PFCS when only the IC engine is operational but the crucial difference comes from the fact that the former does not regulate the IC engine power to rectify the SOC deviation but instead achieves the correction by relying on threshold changing technique.

The threshold power P_{th} which is a function of SOC is the load power at which the control strategy switches from battery to IC engine. As per the literatures, the threshold power is derived using the following expression.

Equation 5-1

$$\mathrm{P}_{\mathrm{IC\ min}}(SOC) = P_{th} + P_{th}(\frac{SOC - SOC_{initial}}{SOC_{range}})$$

It is required to analyze the battery and IC engine efficiencies at various power levels to arrive at an optimum value of P_{th} . It is to be noted that the battery efficiency does not take into account the power loss at the IC engine during the process of charging. Based on the findings of the literature (2), a replenishing efficiency (η_{re}) of 35% is incorporated into the overall battery efficiency.

Mapping the overall battery efficiency alongside the IC engine efficiency shows that there is a point from which IC engine-only operation becomes more efficient than using the battery. The load power corresponding to this point is considered as optimal value of threshold power. Of course, P_{th} is calculated for different SOC levels.

Operationally, the resource usage pattern of the XOS is found to be very similar to that of the GECMS despite the former's simple rules. As per the literature, the operation of XOS can be regarded as a close approximation of GECMS and GEMMS as it mimics their behaviors to a large extent. Thus, XOS, despite its simple implementation and low computation efforts, is generally expected to perform very well.

5.3 IMPLEMENTATION

While the TCS and PFCS involve operations in two distinctly different states of the system (engine on and off), the XOS operations in single state. What this means is, the first two control strategies will need state machines for implantation (In Simulink, these two strategies are implemented with Stateflow) whereas the XOS requires only simple algebraic implementation using arithmetic operators and logic gates.

5.4 TUNING

The sole tuning parameter to optimize the XOS is the base threshold P_{th}. By repeating the simulation of the model for all the two driving cycles within the range of P_{th} [45 85] kW with a step size of 0.2 kW, we arrive at optimal value (minimum fuel consumption).

The base threshold (P_{th}) is different for each driving cycle but even with imperfect tuning of this parameter, the difference in fuel consumption is found to be less than 1%, thus it is not overtly sensitive to tuning parameter value like in the case of GECMS.

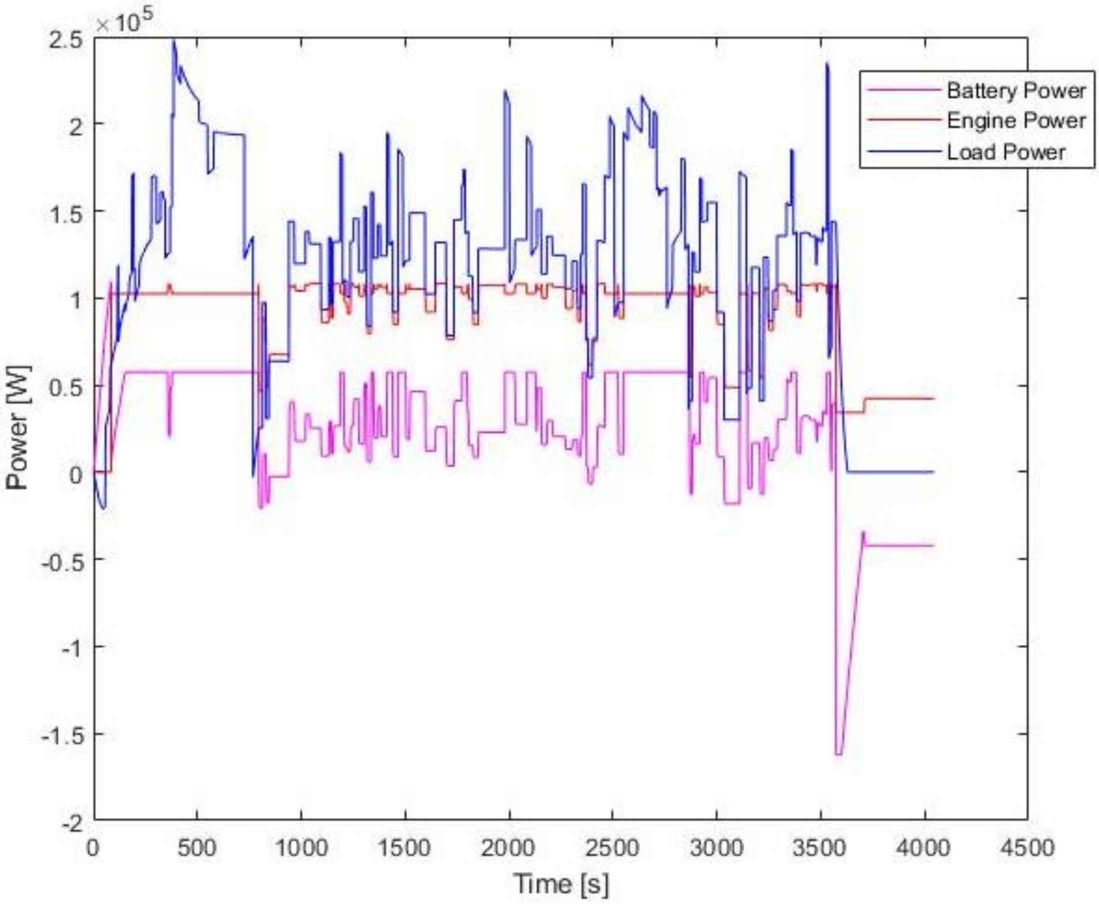


Figure 5-1: Power Time History of Rome to Naples - $SOC_{initial}$ at 50%

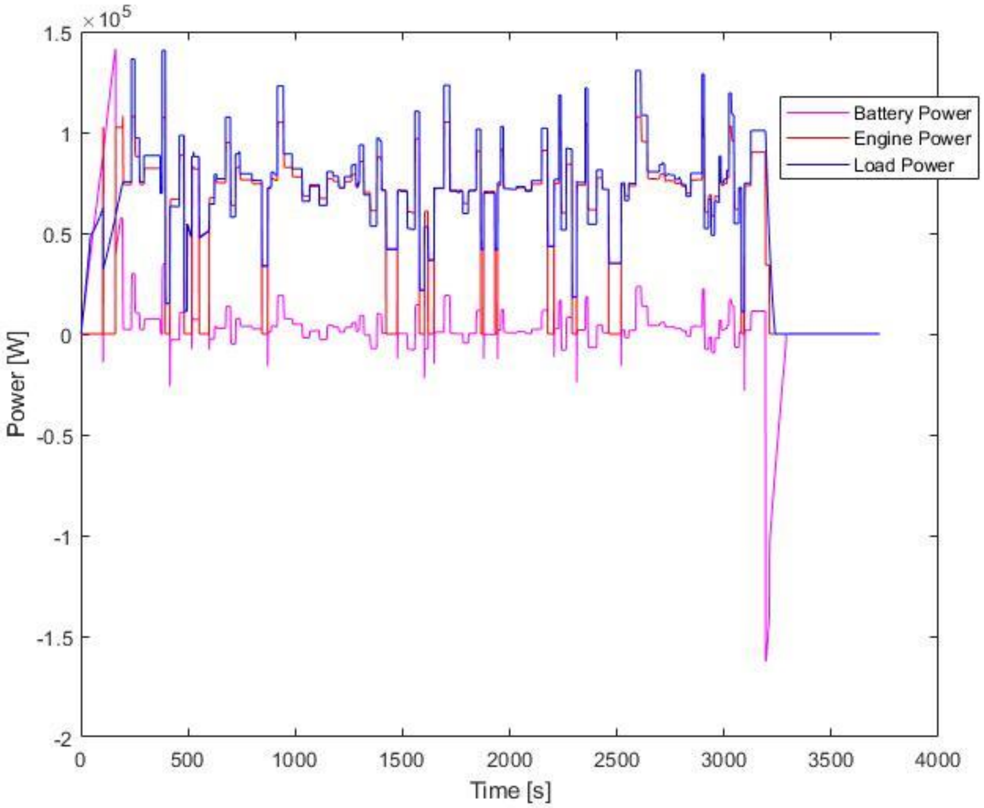


Figure 5-2: Power Time History for Milan to Turin - SOC$_{initial}$ at 50%

Table 2.1: Fuel Economy Calculations

Driving Cycle	Fuel Consumption (liters)	SOC$_{final}$
Milan - Turin	34.2	56%
Rome - Naples	51.4	37%

5.5 SUMMARY

As observed from the fuel economy results, it is clear that the XOS outperforms TCS quite significantly and also has a clear upper hand compared to the PFCS. Interestingly, the operations of PFCS and XOS is very similar in case of the Rome – Naples driving cycle which can be explained by the very high load power that is required throughout the driving cycle. In most time intervals, the system operates both the battery and IC engines at their highest potentials in an attempt to satisfy the load power and hence, both PFCS and XOS have near-identical time histories for this driving cycle.

CHAPTER 6 – CONCLUSION

6 CONCLUSION

This thesis started with describing the need for a robust and efficient energy management controls strategy for HEVs and went on to describe how a relatively simple vehicle model can be used to design, test, study and analyze various types of control strategies.

Through the simulation results, it has been found that the long-standing conventional heuristic control strategies for HEVs are robust but not the best performing when it comes to fuel economy as the primary objective. Also, the TCS and PFCS found to use the IC engine and battery pack sub-optimally at times which could lead to accelerated degradation of respective systems.

The XOS emerges as a very simple yet very effective energy management control strategy whose advantages lies in easy implementation and low hardware requirement. Without adding to the complexity, the XOS demonstrates clear advantages over the conventional heuristic strategies in terms of resource usage as well as fuel economy.

In objective terms, for the Milan to Turin driving cycle, the XOS proved to be 22 % more efficient than the TCS and 26.5 % more efficient than the PFCS. When it comes to Rome to Napoli cycle, the XOS outperforms TCS and PFCS by 21.7 % and 4.7 % respectively.

So, it is safe to conclude that, for a series-hybrid powertrain with diesel engine range extender, the XOS emerges as the clear winner among the heuristic control strategies studied as a part of this thesis.

CHAPTER 7 – APPENDIX A

7 APPENDIX A

7.1 GLOBAL EQUIVALENT CONSUMPTION MINIMIZATION STRATEGY

The GECMS is a global optimization-based control strategy which requires the information about complete driving cycle beforehand. In the literature, it is widely considered as a close approximation of global optimal solution for the particular driving cycle. So, it is widely used as a benchmark in analysis of various supervisory control strategies. This process described here is derived from [5].

As the name suggests, GECMS is globally tuned version of Equivalent Consumption Minimization Strategy (ECMS). It essentially involves construction of an off-line control map with instructions on how to split the required power between engine and battery to achieve optimal equivalent fuel consumption under different driving conditions. The implementation of GECMS would require computation of optimal equivalence factors S_c (charging) and S_d (discharging).

The objective of the GECMS is to minimize the equivalent fuel consumption m_{eq} which is defined as,

Equation 7-1

$$\mathrm{m_{eq}} = \int_0^{\mathrm{t_f}} \dot{\mathrm{m}}_{\mathrm{eq}}\big(t, u(t)\big)dt$$

Equation 7-2

$$\dot{\mathrm{m}}_{\mathrm{eq}} = \begin{cases} \dot{\mathrm{m}}_{\mathrm{f}}\,(\mathrm{P_{IC}}) - \mathrm{S_d}\dfrac{\mathrm{P_{batt}}}{\mathrm{Q_{LHV}}} & \mathrm{P_{batt}} \geq 0 \\ \dot{\mathrm{m}}_{\mathrm{f}}\,(\mathrm{P_{IC}}) - \mathrm{S_c}\dfrac{\mathrm{P_{batt}}}{\mathrm{Q_{LHV}}} & \mathrm{P_{batt}} < 0 \end{cases}$$

Where $\dot{\mathrm{m}}_{\mathrm{f}}$ is the fuel consumption rate of the IC engine and Q_{LHV} is the lower heating value of the fuel. The role of the equivalence factors S_c and S_d is to translate the amount of charge or discharge experienced by the battery into corresponding amount of fuel consumed or replenished. For each driving cycle, the optimal values of the equivalence factors need to be determined. It can be done so either by trail and error method or by employing numerical optimization method.

The optimization problem of the GECMS can be described in the form of a local minimization problem as shown below:

Equation 7-3

$$P_{GECMS}\begin{cases}\underbrace{\min}_{u}\ \dot{m}_{eq}(t,u)\ \forall t\ \in\ [0,t_f]\\ 0\ \leq\ u\ \leq\ \frac{P_{IC,max}}{P_L}\\ SOC_L \leq SOC \leq SOC_U\end{cases}$$

Where, *u* is the powershare factor. For each time instant *t* of the driving cycle and for each set of equivalence factors S_c and S_c, an optimal power share factor u_{opt} is calculated. In order to obtain optimal control input, a sweep of the IC engine's fuel consumption map (shown in Figure 2-2) is done for equation 7-2 with $u\ \in\ [0,\frac{P_{IC,max}}{P_L}]$. The process is repeated for every candidate set of S_c and S_d within the specified range with varying step size of 0.1 for each driving cycle.

Clearly, this process is very time consuming because it will involve several iterations for each time instant of the driving cycle and in our specific case would require several thousand hours of simulation time. Hence, we opted for XOS which could be considered as a close approximation of GECMS but is much simpler and easier to implement.

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