Plug in Hybrid Electric Vehicle Energy Management System for Real World Driving

by

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Declaration

This thesis is presented in accordance with the regulations for the degree of Doctorate of Philosophy. It has been written and complied by myself and has not been submitted anywhere else. The work in this thesis has been undertaken by me except where otherwise stated.

Signed: Date:

Brahmadevan Venniyod Padma Rajan

List of Publications

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ABSTRACT

The energy management system (EMS) of hybrid electric vehicle controls the operation of two power plants; electric machine/battery and typically engine. Hence the fuel economy and emissions of hybrid vehicles strongly depend on the EMS. It is known that considering the future trip demand in devising an EMS control strategy enhance the vehicle and component performances. However existing such acausal EMS cannot be used in real time and would require prior knowledge of the trip vehicle speed profile (trip demand). Therefore rule based EMS which considers instantaneous trip demand in devising a control strategy are used. Such causal EMS are real time capable and simple in design. However rule based EMS are tuned for a set of driving cycles and hence their performance is vulnerable in real world driving. The research question is “How to design a real time capable acausal EMS for a plug in hybrid electric vehicle (PHEV) that can adapt to the uncertainties of real world driving”.

In the research, the design and evaluation of a proposed EMS to deal and demonstrate in scenarios expected in real world driving respectively were considered.

The proposed rule based acausal EMS is formulated over the estimated vehicle trip energy and driving information. Vehicle trip energy is the electric (battery) energy required to meet the trip demand estimated using known driving information. Driving information that can be considered are driver style, route distance and road types like urban and extra urban, with traffic as a sub function. Unlike vehicle speed, vehicle trip energy is shown to be relatively less dynamic in real world driving.

For the proposed EMS evaluation, a commonly used parallel PHEV model was simulated. For driving information EMS was not integrated to a navigation system but manually defined. Evaluation studies were done for a driver, and traffic was not considered for simplicity.

In the thesis, vehicle performance and credentials for real world applicability (real time capability and adaptability) of the proposed acausal EMS are demonstrated for various scenarios in real world driving; varied initial SOC, sequence of road types, trip distance and trip energy estimation. Over the New European Driving Cycle (NEDC) the proposed EMS vehicle performance is compared to a conventional rule based EMS. The proposed EMS fuel economy improvement is up to 11% with 5 times fewer number of engine stop-starts. Similarly in the validation study, with no prior knowledge of trip vehicle speed profile, the fuel economy improvement is up to 29% with 7 times fewer number of engine stop-starts. The simulation duration of the proposed EMS is as good as conventional rule based EMS. Hence the proposed EMS is potentially real time capable. The proposed EMS can adapt to a wide variation in trip energy (±15%) estimation and still perform better than the conventional rule based EMS. The proposed EMS can tolerate variation in trip demand estimation and no prior knowledge of trip vehicle speed profile is required, unlike other acausal EMS studies in the literature.

A new PHEV EMS has been formulated. Through simulation it has been seen to deliver benefit in vehicle performance and real world applicability for varied scenarios as expected in real world driving. The key new step was to use vehicle trip energy in the formulation, which enabled rule based EMS to be acausal and potentially real time capable.

List of Symbols and Acronyms

α	Specific energy, kJ/km
ΔE_L	Local delta energy, kJ
ΔE_t	Delta energy at time t, kJ
λ	Equivalent factor
ρ	Air density, kg/m^3
λ_{chg}	Equivalent factor to charge
λ_{dis}	Equivalent factor to discharge
λ_0	Initial equivalent factor
η_{batt}	Battery efficiency
$\bar{\eta}_{chg}$	Average charging efficiency
$\bar{\eta}_{dis}$	Average discharging efficiency
η_{em}	Electric machine efficiency
θ	Road slope, rad
A	Vehicle frontal area, m^2
ARTEMIS	Assessment and reliability transport emission models and inventory systems driving cycles
ANL	Argonne National laboratory
ANN	Artificial neural network
a	Acceleration, m/s^2
B	Total battery capacity, kJ
BCD	Blended charge depleting
BCFC	Brake specific fuel consumption, g/kW-h
C_d	Vehicle drag co-efficient
C_{rr}	Co-efficient of rolling resistance
C	Mass emissions of CO_2 in g/km
C1	Mass emissions of CO_2 in g/km with a fully charged battery
C2	Mass emissions of CO_2 in g/km with a battery in minimum SOC

CD	Charge depleting
CO_2	Carbon-di-oxide
CS	Charge sustaining
d	Distance, m
D_e	Vehicle's electric range, km
D_{av}	Assumed average distance between two battery recharge, km
DP	Dynamic programming
dt	Distance covered, m
E	Extra urban – speed limit 70 mph
E_{bt}	Available battery energy at time t, kJ
E_o	Total initial estimated energy for a given trip, kJ
E_x	Estimated energy for a given road type x, kJ
E_t	Estimated energy at time t, kJ
E_{dt}	Estimated energy for the distance covered dt, kJ
ECE	Economic Commission for Europe
ECE R15	Economic Commission for Europe Regulation 15 (Urban Driving Cycle)
ECMS	Equivalent consumption minimisation strategy
EMPA	Driving cycle developed by one of the Swiss research institute, EMPA
EMS	Energy management system
EUDC	Extra urban driving cycle
EV	Electric vehicle
F	Vehicle resistive force, N
F_a	Aerodynamic force, N
F_g	Gradient resistance force, N
F_i	Inertia force, N
F_r	Rolling resistance force, N
FE	Fuel economy, MPG
FTD	Fuzzy torque distribution
FUDS	Federal urban driving schedule (also called as FTP-72)

FHDS	Federal highway driving schedule
g	Gravitational acceleration, m/s^2
GPS	Geographical position system
H_{LHV}	Lower heating value of the fuel
HEV	Hybrid electric vehicle
HWFET	Highway fuel economy test
I	Current, Amp
IC	Internal combustion
ICE	Internal combustion engine
IEMA	Intelligent energy management agent
ITS	Intelligent transport system
J	Cost function
J1015	Japanese legislative driving cycle
K_p	Proportionate constant in PI controller
K_i	Integral constant in PI controller
LA-92	Unified driving cycle (used in US)
LDC	Legislative driving cycles
LOS	Level of Service
M	Vehicle mass, Kg
m	Number of road types in a trip
m_f	Fuel consumed, g
$\dot{m}_f$	Instantaneous fuel consumed, g
$\dot{m}_{ic}$	Fuel consumption of IC engine, g
$\dot{m}_{em,equ}$	Equivalent fuel consumption of electric machine, g
MPC	Model predictive control
n	Length of the driving cycle, seconds
NEDC	New European driving cycle
NOVC	Not off-vehicle charging
NREL	National Renewable Energy Laboratory
OOL	Optimal operating line

OOP	Optimal operating point
OVC	Off-vehicle charging
P_{bt}	Battery power, kW
$P_{chg,lim}$	Limit battery charging power, kW
$P_{dis,lim}$	Limit battery discharging power, kW
P_{em}	Electric machine power, kW
$P_{em,max}$	Maximum electric machine power, kW
$P_{em,min}$	Minimum electric machine power, kW
P_{ic}	Engine power, kW
$P_{ic,\ max}$	Maximum engine power, kW
P_{req}	Power demand, kW
PHEV	Plug in hybrid electric vehicle
PI	Proportionate integral
R_{chg}	Battery charging resistance, ohm
R_{dis}	Battery discharging resistance, ohm
REEV	Range extended electric vehicle
SAVE	Sustainable Action on Vehicle Energy
SDP	Stochastic dynamic programming
SOC	Battery state of charge
SOC_0	Initial state of charge
SOC_n	State of charge at the end of driving cycle/trip
SOC_{target}	Target or desired state of charge
t	Time, second
t_f	Time at the end of journey, second
T-ECMS	Telemetry equivalent consumption minimisation strategy
TRAMAQ	Traffic management and air quality driving cycles
U	Urban
u	Power split ratio between the power plants
u_{min}	Minimum power split ratio
u_{max}	Maximum power split ratio

UDDS	Urban dynamometer driving schedule
UDC	Urban Driving Cycle
v	Vehicle speed, m/s
V_{OC}	Battery output circuit voltage, Volt
v_{act}	Actual vehicle speed, m/s
ω_{em}	Electric machine speed, rad/sec
ω_{ic}	Engine speed, rad/sec
WARPSTAR	WARwick Powertrain Simulation Tool for ARchitecture
WMG	Warwick Manufacturing Group
x	Road type
y	Driver style

Chapter 1 – Introduction

1.1 Introduction

Hybrid electric vehicles (HEVs) are typically powered by an internal combustion (IC) engine and at least one electric machine/generator (Chan, 2002). Usually hybrid vehicles deliver superior fuel economy and emissions performance in comparison to conventional vehicles (powered by IC engine alone) (Markel and Simpson, 2006, Elgowainy et al., 2009). Hybrid vehicle performance strongly depends on the energy management system (EMS). The function of the EMS is to decide between the power plants in order to meet the desired vehicle and component performances for varied driving conditions (Chan and Wong, 2004, Musardo et al., 2004). This EMS function also called devising control strategy.

In industry, rule based EMS are used due to their design simplicity and ability to operate in real time (Çagatay Bayindir et al., 2011). Rule based EMS considers only the instantaneous trip demand when devising a control strategy. Such EMS are called a causal (non-predictive) system. A causal system output is dependent on past/current inputs and does not anticipate the future values of input. An acausal system output depends on some future input values and possibly on some input values from the past or present (Oppenheim et al., 1997, Wirasingha and Emadi, 2011). Therefore rule based EMS do not predict and hence do not consider the future whole trip demand as in typical acausal EMS (predictive). Rule based EMS are tuned for a set of driving cycles typically legislative driving cycles. Hence their performances are compromised in real world driving. Also it was found hybrid vehicles performances are more sensitive to driving cycle/trip demand variations than a similar conventional vehicle (Sharer et al., 2007, M.Duoba et al., 2004).

On the other hand acausal EMS are found to enhance the fuel economy, emissions and component performance of HEV (Sciarretta and Guzzella, 2007, Wu et al., 2011). However current acausal systems cannot be used in real time EMS and require knowledge of the trip vehicle speed profile in advance. In real world driving it is not possible to predict the exact vehicle speed profile due to the uncertainty in driving conditions (Guzzella and Sciarretta, 2007, Serrao, 2009).

This research work investigates the design and evaluation of a proposed rule based acausal EMS to adapt to the uncertainties of real world driving.

1.2 Research problem

Owners of HEVs have complained of a much larger deviation between their real-world fuel economy and the certified values in comparison to conventional vehicles (Sharer et al., 2007, Reports, 2004). In one of the Argonne National laboratory (ANL) study it was observed that HEVs fuel economy are found more sensitive to driving cycle variations than a similar conventional vehicle (Sharer et al., 2007, M.Duoba et al., 2004). Plug in HEVs (PHEV) are no different (Tulpule et al., 2009). One of the causes is that EMS employed in industry are causal systems and do not consider the whole trip demand when devising a control strategy. Also they do not adapt to the uncertainties of real world driving.

Based on mathematical models EMS are classified into two types. There are rule based and optimisation based EMS. Rule based EMS are defined using if-then-else conditions and component efficiency maps. Such EMS devises control strategy based on the instantaneous torque demand, vehicle speed and battery state of charge (SOC). Its strengths are ability to perform in real time and design simplicity and hence used in industry (Çagatay Bayindir et al., 2011). Optimisation based EMS determines a series of power split ratios between the vehicle power plants (engine and electric machine) within the component and system constraints at each instances over a given trip vehicle speed profile. Power split ratio defines the ratio of electric and engine power to be used. Optimisation based EMS are typically designed to deliver optimal fuel economy and emissions for a given trip vehicle speed profiles.

All acausal EMS are optimisation based and hence not suitable for real time application (Sciarretta and Guzzella, 2007, Koprubasi, 2008, Çagatay Bayindir et al., 2011). Another limitation is acausal optimisation based EMS requires knowledge of the vehicle speed profile (whole trip demand) in advance. Optimal results like fuel economy of optimisation based EMS depends on the accuracy of the vehicle speed profile prediction (Serrao et al., 2011). Historic vehicle speed profile data, trip modelling using navigation system and of late intelligent transport system (ITS) data are some of the methods used to consider or predict future trip demand in the acausal EMS. Nevertheless prediction of the exact vehicle speed profile in real world driving is not possible due to the dynamic conditions (Guzzella and Sciarretta, 2007, Serrao, 2009). Hence this limits the use of such EMS to conditions where the knowledge of vehicle speed profile is known in advance and for off line application.

Overall, for efficient performance a real-time capable EMS must deal and adapt itself to the uncertainties (traffic, driver, etc) in driving conditions (local) (Sciarretta and Guzzella, 2007) and also consider the whole trip demand (global). A real-time capable acausal EMS able to handle the uncertain real world trip demand is required. The aim of this research work is to propose and evaluate such an EMS.

1.3 Research question

EMS real time capability is paramount for industrial application. Next is to consider limitations and requirements of real world driving in the EMS formulation. Before that, current EMS formulation is briefly examined.

Existing EMS are either tuned for a set of legislative driving cycle (causal) or formulated over vehicle speed profile (acausal). So, existing EMS methods are framed with respect to vehicle speed profile as shown in Figure 1-1. Vehicle speed profile represents the future trip demand or vehicle demand. Typically the effect of driver or variation in trip demand due to the driver is neglected. Hence the vehicle demand is considered directly based on the trip vehicle speed profile by the EMS to define the power plant operations.

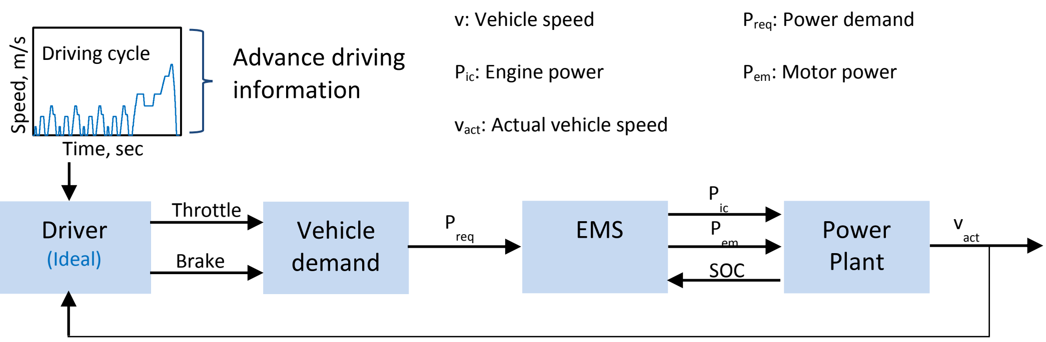

Figure 1-1: A schematic of the existing EMS formulation

In real world driving vehicle speed is primarily a function of driver style, road types (such as urban and extra urban), traffic, elevation, weather, etc.(Ericsson, 2000) called as driving information. Due to dynamic nature of some of these factors such as driver style and traffic, vehicle speed becomes highly dynamic and uncertain trip demand.

As the exact demand is not known in advance in real world driving it is not possible to have optimal vehicle performance by design. The focus of the proposed EMS design has to be in effective execution under uncertain and varied conditions which was often overlooked for optimal performance. That is the system has to be real time capable and adapt to the trip demand uncertainty expected in real world driving to deliver efficient performance. Further this has to be achieved for varied driving conditions.

Due to limitations of vehicle speed profile in real world driving, it is required to formulate EMS over parameter which is relatively less dynamic. The parameter should be conducive in estimating the uncertain trip demand and also for EMS to adapt to changes in real time for efficient performance. In other words the trip demand estimation and adaptability of the EMS shall not be sensitive to small changes in trip demand.

Overall, the research question to be answered is “How to design a real time capable acausal EMS for a PHEV that can adapt to the uncertainties of real world driving”.

1.4 Main contribution and novelty

The main contribution and novelty of this thesis are as discussed below.

1.4.1 Main contribution

A new PHEV EMS has been formulated. The proposed EMS for PHEV is a rule based acausal EMS formulated over driving information and vehicle trip energy and not over vehicle speed profile as usually seen. Vehicle trip energy is the electric (battery) energy required to meet the trip demand estimated using known driving information. Driving information that can be considered are driver style, route distance and road types like urban and extra urban, with traffic as a sub function.

A method is designed to consider the effect of various driving information through a common parameter, specific energy. Specific energy is the average electric required per kilometre for a given driver style and road types.

For the proposed EMS, which is formulated over driving information, it was required to define the vehicle efficient engine operation with respect to the road types. Before this study, there was no literature on the vehicle efficient engine use for hybrid vehicles to suitably define with respect to the trip driving parameters such as road types. This was so, as acausal EMS in the literature are formulated over vehicle speed profile.

Through simulation it has been shown that the proposed EMS is able to deliver benefit in vehicle performance in comparison to conventional rule based EMS and potentially real world applicable for varied real world scenarios.

1.4.2 Novelty

The key novelty was to use vehicle trip energy in the proposed EMS formulation, which enabled the rule based EMS to be acausal and potentially real time capable. This trip energy can be generic i.e. a trip energy for urban and extra urban driving and does not need to be referenced to the trip in question.

Unlike existing acausal EMS, no prior knowledge of the trip vehicle speed profile is required and using known trip driving information the proposed EMS works out the trip demand.

1.5 Thesis outline

The proposed EMS structure and strategy were designed and evaluated keeping the essence of dynamics and uncertainty of real world driving. In the evaluation study a commonly used parallel PHEV model was simulated. As part of evaluation the proposed EMS performance metrics were studied and compared with a conventional rule based EMS. The performance metrics include vehicle performance, real time capability and adaptability to varied trip energy estimation and driving conditions (trip demand). This was followed by a validation study mimicking varied real world scenarios. The vehicle performance metrics considered were the fuel economy, number of engine stop-starts and final SOC. Performance metrics of the proposed EMS were studied over the legislative driving cycle - the new European driving cycle (NEDC) and predominantly over real world driving data.

The thesis consists of three main parts. Chapters 2 - 8 are about requirements, limitations and design of a proposed EMS for real world driving. Chapter 9 - 12 covers its evaluation studies in line with real world driving varied uncertainties. Finally chapters 13 & 14 bring together overall discussion, suggested future work and conclusions.

First part starts with an introduction about hybrid vehicles and EMS in chapter 2. Types of hybrid vehicle architectures are explained. Followed by EMS function and types of controls strategies are discussed.

Chapter 3 gives a background about external vehicle demands considered in EMS research and development, such as driving cycle, real world driving and trip modelling. The difference between driving cycles and real world driving is discussed. This is followed by a review of some of the trip modelling techniques. This chapter along with chapter 2 aids in understanding some of the terms and methods discussed in following chapters.

A review of EMS methods is covered in chapter 4. EMS methods are reviewed based on formulation, vehicle performance, real time capability and limitation with respect to real world driving. On one side this chapter covers from causal to acausal EMS. On the other side from rule based to optimisation based EMS. The chapter ends with a summary and requirements of EMS for real world driving.

Based on two preliminary studies, chapter 5 briefly covered the origin and motive of some of the factors and method considered in the design of the proposed EMS later in chapter 7. In other words observations from preliminary studies gave insight in considering dynamic and uncertain real world trip demand before designing a new EMS. These preliminary studies set the tone of the proposed EMS and this research.

The research approach for the design and evaluation of a proposed EMS is discussed in chapter 6. A vehicle system model considered for simulation followed by the research approach for formulation of the proposed EMS is discussed. Later in the chapter the evaluation study layout imitating real world application is detailed.

The design of a proposed EMS structure and strategy is covered in chapter 7. Formulation and working principle are discussed. Next an illustration of the proposed EMS adaptive principle is shown and a flow chart for devising control strategy is presented.

Vehicle efficient engine operation over driving information was studied in chapter 8. Before this, there was no literature on efficient engine use for hybrid vehicles to suitably define over driving parameters such as road types.

In the second part, a complete system the proposed EMS performance was evaluated. The proposed EMS performance metrics are studied and compared with conventional rule based EMS in the following chapters.

In chapter 9, the proposed and conventional rule based EMS vehicle performance was compared over the NEDC for varied journey distance and initial battery SOC. The proposed EMS was simulated as a complete system to demonstrate the vehicle performance over a standard driving cycle.

Real time capability was studied in chapter 10. In the literature, real time capability is usually overlooked at the cost of maximising the vehicle efficiency. In this study vehicle performance and simulation time was studied for various sampling rate and compared with the conventional rule based EMS. Based on the study an appropriate sampling rate was fixed in the proposed EMS for the real world studies.

In real world driving estimated trip energy can vary either due to limitations of estimation or a change in driving conditions. The proposed EMS vehicle performance was studied for under and over estimation of the trip energy (±15%) along with varied initial SOC and compared with the conventional rule based EMS in chapter 11. This study is called an adaptability study.

In chapter 12 as part of the validation for real world driving, the proposed EMS working was studied over trips with varied sequences of road types and trip distances. This study mimics the real world driving where the destination and route information is known in advance but the actual trip demand is uncertain. Adaptability (chapter 11) and validation (chapter 12) study also demonstrates robustness of the proposed EMS to varied uncertainties of real world driving.

Last part includes an overall discussion about the proposed EMS salient features and its contrast with other EMS methods in chapter 13. Also evaluation results are discussed with the context of significance, and the requirements of real world driving followed by suggestion for future work.

Finally in chapter 14 overall conclusions of the design and evaluation of a proposed EMS for real world driving are presented.

1.6 Summary

This thesis explores the design and evaluation of a proposed EMS considering uncertain trip demand in real world driving for a plug in hybrid electric vehicle (PHEV). The proposed acausal EMS formulation needs to be based on a relatively less dynamic parameter and not over vehicle speed profiles as usually seen. The real time capable EMS has to adapt to the uncertainties of trip demand and varied driving conditions to deliver efficient performance. This thesis concludes with a design and evaluation of such an EMS. The main contribution is the proposed acausal EMS is formulated over driving information and vehicle trip energy. This is in contrast to the existing EMS methods which are focused on the vehicle speed profile. The proposed EMS evaluation demonstrates superior vehicle performance than a conventional rule based for a full parallel PHEV over the uncertain trip demand and varied driving scenarios as in real world driving. The key novelty is to use the vehicle trip energy in the formulation which enabled rule based EMS to be acausal and potentially real time capable.

Chapter 2 – Introduction to Hybrid Electric Vehicle and Energy Management System

2.1 Introduction

This chapter introduces hybrid electric vehicles (HEV) and its EMS. First the main features of HEV are described and contrasted to a conventional vehicle. Next, HEV and plug in HEV (PHEV) differences are compared. Then types of HEV architecture are discussed in view of their power train arrangements followed by their merits and demerits. Next the function of the EMS and the types of control strategies used in HEV and PHEV are explained. This chapter also includes background about hybrid vehicle main powertrain system characteristics and limitations. This aids in understanding some of the terms and methods discussed in following chapters.

2.2 Hybrid electric vehicle

In conventional vehicles internal combustion (IC) engine is the only power plant. The engine meets all the vehicle demand from no load (idle) condition to peak load starting from steady state to transient operating conditions. In conventional vehicle there is no scope for the discrete engine operation.

A vehicle with more than one power plant is known as a hybrid vehicle. The term HEV refers to vehicles with an IC engine and at least one electric motor/generator (Chan, 2002). Hybrid vehicle can also refer to fuel cell hybrid vehicle.

2.2.1 Hybrid and conventional vehicle comparison

HEV fuel economy and emissions are typically better than conventional vehicles due to following main features:

- Energy recovery and reuse – regenerative braking: Part of the braking energy is recovered using regenerative braking and stored in the battery which in conventional vehicles is lost in the form of heat. During regenerative braking, the electric machine is engaged in generator mode to partially recuperate braking energy.
- Engine downsizing: Smaller and more efficient engine can be used. This is due to either engine not being the sole powertrain to meet the peak vehicle demand (such as electric boost) or engine not meeting the vehicle demand directly.
- High efficiency and steady state engine operation control: Unlike in a conventional vehicle, the engine operation is controlled to avoid inefficient and high emissions regions. At these points motor operation is preferred. More about the engine operation in HEV is discussed later in section 2.3.1. During engine operation, any extra engine power generated after meeting the vehicle demand is stored in the battery. Second feature is engine which prefers steady state operation can be used to supply the average vehicle power. The electric motor can be used to supply the dynamic power.

Compared to a conventional vehicle, a typical HEV will reduce gasoline consumption by approximately 30% (Markel and Simpson, 2006). The HEV fuel economy and emissions improvement strongly depends on EMS.

2.2.2 HEV and PHEV comparison

Plug in HEV (PHEV) provides additional flexibility in recharging the vehicle battery using the external electric grid and thus promoting more use of electric power. In PHEV, the major part of the vehicle demand is met by the electricity from the electric grid. Exclusive electric drive or electric vehicle (EV) mode is another distinction of PHEV in comparison to HEV. PHEV comes with a large battery pack which gives greater flexibility to choose between the power plant operating points during the trips. For the same reason, EMS for PHEV is complex in comparison to HEV. However PHEV is expected to reduce gasoline consumption by 40 to 60% to that of conventional vehicle (Elgowainy et al., 2009). Hence some of the latest hybrid vehicles introduced in productions are PHEVs such as Toyota Prius and GM Volt. Due to superior vehicle performance and latest trend in production vehicles, PHEV was considered for the EMS design and evaluation in this thesis.

2.2.3 Types of hybrid electric vehicle

Based on vehicle architecture HEVs are classified as (Chan, 2007)

- Series HEV
- Parallel HEV
- Series-parallel HEV and
- Complex HEV

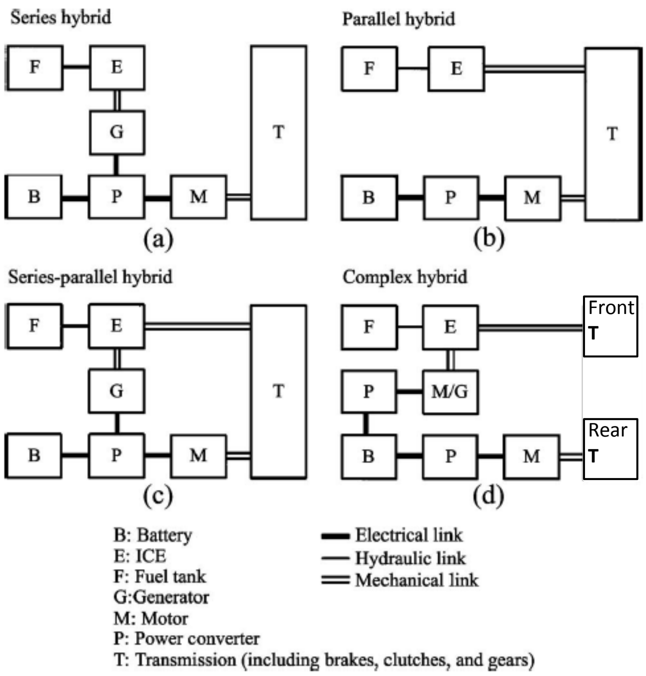

Figure 2-1: Common architecture of HEV (Chan, 2007)

A detailed classification, including benefits and limitation of hybrids is found in Ehsani et al (2004); a brief summary is given here.

2.2.3.1 Series HEV

In a series HEV, the vehicle is always driven by the electric motor like in a (pure) electric vehicle. The IC engine is not coupled to drive the wheels directly. This gives the freedom to operate the engine independent of the vehicle speed and only at the most efficient region. The output from the engine is used to charge the battery or to provide the propulsive power to the wheels through the motor. In PHEVs, as the engine is used only to extend the range it is also called as range extender or range extended electric vehicle (REEV). Series HEV is the simplest architecture as shown in Figure 2-1(a). In the figure, the electric machine M (traction motor) can be operated both as motor and generator. The electric generator G is primarily operated as generator and also can operate as motor to crank the engine E. Single power plant to drive the wheels simplifies control strategy. However a big electric machine M is required since it is the only source of the driven wheels. But this in turn can make multi gear transmission unnecessary due to ideal torque – speed characteristics of electric machine (Ehsani et al., 2004). This results in simpler architecture, drivetrain control and easy packaging. Simple architecture and limited power plant control options leads to the simplest control strategy.

In a series hybrid, the engine mechanical power is converted to electric power and then again to mechanical power which introduces energy conversion losses. From the Figure 2-2, minimum losses can be 25%; Efficiency of motor x battery charge x battery discharge x generator = 0.9 x 0.96 x 0.96 x 0.9.

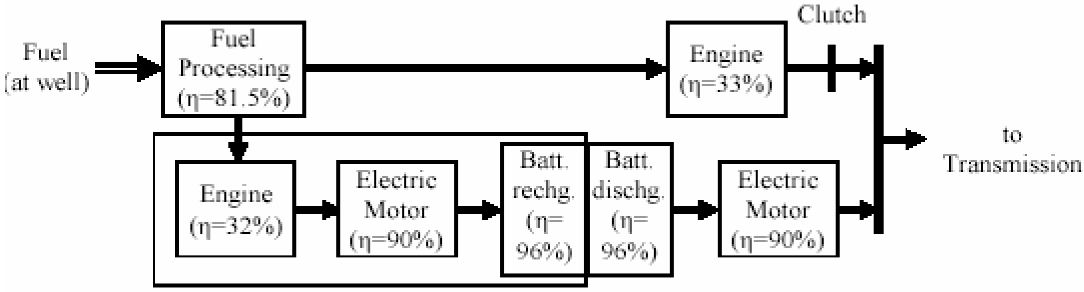

Figure 2-2: Typical HEV efficiency (Miller et al., 2003)

Hence series hybrids are suitable as urban vehicles for short trip and not suitable for long trip due to limited battery range and energy conversion losses. Series architecture is commonly used in heavy vehicles, military vehicles and buses (Ehsani et al., 2007).

2.2.3.2 Parallel HEV

In a parallel HEV (Figure 2-1(b)) both the engine and the motor can directly drive the wheels. Excess power from the engine is absorbed by the electric machine engaged in generator mode to charge the battery. Also if the vehicle power demand is higher than the engine output power, the electric motor can supply the difference, called as the motor boost (or electric boost). Similarly use of supplementary engine power along with motor output power is called the engine boost. Hence control strategy of parallel hybrids is more complex than series as both power plants can drive the vehicle directly and also simultaneously.

Unlike in a series HEV, the engine speed is dictated by the vehicle speed. Parallel hybrids have comparatively smaller electric machine and battery than series HEV, which may reduce the potential for regenerative braking. For long trips, parallel hybrids are suitable as the engine can drive the vehicle directly without energy conversion losses which in turn improves fuel economy. Passenger cars such as Honda Insight and Ford Escape use parallel architecture.

Usually any EMS demonstration using parallel architecture is equally applicable to derivative architectures like series-parallel and complex hybrid. This may be the reason majority of the researchers' (Kutter and Baker, 2010, Wirasingha and Emadi, 2011, Tulpule et al., 2009, Langari and Jong-Seob, 2005) including this author preferred parallel hybrids.

2.2.3.3 Series-parallel HEV

A series-parallel architecture (Figure 2-1(c)) incorporates the features of both series and parallel HEV. Hence they combine the advantages of series and parallel architectures. However they require an additional mechanical link in comparison to series HEV and also an additional generator G in comparison to parallel HEV. Series-parallel HEVs are expensive and complicated. In power-split hybrids, the vehicle behaves as a series or parallel hybrid depending on the control action and planetary gears like in Toyota Prius. In regular series-parallel hybrids it is achieved by engagement/disengagement of one or two clutches. The salient feature of series-parallel over parallel HEV is the ability to operate the engine partially independent of the vehicle speed. In this way, the engine speed can be adjusted to its optimal region. In addition, in comparison to parallel architecture, the engine operation can be less transient (Çagatay Bayindir et al., 2011). Series – parallel HEVs are commonly used in passenger cars such as Toyota Prius and GM Volt.

2.2.3.4 Complex HEV

Vehicle architecture discussed so far are implemented for single axle propulsion; either front or rear wheels. Complex hybrids are designed for dual axle propulsion (Kumar et al., 2013). Complex hybrid architecture is similar to series-parallel. The key difference is in the bidirectional power flow of the electric machine in the complex HEV and the unidirectional power flow of the generator in the series-parallel HEV. The bidirectional power flow feature gives additional flexibility in operating modes. Complex HEV is adopted in production as shown in Figure 2-1(d). With three propulsion power (one engine and two machine) it gives versatile operating modes like regenerative braking and drive on all wheels which can significantly improve vehicle performance and fuel economy. However like series-parallel, complex hybrids are complex in structure and expensive (Chan, 2007).

All architectures have advantages and disadvantages. In a study (Freyermuth et al., 2007) considering series, parallel and power-split PHEVs over urban and extra urban driving cycles; Urban driving dynamometer schedule (UDDS) and highway fuel economy driving cycle (HWFET) was investigated. Power split architecture fuel economy was superior to parallel over UDDS and marginally inferior over HWFET. For both driving cycles series hybrid fuel economy was inferior to other architectures.

2.3 Energy management system

The function of the EMS is to decide between the hybrid vehicle power plants in order to meet the desired vehicle and component performances listed below for varied driving conditions (Chan and Wong, 2004, Musardo et al., 2005);

- Maximise fuel economy
- Minimise emissions
- Achieve good drivability and
- Maintain appropriate battery state of charge level

Also EMS is required to work in real time and at minimum monetary cost. EMS for hybrids is complicated and often has conflicting requirements. EMS are generally nonlinear, parameters are dynamic and operate under uncertain and changing conditions; for example, weather, trip demand, driver. Many of these parameters are difficult to control, formalise or measure (Liu, 2013).

The control strategy of the EMS varies based on the battery state of charge (SOC) and driving conditions, for a given vehicle. Also, the working of a EMS is a function of vehicle architecture and component size (Baumann et al., 2000). Vehicle architecture and component size set the possible layout(s) and limits to interact and control.

In the following sections characteristics and limitations of IC engine, battery and electric machine are discussed. This is followed by discussion about types of control strategies.

2.3.1 Engine operation in hybrid vehicles

In comparison to electric machine, IC engines are efficient only at certain loads and speeds. Typically it is known engine efficiency is higher at higher load (Ehsani et al., 2004) which are studied and leveraged in many EMS (Sharer et al., 2008, Wipke et al., 1999, Chan-Chiao et al., 2003, Miller et al., 2003) including Toyota Prius and Ford hybrid system (Miller, 2006). When it comes to hybrid vehicles, operating the engine in efficient regions alone does not guarantee minimum fuel consumption (Chen et al., 2010) as demonstrated later in chapter 8. This is due to the energy conversion losses associated due to converting mechanical power from engine to electric power and then again to mechanical power to drive the vehicle like in series HEV (Freyermuth et al., 2007). As discussed in a series vehicle architecture (Figure 2-2) this energy conversion minimum losses can be 25% (Miller et al., 2003). Hence energy conversion losses become critical for vehicle efficient engine operation.

During engine operation, it is also required to reduce emissions which may lead to a trade-off between emissions and efficiency to find the optimal operating point (OOP). However the majority of the EMS literature considers only fuel consumption for simplicity, in such cases OOP refers to the most efficient operating point. Normally in a series architecture the engine is operated only at OOP to charge the battery. In other architectures the engine is operated at wider engine speeds. Across the engine speeds optimal operating points are identified called as optimal operating line (OOL) as shown by the dashed line in Figure 2-3. In many EMS studied the engine is operated at or around OOL (Kessels et al., 2008, Baumann et al., 2000, O'Keefe and Markel, 2006) for parallel and its derivative architecture. In these architectures EMS has limited or no control over the engine speed.

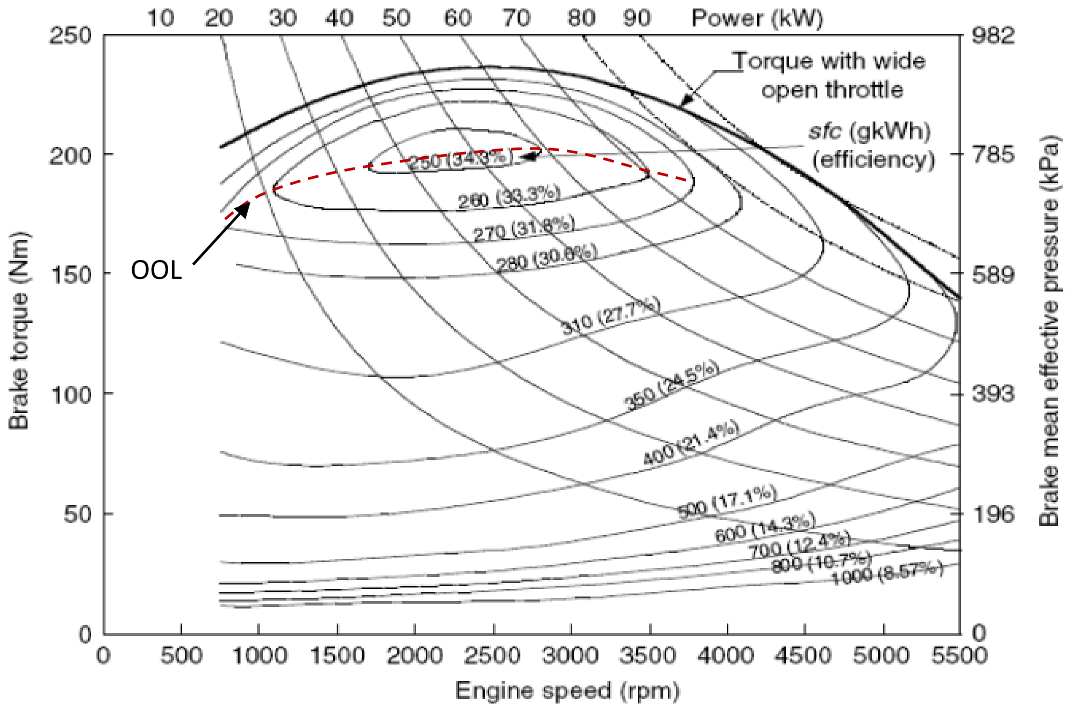

Figure 2-3: Engine optimal operating line (Ehsani et al., 2004)

At non efficient regions engine operation is avoided and the electric motor is used. So that at vehicle stop-start and low vehicle speed conditions only the electric motor is used and transient engine operations are minimised. This is one of the reasons for HEVs being efficient over conventional vehicles.

2.3.2 Battery in hybrid vehicles

Almost all hybrid vehicles use chemical batteries as their reversible energy storage system (Ehsani et al., 2007). Battery and electric machine are the main part of the electric drive train in hybrids. In hybrids the battery acts as buffer energy storage with respect to engine. This helps to avoid the transient operation of engine and operate at higher efficiency region. Also energy recovered during regenerative braking is stored in battery.

Energy density of battery in comparison to conventional fuel such as gasoline and diesel are low as shown in Figure 2-4. In automotive industry vehicle weight is crucial for fuel economy and emissions improvement. Also any increase in battery capacity leads to huge monitory cost. Limited battery capacity leads to limited electric range and peak vehicle performance. Other drawbacks of the battery is long (in hours) charging time.

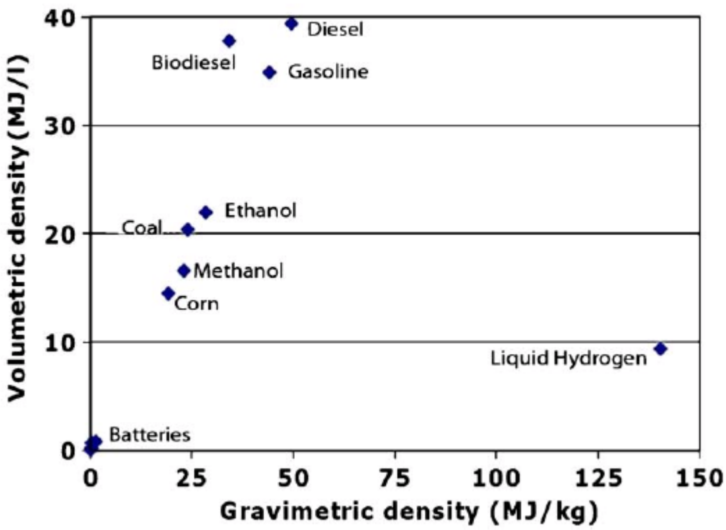

Figure 2-4: Energy density of batteries and liquid fuel (Fischer et al., 2009)

Depending on the battery chemistry, system configuration, battery (charging/discharging) efficiency is typically between 75 to 98% in the operable temperature and SOC range (Liu, 2013). Also the most efficient operation of the battery occurs in the low-power region for both battery charging and discharging (Schouten et al., 2002).

The state of charge (SOC) is the part of the energy remaining in the battery. Usable SOC has impact on battery life time. Life time is the ability of the battery to withstand degradation over time (Axsen et al., 2008). In a typical HEV usable SOC was about 10% - 20% with NiMH battery in order to ensure battery life of 10 to 15 years (Nemry et al., 2009). Hence most of the on board battery energy remains unused. With improved battery technology, the usable SOC window has increased to 80% with Li-Ion (deep discharge) with similar battery life like in PHEV (Contestabile et al., 2011). However this improved SOC window adds significant battery monetary cost (Markel and Simpson, 2006).

The peak current drawn from the battery depends on the battery (capacity and chemistry) and its SOC. Peak current available is proportional to open circuit voltage. In Figure 2-5 the relation between the open circuit voltage and SOC of a lithium-ion battery is shown. Hence this can limit the peak performance of the machine.

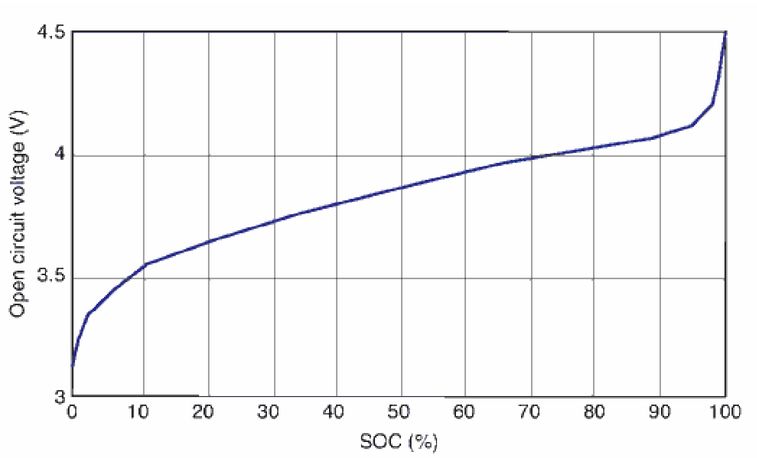

Figure 2-5: Relation between open circuit voltage and SOC of a lithium-ion battery (Liu, 2013)

2.3.3 Electric machine operation in hybrid vehicles

Compared to an engine, an electric machine is highly efficient over a wide range of speed and load condition as shown in Figure 2-6. The contours in the figure represent constant efficiency and can be seen to range from 65 – 92.5% efficiency. Hence the motor operation remains highly efficient irrespective of the vehicle demand. In other words motor can be used at vehicle low speed to high speed operation and at steady state to transient conditions without an appreciable drop in efficiency (unlike in an engine). Also it has been shown that the efficiency of the electric power plant energy path from the battery to the wheels is much higher than the engine power path (Katrašnik, 2011). However the peak electric machine performance can be limited by the peak current drawn from the battery which depends on the battery and its SOC.

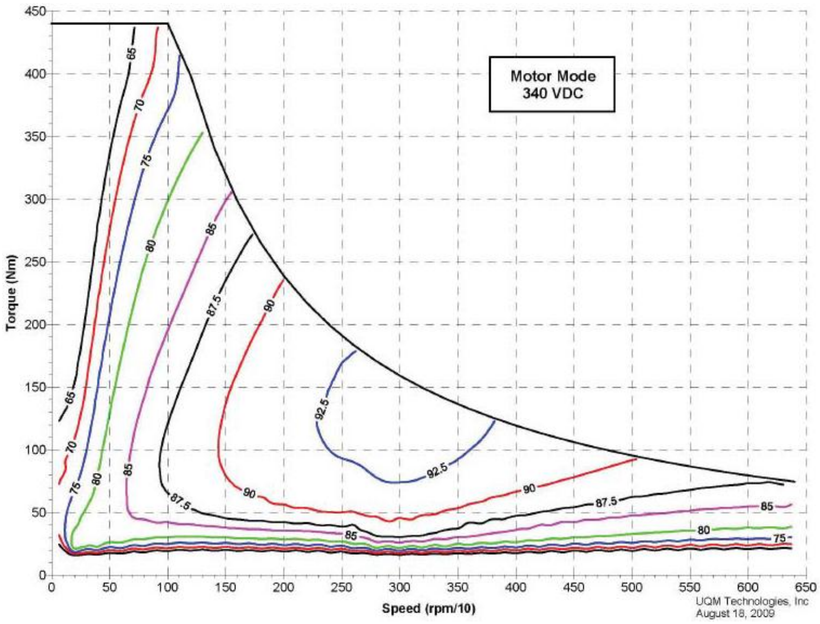

Figure 2-6: Electric motor efficiency map (2009).

Also due to the limited battery capacity electric vehicle (EV) range (distance) is limited in PHEV. Hence in PHEV EMS managing the electric range becomes the critical parameter rather than the electric machine operating point. To supplement the electric vehicle mode driving distance engine is used either by charging the battery or directly meeting the vehicle demand.

2.3.4 Summary of hybrid power train characteristics

In hybrid vehicles, the two power plants, electric power (machine and battery) and internal combustion engine have contrasting characteristics (Katrašnik, 2011). Electric machine operation is comparatively efficient at all vehicle operating conditions but electric range (distance) for PHEV is limited by the battery capacity. Vehicle operating conditions can be low to high vehicle speed and steady state to transient conditions with varying acceleration demands. The engine has comparatively no problem of range but is efficient in limited operating conditions – efficient at higher engine load. For vehicle efficient engine operation energy conversion losses becomes critical factor. In the next section EMS control strategies based on the use of engine and electric power are discussed.

2.3.5 EMS control strategies

Based on the primary use of the hybrid power plants an EMS control strategy can be classified into the following three strategies;

- Charge sustaining strategy (CS)
- Charge depleting – charge sustaining strategy (CD-CS)
- Blended charge depleting strategy (BCD)

2.3.5.1 Charge sustaining strategy

Charge sustaining strategy is used in all HEVs (Gao and Ehsani, 2010). Engine is used to maintain the battery SOC within the narrow limits. This limit SOC window is typically about 10 to 20% of the total battery SOC (Tulpule et al., 2009, Chen et al., 2010). During the trip SOC can increase or decrease within the SOC limits as shown in Figure 2-7. Ideally it is expected that SOC at the end of the trip is same as the initial or target SOC. The target SOC is at the centre of SOC limits. Due to the narrow SOC limits both engine and electric machine operations are constrained.

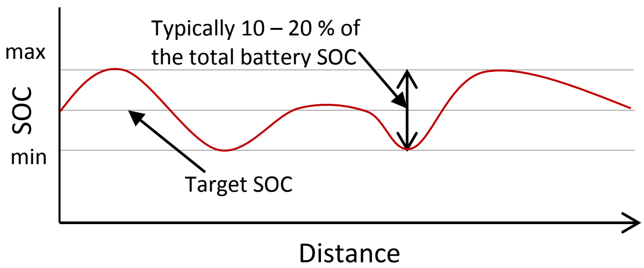

Figure 2-7: Charge sustaining strategy

2.3.5.2 Charge depleting - charge sustaining strategy

In production PHEVs only Charge depleting – charge sustaining (CD-CS) strategy is used as shown in Figure 2-8. The battery used for PHEVs are of larger capacity and have wider usable SOC window (95% to 25%) (Tulpule et al., 2009).

During charge depleting strategy primarily the electric energy is used to drive the vehicle until SOC reaches the minimum threshold. Engine may be used when vehicle demand exceeds motor or battery discharge power. Hence in CD the battery SOC over the trip will have a net decrease in stored energy as shown in Figure 2-8. The CS strategy is same as discussed earlier but with a smaller SOC window of 5% of full (usable) SOC (O'Keefe and Markel, 2006) and operating at lower SOC.

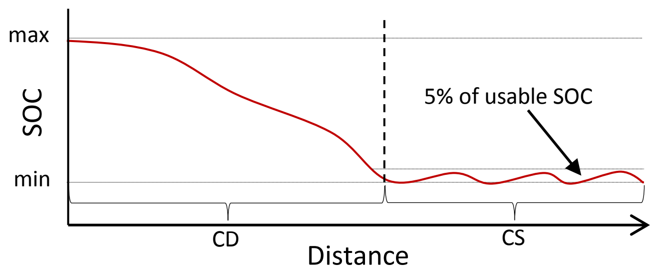

Figure 2-8: Charge depleting and charge sustaining strategy

Therefore for trips with in the electric vehicle range (distance) CD strategy is used initially. For distance beyond EV range CS strategy is used. The assumption is vehicles are frequently used with in electric range and hence only used in CD strategy. However this CD-CS strategy can lead to higher battery capacity to ensure the frequent travel distance is within the electric range (O'Keefe and Markel, 2006). Hence as the trip distance becomes longer the improvement in fuel economy benefits of the CD-CS strategy (PHEV) to that of CS strategy (HEV) becomes narrower (Tulpule et al., 2009). This is so as the CS strategy of the CD-CS strategy becomes prominent with longer trip distance.

2.3.5.3 Blended charge depleting strategy

Blended charge depleting (BCD) strategy use both electric and engine power throughout the journey at times when the system is more efficient (O'Keefe and Markel, 2006). BCD is used only in PHEVs. It is ideally expected SOC to be at the minimum towards the end of the trip as shown in Figure 2-9. Hence it is required to know the trip demand in advance to design the BCD strategy (Stockar et al., 2011). Based on the trip demand the efficient engine and motor operations over the trip are identified. In practice it is not possible to know the exact trip demand due to uncertainty. Hence under the uncertain trip demand conditions BCD strategy may be followed by a brief CS strategy (Gao and Ehsani, 2010, Overington and Rajakaruna, 2012). In current production PHEV, EMS considers only the current or instantaneous trip demand in devising the control strategy and hence BCD strategy is not used.

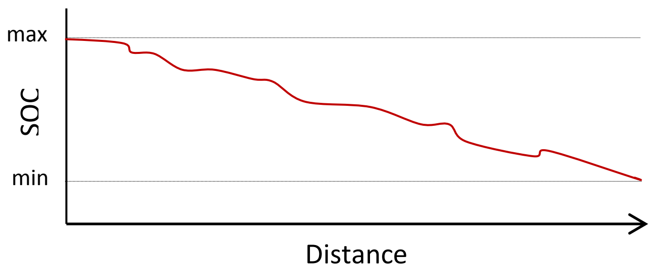

Figure 2-9: Blended charge depleting strategy

BCD strategy is also known as CD blended strategy. In many fuel economy comparison studies the BCD strategy was found superior to the CD-CS strategy (He et al., 2012a, Karbowski, 2006). However adaptability to changes in trip demand is paramount with BCD strategy which otherwise can compromise the fuel economy. Also use of the engine with higher SOC left at the end of the trip reduces PHEV fuel economy. It was demonstrated in a study (O'Keefe and Markel, 2006) in blended mode if the vehicle deviates from the target distance, the strategy uses more fuel than the CD-CS strategy.

2.3.5.4 Summary of control strategies

From the EMS perspective, PHEV control strategies (CD-CS and BCD strategy) are more complex than the HEV control strategy. BCD control strategy offers superior fuel economy in comparison to CD-CS strategy. Further EMS using BCD strategy is demanding and requires being anticipative of the trip demand and requires to be adaptive for efficient performance. This adds to the existing complication of the EMS. In current production vehicles CS and CD-CS strategy is used for HEV and PHEV respectively. Further these control strategies are discussed in review of the EMS methods in chapter 4.

2.4 European vehicle regulations

The Economic Commission for Europe (ECE) vehicle regulations governs the vehicle legislations such as the fuel economy and emissions for vehicles sold in the European market. As per the ECE vehicle regulation 101 (Nations, 2005) HEVs are categorised as not off-vehicle charging (NOVC) and off-vehicle charging (OVC) for non-plug in and plug in HEVs respectively.

2.4.1 NOVC vehicle regulations

Emissions of CO_2 and fuel consumption are determined for the specified driving cycle. Non-plug in HEVs pursues CS strategy. To account for the change in vehicle SOC as recorded during the test, the final fuel consumption and CO_2 emissions are corrected by a factor. The aim of this approach is to estimate the fuel consumption and emissions that represents zero energy balance of the battery throughout the test. The correction factors are determined by performing a series of tests starting at different initial SOC by the vehicle manufacturer.

2.4.2 OVC vehicle regulations (PHEV)

For PHEVs two tests are performed to determine the fuel consumption and CO_2 emissions for the specified driving cycle under the following conditions:

Condition A: Test with a fully charged electrical energy/power storage device (battery).

Condition B: Test with an electrical energy/power storage device in minimum SOC (fully depleted)

These two test results are combined with the vehicle's electric vehicle (EV) range and assumed distance of 25km between opportunities to recharge to determine an overall the final fuel consumption and CO_2 emissions results. To determine the EV range, the testing starts with the discharge of the battery by operating at a steady speed of 50 Kmph or as defined by the manufacturer till the battery reaches the minimum SOC without switching the engine on.

Say for CO_2 emissions weighted calculation,

$$C = (D_e\, C_1 + \ D_{av}\, C_2)/(D_e\ +\ D_{av}\,) \tag{2-1}$$

Where, C = mass emissions of CO_2 in gm/km; C_1 = mass emissions of CO_2 in gm/km with a fully charged battery; C_2 = mass emissions of CO_2 in gm/km with a battery in minimum SOC; D_e = vehicle's electric range and D_{av} = assumed average distance between two battery recharge, 25 km.

Similarly weighted vehicle fuel economy is calculated.

The test procedures with condition A and B reflects with respect to the CD and CS strategy respectively used in current production vehicles. Irrespective of the trip demand, first CD and then CS strategy is followed. But in BCD strategy there is no exclusive electric range as in CD-CS strategy. The engine and motor operations are defined with respective to the trip demand. Therefore the current test procedure does not capture the essence of the BCD strategy (Gerrit et al., 2012) and the test procedure development for such control strategy is a work in progress. In other words the test procedure as per the current regulation is not specifically addressed for the vehicle with BCD strategy. Hence this may not reflect the true benefit of the vehicle pursuing BCD strategy.

2.5 Summary

Hybrid vehicles typically deliver superior fuel economy and emissions performance in comparison to conventional vehicles. Hybrid vehicle is a complex system of electric and mechanical components. Further PHEV usually offers superior performance over HEV due to deep battery discharge and additional modes of powertrain operation. PHEV is considered for the EMS design and evaluation in this thesis.

Series and parallel are primary hybrid vehicle architecture used to derive series-parallel and complex architectures. Parallel hybrid architecture is widely used in EMS research and demonstration like in this thesis.

EMS plays a significant role in fuel economy and emissions performance of a vehicle. EMS for hybrids is complicated due to dynamic, multivariable and uncertain conditions with conflicting requirements.

Two power trains in hybrid vehicles have contrasting characteristics. Electric powertrain is relatively highly efficient over wide operating range but limited by battery capacity (EV distance). IC engines are efficient only at higher load but relatively not constrained by range (distance). Energy conversion loss is critical for vehicle efficient engine operation.

HEV use only CS strategy. In production PHEV only CD-CS strategy is used. EMS with the BCD strategy offers better fuel economy than the CD-CS strategy for a PHEV. However they need to be anticipative and adaptive to trip demand which can be demanding on EMS. The test procedures in the current ECE regulation for PHEVs reflect the CD-CS strategy only and not specifically addressed for BCD strategy.

Chapter 3 – Introduction to Driving cycles, Real World Driving and Review of Trip Modelling

3.1 Introduction

In the context of the vehicle trip demand considered in EMS design and evaluation, driving cycles and real world driving is introduced in this chapter. Also in real world driving the various factors which make vehicle speed highly dynamic, and trip demand uncertain, are discussed. Next in this chapter, real world driving and driving cycles are compared.

Later in this chapter some of the trip modelling techniques and intelligent transport system (ITS) and other data used to predict the trip vehicle speed profile is explained and reviewed. Trip modelling techniques which come across during the review of the EMS (in chapter 4) are considered for review. Like chapter 2, this chapter helps to understand some of the concepts, techniques and terms regarding vehicle trip demand used in following chapters.

3.2 Driving cycle

Vehicle speed (v) profile over the time (t) or distance (d) which is widely used for vehicle testing or other purpose is commonly referred as a driving cycle; v(t) or v(d). The vehicle speed profile for respective driving cycles is static and hence known in advance. The driving cycles can be legislative or non-legislative.

3.2.1 Legislative driving cycles

Legislative driving cycles (LDC) have been developed to measure the vehicle emissions and fuel economy, for a particular, or a combination of, driving conditions. Many LDCs representing each driving condition such as urban driving, extra urban driving, extra urban aggressive driving and low speed city driving exist. LDC varies from region to region (USA/EU/Japan).

To certify vehicle performances such as fuel economy, emissions and durability before introduction to market, vehicles are tested on LDCs relevant to their respective country. Hence both conventional and hybrid vehicles are engineered over legislative driving cycles to meet emission norms (such as EURO V) and to get the best fuel economy certified. Some examples of LDCs are NEDC (Figure 3-1) and Highway fuel economy test (HWFET).

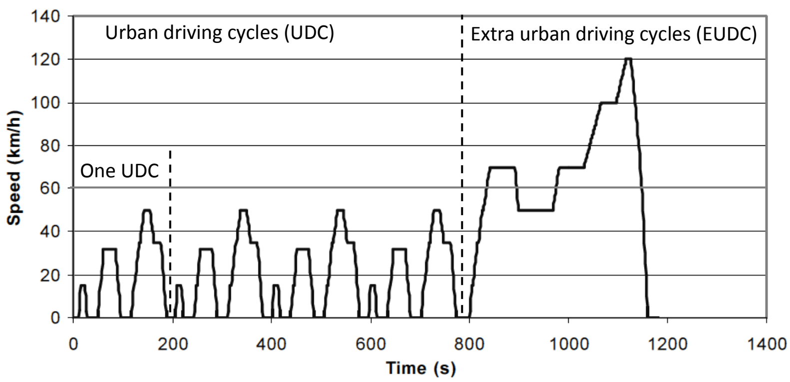

Figure 3-1: Legislative driving cycle - The NEDC (T J Barlow, 2009).

The NEDC has four ECE R15 cycles followed by one Extra Urban Driving Cycle (EUDC). ECE R15 cycle is an urban driving cycle, also known as Urban Driving Cycle (UDC) introduced by Economic Commission for Europe (ECE). UDC represents city driving conditions. R15 represents the type of regulation and in this case it is emissions and fuel consumption. EUDC represents high speed driving motorway or highway conditions. The NEDC is commonly used in EMS studies for comparison and validation.

3.2.2 Non-legislative driving cycles

As the name indicates driving cycles which are not used to certify vehicle performance can be called non-legislative driving cycles. They are mainly used for vehicular emissions calculation and emission modelling based on time (per day, month and year) and region (urban, rural and national level)(Michel, 2004, Andre et al., 2008). Some examples are Assessment and Reliability Transport Emission Models and Inventory Systems (ARTEMIS) driving cycles as shown in Figure 3-2, EMPA (test cycle developed by one of the Swiss research institute, EMPA) driving cycles and Traffic management and air quality (TRAMAQ) driving cycles (T J. Barlow et al., 2009). These driving cycles are also used for vehicle durability assessment and study.

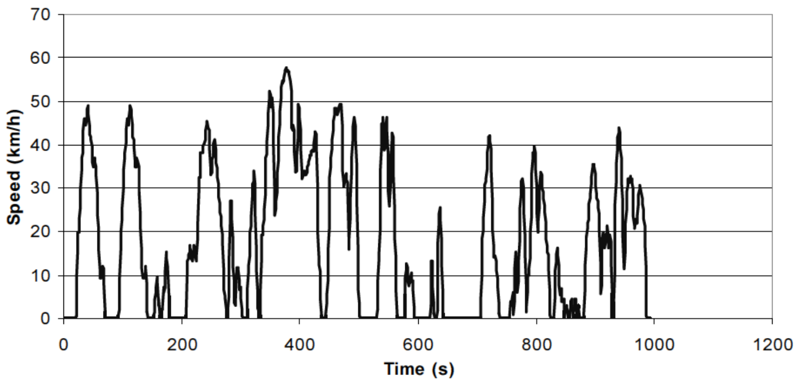

Figure 3-2: Real world driving cycle - Artemis urban driving cycle (T J Barlow, 2009).

Next the Sierra driving cycles which were used in one of the EMS research work reviewed in the next chapter are discussed. The Sierra research institute developed a set of 11 driving cycles (Carlson and Austin, 1997) that represents passenger car and light truck operation over a variety of road types for a variety of congestion levels, as shown in Figure 3-3. These driving cycles are referred as Sierra driving cycles. The road types considered are motorway, arterial or ring road and local roadway are categorised into a specific driving cycle based on the concept of Level of Service (LOS). This is a qualitative measure describing operational conditions such as vehicle speed, travel time, freedom to manoeuvre, traffic interruptions, comfort and convenience. Six types of LOS are defined for each road types. These are labelled from A to F, with LOS A representing the less transient (best) operating conditions and LOS F the more transient operation (worst) (Langari and Jong-Seob, 2005).

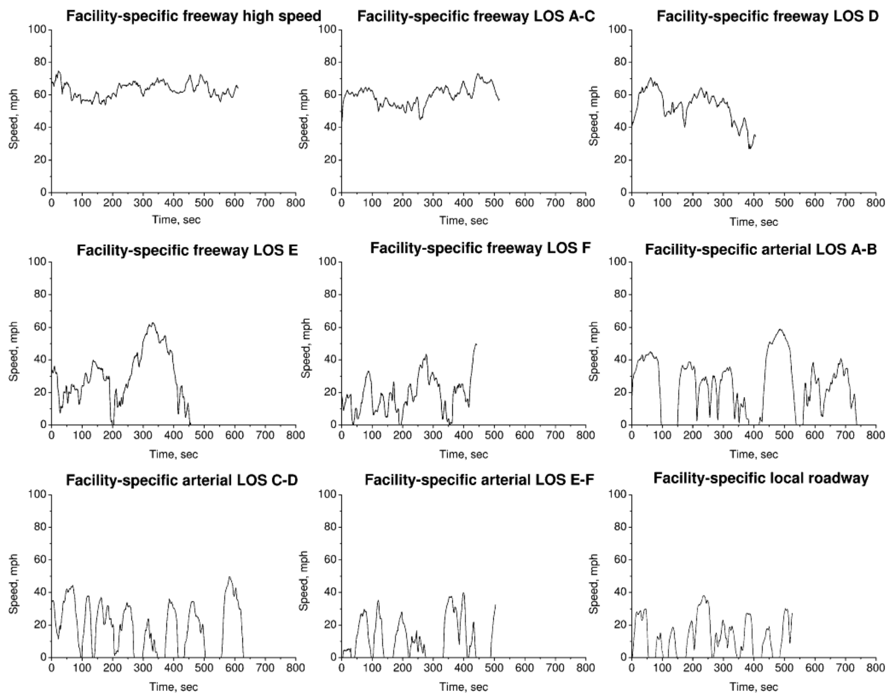

Figure 3-3: Sierra driving cycles (Langari and Jong-Seob, 2005).

In EMS research and development some of the legislative and non-legislative driving cycles are commonly used for calibration, validation and comparison studies. These driving cycles are also used for trip modelling which is discussed later in this chapter. In the next section the term 'real world driving' which is frequently referred to in EMS discussion and in specific to this thesis is discussed.

3.3 Real world driving

The interaction of vehicle, driver and driving environment (real world) is called real world driving in this thesis based on (Cacciabue and Carsten, 2010). Even though real world driving is frequently used in automotive industry it is not very well defined. In real world driving vehicle speed or trip demand is mainly influenced by type of vehicle, driver style, traffic, road type, elevation and weather (Ericsson, 2000). In the following sections some of the terms used in the thesis with respect to real world driving are explained.

3.3.1 Vehicle type

Vehicle type refers to specific kind and make of a vehicle. In terms of kind, vehicle type can be a car, bus, trucks and other vehicles. For a given type of car say a sports car from different manufacturers' (make) car can be of different vehicle specification and performance. Similarly for a given manufacturer type of cars say sports or regular can be different. This can be due to the vehicle weight or powertrain performance. Vehicle type refers to these aspects of vehicles.

In real world driving, an individual may drive a sports car different from a commuting or basic car for the same route because of rich vehicle dynamics, feel and higher vehicle power. Similar logic applies to bus and trucks may be for same or different reason such as driver objective. Hence type of vehicle influence vehicle speed. However in this thesis the research is carried out for a given vehicle and hence there is no scope for the vehicle type.

3.3.2 Road type

A driving route can be divided into many types based on their main characteristics such as speed limits, street furniture (traffic light, crossing, etc.), traffic, and road width. In this thesis considering characteristic differences in vehicle speed or trip demand road types mainly refers to urban and extra urban driving.

3.3.3 Driver style

Driver has own characteristic way of driving a vehicle like starting, accelerating, stopping and cruising. For a given condition, the variation in vehicle speed due to the driver behaviour is called as driver style. This is defined based on literature (Ericsson, 2000, Cacciabue and Carsten, 2010).

In terms of vehicle speed, even for a given driver and event – for example accelerating from stop in urban driving, it can be a range of speed profile as shown in Figure 3-4. Variation in speed may be due to the natural variation of the driver (as drivers are not robot), driver style and perception of external factors like location, traffic and other vehicles around at that time. Figure 3-4 is part of the preliminary real world data study explained later in chapter 5 with Figure 5-3.

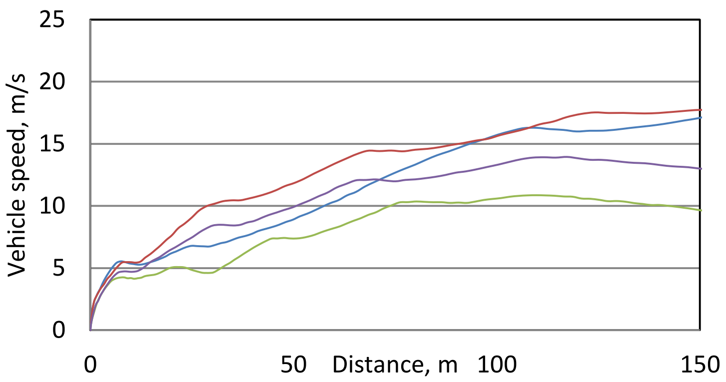

Figure 3-4: Accelerating vehicle speed profile of a driver at different points in a trip.

Further the variation of traffic, elevation and weather can effect vehicle speed in real world driving. These factors if required can be considered through road types either as a separate road type or as sub-functions of the main road types. In a study (Ericsson, 2000) it was found road type had the greatest influence on vehicle speed profiles. This is followed by driver styles and traffic. Road types, driver style and traffic are considered as part of driving information in the formulation and design of a proposed EMS as discussed in section 7.2. Later for the evaluation studies of a proposed EMS in this thesis influence of road types for a given driver style was considered. However the influence of traffic was not considered in the proposed EMS performance studies for simplicity.

3.3.4 Difference between driving cycles and real world driving

In real world driving vehicle speed (or profile) has no concept of v(t) or v(d) as discussed with driving cycles. Driving cycles are static in nature. In real world driving, vehicle is not driven with respect to a driving cycle but to a particular conditions or situations to reach the destination. A driver perceives to drive or reacts to a situation (or event) and *generates* a vehicle speed profile. These reactions (vehicle speed) are also restrained by the type of vehicle (vehicle type) and road type (urban / extra urban) for a given driver but may not be repetitive.

This vehicle speed profile most likely to be different from day to day / time to time in real world driving. This situation or event need not be repetitive, due to variability in external factors. In addition the driver himself need not display the same vehicle speed profile for a given situation, leading to no repeatability even for given factors.

The dynamic nature of driver style and other external factors such as traffic makes vehicle speed profile highly dynamic in real world driving. Therefore the prediction of exact vehicle speed profile is not possible (Guzzella and Sciarretta, 2007, Serrao, 2009). Hence it is advisable to consider the trip demand not in terms of vehicle speed profile for real world driving. In real world driving the trip demand is a function of situation or events such as road types, driver style and vehicle type. Finally trip demand need not be repetitive and can have variation within the limits set by driver style and road types for a given vehicle. Trip demand in real world driving is not a fixed series of vehicle speed based on time or distance (v(t) or v(d)) like in the driving cycles. From EMS point of view to address dynamic and uncertain trip demand, EMS has to be adaptive in real world driving.

3.3.5 Summary of real world driving

In real world driving, vehicle speed profile is highly dynamic and difficult to predict. Hence it is advisable to consider the trip demand not in terms of vehicle speed profile for real world driving. Trip demand in real world driving has no correlation to driving cycles which is static. It is a function of series of situation or events such as road types for a given vehicle and driver. In real world driving trip demand is stochastic. Variation may be due to driver natural variation or external factors. To address uncertain trip demand EMS has to be adaptive in real world driving.

However there are many methods used for vehicle speed profile prediction for a trip known as trip modelling discussed in the following sections.

3.4 Trip modelling methods

In this section some of the widely used techniques and data in trip modelling for EMS are discussed and reviewed. Trip vehicle speed profile prediction models are known as trip modelling in this thesis. Based on the predicted vehicle speed profile for the trip, EMS devises control strategy which is reviewed in the next chapter. Before that the use of intelligent transport system (ITS) and logged historic data as trip vehicle speed profile is discussed and reviewed.

3.4.1 Intelligent Transport System data

Intelligent transport system (ITS) data are used either as a primary data (as it is) or as a secondary data (with trip modelling) as discussed below.

In recent studies instead of prediction, historic vehicle speed profile data collected by ITS is used in EMS as future vehicle speed profile (Qiuming et al., 2007). In Qiuming et al study vehicle speed - time series aggregate data for ten weekdays was used to develop an extra urban driving cycle.

As part of ITS, WisTransPortal supported by the University of Wisconsin – Madison, data is collected from detectors placed along the road to measure vehicle volume, speed and occupancy for purposes of corridor-based performance analysis and extra urban management. In WisTransPortal, corridor-based performance refers to the data related to a particular region/geography. Each detector records data at 5 minute intervals. From this aggregate data vehicle speed and occupancy for a region (vehicle density) is generated (Parker et al., 2007). So, ITS vehicle speed data is an aggregate data of various vehicle type and driver style. Due to dynamic variance in vehicle speed this cannot reflect the true trip demand.

However use of ITS data as a future driving cycle in EMS may be better than prediction model based on legislative driving cycle like in (Dean et al., 2008, Chan-Chiao et al., 2004) and simpler to implement than the vehicle speed trip model which is computationally demanding. But ITS data is an aggregate data using it as a secondary data may be ideally recommended. As secondary data it may serve as a base data upon which actual prediction model may be developed with calibration of fewer parameters. This in turn can save precious computational resource.

3.4.2 Logged historic data

Logged historic vehicle speed profile data refers to data logged for a given vehicle, driver style and destination. Similar to ITS data other logged (historic) vehicle speed profile data for a given vehicle and driver is used in study assuming to remain same for the future trip (Kessels, 2007). Logged data are better than ITS data as they are specific to a vehicle and driver. However such data assuming to be the same for the future trip is not realistic in real world driving.

3.4.3 Trip modelling

In the following section prominent trip modelling techniques are described and reviewed.

3.4.3.1 Markov process

A Markov process is a stochastic process with the following properties:

- The number of possible outcomes or states is finite.
- The outcome at any stage depends only on the outcome of the previous stage.
- The probabilities are constant over time.

Markov process is useful to analyse dependent random events – events whose likelihood depends upon what happened last. A Markov model can look at a series of events and analyse the likelihood that one kind of event is followed by another based on probabilities. The model output stream of events would reflect the transition probabilities derived from the observed data. This stream of events is called as Markov chain (Grinstead and Snell, 1997).

For EMS, Markov model is used for trip modelling where the transition probabilities of vehicle speed are determined based on legislative and/or non-legislative driving cycles (Chan-Chiao et al., 2004, Dean et al., 2008, Cairano et al., 2013). In this set up it is called as Markovian driver. However in real world driving the vehicle speed is not deterministic and transition happens based on various driving factors and some of these may be fixed for a given route and time. Transition of vehicle speeds in real world driving is dynamic and difficult to model especially based on driving cycles.

Similarly a trip prediction model was presented (Johannesson, 2009) for a prescribed route. In the study vehicle speed profiles were collected 37 times for a given route and driver. The route considered was divided into several sections. For each section a Markov position dependent transition matrix as a function of speed and acceleration was developed. Based on current vehicle location and speed, acceleration was predicted. Effect of dynamic factors like traffic or time of travel and influence of driver style was not considered. The prediction model was not validated against an individual logged vehicle speed profile to get insight about effectiveness of prediction. However this method may be applicable for a known mean and variance of the speed. Further this method requires a set of Markov transition models for each section in the route composed of many sections. This may be computationally demanding considering varied real world driving conditions.

Note that these models perform only limited prediction at each time and not the entire trip vehicle speed profile. These limited predictions are dependent on current and past data.

3.4.3.2 Model predictive control (MPC)

Model predictive control (MPC) can easily handle non-linear time varying system, since the controller is explicitly the function of the model that can be modified in real time.

Future values of output variables are predicted using a dynamic model of the process and current measurements. A history of past system data is required. A reference trajectory to the prediction has to be defined. The predictions are made for more than one time delay ahead as shown in Figure 3-5.

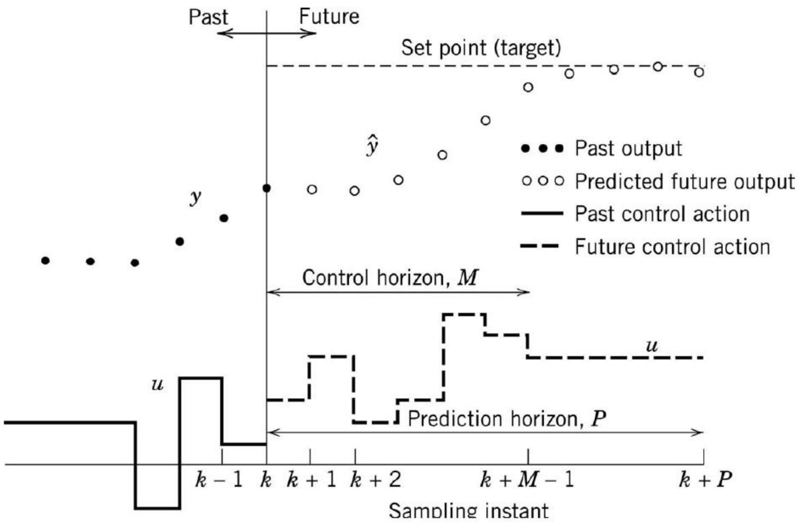

Figure 3-5: Model predictive control - Basic concept (Re et al., 2009)

The window of time (or distance) considered for prediction is known as prediction horizon (P). Then there is control horizon (M) which revises prediction made based on the deviations in predictions from the reference trajectory over the next prediction horizon while satisfying the constraint. Based on the control action, prediction horizons are revised. However only the prediction variable values u(k) (input) corresponding to the next sampling time is implemented. At the next sampling instant (k+1), based on deviation the control horizon is re-calculated to take control action. This continues with each time step and this approach is known as receding horizon approach (Qina and Badgwellb, 2003, Allgöwer et al., 2004). Set point in trip modelling is the trip destination point.

One of the techniques used in the prediction horizon is assuming constant speed and elevation using geographical position system (GPS)(Koot et al., 2005). MPC may also use detailed navigation system with curve radius, speed limits, crossing, traffic light, etc., In MPC updated prediction is made at each time step over a limited prediction horizon during the trip (Koot et al., 2005, Maciejowski, 2001). MPC requires high computational effort (Serrao et al., 2011).

3.4.3.3 Artificial Neural Network (ANN)

Artificial Neural Network (ANN) is a system based on the operation of biological neural networks. A neural network is a parallel system, capable of resolving models that linear computing cannot. When an element of the network fails, it continues to perform without any problem due to parallel nature as shown in Figure 3-6. A neural network learns on its own and may not require reprogramming.

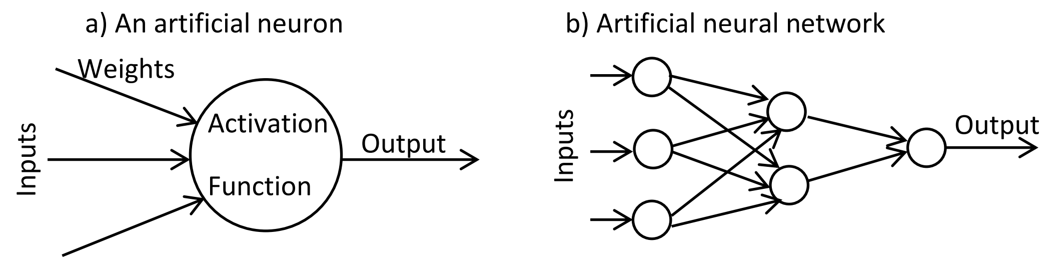

Figure 3-6: Artificial neural network

ANNs combine artificial neurons in order to process information. The higher the weight of an artificial neuron is, the stronger the input which is multiplied by. Weights can also be negative, so we can say that the signal is inhibited by the negative weight. Depending on the weights, the computation of the neuron will be different. By adjusting the weights of an artificial neuron, the desired output is obtained for a set of specific inputs. For a large network algorithms are used to find appropriate weights in order to obtain the desired output from the network. This process of adjusting the weights is called learning or training (Gershenson, 2008). The limitations of ANN are a large data is required to train ANN to operate and requires high computational time for large networks (Wirasingha and Emadi, 2011).

For vehicle speed profile prediction, function of vehicle speed like location, speed limits, vehicle and other parameters speed can be considered as input. The weights to inputs can be identified based on training over actual data.

A feed forward artificial neural network (ANN) was used for trip modelling using ITS data (Qiuming and Yaoyu, 2009) and compared against real test data for extra urban driving. Real test data is GPS logged data (10 days) for the same route as the ITS data considered. ANN is trained using real test data and ITS data of that particular destination. The prediction method was validated against real test data with ITS data which were not part of the training. In the study trip prediction of ANN model with ITS data was more accurate than ITS data alone. In this study vehicle speed profile for the whole trip was predicted. In the study the scope for the trip prediction update on the fly was not considered. Considering real world driving being dynamic and uncertain in nature, prediction correction is necessary. However, ANN approach needs a large processor and slow processing times adding to the system complexity (Wirasingha and Emadi, 2011). More importantly prior knowledge of the trip vehicle speed profile is required to make prediction.

3.4.3.4 Summary of trip modelling

Trip prediction models are studied most of the time in predicting known vehicle speed profile such as legislative driving cycles. In such cases there is no role for disturbance or uncertainty. Prediction using historic logged data and ITS data of a given trip was also considered in a few studies. However prediction validation was considered in one of the ANN study. But the validation was done for the same trip of which historic measured and ITS data was considered. Hence for the current trip modelling techniques prior knowledge of the trip vehicle speed profile is required. In other words these trip modelling approaches are vulnerable outside the destination (or historic) data considered. These methods are data intensive and for varied trip conditions like in real world driving it becomes aggravated. In addition they are computationally demanding to operate in real time.

In both Markovian and MPC models predictions are for a limited period (or window) which gets updated during the journey. They do not predict the entire vehicle speed profile. In the ANN study the entire vehicle speed profile was predicted.

MPC updates the prediction to minimise the deviation and this is necessary consider dynamic and uncertainty of real world driving. However the prediction updates depends on the reference value considered in the MPC model. Similarly in Markovian driver's prediction depends on the data set considered. In ANN study prediction correction was not considered which is required in real world driving. But this can complicate the computation further.

Further in trip modelling, trip demand is modelled to predict in terms of vehicle speed profile. In real world driving vehicle speeds are highly dynamic and uncertain nature risks prediction accuracy (discussed earlier in section 3.3).

3.5 Summary

In driving cycles vehicle speeds are predefined over time or distance; v(t) or v(d). In real world driving vehicle speed is a function of driving information such as driver style, vehicle type, road type and traffic. Many of these factors are dynamic and hence not possible to predict the exact vehicle speed profile in real world driving. Hence it is advisable to consider the trip demand not in terms of vehicle speed profile for real world driving. Trip demand in real world driving has no correlation to driving cycles. It is a function of series of situation or events such as road types for a given vehicle and driver. For real world driving trip demand is not exact and has variation; natural driver induced or due to external factors. Therefore from the EMS point of view as the trip demand is uncertain it has to be adaptive in real world driving. Driving information is to be considered in the design and formulation of a proposed EMS.

Most of the trip modelling studies used driving cycles. In a few studies real world logged or ITS data was used for prediction. MPC has the ability to update the prediction which is necessary considering uncertain and dynamic nature of real world driving. Prediction correction was not considered in ANN model. Only in one of the ANN trip modelling predicted vehicle speed profile was validated against real test data of the destination considered.

In all trip modelling techniques prior knowledge of the trip vehicle speed profile is required to make the prediction. No model was validated for the destination outside the test destination considered for modelling. Hence prediction outside the historic data or trip destination considered is a suspect.

Trip modelling methods are data intensive and computationally demanding. Trip modelling techniques predict trip demand in terms of vehicle speed profile which has limitations in real world driving.

Chapter 4 – Review of Energy Management System

4.1 Introduction

Purpose of this chapter is to show the state of the art and research gap in EMS methods for real world driving. Before the review of EMS, simulation model classification used in EMS study and EMS classification based on type of inputs are introduced. From the literature EMS methods are reviewed based on formulation, vehicle performance, real time capability and limitation with respect to real world driving. Later in the chapter the requirement and limitations of EMS for real world driving is summarised.

4.2 Simulation model classification

Simulation models used in EMS literature are classified based on the direction of power flow calculation as discussed below; a) backward and b) forward facing model.

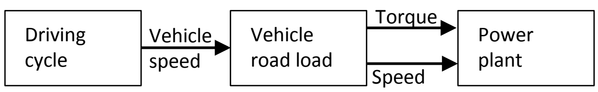

Figure 4-1: A schematic of backward facing model

4.2.1 Backward facing model:

In backward-facing simulation model, power flow calculations are conducted backwards relative to the flow of tractive power in the real vehicle. Such models are used only for simulation and are computationally less demanding. They consider only the vehicle road load with respect to the driving cycle considered as shown in Figure 4-1. In these EMS models the role of a driver is not considered and the required vehicle speed is directly sent to the vehicle road load model. The required vehicle torque and speed is calculated by the vehicle road load model based on the driving cycle vehicle speed and vehicle road load resistance. Regarding vehicle road load resistance calculation refer M Ehsani et al (2004). Powertrain performance is determined based on required vehicle torque and speed.

4.2.2 Forward facing model

In a forward-facing model, the power flow calculations are conducted in the direction of tractive energy flow. Therefore, this approach simulates the real driving process, in which the vehicle is accelerated according to the driver's acceleration and braking commands. Such models are widely used for simulation and vehicle implementation of EMS. These models are computationally demanding as they require more detailed modelling like vehicle dynamics in vehicle model and driver model as shown in Figure 4-2. In the typical simulation the driver model give out command to define throttle and brake pedal position to follow the predefined vehicle speed profile. From the figure it is also clear that it is closed loop approach based on actual and desired vehicle speed. Typically Proportional – Integral – Derivative (PID) controllers are used for the driver model during simulation.

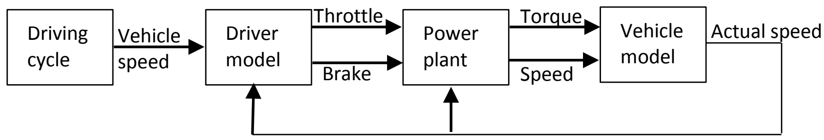

Figure 4-2: A schematic of forward facing model

From an EMS point of view, a forward facing model is preferred as it mimics the physical causality of the real system (Serrao et al., 2011).

4.3 EMS classification

Based on the type of inputs used EMS is divided into causal and acausal EMS.

4.3.1 Causal EMS

A causal system output is dependent on past/current inputs and does not anticipate the future values of input (Oppenheim et al., 1997, Wirasingha and Emadi, 2011) . A causal EMS devises control strategy based on instantaneous vehicle demand, current vehicle parameters and set threshold values (Wirasingha and Emadi, 2011). These threshold values are typically tuned over a set of legislative driving cycles. They do not consider future trip demand.

4.3.2 Acausal EMS

An acausal system output depends on some future input values and possibly on some input values from the past or present (Oppenheim et al., 1997, Wirasingha and Emadi, 2011). Typical acausal EMS considers inputs about the predicted/estimated whole (or global) trip demand in devising the control strategy along with other variables (Wirasingha and Emadi, 2011, Salmasi, 2007). Acausal system is also known as non-causal system.

In comparison to causal EMS, acausal EMS enhances the fuel economy, emission and component performance of hybrid vehicles (Sciarretta and Guzzella, 2007, Wu et al., 2011). Acausal EMS devises control strategy based on the respective future trip demand and battery SOC.

4.4 Review of energy management system

In this section EMS methods are reviewed over their objective, method, formulation, vehicle performance, real time capability and limitations in terms of real world driving. Based on the mathematical models EMS are commonly classified into two types. They are,

- Rule based EMS
- Optimisation based EMS

Many methods under these two models are reviewed in the following sections.

4.4.1 Rule based EMS

Rule based EMS is also called heuristic EMS. A typical rule based EMS is defined based on the instantaneous torque demand, vehicle speed and battery SOC. Such EMS are defined using if-then-else condition and efficiency maps. The optimality of a solution for rule based

EMS cannot be guaranteed. Its strength lies in the real time capability and conceptual simplicity (Çagatay Bayindir et al., 2011).

Typically it is known engine efficiency is higher at higher load (Ehsani et al., 2004) which are studied and leveraged in many EMS (Sharer et al., 2008, Wipke et al., 1999, Chan-Chiao et al., 2003, Miller et al., 2003) including the Toyota and Ford hybrid systems (Miller, 2006).

Most prominent rule based EMS are;

- Power follower control strategy
- Thermostat control strategy.

1) Power follower control strategy: Power follower control strategy (Salmasi, 2007) where engine is the primary source of power and motor power is used in producing additional power when needed by the vehicle within the battery charge sustaining constraints (charge sustaining (CS) strategy). The rules are based on the following heuristics,

- Only the electric motor is used at lower vehicle speed.
- Motor assist is used to meet the power demand above engine power at its operating speed.
- The batteries are charged using generator during regenerative braking.
- At lower power demand the engine shuts OFF to prevent inefficient engine operation.
- When the battery state of charge (SOC) is at its minimum, the engine should provide additional power to recharge the battery via the electric generator.

Power follower control strategy is used in Toyota Prius and Honda Insight hybrid electric vehicles (HEV) with some changes (Salmasi, 2007). Noticeable difference is there is no only electric machine operation in Honda insight (Kelly and Rajagopalan, 2001). With respect to engine operation, based on National Renewable Energy Laboratory (NREL) testing of

Toyota Prius 2010 year model, engine operation does not always operate at the best efficiency region but that is the target (Kim et al., 2012). By using the electric power as supplementary power enables to operate the engine more efficiently independent of vehicle load known as load –leveling (Jinming and Huei, 2008).

Toyota Prius engine operation control is shown in Figure 4-3. Less than 7kW of vehicle demand electric machine is preferred. Further engine operation less than 30% engine efficiency is avoided.

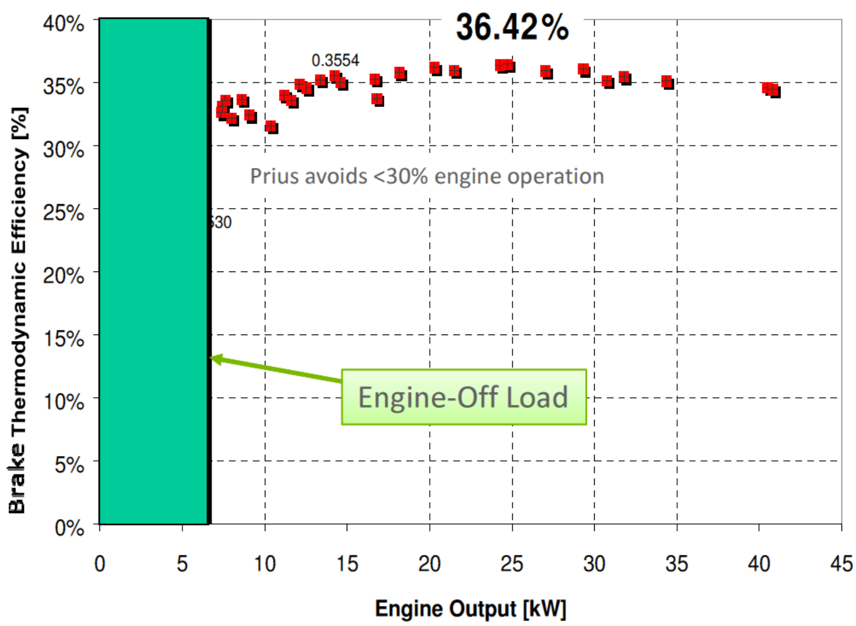

Figure 4-3: Toyota Prius engine operation(Duoba, 2011)

The engine operation duration for the Toyota Prius and Honda Insight control strategy over the driving cycle, urban dynamometer driving schedule (UDDS) is shown in Figure 4-4. Engine shuts down more frequently in Prius in comparison to Insight over the same driving cycles. Similarly it was observed the engine operations are less transient in the Prius (Kelly and Rajagopalan, 2001).

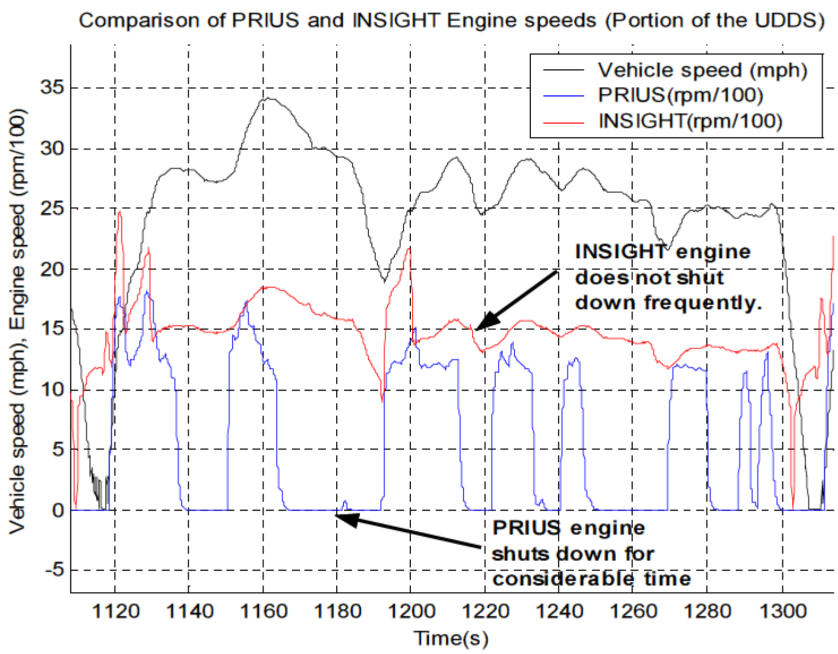

Figure 4-4: Engine performance comparison of Toyota Prius and Honda Insight control strategy over the UDDS (Kelly and Rajagopalan, 2001)

2) Thermostat controls strategy: For a series HEV, thermostat control strategy is used where the engine will switch ON/OFF based on lower and upper limit set for the battery SOC (Brahma et al., 2000). This EMS is the simplest.

Power follower and thermostat control strategy EMS serves as a template based on which many derivatives EMS are designed. These are designed for HEVs and hence operate in charge sustaining (CS) strategy.

Fuzzy logic (FL) controller is an extension of rule based (If – then) EMS which helps to define in range instead of being deterministic to accommodate component and other variation (Mendel, 1995). Power following method as discussed earlier was used in developing a FL controller in (Schouten et al., 2002, Baumann et al., 2000).

A causal FL based EMS called intelligent energy management agent (IEMA) was presented (Langari and Jong-Seob, 2005, Jong-Seob and Langari, 2005) as two papers. IEMA works based on following agents: Fuzzy torque distribution (FTD), identification of the micro or instantaneous driving pattern and driving environment. Battery SOC was limited to CS strategy like in typical HEVs. The function of FTD was to determine the power split between the electric machine and engine within the SOC limits. Based on the key statistical feature of driving, instantaneous driving pattern was identified with respect to Sierra driving cycles. This will in turn help in identifying driver style and trend. Sierra driving cycles were used to arrive at the base driving pattern (Sierra driving cycles are explained in section 2.4). Overall driving intensity and vehicle mode was accessed using driving environment based on idle, cruise, acceleration and deceleration. Driver style was classified into calm, normal and aggressive driving based on acceleration over a specific driving range. For aggressive driver less use of engine was allowed. During driving, the driving cycle was studied piece wise (only micro/instantaneous driving cycle) to access the pattern, driving mode and driver style. Using current SOC and pattern recognised a predetermined power split was arrived. Overall this method comes as the most skilful fuzzy logic EMS and the logic behind the rule is still the power following with the intention to minimise the fuel consumption.

It was stated in the study IEMA assumes the initial part of the driving pattern, and the final performance was found sensitive to the initial estimate. For the corresponding driving pattern identified and the current SOC, predefined power split was executed. Other limitations are in real world driving, Sierra driving cycle considered may not reflect all the variation in real world driving and a significant amount of driving cycle may be required to arrive at the patterns. Piece wise analysis of the pattern leads to neglect the total trip demand in devising control strategy. Hence IEMA remains as a causal EMS even after considering various aspects of driving. Also, in the simulation study the effect of driver style was not considered.

In electric dominated hybrids like PHEVs with charge depleting – charge sustaining (CD – CS) strategy, the electric machine takes the centre stage during CD strategy and primarily the engine is used only when the battery power is not sufficient or constrained. Similar EMS designed for HEV is used in PHEV during CS strategy after electric dominated CD strategy.

Hence for rule based PHEV EMS typically only CS strategy changes. Like one EMS used in (Karbowski, 2006, Qiuming et al., 2008) their study, during CS strategy the engine operates only to meet the vehicle demand. Hence during the engine operation no extra power is generated to charge the battery. Therefore battery charging is only by regenerative braking. Similarly in other EMS (Freyermuth et al., 2007) during CS engine operates only at optimal operating line (OOL). Hence any extra engine power is used to charge battery along with regenerative braking. Both these methods are part of simulation suite, Powertrain Systems and Analysis Toolkit (PSAT) developed by Argonne National Laboratory (ANL) for PHEV. These are frequently used in comparison studies (Karbowski, 2006, Qiuming et al., 2008, Freyermuth et al., 2007).

As said earlier for PHEV, typically rule based EMS use CD-CS strategy. In practice, to design blended charge depleting (BCD) strategy EMS has to be acausal to know the whole trip demand (Stockar et al., 2011). Hence BCD strategy often studied with optimisation based EMS (Qiuming et al., 2008, Lars et al., 2007, He et al., 2012b) which are discussed later. Exceptions are causal rule based BCD strategy studied tuned for a particular driving cycle, UDDS (Sharer et al., 2008, Rousseau and Moawad, 2010). Similarly rule based EMS designed over driving cycle, LA-92 (Dongsuk et al., 2013). Hence performance of such EMS outside the considered driving cycle is vulnerable. Being causal, they fail to identify the efficient engine and motor conditions over the trip.

4.4.1.1 Rule based EMS in industry

Rule based EMS are causal system. Due to design simplicity and real time capability they are successfully employed in industry (Stockar et al., 2011, Serrao, 2009). Low level dynamic behaviour of the powertrain components can be included unlike in optimisation based EMS (Salmasi, 2007). The behaviour of rule based EMS strongly depends upon the choice of the thresholds involved like torque demand, vehicle speed and battery SOC, which varies substantially with the driving conditions (Guzzella and Sciarretta, 2007).

Typically in industry EMS are tuned over a set of driving cycles to meet emissions norms and get the best fuel economy certified. This is the case in conventional vehicles (only engine) also. However owners of HEVs have complained of a much larger difference between their real-world fuel economy and the certified values in comparison to conventional vehicles (Sharer et al., 2007, Reports, 2004). In one of the study at ANL it was observed HEVs were more sensitive to driving cycle variations than a similar conventional vehicle (Sharer et al., 2007, M.Duoba et al., 2004). So, rule based EMS being causal is not helping the cause. Unlike acausal systems, they do not consider the whole trip demand and do not adapt globally to the uncertainties of real world driving.

4.4.1.2 Summary of rule based EMS

Rule based EMS are used in industry due to design simplicity and real time capability. Rule based EMS are causal. Hence in PHEV rule based EMS can pursue only CD-CS strategy. Rule based EMS performances are vulnerable in real world driving as the tuned over a set of legislative driving cycles. Hybrid vehicle performances are more sensitive to trip demand than a similar conventional vehicle. To improve fuel economy and address variation for varied trip conditions of real world driving, acausal and adaptive EMS in real time is required.

4.4.2 Optimisation based EMS

The main objective of EMS optimisation is to minimise the fuel consumption and emissions during a driving mission. In optimisation based EMS it may not necessarily optimise at each instance but consider the overall vehicle performance optimisation (such as fuel consumption) during the journey. This is achieved by arriving at the optimal power split between the vehicle power plants within the constraints such as SOC and component performance limits. Power split ratio defines the ratio of electric and engine power to be used. The majority of the research on optimisation methods considers only minimisation of fuel consumption and emissions are not part of the cost function J as shown in equation 4.1 (Guzzella and Sciarretta, 2007). m_f is the fuel consumed during the journey of duration t_f. $\dot{m}_f$ is the instantaneous fuel consumption. u is the power split ratio between the power plants. Where at u_{min} and u_{max} only one power plant is used.

$$J = \int_0^{t_f} \dot{m}_f \left(t, u(t)\right) dt \tag{4-1}$$

The cost function is subjected to constraints such as the maximum motor and engine power and the battery peak current rate and SOC limits.

$$\left.\begin{aligned}
&P_{ic}(t) + P_{em}(t) \leq P_{req}(t) \\
&P_{ic}(t) \leq P_{ic,max}\left(\omega_{ic}(t)\right) \\
&P_{em,min}\left(\omega_{em}(t)\right) \leq P_{em}(t) \leq P_{em,max}\left(\omega_{em}(t)\right) \\
&SOC_{min}(t) \leq SOC(t) \leq SOC_{max}(t) \\
&P_{chg,lim}(SOC) \leq P_{bt}(t) \leq P_{dis,lim}(SOC)
\end{aligned}\right\} \tag{4-2}$$

The optimised solution is minimum of cost function J.

Various optimisation methods are used in EMS research. However, the two principal optimization methods are,

- Dynamic programming (DP)
- Equivalent consumption minimisation strategy (ECMS)

In the following sections both DP and ECMS methods in terms of causal followed by acausal EMS are reviewed. Next use of BCD strategy with these methods is considered. Later in the section use of driving information in acausal optimisation based EMS, computational burden of optimisation based EMS and rule based EMS derived from the optimisation based EMS are discussed in that order.

4.4.2.1 Dynamic programming

Dynamic programming (DP) is a powerful tool to solve the global optimisation problem (Guzzella and Sciarretta, 2007). A state variable is a set of variables used to describe the mathematical state of a dynamic system. The state of a system describes enough about the system to determine its future behaviour. Meshing of the state and time variable is required in dynamic programming. In the Figure 4-5, n is the length of the driving cycle (in seconds). Each node in the figure represents a state variable with information about vehicle speed, SOC, etc.

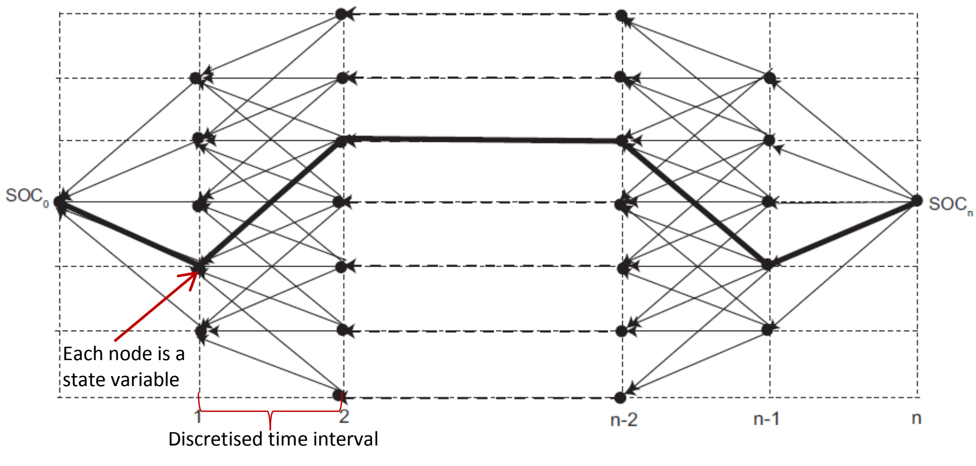

Figure 4-5: Illustration of state transition of backward DP (Adhikari, 2010)

The optimal path is calculated only for the discretised values of time and battery SOC that minimises the overall fuel consumption and emissions. For discretisation of large value of time the optimality of the solution deteriorates but computational time reduces due to less number of state transitions (Adhikari, 2010, Guzzella and Sciarretta, 2007).

4.4.2.1.1 Causal dynamic programming

DP requires the exact trip vehicle speed profile to be capable of delivering global optimal solutions. For that matter in any system optimal solutions can be found by design only if the exact demand and system environment is known in advance. DP is used to optimise over legislative driving cycle. Such a system is therefore causal. Causal DP was studied across various legislative driving cycles of different durations by (Adhikari, 2010). From the study it was observed that, with the increase in number of state variables, the computational burden increases exponentially. In other words the increase in the number of state changes (like vehicle speed, SOC) in the driving cycle increases the computational burden. For optimal solution, the number of state variables is such that among the immediate vicinity the change in value of variable is small. The duration of the driving cycle has relatively less effect.

Various improved algorithms, approximation of the original optimisation problem and linearisation of the cost function with respect to the control variable have been proposed to reduce the computational burden. All of these simplifications yield suboptimal solutions (Sciarretta and Guzzella, 2007). Hence DP is widely used for performance benchmarking against other optimisation methods rather than direct implementation.

4.4.2.1.2 Acausal dynamic programming

By considering whole trip demand of a future trip which is as vehicle speed profile, acausal EMS is able to arrive at optimal power split for that specific trip demand.

Normally for acausal EMS using dynamic programming, stochastic dynamic programming (SDP) is applied. In SDP, EMS can be optimised for a set of random driving cycles in an average sense instead of optimising for a given driving cycle. In this way the vehicle demand is considered and assumed to take a finite number of values. At each time interval, the EMS will decide the power split of the energy sources based on the vehicle demand. The goal of the EMS is to maximise the fuel economy in the worst – case scenario while meeting the vehicle demand and keeping the SOC constraints (Wirasingha and Emadi, 2011). EMS designed using SDP is optimal for the most likely load sequence or vehicle speed profiles (Salmasi, 2007). Hence for varied and uncertain trip demand conditions like in real world driving SDP is not suitable to implement.

Using SDP based EMS, Markovian driver models can be used for the prediction of vehicle speed or trip modelling (Chan-Chiao et al., 2004, Dean et al., 2008). Similarly, using approximate dynamic programming (ADP) a predictive EMS was presented (Johannesson, 2009) for a prescribed route using Markovian driver model. ADP is similar as SDP but with different terminology and vocabulary (Powell, 2012). The limitations of Markovian driver models with respect to real world driving were discussed earlier in section 3.4.3.1. They require prior knowledge of the trip vehicle speed profile. Therefore SDP and ADP with Markovian driver are not suitable for real world driving.

Model predictive control (MPC) along with SDP EMS was presented (Koot et al., 2005, Maciejowski, 2001). In this method optimisation is carried out at each time step over a limited prediction horizon. At each time step the optimal power split ratio of the energy source is determined based on the updated prediction and measured data. The EMS optimal results depends on the accuracy of the prediction (Serrao et al., 2011). Adaptability of trip demand and updated EMS as discussed in this study is required for real world driving with uncertain trip demand. The limitation here is prior vehicle speed profile knowledge requirement for MPC, accuracy of vehicle speed profile prediction considering dynamic variation and real time execution challenge of EMS which are equally important for real world application.

An EMS was proposed for a PHEV using vehicle speed profile data from intelligent transport system (ITS) (Qiuming et al., 2007). Limitation of using ITS data as future trip demand was discussed earlier in section 3.4.1. ITS data is an aggregate data of various vehicle types and driver styles that do not represent actual demand.

Gong and Yaoyu et al (2009) presented an EMS with artificial neural network (ANN) for trip modelling. More about ANN and trip modelling done in this study and its limitation was discussed in section 3.4.3.3. In the study ITS data was used as secondary data for the ANN model. ANN was trained using real test data for a given destination. This is the only study came across in which using real test data, prediction made was validated for a given destination by comparing the fuel economy. Applying the power split obtained from SDP results directly over ITS data without ANN to the real test showed deterioration of 16.7% in fuel economy. Improvement of 17.5% in fuel economy was observed when combining ITS data with ANN. This study demonstrates the importance of getting the predicted vehicle speed profile right. In this study the whole trip vehicle speed profile is predicted in advance. However like other trip prediction models, prior knowledge of the trip vehicle speed profile is required. Hence considering varied and uncertain condition of real world driving the model becomes cumbersome and data intensive. Also updating prediction during the journey is vital in real world driving which was not considered in the study. Therefore they are not suitable for real world driving.

4.4.2.1.3 Blended charge depleting control strategy using DP

In this section, studies using blended charge depleting (BCD) strategy with DP are discussed and reviewed. BCD control strategy was introduced earlier in section 2.3.5.3.

In Qiuming et al., (2007) study optimal blended SOC profiles were determined based on the power split calculated using DP over a driving cycle. To arrive at the optimal blended SOC profile the driving cycle/vehicle speed profile is required in advance. Optimal blended SOC are determined such that energy sources are used throughout the trip at times when they system is optimal.

Karbowski et al., (2006) compared BCD strategy with a typical CD-CS control strategy for a legislative driving cycle, the NEDC considered 10 times successively. Total energy consumption was found 60% less with the BCD strategy. This was due to the operation of engine at higher efficient regions by operating at higher acceleration and vehicle speed identified over the whole driving cycle. However in another study by (O'Keefe and Markel, 2006) in BCD strategy if the vehicle deviates from the target distance, the strategy uses more fuel than the CD-CS strategy. If the actual distance travelled is less than the target distance, the engine may be used early in BCD strategy for which in CD-CS strategy the engine is not used.

From the Markel et al study, it can also be inferred that a high penalty in BCD strategy can also apply to conditions when there is a deviation from the predicted and actual driving cycle as the optimisation was worked out for a specific vehicle speed profile or trip demand. Considering the uncertainty of trip demand in real world driving and further considering the trip demand in terms of vehicle speed profile which representing an exact demand it is that much difficult for the EMS with BCD strategy to perform effectively. As the exact prediction of trip demand for real world driving is not possible, trip demand is bound to be updated. This study shows the importance of EMS adaptability and also suggesting to considering the trip demand other than the vehicle speed profile in real world driving.

4.4.2.2 Equivalent consumption minimisation strategy (ECMS)

In ECMS the global optimisation is reduced to local or instantaneous optimisations by introducing a cost function dependent only on the system variable at the current time. For this reason ECMS is also called as an instantaneous optimisation. Causal ECMS compared to

DP are computationally efficient but does not deliver global optimal solution (Musardo et al., 2005).

4.4.2.2.1 Causal ECMS

In ECMS the equivalent fuel consumption of an electric machine $\dot{m}_{em,equ}$ converts the battery power to the equivalent fuel power required that must be added to the actual fuel power to attain the target SOC at the end of the driving cycle. The assumption here is the battery energy consumed will be compensated in the future by the engine running at the current operating point. The objective is to find the local minimum for the equivalent fuel consumption $\dot{m}_f$ within the set constraints such as SOC limits. The fuel consumption $\dot{m}_f$ in equation 4.1 becomes equivalent fuel consumption in ECMS as defined below (Musardo et al., 2004).

$$\dot{m}_f\,(t) = \dot{m}_{ic}(t) + \dot{m}_{em,equ}(t) \tag{4-3}$$

Where $\dot{m}_{ic}$ is the fuel consumption of IC engine and $\dot{m}_{em,equ}$ is defined as

$$\dot{m}_{em,equ}(t) = \lambda(\frac{P_{em}(t)}{H_{LHV}}) \tag{4-4}$$

In the above equation, λ is called as equivalent factor, P_{em} is the electric machine power at time t and H_{LHV} is the lower heating value of the fuel. Further equivalent factor is defined based on the charge and discharge status of the system called as λ_{chg} and λ_{dis} respectively.

There are many methods to define or calculate equivalent factors. The equivalent factors are simply assumed to be unity as in (Jong-Seob et al., 2005) which is the simplest approach. Also the factors can be derived based on the average charging and discharging efficiency of the system over a driving cycle as done in (Musardo et al., 2004). Musardo defined equivalent factors for a parallel HEV as below.

$$\lambda = \begin{cases} \lambda_{dis} = \frac{1}{\bar{\eta}_{chg}} \cdot \frac{1}{\eta_{em}(P_{em}(t)) \cdot \eta_{batt}(P_{em}(t))} & if\ P_{em} > 0\ (discharge) \\ \lambda_{chg} = \bar{\eta}_{dis} \cdot \eta_{em}(P_{em}(t)) \cdot \eta_{batt}(P_{em}(t)) & if\ P_{em} < 0\ (recharge) \end{cases} \tag{4-5}$$

Where: $\bar{\eta}_{chg}$ and $\bar{\eta}_{dis}$ are the average charging and discharging efficiency respectively for a given driving cycle and; η_{em} and η_{batt} are the electric machine and battery efficiency respectively.

Similarly, equivalent factors for a power split architecture was studied in (He et al., 2012a) which is based on equation 4.4. Another method to determine equivalent factors is by finding the optimal value iteratively like in (Tulpule et al., 2009). Later method can be time consuming.

From the equation 4.4 it is clear that equivalent factor is determined considering a vehicle speed profile of a trip. Hence the trip exact vehicle speed profile has to be known in advance like in DP.

4.4.2.2.2 Acausal ECMS

An adaptive ECMS (A-ECMS) (Musardo et al., 2005) has been investigated. The objective was to identify the equivalent factors according to the driving conditions. In other words, to use changeable equivalent factors based on the driving conditions identified. The results were close to DP for a set of legislative driving cycles considered (FUDS, FHDS, EUDC, NEDC and JP1015). A library of optimal equivalent factors for each driving condition were developed however each driving condition is nothing but a legislative driving cycle. The problem of sensitivity and arriving at optimal equivalent factors still persists as it is not possible to have the exact vehicle speed profile of the trip in advance, in real world driving. Like in causal EMS method, equivalent factors were calculated based on the average efficiency of charging and discharging over a driving cycle. Also in the study the value of equivalent factors for each driving cycle were very close (such as FHDS – 2.54, NEDC – 2.51, EUDC – 2.48, etc.,) indicating their sensitivity which can be an issue. That is a small change in equivalent factors or vehicle speed profile can disturb the control performance objective. More importantly in real world driving vehicle is not driven according to a specific legislative driving cycles. Hence there is no correlation in terms of application in real world driving.

ECMS performance strongly depends upon the definition of the equivalent factors. These factors vary with the driving cycle (Tulpule et al., 2009, Sciarretta and Guzzella, 2007). ECMS delivers optimal solution only if the equivalent factors are tuned perfectly to the precise driving cycle. In such a scenario for real world driving this leads to vulnerable results. It is not possible to predict the trip vehicle speed profile in advance for real world driving. Considering uncertain and dynamic nature of real world driving such EMS are not suitable due to sensitivity to equivalent factors.

For an acausal system some kind of feedback to equivalent factors is required to adapt online for uncertainties. Such a system was presented (Kessels et al., 2006, Koot et al., 2005) using a proportional – integral (PI) controller. The deviation in reference SOC was used as feedback to adjust the equivalent factor. Reference SOC was determined based on past driving vehicle speed profile(s). The objective was to achieve optimal charge sustaining (CS). The conclusion by both authors was that near-optimal results can be achieved with no prediction of future driving cycle. Based on past driving conditions initial equivalent factors were estimated and using PI controller the deviation in SOC between present actual and reference value were addressed during the trip. The limitation in the method is the estimation of the initial equivalent factor and the value of the PI controller parameters (K_p and K_i) selected as these parameters determine the result optimality. Also this method assumes that future driving conditions remains same as the past driving. For determining reference SOC, prior knowledge of the trip vehicle speed profile is required. The above issues make it not suitable to apply for real world driving.

Similar method was used in (Johnson et al., 2000, Jeanneret and Markel, 2004) where the current equivalent factor λ adapts based on a linear equation developed used initial equivalent factor λ_0 and varying SOC as shown below.

$$\lambda = \lambda_0 + K_p\big(SOC_0 - SOC(t)\big) + K_i \int_0^t (SOC_0 - SOC(t))\, dt \qquad (4\text{-}6)$$

Like MPC discussed with DP, telemetry ECMS (T-ECMS) uses navigation system, speed limits, traffic condition and other sensors information to estimate the optimal equivalent factor based on the predicted vehicle speed profile. As soon as a new piece of information is obtained from telemetry the future vehicle speed profile is updated (Guzzella and Sciarretta, 2007).

4.4.2.2.3 Blended charge depleting control strategy using ECMS

Like in DP, using ECMS a BCD control strategy was compared against CD-CS strategy using PHEV (Tulpule et al., 2009, He et al., 2012a). In CS mode ECMS was used for optimisation over a narrow SOC window. In both studies the SOC constraint was set to linearly decrease with the distance travelled by the vehicle.

$$SOC_{target}(t) = SOC_0 - \frac{Distance\ traveled(t)}{Total\ distance}(SOC_0 - SOC_n) \qquad (4\text{-}7)$$

Improvement in fuel economy was observed with the BCD in both studies compared to CD-CS strategy when simulated over various legislative driving cycles. Improvements are up to 16% and 13% in Tulpule et al and Y He et al studies respectively. Y He et al also observed that the improvement over CD-CS increases with increase in distance. However in this study to simulate the increased trip distance, a given driving cycle was considered multiple times successively. The fuel economy improvement with increase in trip distance is due to the extended use of the CS strategy with increase in distance once CD strategy was used. In CS strategy with limited battery energy (5% of usable of SOC), engine is forced to be used for a long time and not necessarily at the conditions efficient at the vehicle level (energy conversion losses as discussed earlier). In other words the difference in fuel economy in the initial driving cycle is getting multiplied with subsequent number of times driving cycles was considered. Hence the fuel economy is improving with distance. In real world driving this may not be the case as discussed later in chapter 12. Also from the equation (4.6) it appears that the ECMS optimisation is constrained to find the best power split between the engine and electric machine at a given time or distance (local) instead of considering the complete trip information (global).

4.4.2.3 Use of driving information in acausal optimisation based EMS

In this section the focus is on the use of driving information in acausal optimisation based EMS (both DP and ECMS together) is reviewed. This includes consideration of driver style which is known to have significant influence over trip demand in EMS is studied. Later in the section preview or look – ahead window studied with EMS is reviewed. Look – ahead or preview window is the duration of the prediction considered to determine an optimal power split.

4.4.2.3.1 Driving information study

In the driving information studies use of elevation along with vehicle speed with EMS were found beneficial in HEVs (Adhikari, 2010, Kessels and van den Bosch, 2007). Various kind of driving information such as elevation, traffic, traffic signal, route geometry were used as part of the trip modelling to predict future velocity profile and were found to improve fuel economy (Montazeri-Gh and Asadi, 2008, Qiuming et al., 2008). The amount of possible improvement to fuel economy has not clearly been explored in these studies. But in Chen et al.,(2010) study with HEV found that the use of elevation, in a hilly terrain preview of whole trip an average 1 to 4% improvement was observed and the improvement decreases for a large battery pack. This study was with CS strategy – narrow SOC window. This would be because, with a large battery pack, the electric machine is used more than engine.

Electric machine being highly efficient over wide operating speed as discussed in section 2.3.3, the effect of elevation is getting alleviated. During the use of engine the effect may have got accentuated due to limited efficiency region as discussed in section 2.3.1. Hence for PHEVs which comes with a large battery pack and wider usable SOC window, it can be inferred that only extreme elevation changes has to be addressed.

Other driving information is driver style which has a significant bearing on fuel consumption and emissions (Ericsson, 2001, Ericsson, 2000, Holmén and Niemeier, 1998, De Vlieger et al., 2000, DeVlieger, 1997, McGordon et al., 2011).

(Phuc et al., 2006) proposed a torque distribution strategy for a parallel HEV, which incorporates driving characteristics by interpreting accelerator pedal operation during vehicle following conditions. For driver using large accelerator pedal position, the required motor torque was reduced to avoid engine operation in low efficiency areas. This strategy is questionable, as reducing performance may not be acceptable to the driver.

The effects of driver style during vehicle cruising on control strategy was presented in (Cheng et al., 2010b). Two drivers were compared for fuel economy. It was concluded the smoother acceleration pedal movement in cruise driving could reduce the fuel consumption and show less switching between operating points of the hybrid vehicle.

Johannesson (2009) used a driver model with fixed acceleration and deceleration values and hence lacked scope to make control strategy adaptive to driver or address variation due to individual drivers.

Except few studies attempted above, little is understood about actively considering driver style in EMS for devising the control strategy or in predicting trip demand. Thus variation in energy demand due to driver style is neglected.

4.4.2.3.2 Preview window study

The wider the preview window longer the driving cycle has to be predicted. Also the flexibility of optimal power split decreases with increase in window size (He et al., 2012a). Couple of studies have shown that the optimal duration of the look-ahead window in predictive EMS varies with the driving cycle (Adhikari, 2010, He et al., 2012a). In both studies only legislative driving cycles were considered. Adhikari et al observed that the optimal window size varied from 80 to 150s seconds. In case of Y HE et al study it was 10 to 30 seconds. Not many studies were come across on knowing the factors in the driving cycle that affect the optimal window. In one of the few studies Y He et al., observed that distance of the driving cycle has no obvious effect on the optimal window size. Also in the study, BCD strategy required a narrower window (11 to 18 seconds) in comparison to CD-CS mode (11 to 28 seconds). In the study the trip distance is varied by repeating the legislative driving cycle many times. However in real world driving, driving pattern need not be repetitive as it was considered in the study. Hence the trip distance may not be able to separate from the driving cycle in the optimal window size study.

In terms of computational requirement both studies above did not gave insight. In case of narrow preview window frequent prediction of short driving cycle and formulation of power split is required. With wider preview window prediction of longer driving cycle is required. So overall computational requirement depends on whether the prediction of driving cycle or the power split calculation is more resource intensive. As acausal EMS is incorporated with more parameter to improve the estimation of vehicle demand or trip model, the computational burden increases with the number of states and variables.

4.4.2.4 Computational burden of optimisation based EMS

Optimisation based EMS are computationally demanding and hence cannot be used in real time EMS (Sciarretta and Guzzella, 2007, Koprubasi, 2008, Çagatay Bayindir et al., 2011).

Implementing just an adaptive causal ECMS can be resource intensive. (Koprubasi, 2008) implemented adaptive causal ECMS over rapid proto type controller (dSAPCE MicroAutoBox 1401: 800MHz) using a local search technique. Local search method considering all possible power split ratios was found impossible to implement. Majority of the power split ratios of ECMS are neglected based on power demand constraints such that driver's demand is continuous and it changes smoothly. This lead to confine the power split search space to a neighbourhood of the current operating point. Hence this strategy requires the torque feedback of the previous operating point. So, this study indicates even an indirect implementation of optimisation based method using local search method is computationally demanding.

4.4.2.5 Rule based EMS derived from optimisation based EMS

In some of the research, rule based EMS derived from the optimisation methods like DP (Chan-Chiao et al., 2003, Dongsuk et al., 2013) and ECMS (T. Hofman et al., 2008) are studied. The problem here is like a causal EMS, the optimal results are limited to the boundary or set of driving cycles considered in optimisation. And such systems are causal system with the degree of optimality proportionate to the likelihood of the driving cycle considered.

4.4.2.6 Summary of optimisation based EMS

All optimisation based EMS methods are either optimised for a set of driving cycle (causal) or a prior knowledge of trip vehicle speed profile is required (acausal). Optimal results like fuel economy of optimisation based EMS depends on the accuracy of the vehicle speed profile prediction (Serrao et al., 2011). However accurate prediction of trip vehicle speed profile is not possible due to the dynamic nature of real world driving (Guzzella and Sciarretta, 2007, Serrao, 2009) as explained in previous chapter. Further even the trip prediction models and techniques such as ANN and MPC used are computationally demanding. More significantly optimisation based EMS cannot be used in real time EMS.

All acausal EMS using both DP and ECMS were designed assuming finite vehicle demand arrived based on legislative driving cycles or considering prior knowledge of the real world vehicle speed profile of that particular destination. Only in one study (Qiuming et al., 2008) prediction is validated in terms of fuel economy. However this was done for the particular destination for which prior knowledge of the vehicle speed profile was used in trip modelling. In the literature no EMS was found about study or validation for a destination without using prior knowledge of the vehicle speed profile of the destination considered. This is exactly what is expected of EMS to perform in real world driving.

Optimization methods are developed in a way that requires the exact information about vehicle speed for formulating a control strategy over average component efficiency like in ECMS and DP. The dynamic and non-linear behaviour of the various powertrain components is neglected in computing (Pisu and Rizzoni, 2007, Salmasi, 2007). If this can be turned around in a way that requires average information about trip demand for formulating a control strategy over dynamic component efficiency, then such an EMS method may be effective for real world driving.

4.5 A schematic summary of the reviewed EMS methods

In this section a schematic summary of the reviewed EMS methods and their relation to each other are shown in Figure 4-6. EMS are mainly classified into causal and acausal EMS. All rule based EMS are causal system and hence follow CS (in HEV) or CD-CS (in PHEV) strategy. Rule based EMS can be of three types; Power follower, thermostat and derived rule based EMS. The derived rule based EMS are based on the optimisation based EMS. Optimisation based EMS can be causal and acausal system. Acausal system follows CS strategy in HEV. In PHEV they can follow either CD-CS or BCD strategy. Optimisation based

EMS can be adaptive (such as preview window, etc) or non-adaptive. DP and ECMS are the two main optimisation based EMS techniques considered for review in this chapter.

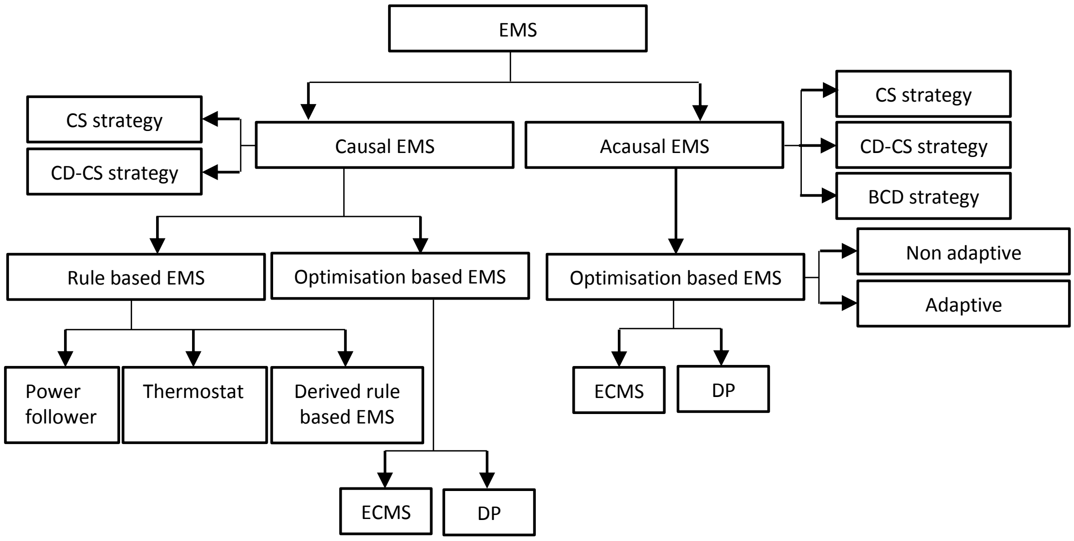

Figure 4-6: A schematic summary of the EMS methods

4.6 Limitations and requirements of EMS for real world driving

Overall,

1) Prominent drawback of existing EMS methods is the formulation over vehicle speed profile. In the literature to predict vehicle speed profile prior knowledge of the vehicle speed profile of the destination considered is required. Further this approach can become data intensive in real world driving due to varied trip and driving conditions.

2) Optimisation based EMS:

- Only DP gives global optimal result when the exact vehicle speed profile is known in advance.
- ECMS results are sensitive to the equivalent factor set and hence to the variation in vehicle speed profile.

- Optimisation based EMS are computationally demanding and hence cannot be used in real time EMS.
- The dynamic behaviour of the various powertrain components is neglected.

3) Rule based EMS:

- They are used in industry due to design simplicity and real time capability.
- Low level dynamic behaviour of the powertrain components can be included.
- Performances are specific to rule dependent and driving cycle. Also it was observed productions hybrid vehicles fuel economies are more sensitive to driving cycle variation than a conventional vehicle.

4) Causal EMS:

- Causal EMS are tuned or optimised for a set of driving cycles.
- All rule based EMS are causal system.
- Causal EMS can pursue only CD-CS strategy.

5) Acausal EMS:

- Acausal EMS enhances the fuel economy, emission and component performance of hybrid vehicles.
- All acausal EMS are optimisation based and hence limited by real time application.
- Optimal results such as fuel economy depend on the accuracy of the vehicle speed profile prediction. Prediction of exact vehicle speed profile in real world driving is not possible as discussed in previous chapter.

6) BCD strategy requires acausal EMS and is superior in vehicle performance to CD-CS strategy. But in the literature the performance was demonstrated with the prior knowledge of the vehicle speed profile.

7) Effect of drive style which has significant influence on real world trip demand and hence on EMS performance was not studied with any detail.

Further the objective in most of the EMS optimisation was only minimisation of fuel efficiency over a trip. The requirement is to include multi objective in optimisation like emission (Bingzhan et al., 2009), transmission (Kutter and Baker, 2010), drivability (Pisu et al., 2005), vehicle dynamics, durability (Wu et al., 2011) and other aspects of drivetrain components together. Development of a such a complex control structure can be cumbersome, specifically for optimisation based approaches (Salmasi, 2007).

In a quest to improve EMS performance, requirement to address real time capability and uncertainties of real world driving (adaptability) are over looked in the research.

For efficient vehicle performance, a real-time controller must deal and adapt itself to the uncertainties in driving conditions (local) (Sciarretta and Guzzella, 2007) and also consider the whole trip demand (global). A real-time capable acausal EMS able to handle uncertain real world trip demand is required.

4.7 Summary

- For design simplicity and real time capability rule based EMS are used in industry. All rule based EMS are causal. Production HEVs fuel economy was found more sensitive to driving cycle variation than a conventional vehicle.
- Acausal EMS enhances the fuel economy, emissions and component performance of hybrid vehicle. All acausal EMS are optimisation based. Optimisation based EMS are not suitable for real time application.
- EMS are formulated over vehicle speed profile directly (acausal) or indirectly (causal). Acausal EMS performance depends on the prediction of vehicle speed

profile. However prediction of exact vehicle speed in real world driving is not possible.

- For plug in hybrid electric vehicles (PHEV), blended charge depleting (BCD) strategy is superior to charge depleting – charge sustaining (CD-CS) strategy. However as rule based EMS are not acausal only CD-CS strategy is used in practice.
- Driver style has a significant effect on vehicle performance but was not considered in EMS study with any detail.
- No EMS was studied or validated for a destination without using prior knowledge of the vehicle speed profile of the destination considered.
- For efficient performance, a real-time controller must deal and adapt itself to the uncertainties in driving conditions (local) and also consider the whole trip demand (global). A real-time capable acausal EMS able to handle uncertain real world trip demand is required.
- No method investigated was able to design an acausal EMS for the requirements of real world driving.

Chapter 5 – Overview of Preliminary Real World Driving Data Study

5.1 Introduction

This chapter gives an overview of two preliminary real world driving data studies in leading to the approach and design of a proposed EMS method. Observation from these studies gives insight in considering real world trip demand in the proposed EMS. To be specific it is to know how to consider the trip demand before designing a new EMS. It is to learn the characteristics and limitations of a trip demand in real world driving. Based on which the next step is to decide a suitable method to capture the dynamic and uncertain trip demand conducive to design a real time adaptive EMS.

In this context observations from two preliminary studies are briefly discussed; micro driving cycle study and effect of driving factors on vehicle energy. This chapter gives an indication of these studies that set the tone of this research – PHEV energy management system for real world driving.

5.2 Preliminary real world driving data study

The two preliminary studies are:

- Micro driving cycle study
- Effect of driving factors on vehicle energy

In the first study, real world driving trip demand was studied in terms of vehicle speed profile whereas in the second case in terms of vehicle energy. As it was discussed earlier (section 3.3) in real world driving trip demand is driven by series of situations or events for a given vehicle, driver and journey. In both studies these situations or events are considered to different degrees; micro level (to stop/to start) to road type (urban/extra urban) level.

Real world driving data for twenty drivers collected as part of the Sustainable Action on Vehicle Energy (SAVE) project at WMG was considered to represent real world driving over a particular journey. For the SAVE project driving data such as vehicle speed profile was collected for a given vehicle and route of urban and extra urban driving. Similarly for one of these drivers repetitive trip data for their daily commuting route was also logged. These data were logged for a conventional vehicle. For demonstration of the EMS concept throughout this thesis vehicle speed profile data from SAVE are considered valid for the hybrid vehicle. Part of this SAVE data was used in this preliminary study.

5.2.1 Micro driving cycle study

The specific aim of this study was to predict trip vehicle speed profile to any destination using micro driving cycle library for a given vehicle and driver style. It was a study of real world driving vehicle speed profile based on events. This was initially considered with the objective to develop a micro driving cycle library based on trip events. Trip events considered were, Idle to start, to stop, round-about, etc. A micro driving cycle library as shown in Figure 5-1 could be developed using real world vehicle speed profiles.

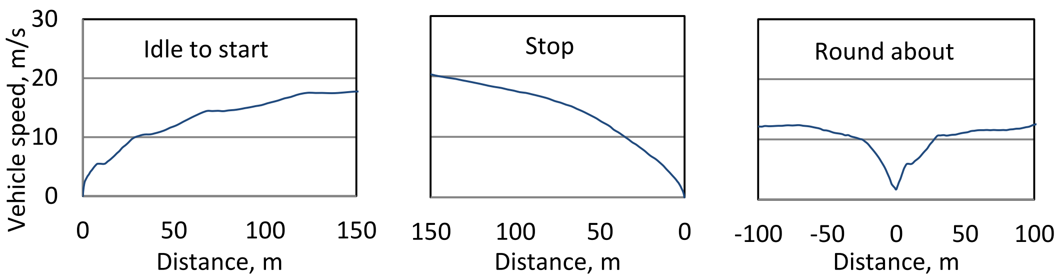

Figure 5-1: Micro driving cycle library for a given driven style and event

After knowing the trip destination, the route was broken down into respective micro events. Using the micro driving cycle library for a given driver style, the trip vehicle speed profile could be constructed based on trip micro events as shown in Figure 5-2.

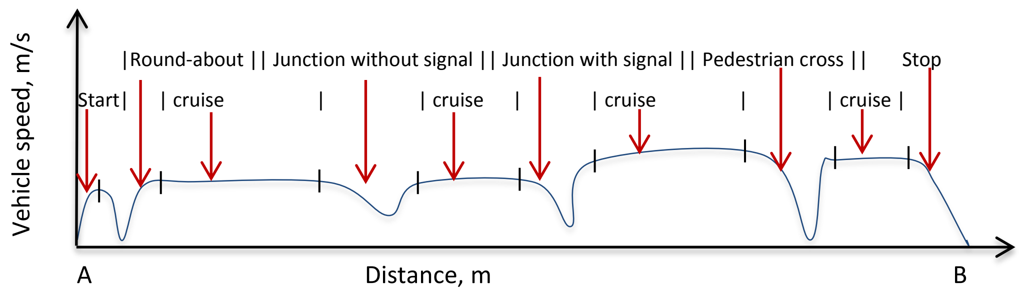

Figure 5-2: An indicative trip vehicle speed profile constructed using micro driving cycle library based on events

During development of micro driving cycle library using SAVE data for a given events there was considerable variation in speed profiles as shown in Figure 5-3. Vehicle speed profiles for round about event were relatively consistent.

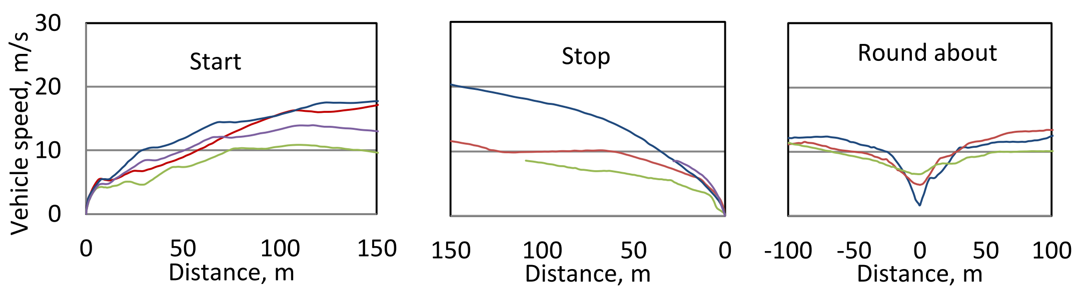

Figure 5-3: Micro driving cycle library - varied vehicle speed profiles for a given event but varied conditions

Considerable variance in micro driving cycles for a given event indicates large probability leading to huge data to make prediction for a specific condition. In addition for the same reason the chance of getting the prediction right is highly likely. Further considering the gamut of varied real world driving conditions along with driver styles it is expected to multiply the above problem many times. Shortcoming observed in micro driving cycles study sound similar to the review summary of the trip modelling discussed earlier.

In the meantime repetitive trip data from SAVE for a given daily commuting route, driver and vehicle was considered for study. This data was collected for commuting from home to office with a narrow variation in starting time from 7.10 to 7.33 am (start time bandwidth is just 23 minutes) on weekdays (Figure 5-4). A substantial variation in vehicle speed profiles was observed even for a given route, driver, vehicle and almost the same time. The vehicle speed variance is due to traffic, natural variation of the driver and other external factors.

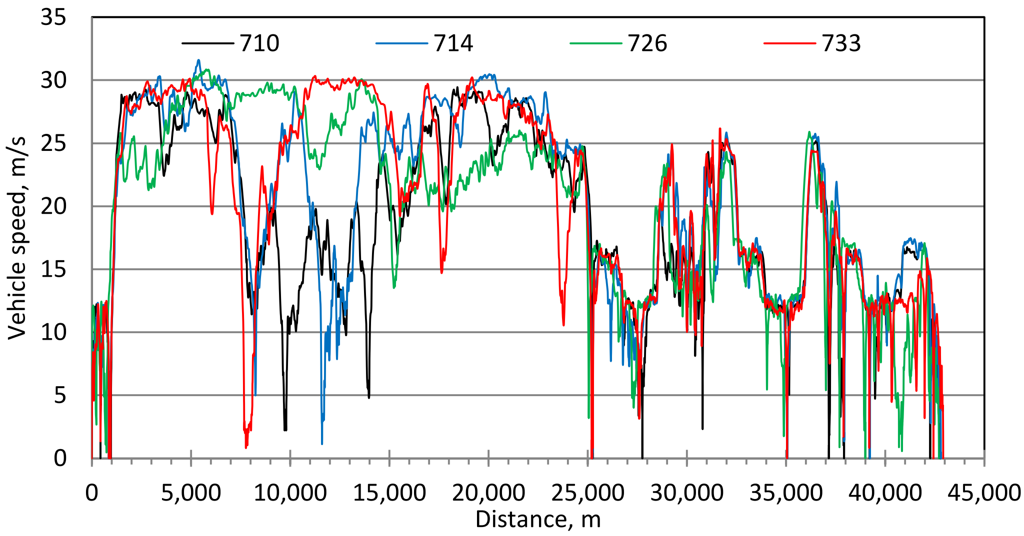

Figure 5-4: Vehicle speed profile for a given driver, daily commuting route and vehicle

Overall considerable variation in vehicle speed profile observed even for a given vehicle and driver in both micro driving cycle study and repetitive data study. This can be due to traffic and natural variation of a driver. Hence this approach can become data intensive like other trip modelling methods discussed in section 3.4, especially when varied real world driving conditions like routes and driver styles are considered. Also like other trip modelling methods this may not be able to predict the exact trip vehicle speed profile. Largely these are in concurrence with conclusion from the trip modelling literature review discussed in chapter 3. In real world driving vehicle speed profile is highly dynamic and makes exact prediction impossible. Hence it is recommended not to consider trip demand prediction in terms of vehicle speed profile for real world driving.

In the next section, the effect of driver style and road type on vehicle energy study is deliberated.

5.2.2 Effect of driving factors on vehicle energy

In this study the effect of driver style for urban and extra urban road types in terms of vehicle energy consumed was considered. Vehicle energy was considered as a common measure, to measure the power consumption from two different power plants of PHEV. For this study a readily available backward facing parallel PHEV model representing a typical saloon car was simulated over real world vehicle speed profiles. For the study three drivers who had exhibited distinct fuel economy in the conventional vehicle; most fuel efficient (driver 1), least efficient (driver 3) and mean efficient (driver 2) out of 20 driver study from SAVE was considered. In addition the NEDC was considered.

In Figure 5-5 even for a wide variation of vehicle speed profile, a relative small variation in the net vehicle energy was observed. This is due to the primary use of the electric motor operation. The electric power train being highly efficient over wide operating speed as discussed in section 2.3.2, the effect of vehicle speed (or external demand) on vehicle energy is dampened. Hence the hybrid vehicle energy, in particular the vehicle electric energy, can be same or almost same for a range of external demand such as speed and acceleration.

In Figure 5-5 the net vehicle energy over distance is fairly linear over distance. Also for different vehicle speed profiles of drivers and the NEDC, the respective net vehicle energy profiles lie close to each other.

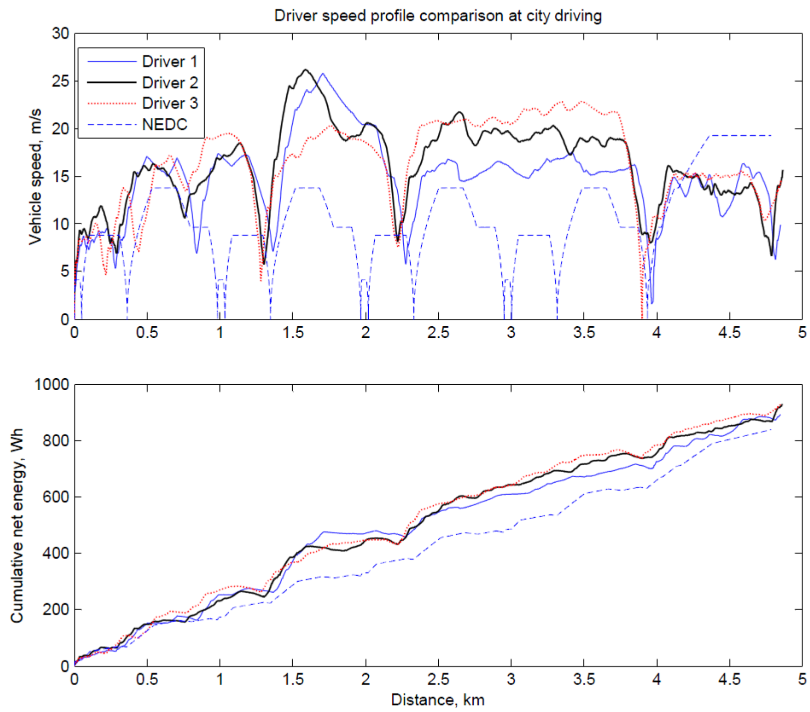

Figure 5-5: Vehicle speed profile and vehicle energy comparison

Next in this preliminary study specific energy was studied. Vehicle energy demand per kilometre is defined as specific energy in this thesis. To study the effect of road types, urban and extra urban driving of all three drivers' specific energy was studied. After this preliminary study it was realised specific energy as a common parameter can be used to consider the effect of various factors affecting the vehicle trip demand.

5.3 Implication of preliminary studies on the design consideration of the proposed EMS

Vehicle speed represents an exact load and is highly dynamic in real world driving. Considering varied and uncertain real world driving conditions, trip demand prediction based on a vehicle speed profile becomes data intensive and may become compromised to accuracy. These limitations are in concurrence with the conclusions from the trip modelling review and other literature discussed in chapter 3. Based on micro driving cycle study and the literature, vehicle speed profile based trip demand estimation for real world driving is not suitable.

Vehicle energy in the second preliminary study was found encouraging due to gradual change for wide variation in vehicle speed (or external demand). This is due to the high electric power train efficiency over a wide operating range. Hence the trip demand when considered in terms of vehicle energy deals at the macro level representing a range of external demand. This can be observed in Figure 5-5 where the respective net vehicle energy profile of different driver styles and the NEDC was observed to be quite close to each other. Also the net vehicle energy profile is fairly linear over the distance. At the same time the total trip demand can be quantified by a tentative value in terms of vehicle energy. Under uncertain conditions this feature can be helpful in trip demand estimation and holding EMS insensitive to small changes. Hence it is expected to save computational resource and time.

Specific energy can be used as a common parameter to consider the effect of various real world driving factors. Road type, driver style and traffic which are considered critical driving factors in influencing the trip demand can be considered in estimating the trip demand. As the net vehicle energy is linear over the distance using specific energy values, the trip demand can be linearly estimated.

Considering the trip demand in terms of vehicle energy by itself does not help in estimating the exact trip demand in real world driving. However the vehicle energy characteristic of gradual change with external load narrows down possible variation limits. This feature along with EMS adaptability is expected to aid in meeting the gap between the estimated and actual trip demand.

These critical observations are considered in the approach and design of the proposed EMS in chapter 6 and 7 respectively. Vehicle energy and specific energy is discussed and studied in detail throughout the thesis in the following chapters.

5.4 Summary

Observations from the preliminary real world data studies are used to explain the origin of some of the factors and methods considered in the proposed EMS design discussed later in chapter 7.

Based on micro driving cycle study and literature the vehicle speed profile based trip demand estimation for real world driving is not suitable. Vehicle speed represents an exact demand and hence the vehicle speed profiles are highly dynamic. First-hand the limitation of considering trip demand in terms of vehicle speed profiles was demonstrated.

On the other hand, vehicle energy consumed varies gradually with external demand, courtesy of high electric power train efficiency over a wide operating range. Hence the trip demand when considered in terms of vehicle energy deals at the macro level representing a range of demand. Also the total trip demand can be quantified to a tentative value in terms of vehicle energy. Under uncertain conditions this feature can be handy in trip demand estimation by holding EMS insensitive to small changes. Hence it is expected to save computational resource and time. Further the gradual and narrow variation of vehicle energy to external load is also expected to aid in two ways: Closer to actual trip demand estimation and EMS adaptability to the uncertain trip demand of real world driving.

Various driving factors influencing trip demand such as road type, driver style and traffic can be considered in trip demand estimation using specific energy as a common parameter.

Therefore it is proposed to investigate the vehicle energy as a parameter in the estimation of real world trip demand and design of the proposed EMS.

Chapter 6 – Approach for the Design and Evaluation of a Proposed PHEV EMS for Real World Driving

6.1 Introduction

The purpose of this chapter is to illustrate the approach to design and evaluate a proposed EMS structure and strategy. As part of evaluation the proposed EMS performance metrics include vehicle performance, real time capability and adaptability to varied driving conditions. The vehicle performance covers fuel economy, the number of engine stop – starts and final SOC. The research objective is to design a real time capable acausal rule based PHEV EMS that can adapt to the uncertainties of real world driving.

6.2 Research approach

The research approach is to design and evaluate a proposed EMS for real world driving. The proposed EMS method is designed considering the real world driving limitations/characteristics and power train characteristics of PHEVs. The proposed EMS is a rule based acausal EMS formulated over vehicle energy and driving information as discussed later in section 6.2.2. This EMS works on blended charge depleting (BCD) control strategy. The EMS design needs to be real time capable and adaptive to the uncertainty of real world driving.

The proposed EMS evaluations are designed to demonstrate the real world applicability and vehicle performance. A parallel PHEV model was simulated to study the performance metrics such as vehicle performance, real time capability and adaptability to varied trip conditions. Vehicle performance covers fuel economy, the number of engine stop – starts and final SOC. Vehicle performance of the proposed EMS is studied over the legislative driving cycle – the NEDC and predominantly over real world data. Later as part of the validation study discussed in section 6.2.7, the proposed EMS working was studied for the uncertain trip demand and varied driving conditions as in real world driving.

The above approach for the design and evaluation of a proposed EMS is broken down and described as following sections in this chapter.

1. Choose and modelling of PHEV system
2. Design of the proposed EMS structure and strategy for real world driving
3. Study of vehicle efficient modes of engine operation over driving information
4. Comparison study of the proposed and conventional EMS over the NEDC
5. Real time capability and sampling rate study
6. Adaptability study
7. Validation study over the uncertain trip demand

Before discussing the above sections in detail, a schematic of the research approach and its navigation with respect to the chapters following in the thesis is shown in Figure 6-1.

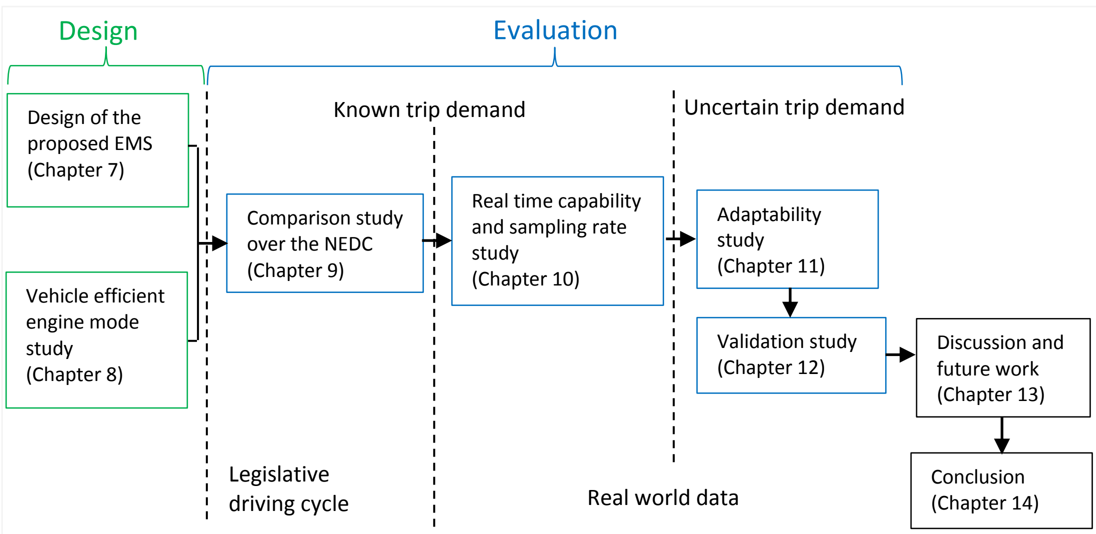

Figure 6-1: A schematic of the research approach

6.2.1 Modelling of PHEV system

The EMS design for PHEV was considered as PHEVs offer superior fuel economy than HEVs.

Parallel vehicle architecture was considered as it has more freedom to control and drive powertrain in comparison to series architecture. However this architecture makes control problem more challenging. Often any demonstration using parallel architecture is equally applicable to derivative architectures like series-parallel and complex hybrid. This may be the reason majority of the researchers' preferred parallel hybrids (Kutter and Baker, 2010, Wirasingha and Emadi, 2011, Tulpule et al., 2009, Langari and Jong-Seob, 2005).

As in any typical research, modelling and simulation was considered as a basis due to easiness to define, visualise, quantify and understand the proposed EMS. From the EMS design point of view, forward facing model is preferred as they mimic the physical causality of the real system which makes implementation ease with confident result (Serrao et al., 2011).

In this research, a forward facing, in house, modelling suite for different hybrid architectures, Warwick Powertrain Simulation Tool for Architecture (WARPSTAR) (Figure 6-2), was used as base model (Cheng et al., 2010a).

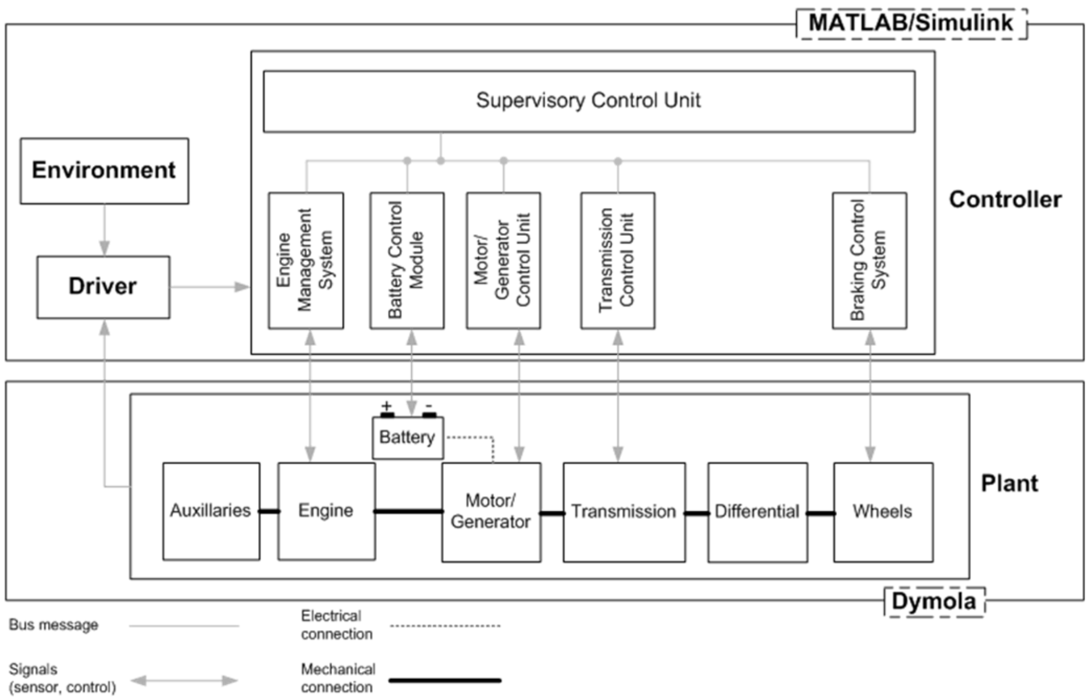

Figure 6-2: Schematic diagram of the flexible hybrid architecture WARPSTAR 2 model

In the suite the physical vehicle and powertrain components were modelled in Dymola. Component controllers and hybrid supervisory controllers (energy management system) and the driver model were modelled in MATLAB/Simulink. The parallel hybrid model of WARPSTAR was extended in this study to a plug in parallel hybrid model by developing a new rule based EMS (Figure 6-3). Also a larger battery pack was incorporated.

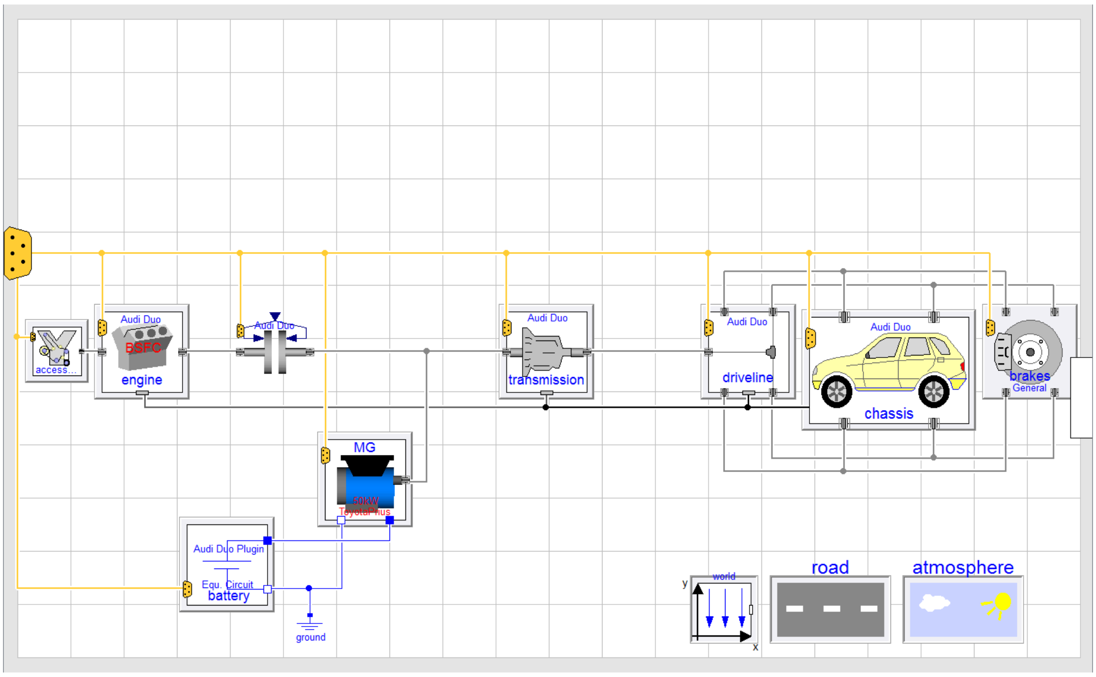

Figure 6-3: Parallel plug-in HEV vehicle architecture modelled in Dymola

Vehicle specifications were selected representing a typical five seat saloon as shown in Table 6-1.

Table 6-1: Vehicle specification

Vehicle	Audi Duo	Vehicle architecture	Parallel plug-in
Vehicle mass (m)	1450 kg	IC engine	67 kW (1.9l diesel)
Frontal area (*A*)	2.14 m^2	Electric machine	50 kW
Aerodynamic drag coefficient (C_d)	0.28	Battery	8.6 kWh
Wheel radius	0.239 m	Transmission (Ratio)	5-speed automatic (3.78/2.18/1.36/0.9/0.65)
Coefficient of rolling resistance (C_{rr})	0.0113	Final drive ratio	3.56

The main components of the vehicle architecture modelled in the Dymola are explained in the following sections.

6.2.1.1 Chassis model

The traction force required form the vehicle power sources, overcomes the total vehicle resistive force at the wheels is considered in the chassis model. The total vehicle resistive force is the summation of aerodynamic drag (F_a), rolling resistance (F_r), gradient resistance (F_g) and inertia forces (F_i).

$$F = \underbrace{\frac{1}{2} C_d A \rho v^2}_{(F_a)} + \underbrace{C_{rr} Mg.\cos\theta}_{(F_r)} + \underbrace{Mg.\sin\theta}_{(F_g)} + \underbrace{Ma}_{(F_i)} \tag{6.1}$$

Where, C_d is the aerodynamic drag coefficient, A is the vehicle frontal area, ρ is the air density, v is the vehicle speed, C_{rr} is the coefficient of rolling resistance, M is the vehicle mass, g is the gravitational acceleration, θ is the road slope and a is the vehicle acceleration.

The inertia of the rotating masses of the powertrain is taken into account in the respective sub-models.

6.2.1.2 Engine model

In the engine model steady state engine fuel flow rate map is used with respect to the torque and engine speed request. This steady state look-up table method is commonly used neglecting the effect of ambient temperature and other factors unlike in the real operation. In the simulation, fuel flow rate is calculated by linear interpolation between the steady state data. The engine torque request is filtered by the first order transfer function (order =1 and cut-off frequency = 10 Hz). The peak engine torque is defined as the function of engine speed. The engine model also considers flywheel inertia. The clutch between the engine and transmission is modelled to engage and disengage based on the engine ON and OFF status defined by the EMS.

6.2.1.3 Battery model

The battery is modelled by an internal resistance circuit as shown in Figure 6-4. The minimum and maximum battery state of charge (SOC) is defined as 0 and 1 respectively. The open circuit voltage V_{OC} and the resistances (charge resistance R_{chg} and discharge resistance R_{dis}) depend on the SOC. P_r is the power request at the terminal and I is the current.

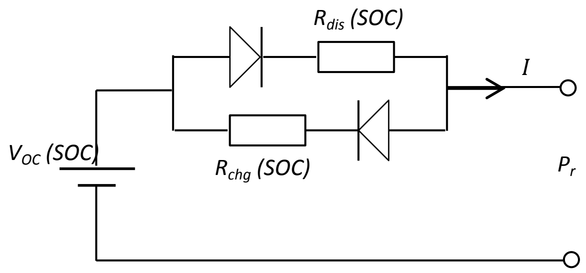

Figure 6-4: The equivalent battery circuit model

From Ohm's law, current flow I through the battery is given by,

$$I = \frac{V_{oc}(SOC) - \sqrt{V_{OC}(SOC)^2 - 4P_r R_{chg/dis}(SOC)}}{2R_{chg/dis}(SOC)} \tag{6.2}$$

Note that the P_r at the terminal is limited by the peak current available which is in turn proportional to the V_{oc} as discussed with Figure 2-5.

6.2.1.4 Electric machine model

The maximum torque that can be delivered or regenerated by the electric machine is defined as the function of the electric machine speed. The effect of temperature and cooling of the electric machine is neglected. Electric machine rotor inertia is considered.

6.2.1.5 Transmission model

Automatic transmission efficiency and gear switching time is considered as constant. The up and down shift of gears are defined with respect to the vehicle speed. Constant drive line efficiency is considered.

6.2.1.6 Auxiliary model

Vehicle auxiliary load such as air conditioner, etc., is considered as known and constant.

Refer appendix for the vehicle and component model parameter details.

6.2.2 Design of the proposed PHEV EMS structure and strategy for real world driving

The proposed EMS is formulated over driving information and vehicle trip energy and not over dynamic vehicle speed profiles as usually seen. The proposed EMS is rule based methods as rule based EMS are known for real time capability.

For the proposed EMS, real world driving information need to be considered based on its characteristic difference in energy demand that can help in trip demand estimation or aid in devising control strategy. To start with the driving information considered were driver style, route distance and road types like urban and extra urban with traffic as sub functions. In a study (Ericsson, 2000), it was found road type, driver style and traffic in that order had the greatest influence on vehicle trip demand.

In the proposed EMS, selected driving information is used in advance to estimate the future vehicle trip demand in terms of vehicle energy over driving information (road type and distance) and not as vehicle speed. The expected benefit of formulation of the EMS over vehicle energy was discussed earlier in section 5.4.

The proposed EMS use blended charge depleting (BCD) control strategy. In many literatures BCD strategy was found to deliver superior performance in comparison with charge depleting – charge sustaining (CD-CS) strategy. The risk of BCD strategy performance being sensitive to change or variation in trip demand is addressed by real time adaptive capability. Also real time adaptive capability is necessary for course correction and revising control strategy under uncertain demand conditions. This is achieved by periodic sampling (or sampling rate) of system parameters and driving information during the journey. The control strategy of the proposed EMS along with adaptive principle is discussed in section 7.2.4.

In summary, first time EMS is formulated over driving information and vehicle trip energy. First time rule based EMS is designed to be an acausal system. Hence the approach and method of both estimation of trip demand and EMS devising control strategy (structure and operation) are new. The proposed rule based and blended EMS formulation and working principle that covers the system structure and strategy is covered in chapter 7. As the proposed EMS was formulated over driving information, it was required to identify vehicle efficient engine operation over driving information as discussed in next section.

6.2.3 Study of vehicle efficient modes of engine operation over driving information

In hybrid vehicles while operating the engine, energy conversion losses has to be reduced to improve vehicle efficiency. As existing acausal EMS are formulated over trip vehicle speed profile, higher loads were determined of each trip for the engine operations by optimisation methods.

The proposed EMS formulated over vehicle trip energy and driving information was considered for the first time. It was found that there is no literature on efficient engine use for a hybrid vehicle to suitably define over driving parameters; such as road types. Hence it was required to find under what engine conditions, and trip conditions, the engine operation can be vehicle efficient with respect to road types.

In chapter 8, six modes of engine operation are investigated over the NEDC for the total vehicle energy consumed, potential real world driving issues and energy conversion losses. Based on which engine operation with respect to road types are implemented for the proposed EMS.

Finally as a complete system, the proposed rule based acausal PHEV EMS was evaluated in the following sections. In the evaluation studies, for driving information EMS was not integrated to the navigation system but manually defined using real world driving information model. Also in the evaluation, studies were done for a driver style and traffic was not considered for simplicity.

6.2.4 Comparison study of the proposed and conventional EMS over the NEDC

The proposed EMS method was evaluated as a complete system and compared with conventional rule based EMS for PHEVs in chapter 9. Conventional rule based EMS was considered for comparison as they are used in industry due to their real time capability. Also in many literature optimisation based EMS are compared with conventional rule based for performance (Qiuming et al., 2008, Pisu and Rizzoni, 2007). A legislative driving cycle, the NEDC was considered as it is commonly used for comparison study. Also this driving cycle has urban and extra urban driving section in a given driving cycle; useful in demonstrating driving information and performance over a familiar driving cycle.

6.2.5 Real time capability and sampling rate study

In EMS research real time capability is overlooked at the cost of maximising the vehicle efficiency. However for application in industry real time capability is essential and overrides vehicle efficiency.

In chapter 10, simulation duration of the proposed EMS was studied for various sampling rates of the system parameters and driving information over a given real world vehicle speed profile from SAVE data. As conventional rule based EMS are known for real time capability, simulation duration are compared with that of the proposed EMS. Further based on vehicle performance and simulation duration the appropriate sampling rate for the proposed EMS is selected for the future studies.

6.2.6 Adaptability study

To address uncertain conditions along with real time capability another critical requirement is adaptability. In chapter 11 vehicle performance of the proposed EMS for under and over-estimation of the vehicle trip energy is studied and compared with conventional rule based EMS. In real world driving due to the uncertainty it is not possible to estimate the exact vehicle trip energy required in advance. The proposed EMS vehicle performance even when the trip demand estimation is not exact is compared with respect to conventional rule based EMS vehicle performance.

6.2.7 Validation study over the uncertain trip demand

In chapter 12 to validate, the proposed EMS was simulated over uncertain trip demand for a given destination as would be the case in real world driving.

For validation study four real world trips of different conditions (sequence of road types and trip distance) were considered for a driver. The driver was considered based on the real world driving data ready availability (from SAVE) for the study. Trip demand was estimated without prior knowledge of trip vehicle speed profile and vehicle performances were compared to that of conventional EMS. Thus the proposed EMS is validated.

In existing acausal EMS studies in literature (Chan-Chiao et al., 2004, Qiuming et al., 2007, Kessels, 2007, Dean et al., 2008, Johannesson, 2009, Qiuming and Yaoyu, 2009, Cairano et al., 2013) prior knowledge of trip demand (in terms of historic vehicle speed profiles) of a given destination were used to predict trip demand for the same destination.

Validation study and adaptability study discussed in previous section also demonstrates robustness of the proposed EMS for varied and uncertain conditions as in real world driving.

Overall discussion is covered in chapter 13 which brings together the proposed EMS and its evaluation results. This chapter discuss about main conclusions about the proposed EMS efficacy followed by suggestion for future work. To finish, overall conclusions of the design and evaluation of the proposed EMS is presented in chapter 14.

6.3 Summary

A summary of the research is shown in Figure 6-5.

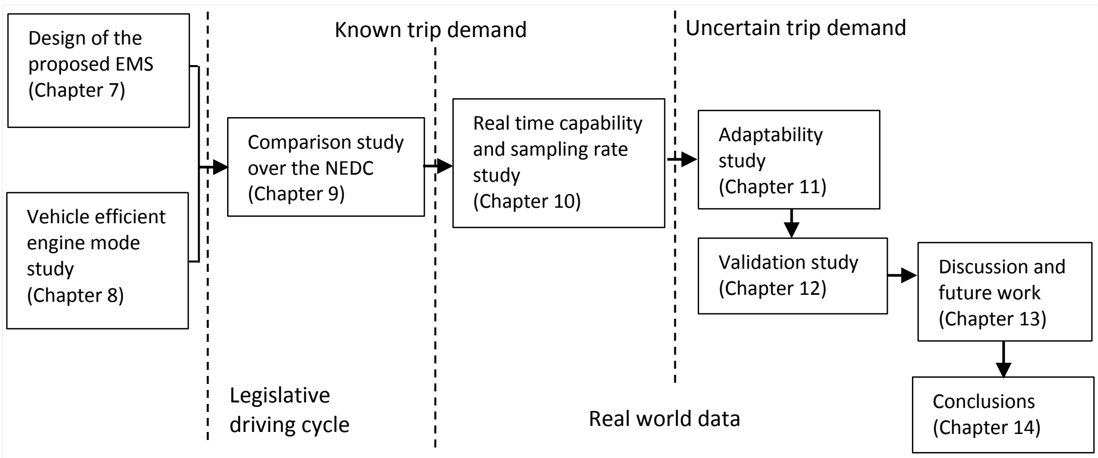

Figure 6-5: A summary of the research approach

An approach to design a real time capable acausal EMS for a PHEV that can adapt to the uncertainties of real world driving to deliver efficient performance was presented. The approach is at two level; design of a proposed EMS followed by evaluation studies.

The proposed EMS is a rule based acausal EMS formulated over vehicle energy and driving information. This EMS works on blended charge depleting (BCD) control strategy. The proposed EMS is expected to be adaptive to the uncertainty of real world driving in real time.

Evaluation studies are designed considering requirements and imitation of real world application. Performance metrics includes vehicle performance, real time capability and adaptability to varied trip demand and estimation. Performance metrics of the proposed EMS was studied over the legislative driving cycle - the NEDC (known trip demand) and predominantly over real world data. Later the proposed EMS is validated over uncertain trip demand for a given destination as would be the case in real world driving.

Chapter 7 – Design of the Blended Rule Based EMS method for Real World Driving

7.1 Introduction

In real world driving as the exact demand is not known in advance it is not possible to have optimal vehicle performance by design. The focus of the proposed EMS design is in execution under dynamic and uncertain trip demand conditions which is often overlooked for optimal performance. The system has to be real-time capable and adapt to trip demand uncertainty expected in real world driving to deliver efficient performance. Further this has to be achieved for varied driving conditions.

This chapter describe the fundamental structure and strategy of a proposed blended rule based EMS method design. The proposed EMS has two parts; estimation of trip demand and devising control strategy. Both are designed together as one system rooted to meet the challenges of real world driving. In the next section the framework and working principles of the proposed EMS are explained.

7.2 Proposed EMS method structure and strategy

The proposed blended rule based EMS for real world driving is formulated over driving information and vehicle trip energy. The emphasis of the proposed EMS is effective adaptability to the uncertainties of real world driving in real time to deliver efficient performance. In the following sections the framework and working principle of the proposed EMS are explained.

7.2.1 Framework

The proposed EMS framework is based on hybrid powertrain characteristics. Electric and engine powertrains in hybrids have contrasting characteristics in terms of efficiency and resource limitation. For efficient EMS performance over a trip, two critical aspects considered are,

- To manage the vehicle electric energy (battery) – in the proposed EMS, the vehicle trip energy estimation (trip demand) accounts for only the electric energy required. The electric machine operation is not monitored for efficiency due to relatively high efficiency. Only the battery energy which has limited capacity is monitored against the estimated vehicle trip energy.
- Efficient use and control of engine operation – vehicle efficient (reducing energy conversion losses) engine operation over driving information is identified and incorporated in the proposed EMS as discussed in the next chapter.

For effective management of these two critical aspects by the EMS under uncertain trip demand adaptability becomes a necessity. Adaptability is also required to pursue the blended charge depleting (BCD) control strategy. Hence periodically the system parameter and driving information considered throughout the journey is monitored to update the control strategy. The working principle of the proposed EMS formulated over driving information and vehicle trip energy is discussed in the following sections.

7.2.2 Working principle

The proposed EMS has two major sections as shown in Figure 7-1, they are

- Estimation of vehicle trip energy demand and
- Devising control strategy

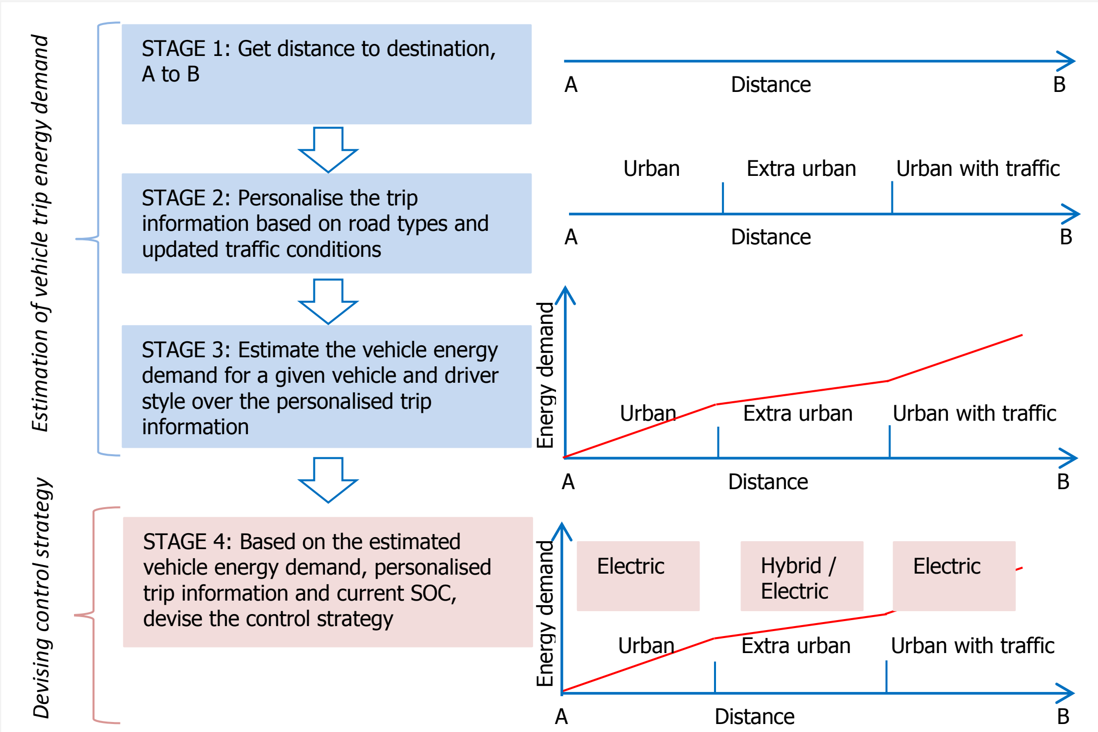

Figure 7-1: Working principle of the proposed blended rule based EMS for real world driving

Driving information needs to be selected based on its characteristic difference in energy demand that can improve the trip demand estimation or in devising the control strategy. To start with the driving information considered was driver style, route distance and road types such as urban and extra urban with traffic as sub function. After determining and personalising the driving information for a trip, the vehicle energy required is estimated. Based on the estimated vehicle energy profile over driving information (STAGE 3 in Figure 7-1) and current battery SOC, the control strategy is devised (STAGE 4). Hence the control strategy is personalised for each trip demand and updated throughout the journey. Driving information is used for both estimation of trip energy demand and devising control strategy. Thus the operation of motor and the engine duration and time for the trip are planned and updated.

A flow chart of the proposed EMS is shown in Figure 7-2, which is explained in the following two sections, estimation of vehicle trip energy (7.2.3) and devising control strategy (7.2.4).

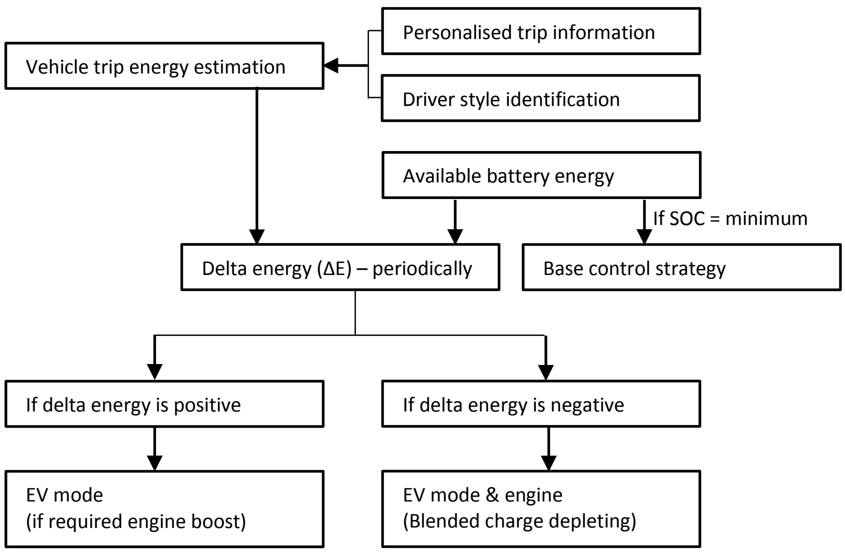

Figure 7-2: A flow chart of the proposed blended rule based EMS

7.2.3 Estimation of vehicle trip energy demand

Normally trip demand is predicted in terms of vehicle speed profile and based on which optimisation based EMS formulate the control strategy as observed in chapter 4. In the proposed EMS method the trip demand is estimated in terms of vehicle energy required.

In this section the method for estimation of vehicle trip energy demand is explained in three parts; personalised trip information, driver style identification and trip energy estimation. For a given vehicle and driver style, the energy demand profile is estimated over the personalised trip data. As one of the aspects of EMS is to effectively manage the battery energy, for the trip demand estimation only the electric energy (battery energy) required is considered.

7.2.3.1 Personalised trip information

Once the destination is known (STAGE 1 in Figure 7-1), trip information is personalised over distance according to road types and traffic condition as shown in Figure 7-3.

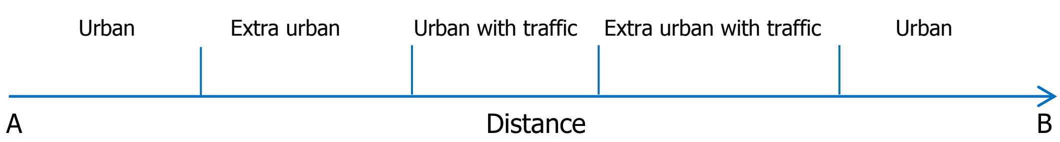

Figure 7-3: A schematic of personalised route information

To personalise the trip say from destination A to B, distance and road type information can be obtained using global positioning system (GPS). Traffic information for the trip planned can be accessed using intelligent transport system (ITS), GPS or vehicle navigation system or other highway agencies like www.trafficengland.com. However traffic information currently may not be available to all location but in the future it is expected to be available to vehicles. This leads to an end of STAGE 2 in Figure 7-1. Personalised trip information shown in Figure 7-3 for a trip are driver style, road types and distance. This information for a planned destination can be known in real world driving.

In this research, personalised trip information was done manually instead of directly integrating with GPS or ITS. This aspect was not part of the research, which is focused on demonstration of the proposed EMS principles.

7.2.3.2 Driver style identification

Based on the identified driver style, vehicle energy is estimated over the personalised trip information. A system to identify or select a specific driver style in vehicle is required which is part of the suggested future work. To start with a single driver style will be manually selected. The relation of driver style and road type in terms of vehicle energy is explained below.

Specific energy (α) is the vehicle electric energy required per kilometre for each road type. In Figure 7-4, a schematic database of specific energy data matrix for driver styles (x) and road types (y) is shown. x and y are index number for driver styles and road types respectively. In the figure the horizontal line represents the specific energy value (in kJ/km) which will be determined studying real world driving data as discussed below.

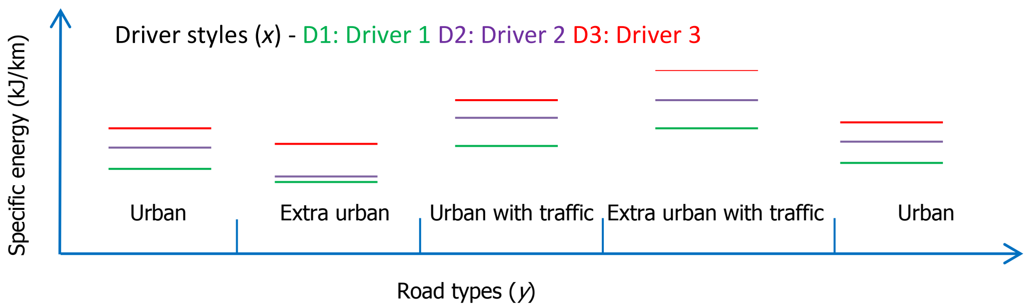

Figure 7-4: A schematic of specific energy matrix of each driver style for a given road type

For a given vehicle and driver (style), historic real world driving (vehicle speed profiles or actual electric energy consumed) data of a few trips can be used to calculate specific energy for the respective road types. In the case of historic vehicle speed profiles for the respective road types, the total electric energy (kJ) required can be found out (by simulation) which is then divided by the distance (km) of data considered. Similarly this can be done for various driver styles. Specific energy calculation and use in trip demand estimation is illustrated for known trip demand (NEDC) in the next chapter and for uncertain trip demand (real world driving) in chapter 12. In summary specific energy is an average trip demand in terms of vehicle energy for a driver style and road type. This is calculated using historic real world data. Specific energy matrix gives a specific energy value for a driver style against each road type.

In the schematic Figure 7-4 traffic is shown as sub function of road types. Similar sub function can be considered for weather and extreme elevation change. Extreme elevation change can be considered as small changes in elevation has less effect on vehicle trip demand with large battery pack like PHEVs as discussed in EMS review chapter (Chen et al., 2010). Indicative lists of factors that can be considered are shown in Table 7-1. Like elevation and road types grading of other factors can be done based on influence in estimation of vehicle trip energy and/or in devising control strategy. Some of these factors such as traffic grading can be considered for future work.

Table 7-1: An Indicative list of driving factors

Road types	**Traffic**	**Weather**	**Elevation**	**…………….**
Urban	No	Good	Normal	…………..
Extra urban	Low	Poor	Extreme change	…………..
…………….	Medium			
……………..	High			

7.2.3.3 Trip energy estimation

Based on the identified driver style, using the specific energy matrix the vehicle electric energy demand for the trip can be determined. This section discuss about STAGE 3 in Figure 7-1.

Estimated energy for a given road type is determined by,

$$E_x = \alpha_{x,y} \, . \, d \tag{7-1}$$

Where, α is the specific energy (kJ/km) value for a given road type x and driver style y and d is the distance of the road type considered.

The trip energy estimation for each road type is a linear estimation using specific energy over distance as shown in Figure 7-5.

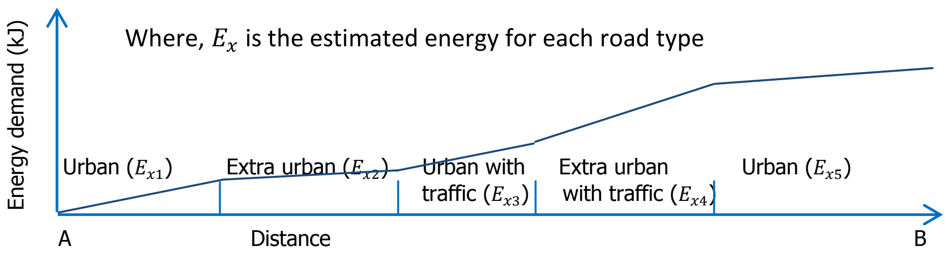

Figure 7-5: A schematic of trip energy estimation over personalised trip information

The total estimated trip energy E_0 is the summation of estimated energy for each road type

$$E_0 = E_{x1} + E_{x2} + E_{x3} \dots \dots \dots \dots \dots + E_{xm} \tag{7-2}$$

Where, 1,2,3….m are the number of road types in a trip.

Based on known driving information (driver style, road types and distance) of a planned trip (A to B) and using the respective specific energy, the vehicle trip energy is estimated.

7.2.4 Devising control strategy

Devising control strategy (STAGE 4 in Figure 7-1) of the proposed EMS for varied trip conditions are explained in four parts. First an illustration of the EMS adaptive principle to address uncertain driving conditions is given. Next the method of devising the control strategy is explained with a flow chart (section 7.2.4.2). Later the vehicle efficient engine on/off control over driving information is discussed (section 7.2.4.3) followed by the base control strategy (section 7.2.4.4).

7.2.4.1 Illustration of the EMS adaptive principle

For uncertain real world driving conditions, adaption to change in demand in real time is the key requirement for an effective EMS. The estimated trip energy demand profile serves as a base for the whole trip and allows the EMS to devise a control strategy. Personalised trip data (driving information) is also part of the EMS decision making. The adaptive part of the EMS is realised by comparing the estimated trip energy demand (E_t) against the total available battery energy E_{bt}. The available battery energy (E_{bt}) at time t is the indicative battery energy available calculated between the current SOC and the target SOC. Where, the target SOC is the SOC that needs to be achieved at the end of the trip. This is usually the minimum battery SOC. The available battery energy calculation is as shown below,

$$E_{bt} = \left(SOC(t) - SOC_{target}\right) * B \tag{7-3}$$

Where, *B* is the total battery capacity in kJ. Total battery capacity or total useable energy is calculated at fixed current but the current drawn actually varies with the vehicle speed. Hence the available battery energy calculation introduces a small deviation.

For example, over the NEDC the actual battery energy required for the considered saloon vehicle simulation in electric only mode was 4662 kJ (shown later in section 8.3). Using the equation 7.3, the calculated battery energy using the initial and final SOC was 4858 kJ. This leads to a difference of 196 kJ which makes a difference of 0.016 of SOC. In other words this led to a deviation of 1.6% of the total battery capacity. Considering a large battery pack and wide usable SOC window in PHEV, the deviation in calculated battery energy will have minimal effect.

Based on a surplus or deficit of battery energy, the proposed EMS control strategy is formulated over driving information. Adaption of the EMS during the trip helps to bridge the gap between the actual and estimated trip demand. To do so, the available battery energy is monitored periodically during the trip and compared against the remaining estimated trip demand. Each time, based on the surplus or deficit available battery energy condition, the control strategy is revised.

A schematic representation of the EMS adaptive principle is shown in Figure 7-6. At periodic times the difference between the remaining estimated trip energy E_t and the available battery energy E_{bt} is calculated, called delta energy ΔE_t, where t = 0, 1, 2, 3…m. zero and m are the initial and final instantaneous delta energy at the start and end of the trip respectively.

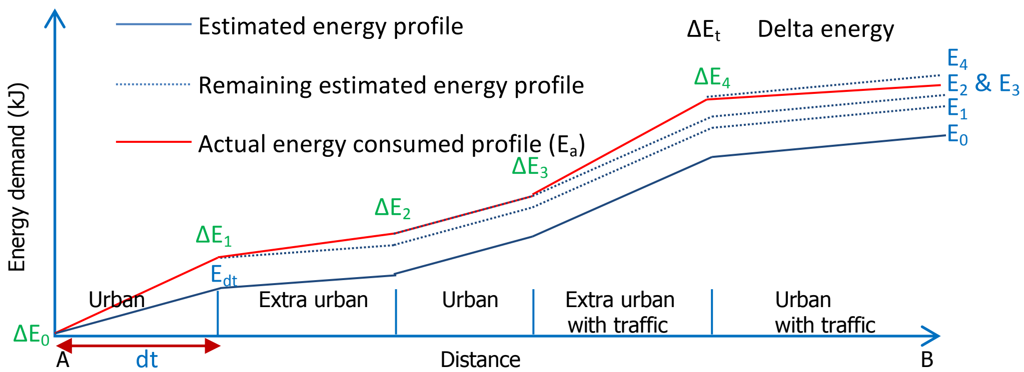

Figure 7-6: A schematic representation of the blended rule based EMS adaptive principle

Say after time *t* in Figure 7-6, the distance covered is *dt*, then the instantaneous remaining trip estimation energy E_t will be,

$$E_t = E_0 - E_{dt} \tag{7-4}$$

Where, E_0 is the total trip estimated energy and E_{dt} is the estimated energy for the distance covered (dt).

From this, delta energy (ΔE_t) is calculated using equation (7.3) and (7.4) as shown below,

$$\Delta E_t = E_{bt} - E_t \tag{7-5}$$

During the trip the available battery energy at time t, reflects the variation in actual vehicle energy consumed is compared to the estimated trip energy. In Figure 7-6 at ΔE_1, the actual vehicle energy consumed (red line) is more than the initial estimation (solid blue line). This is reflected in the available battery energy for the rest of the trip which will be less than the anticipated and hence change in ΔE_1. Based on the latest ΔE_t a corrective control strategy is decided (if required) by the EMS. Noticeably, in the case of a big deviation in the actual vehicle energy consumed, the earlier the better for the EMS to take corrective action. However periodic sampling of delta energy can alleviate this problem.

Thus a dynamic adaptability of the proposed EMS through delta energy is achieved. This is required to address the uncertain trip demand in real world driving. Delta energy is a vital parameter of the proposed EMS which also controls the duration of engine operation as discussed in the next section. Delta energy is a function of trip demand and battery SOC. Thus personalised control strategy is devised for varied real world driving conditions.

Periodic sampling of the proposed EMS is similar to look-ahead or preview window of the optimisation based EMS discussed in the literature (section 4.4.2.3.2). But in look-ahead or preview window the duration of the prediction is considered to determine an optimal power split ratio. In the proposed EMS, the periodic sampling is used to monitor variation in trip demand for control strategy correction.

7.2.4.2 Delta energy positive

If the available battery energy is more than the estimated trip energy, then ΔE_t is positive (surplus). In this case only the electric power (EV mode) is used in the trip unless the instantaneous demand exceeds the maximum motor power or battery discharge rate as shown in flow chart Figure 7-7.

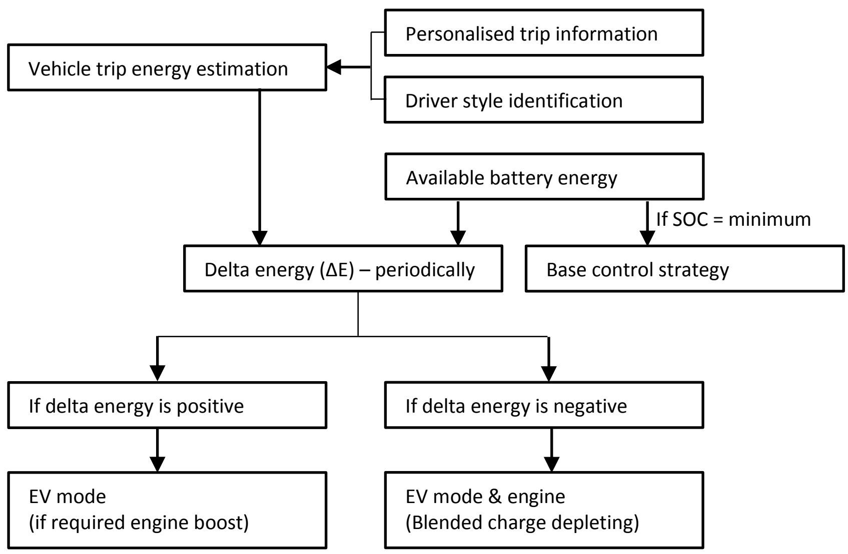

Figure 7-7: Flow chart of the blended rule based EMS devising control strategy

7.2.4.3 Delta energy negative

If the available battery energy is less than the estimated trip energy, then ΔE_t is negative (deficit). Therefore the engine is used to meet the deficit energy required as shown in Figure 7-7. Delta energy not only indicates either being positive or negative, but it also indicates how much energy is in deficit or surplus based on equation (7.5). Hence the delta energy negative value also controls the duration of engine operation. In PHEVs, duration is critical as excess charging of the battery or not using the available battery charge adds to overall vehicle inefficiency as discussed in section 2.3.5.

In the proposed EMS the engine is switched on/off at predetermined operating conditions and at assigned road types in the trips called as primary and secondary modes. These modes were determined based on the vehicle efficiency study discussed in the next chapter. The reason for such a study was explained in section 6.2.3. It was found that there is no literature on efficient engine use for a hybrid vehicle to suitably define over driving parameters; such as road types. Based on the study in the next chapter, the engine is operated at vehicle efficient conditions in leading to BCD strategy.

The third option of the proposed EMS (as shown in Figure 7-7) called the base control strategy is explained in next section.

7.2.4.4 Base control strategy

The base control strategy acts as a fall back strategy in the proposed EMS to fill in for infrequent or unexpected scenario leading to minimum battery SOC. Base control strategy is triggered when SOC reaches the minimum during the journey to switch the engine ON to operate at predetermined condition.

7.3 Conclusion

Design of the proposed blended rule based EMS structure and strategy was presented in two parts; estimation of vehicle trip energy and devising control strategy.

- In the proposed EMS the trip demand in terms of vehicle trip energy is estimated using known trip driving information of a planned trip (A to B) and respective specific energy. Method to estimate vehicle trip energy using driving information such as road types, driver style and traffic through specific energy as a common parameter is explained.
- The proposed EMS considers whole trip demand in terms of estimated vehicle trip energy profile and driving information to devise a control strategy using delta energy.
    - Delta energy is the measure of difference between the estimated vehicle trip energy and battery energy available which is periodically monitored

throughout the trip – to achieve adaptability to address real world uncertainty.

- Delta energy is a function of trip demand and battery state of charge (SOC). Based on trip driving information and delta energy, a personalised control strategy is devised for varied real world driving conditions.
- To meet the deficit trip energy (delta energy negative), the engine operates at predetermined but at vehicle efficient conditions to pursue blended charge depleting (BCD) strategy.

These vehicle efficient engine operations are studied in the next chapter.

Chapter 8 – Study of Vehicle Efficient Modes of Engine Operation over Driving Information

8.1 Introduction

In hybrid vehicles to operate engine efficiently at vehicle level, the engine operating efficiency and energy conversion losses both has to be considered. The purpose of this chapter is to study and identify vehicle efficient modes of engine operation based on driving information such as road types.

This study is required to define the vehicle efficient engine operation in the proposed EMS based on road types to overcome the deficit battery energy. It was found there is no literature to suitably define the vehicle efficient engine operation based on road types for a hybrid vehicle.

Six modes of engine operation are designed considering various engine operating conditions activated over various trip conditions such as vehicle idle, urban and extra urban driving (road types). All modes are simulated and analysed for the total vehicle energy consumed. Later in this chapter, these modes are short listed and ranked, based on potential real world driving issues and energy conversion losses.

In study method, personalisation of driving information for the NEDC is described in section 8.2.1. Vehicle trip energy estimation discussed in the previous chapter is illustrated with the NEDC in section 8.2.2. Followed by in section 8.2.3 parameterisation of the proposed EMS considered in this study is discussed.

8.2 Study method

Driving information personalisation for the NEDC and parameterisation of the proposed EMS considered for simulation are explained in this section. Followed by vehicle trip energy estimation for the driving cycle considered is described. Next the six modes of engine operation considered and their significance in terms of vehicle efficiency are discussed.

8.2.1 Driving information

In this section, the driving cycle and other driving information considered which are required for the proposed EMS method are explained.

8.2.1.1 Driving cycle

The study is carried over a legislative driving cycle, the NEDC.

8.2.1.2 Road types

Urban driving cycle (UDC) and extra urban driving cycle (EUDC) of the NEDC is considered into two road types, urban and extra urban respectively as shown in Figure 8-1/a.

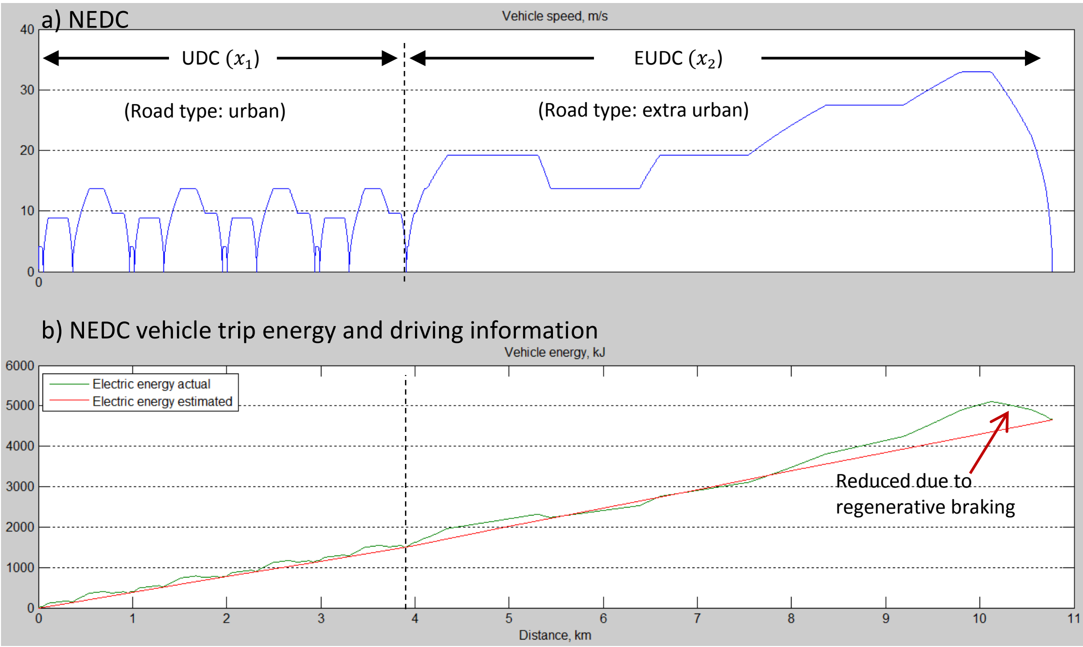

Figure 8-1: Personalisation of driving information based on road types and vehicle trip energy estimation for the NEDC.

8.2.1.3 Driver style

The NEDC is a standard driving cycle having fixed vehicle speed profile which has to be followed; hence there is no role or effect of driver style. Similarly there is no role for traffic. Hence in this study the vehicle trip demand is known in advance.

8.2.2 Vehicle trip energy estimation for the NEDC

Vehicle trip energy estimation for the proposed EMS was described earlier in section 7.2.3.3. It is illustrated with the NEDC here.

Being a study over a known (or predefined) trip vehicle speed profile the actual total vehicle electric energy (kJ) required for the considered vehicle and EMS for each road type is found for the NEDC by simulation in electric vehicle (EV) mode. From the actual vehicle electric energy consumed for urban and extra urban, the specific energy (α) for each road type is calculated by dividing these values by their respective distance. For urban part (x_1) of the NEDC, the total electric energy consumed was 1508 kJ which is then divided by its distance of 3.91 km, to get the specific energy value of 385.6 kJ/km. Similarly for extra urban part (x_2) it was 459.7 kJ/km. For vehicle trip energy estimation, the specific energy values are linearly extrapolated over distance (d) for the respective road types – red line in Figure 8-1/b.

For real world driving with uncertain trip demand and with active role of driver, the specific energy values will be considered from the specific energy matrix for the respective driver styles and road types. A schematic of specific energy matrix was discussed earlier with Figure 7-4.

Vehicle trip energy (actual/estimated) is the summation of regenerative brake and positive vehicle drive energy. The actual total vehicle energy required at local or global can be higher or lower than the estimate as seen throughout the trip distance in Figure 8-1/b. Also locally, the actual positive vehicle drive or regenerative brake energy can be higher or lower than the estimate. This can be observed in Figure 8-1/b at distance 10 km where the total vehicle energy required is higher than the estimated energy before the high speed regenerative braking happens.

Even though the vehicle speed profile of the NEDC is known in advance, it is not part of the proposed EMS input parameter. The vehicle trip energy profile estimated using driving information and specific energy is part of the proposed EMS input. Hence only the Figure 8-1/b without the green line (actual trip energy) represents the proposed EMS inputs; distance, road types and estimated vehicle energy profile. Other inputs are current vehicle speed and battery state of charge (SOC) like in any conventional EMS.

8.2.3 Parameterisation of the proposed EMS

The Proposed EMS objective is to manage the battery energy to achieve the target SOC at the end of the trip with minimum engine fuel consumption. Minimum SOC is set as the target SOC. In this study the initial SOC was set at 0.5 to simulate the trip energy deficit scenario. The minimum SOC is set to 0.4. The base control strategy for this study is such that when SOC reaches minimum (0.4), the engine operates to meet only the vehicle demand and there is no battery charging by the engine.

As part of the proposed EMS strategy, engine operation mode is activated to meet the deficit energy (refer Figure 7-7). Otherwise the primary mode is only electric mode. Deficit energy is reflected by delta energy (ΔE_t) threshold value. In the study, modes of engine are activated when the delta energy falls below the threshold value and during the assigned road types. The engine mode considered keeps operating until the delta energy is above zero.

It was initially observed when the delta energy was around zero, there was a frequent switch between positive and negative values. This was caused by local variation in actual and estimation of vehicle trip energy, due to regenerative braking (as explained in the previous section) and the way the available battery energy was estimated (using SOC at fixed current). Due to fluctuation in delta energy as shown later in Figure 8-3 the engine was switched on and off frequently. To avoid this problem a delta energy threshold of -300 kJ (lower limit) was set in the study for the mode of engine operations considered to be activated. This was so as the typical regenerative energy recovered was about 300kJ or less. To start with the periodic sampling of driving information such as delta energy and road type was set at 0.01 second. Based on real time capability study (chapter 8) appropriate sampling rate will be fixed.

The proposed EMS parameterisation is summarised below.

Table 8-1: Summary of the proposed EMS parameterisation

Parameter	Description / Value
Initial SOC	0.5
Delta energy lower limit	-300kJ
Base control strategy	Engine only
Minimum SOC (Target)	0.4
Sampling rate	0.01 second

In summary,

- Modes of engine operation are activated when delta energy is below threshold and at assigned driving conditions (vehicle speed/road type).
- Base control strategy: Engine operates to meet only the vehicle demand when SOC ≤ minimum (0.4). Battery charging only by regenerative braking or external grid.
- Otherwise EMS operates only in the electric vehicle mode.

8.2.4 Modes of engine operation

Six modes of engine operation as seen in Table 8-2 are considered to study over the urban and extra urban driving part of the NEDC. In this study the engine optimal operating line (OOL) and optimal operating point (OOP) were selected based on fuel efficiency only. Emission was not considered for simplicity. More about OOP and OOL is discussed in section 2.3.1.

Table 8-2: Six modes of engine operation studied over the NEDC

Mode No.	Description	Road type	Engine power request
1	Stationary charge at OOP	Urban	Always at OOP
2	OOL smart charging – urban	Urban	Always at OOL
3	OOL smart charging – extra urban	Extra urban	Always at OOL
4	X times smart charging – urban	Urban	1.2 times vehicle demand
5	X times smart charging – extra urban	Extra urban	1.2 times vehicle demand
6	Engine only – extra urban	Extra urban	Same as vehicle demand

8.2.4.1 Stationary charging

In this mode (mode no. 1) the battery is charged by the engine, only when the vehicle is stationary (vehicle speed is zero). This mode is considered as the engine can be operated at predefined conditions. In this study it is operated at OOP. As the likelihood of the vehicle being stationary is high only in urban driving, it is studied only for the urban road type.

8.2.4.2 OOL smart charging

The engine is always operated at OOL in this mode irrespective of the vehicle demand. When the mode is active, all vehicle demand is met directly by the engine and any excess engine power is used to charge the battery. In the case where the vehicle power demand exceeds the peak engine power, then the electric motor provides supplement power called motor boost. This mode is studied separately for urban (mode no. 2) and extra urban (mode no. 3) road types.

8.2.4.3 X times smart charging

The engine is operated at 'X' times more than the required vehicle demand. Like OOL smart charging, any excess engine power is used to charge the battery. By operating the engine 'X' times the portion of excess engine power can be controlled unlike in OOL smart charging. This mode of engine operation was considered from the battery charging point of view. It was found that the most efficient operation of the battery occurs in the low-power region for both battery charging and discharging (Schouten et al., 2002). Therefore the battery should be frequently charged at low power levels for high battery efficiency. When ‘X’ times the vehicle demand is more than the peak engine output, the engine is operated at peak with remaining excess engine power, if any, going to the battery charging. In this study ‘X’ times is set at 1.2 times. So the total engine power request will be 1.2 times the vehicle power demand. This mode is studied separately for urban (mode no. 4) and extra urban (mode no. 5) road types.

8.2.4.4 Engine only

In this mode (mode no. 6) the engine operates to meet only the vehicle demand directly, hence, there is no battery charging. This mode was considered for simplicity, no energy conversion losses and also used in many conventional rule based EMS (Qiuming et al., 2008, Karbowski, 2006). In conventional rule based EMS, the engine only mode is switched on when SOC reaches minimum. But for this strategy the engine only mode is activated based on delta energy and road type. This mode was studied only for extra urban driving. In urban driving, due to lower vehicle speeds the engine is expected to operate in inefficient regions and hence is not considered.

In these six modes considered the engine is operated at OOL, OOP, ‘X’ times and engine only conditions. These engine operations are frequently studied in literature mainly for conventional rule based EMS. The ‘X’ time’s engine operation was designed considering the battery efficiency.

8.3 Results and analysis

The six modes of engine operation considered were simulated over the NEDC. Modes were studied for vehicle efficiency and potential real world driving issues. The possible modes were reduced to a final two which were studied further to understand energy conversion losses with respect to road types.

In the electric vehicle (EV) mode at higher initial SOC, the battery energy consumed was 4662 kJ. For this study the initial SOC and target SOC was set at 0.5 and 0.4 respectively. The total vehicle energy consumed for all modes of operation are tabulated in Table 8-3. Diesel fuel calorific value considered is 42.426 kJ/g. From the table it can be observed that the OOL smart charging – extra urban has the lowest total vehicle energy consumed. Total vehicle energy is the summation of the engine and battery energy. Before doing the final ranking based on the total vehicle energy, each mode are studied and assessed for potential real world driving issues.

Table 8-3: Vehicle energy comparison of all six modes of engine operation

Mode No.	Modes of engine operation	Final SOC	Engine energy,	Battery energy, kJ	Total vehicle energy, kJ
1	Stationary charging at OOP	0.414	6961	2311	9272
2	OOL smart charging – urban	0.414	7173	2293	9466
3	OOL smart charging – extra urban	0.417	6764	2214	8978
4	X times Smart charging – urban	0.414	9662	2416	12078
5	X times Smart charging – extra urban	0.419	8062	2187	10249
6	Engine only – extra urban	0.422	8383	2190	10573

8.3.1 Stationary charging at OOP

Engine maximum torque, OOP and OOL are as shown in Figure 8-2. The engine operating points are shown in green dots. This mode was the second most efficient in terms of total vehicle energy. However the biggest risk with stationary charging is that no charging occurs if the vehicle does not become stationary during the trip. Another disadvantage is the frequent engine switching between ON and OFF during the journey can contribute to deterioration of engine life. Also running the engine when the vehicle is stationary is not attractive due to the engine noise.

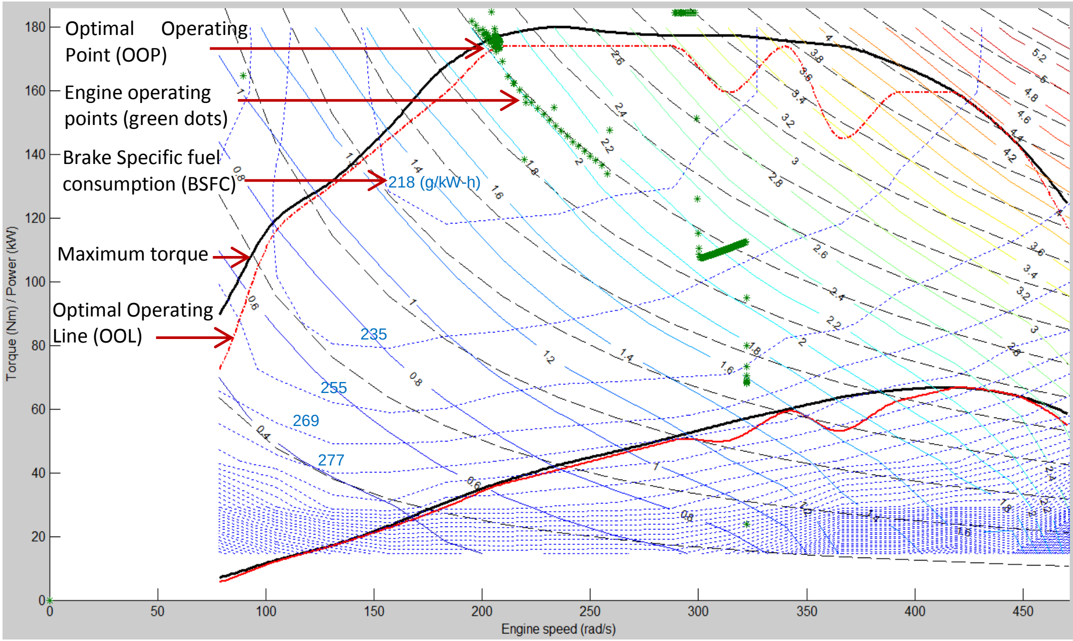

Figure 8-2: Engine operation during stationary charging at OOP over the NEDC urban road type

In the study considering the estimated vehicle trip energy for the NEDC and the initial SOC of 0.5, delta energy (ΔE_t) is calculated using equation 7.5. As shown in Figure 8-3, the delta energy is in deficit of about -1500 kJ at the start of the trip. The deficit energy (initial delta energy value) remains same for all six modes study as the initial SOC and the trip demand (the NEDC) is same.

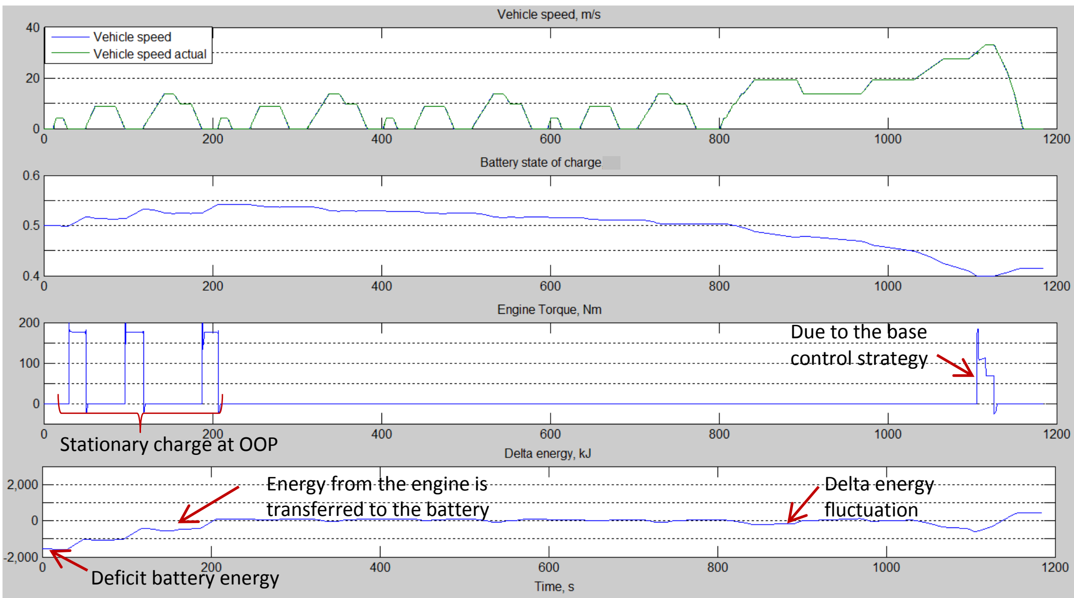

Figure 8-3: Stationary charge performance for the urban road type of the NEDC

In the study stationary charge was activated three times during the initial three stops of the NEDC to meet the deficit energy required. At each instances of stationary charge at OOP, the engine has transferred energy to the battery till the delta energy is above zero as seen in Figure 8-3. Positive delta energy value indicates that enough battery energy is available at that point to drive the vehicle in only electric vehicle mode for the remaining trip. Hence after the delta energy is above zero the engine is not turned ON when the vehicle comes to stationary.

Later in the driving cycle, engine only mode was active when SOC reached minimum value of 0.4 as part of the base control strategy. This was due to the way vehicle energy estimation was done and local variation in the estimation and actual vehicle energy as discussed in section 8.2.2. Locally around 1100 second the actual vehicle energy was higher than the estimate leading to minimum SOC. This was followed by higher actual regenerative energy than the estimate leading to a marginally higher final SOC of 0.414 instead of 0.4. Both events and sequence of happening towards the end of the trip when SOC is around minimum was not helping the EMS to adapt. This was the case in all other modes of operation and was reflected in final SOC in Table 8-3.

8.3.2 OOL Smart charging

The engine operating points during smart charge at OOL for urban and extra urban road types of the NEDC are shown in Figure 8-4, a) and b) respectively. In comparison during extra urban driving, the engine was operated more at mid-range speed from 200 to 300 rad/s which falls under the most efficient speed range with brake specific fuel consumption (BSFC) of 218 g/kW-h as shown in Figure 8-4. Typically engines are most efficient at higher load operating at engine mid-range speed.

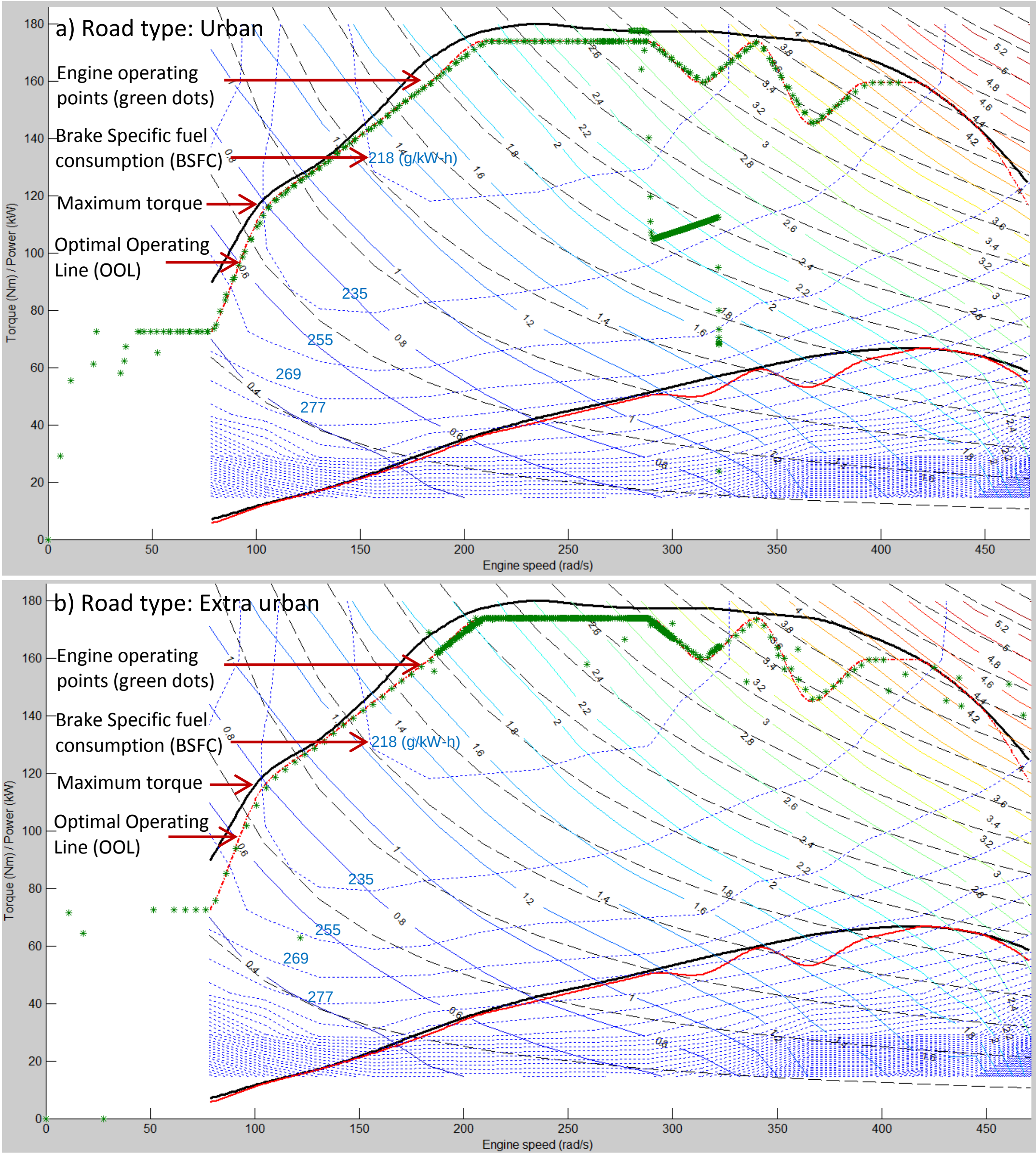

Figure 8-4: Engine operation during OOL smart charging over the NEDC urban and extra urban road types

OOL smart charging both in urban and extra urban driving were among the efficient modes of engine operation along with stationary charging. However OOL smart charging in extra urban driving was the most efficient. This also demonstrates in hybrid vehicles controlling the engine operation at OOL (fuel efficient) conditions alone does not guarantee efficient performance at vehicle level as in this case. The superior performance of OOL smart charging in extra urban over that of urban driving is discussed later in more detail later in section 8.3.6.

OOL smart charging performances for urban and extra urban road types of the NEDC are shown in Figure 8-5 a) and b) respectively.

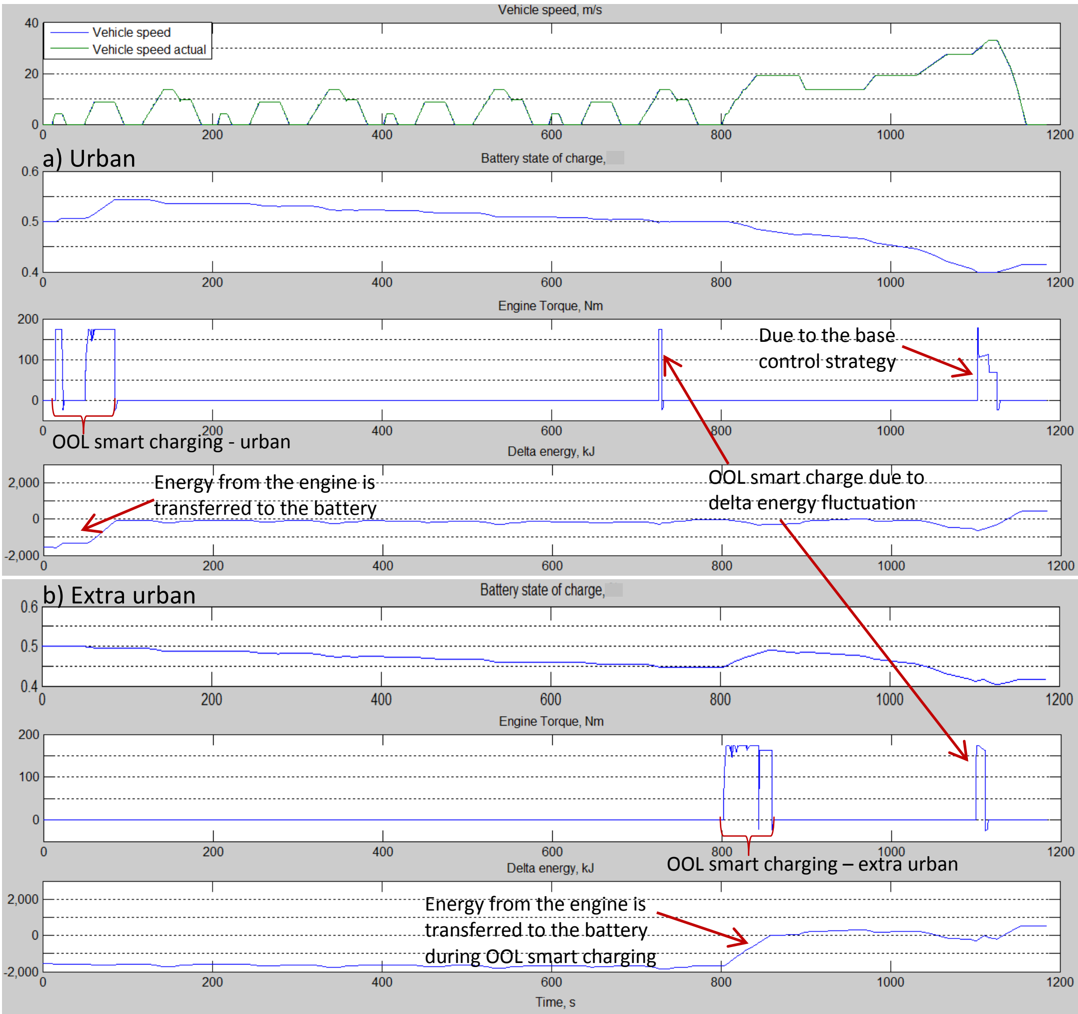

Figure 8-5: OOL smart charging performance for the urban and extra urban road types of the NEDC

The OOL smart charging for urban and extra urban road types of the NEDC are activated only when the delta energy is negative and during the respective assigned road type. In both cases, the smart charge was switched on for the second time when the delta energy value was momentarily less than the threshold. In addition for smart charging – urban mode, the base control strategy was activated like in stationary charging. Hence like in stationary charging, the final SOC was 0.414 for OOL smart charging in urban mode.

Whereas for smart charging in extra urban mode final SOC was 0.417 due to the second OOL smart charge activated by the delta energy fluctuation towards the end of the trip.

8.3.3 X times smart charging

This mode vehicle energy consumed was among the highest for both urban and extra urban driving due to the EMS having no direct control over the engine operation (Figure 8-6).

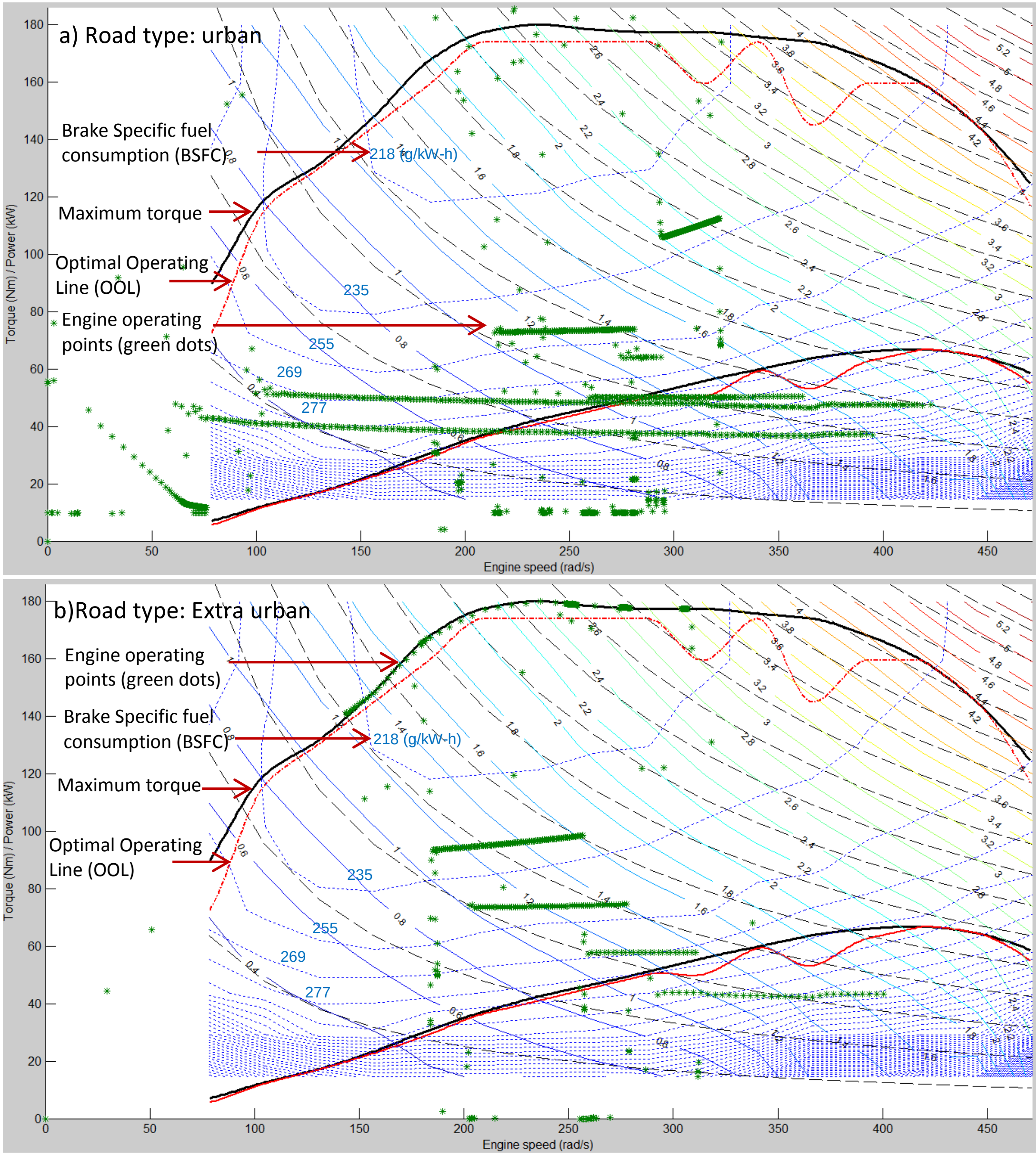

Figure 8-6: Engine operation during X times smart charging over the NEDC urban and extra urban road types

The engine operation was dictated by the vehicle demand. This was reflected in the total engine energy values earlier in Table 8-3 which were distinctly higher compared to stationary charging and OOL smart charging.

X times smart charging performance for urban and extra urban road types of the NEDC is shown in Figure 8-7, a) and b) respectively. This mode of operation with respect to delta energy is similar to previous modes discussed. But the engine operation is longer compared to other modes which may impact customer perception due to noise.

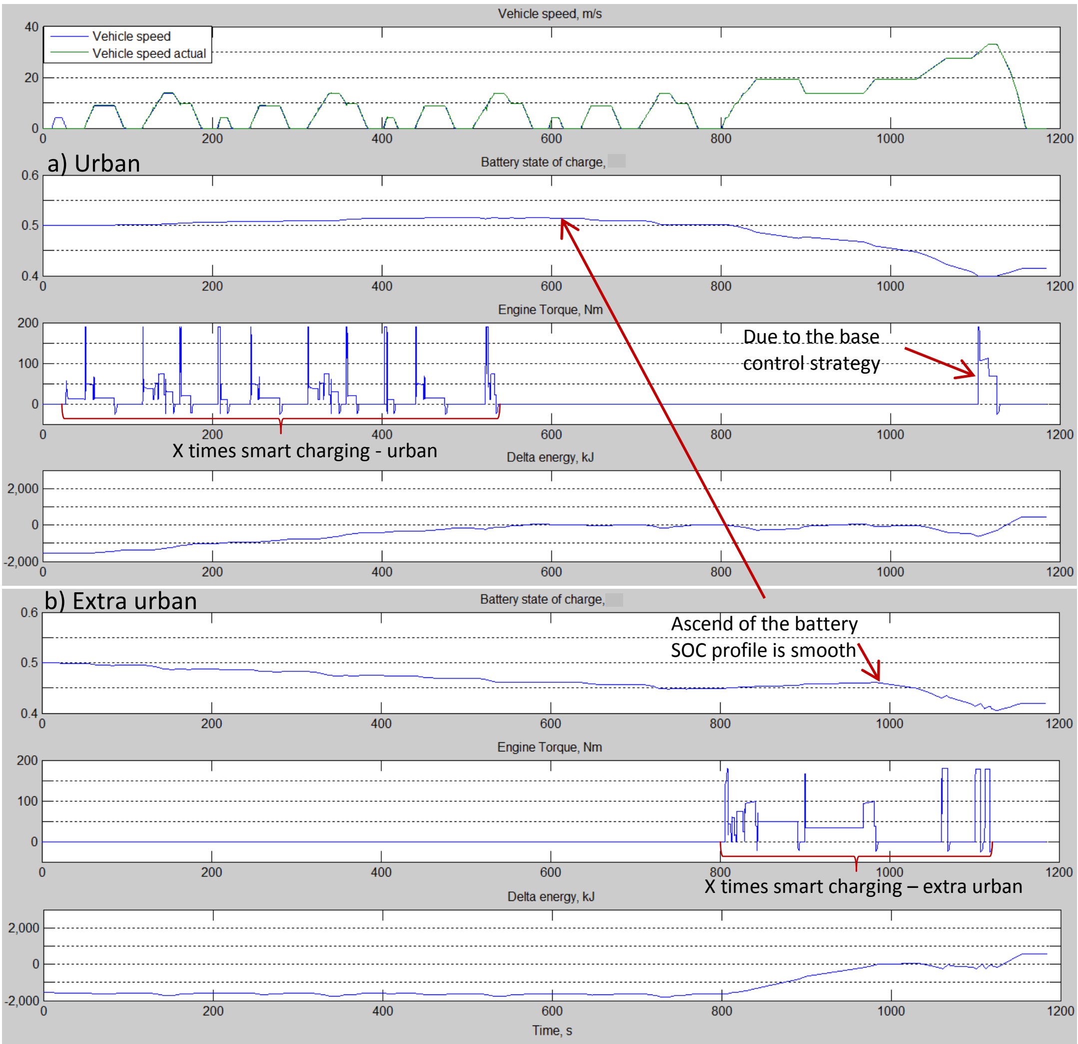

Figure 8-7: X times smart charging performances for urban and extra urban road types of the NEDC

Due to controlled engine charging, this mode was found to have smooth and gradual ascend of SOC profile during smart charge as shown in Figure 8-7, in comparison to previous modes of engine operations. Smooth and gradual ascend and descend (charge and discharge) of the battery SOC profile helps battery lifetime. But the cost in terms of vehicle energy consumed is too high for the X times smart charging mode in comparison to other modes and hence is not considered for further study.

8.3.4 Engine only

The engine only operation was similar to the X times smart charging both in terms of vehicle energy and the reason for such a performance. Even though the engine only mode was considered only for the extra urban road type owing to higher vehicle speed, this mode was still not good enough in terms of total vehicle energy consumed. The engine only operating points were as shown in Figure 8-8.

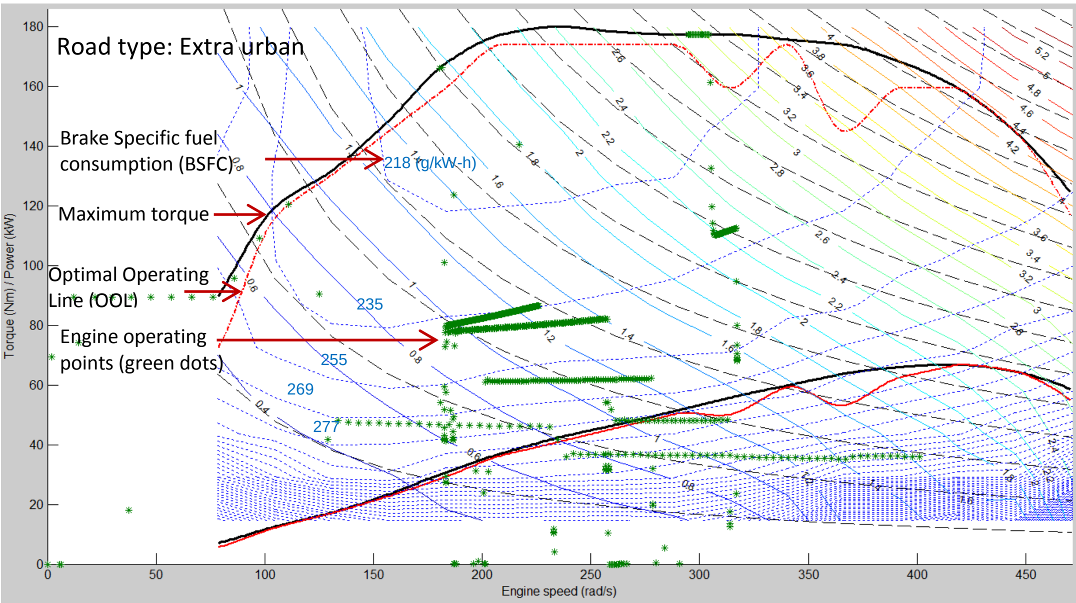

Figure 8-8: Engine operation during Engine only over the NEDC extra urban road type

In the engine only mode performance over the NEDC for the extra urban was as shown in Figure 8-9. In this mode there is battery charge only by regenerative braking and not by the engine. However in the figure delta energy profile is rising towards zero delta energy during engine operation. At the same time there is no change in battery SOC value. This confirms that engine is not charging the battery. But the increase in delta energy is the reflection of the reduced deficit trip energy required as that part of the trip energy is met by other source. In other words the reduced deficit energy as the vehicle moves towards the destination by operating only the engine led to decrease in negative delta energy. Delta energy indicates the electric energy required to meet the planned trip in EV mode.

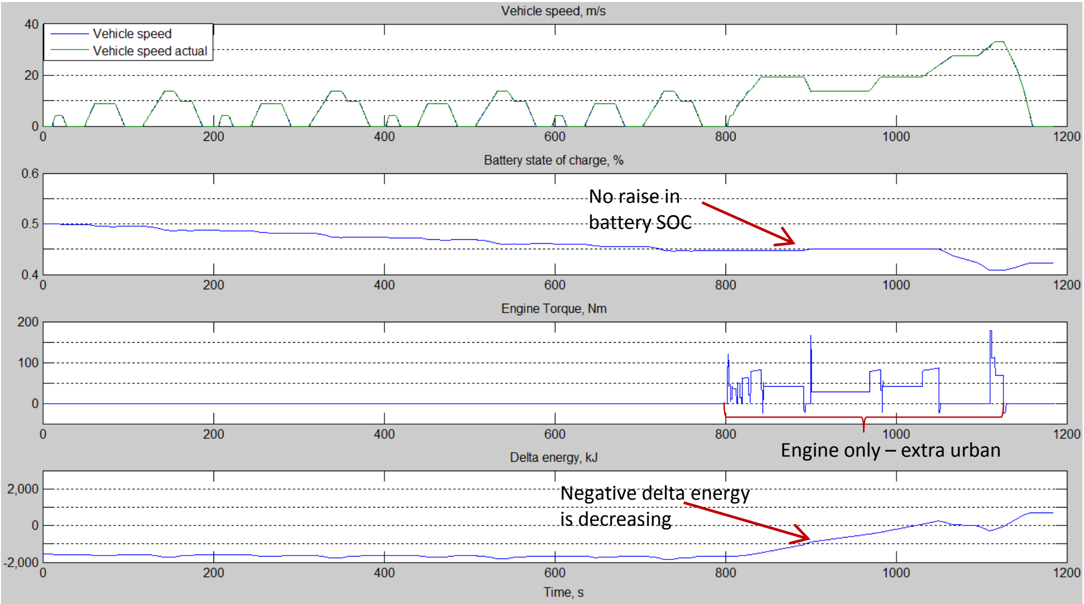

Figure 8-9: Engine only performance over the NEDC for the extra urban road type

8.3.5 Summary of the six engine modes study

Overall the most vehicle efficient engine operation is at OOL over the extra urban road type of the NEDC. After ruling out stationary charging, OOL smart charging urban is the second most efficient. Also it was shown in hybrid vehicles operating the engine in efficient regions alone does not guarantee vehicle efficient performance. In the next section energy conversion losses when operated over urban and extra urban road types are analysed.

8.3.6 Analysis of energy conversion losses over urban and extra urban driving

It is known that when the engine power is used to charge the battery, there are energy conversion losses due to backward and forward power flow from the electric machine and battery. In this study the average efficiency of the motor and battery during charge and discharge observed over the NEDC is tabulated in Table 8-4. These are typical efficiency values observed for the battery and motor at steady speeds over the NEDC. The average loss in power to convert the mechanical to electrical and back to mechanical energy is more than 40%. Hence energy conversion losses become one of the important criteria for vehicle efficiency in hybrid vehicles.

Table 8-4: Average efficiency observed over the NEDC

Parameter	Value
Generator charging efficiency, %	0.84
Motor driving efficiency, %	0.80
Battery charging efficiency, %	0.86

In Figure 8-10, during smart charging at OOL in urban and extra urban driving, the engine and generator (charging) power distributions along with vehicle power are shown. In the figure, the excess power produced by the engine after meeting the vehicle power demand is used to charge the battery through the generator. In the figure the difference between the vehicle and generator power is wider in urban and narrower in extra urban of the NEDC. This indicates energy conversion losses are higher in urban than in extra urban of the NEDC. To reduce energy conversion losses, the contribution to generator power should be reduced. In other words increase the portion of the engine power directly driving the vehicle. However, operating the engine at other than OOL is not efficient as observed in previous section. So the engine has to be operated at driving conditions, when the portion of the engine power directly driving the vehicle is higher. Also in Figure 8-10, during acceleration the contribution to generator power is lower. Hence at higher vehicle speed and acceleration, a greater portion of the engine power was used to directly drive the vehicle as indicated by the vehicle power. In order to reduce energy conversion losses, smart charging at OOL is recommended to use at higher vehicle loads or speeds. This is also in agreement with the OOL smart charging study in the previous section where the total vehicle energy results observed in Table 8-3. Also, by meeting the higher vehicle demand directly by the engine at higher vehicle speeds, more battery power is saved.

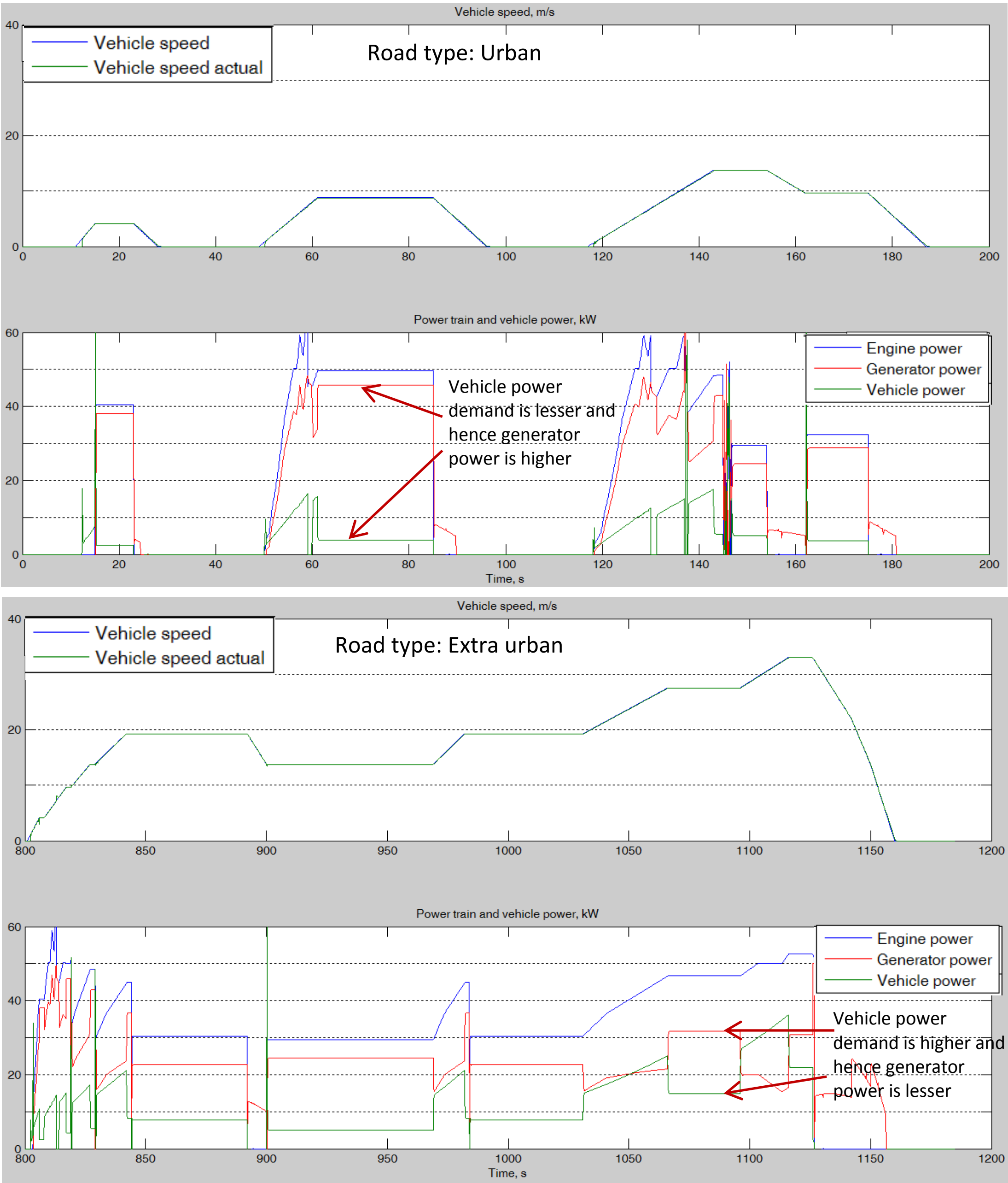

Figure 8-10: Engine and generator (motor charging) power distribution along with vehicle power in urban and extra urban driving over the NEDC during smart charging at OOL. Generator power is actually negative, but for the comparison purpose it is shown as positive power.

8.3.7 Engine operating modes considered for the proposed EMS

In the proposed blended rule based EMS, OOL smart charge in extra urban driving is set as the preferred mode to meet the battery energy deficit for a given trip. This mode is triggered and controlled by delta energy (ΔE_t) which reflects the overall (global) trip energy status.

OOL smart charge in urban driving is implemented as a secondary mode which gets activated if there is not sufficient battery energy to meet only the current urban road type. This may happen if extra urban road type comes later in the trip after long urban driving or extra urban smart charging was not sufficient. OOL smart charge in urban is triggered and controlled by local delta energy (ΔE_L). The local delta energy is calculated similar to delta energy but only considers energy status for the current urban road type and not the entire trip energy. Therefore the OOL smart charge in urban if triggered meets only the deficit of the current urban road type. Hence the battery SOC is expected to reach minimum at the end of the current urban road type. The local delta energy operation is demonstrated later in the validation study (section 12.4.1.4).

Thus the proposed EMS will adapt once identified vehicle efficient engine operations to varied trip conditions. This is in contrast to the optimisation based EMS where the optimal operating points of the power train are determined ever time from scratch based on trip vehicle speed profiles. Hence overall this method is expected to bring down computational time without much trade off on efficiency under uncertain conditions.

Along with the engine operation, road types as part of driving information play an important role due to the distinct vehicle speed (or load) characteristic in devising control strategy.

After this study, the base control strategy of the proposed EMS is switched from engine only operation to engine operating at OOL. With this change the proposed EMS is compared with conventional rule based EMS for varied initial SOC and distance in the next chapter.

8.4 Conclusion

- The proposed blended rule based EMS was applied in a study over the NEDC.
  - Delta energy was shown to be a good parameter for the proposed EMS to use as an input to decide and control engine operation.
  - Vehicle efficient mode of engine operation with respect to driving information such as road type is identified. Six modes of engine operation over road types – urban and extra urban driving, were studied. The most vehicle efficient mode was engine operation at optimal operating line (OOL) over extra urban. Before this, there was no literature on efficient engine use for hybrid vehicles to suitably define over driving information.
  - In the proposed EMS OOL smart charging extra urban and urban are considered as the primary and secondary mode respectively to overcome the deficit battery energy.
- In the proposed EMS once identified vehicle efficient engine operating conditions adapts to varied trip conditions. In optimisation based EMS optimal operating power train points are determined from scratch based on each trip vehicle speed profile.
- It was shown in hybrid vehicles, operating the engine in efficient regions alone does not guarantee vehicle efficient performance. Energy conversion losses become critical in deciding vehicle efficient engine operation.
- Due to distinct vehicle speed characteristics, road type plays an important role in vehicle efficient engine operation and in decision making of the proposed EMS.

Chapter 9 – Comparison Study of the Proposed and Conventional EMS over the NEDC

9.1 Introduction

In this chapter, the proposed, blended rule based EMS method is studied as a complete system and compared with conventional rule based EMS for plug in hybrid electric vehicles (PHEV) over a commonly used legislative drive cycle - the New European Drive Cycle (NEDC). In the comparison study, vehicle performance such as the fuel economy, number of engine stop-starts and final battery state of charge (SOC) are compared for varied trip distance and initial battery SOC. The trip distance is varied by considering the NEDC multiple times. The varied trip distance and initial battery SOC is considered to study the adaptability of the proposed EMS for varied trip demand and trip deficit (delta energy). Delta energy of the proposed EMS is the function of the trip demand and battery SOC.

This study is also a performance comparison study of the blended charge depleting (BCD) strategy and charge depleting – charge sustaining (CD-CS) strategy used in the proposed and conventional rule based EMS respectively. For detailed description of BCD and CD-CS strategy refer section 2.3.5. Varied trip distance comparison study between the BCD and CD-CS strategy results in this chapter is compared with a similar comparison study from the literature (He et al., 2012a) with an optimisation based EMS.

In the next section parameterisation of the proposed and conventional EMS methods considered in this study is discussed. Commonly used two conventional EMS methods are considered for comparison. After this study the better performing conventional EMS method is considered for future studies. Next in the study method, the driving cycle considered and correction of fuel economy based on final SOC is described. Later in the chapter, in the result and analysis section vehicle performance of all EMS methods are compared and studied.

In summary the objective of the comparison study over the NEDC is:

- To study the effect of varied trip demand through varied trip distance and initial SOC on the proposed EMS performance and adaptability.
- The proposed EMS comparison results with CD-CS strategy of the conventional EMS for varied trip distance is compared with a similar comparison study from the literature using optimisation based EMS.
- Compare two conventional rule based EMS performance with the proposed EMS and select the best conventional EMS for future comparison studies.

9.2 EMS methods

For comparison study, two commonly used conventional rule based EMS for PHEVS were considered along with the proposed EMS. The control strategy and parameterisation of all three EMS considered are explained in the following sections.

9.2.1 Conventional rule based EMS

Conventional rule based EMS are causal system hence work on only CD-CS strategy. The two rule based EMS considered are part of simulation suite, Powertrain Systems and Analysis Toolkit (PSAT) developed by ANL. The two rule based EMS are different only in the CS strategy as discussed below.

9.2.1.1 Method 1 – Only engine

This conventional rule based EMS was used for performance comparison of optimisation based EMS in studies from Karbowski et al (2006) and Qiuming et al (2008). The rule based control strategy during CS mode is as explained below,

- Only the engine meets the vehicle demand when SOC is ≤ 0.4.

- During the engine operation, no battery charging by the engine.
- Battery charging only by regenerative braking.

When SOC is > 0.4, it is CD mode. This method is referred as ‘C#1’ in the study.

9.2.1.2 Method 2 – engine operates only at OOL

For controlled engine operation at high efficiency this method was considered where the engine operates only at optimal operating line (OOL). This method is called as optimal engine power strategy in PSAT (Freyermuth et al., 2007). The engine operates based on SOC limits and vehicle demand to maintain the battery SOC during the CS strategy.

To reduce energy conversion losses as studied in chapter 8, the engine operation at lower vehicle demand is avoided unless the SOC reaches minimum. The trade-off is such that, the energy conversion losses are reduced and also the battery SOC does not reach minimum frequently (which may lead to frequent engine stop-start condition). In this study the minimum vehicle speed for engine ON was selected as 12m/s (27mph). This was arrived at based on the typical urban vehicle speed limit which varies from 13.33 to 17.78 m/s (30 to 40 mph) and hence the actual driving speed can vary from 12m/s and above during normal traffic. Also 12 m/s threshold ensures the engine is not switched OFF frequently due to speed threshold and also vehicle speed is high.

The CD mode is active when SOC is > 0.45. The CS mode is active between the SOC of 0.4 to 0.45. The rules of CS mode is as explained below,

- Engine always operates at optimal operating line (OOL)
- Engine is switched ON when SOC ≤ 0.4; OR SOC < 0.45 AND vehicle speed > 12m/s
- Engine is OFF (enters electric mode) when SOC > 0.45 OR vehicle speed <12m/s AND SOC>0.4

This method is referred as ‘C#2’ in the study.

9.2.2 The proposed EMS method

Details about working principle and implementation of the proposed blended rule based EMS method formulated over driving information and vehicle trip energy was explained in chapter 7. In this section changes in parameterisation and threshold values from the chapter 8 study for the proposed EMS methods are defined and rules are summarised. These changes are based on learning from the chapter 8 study.

Primary and secondary modes of smart charging for the proposed are decided based on study in the previous chapter. Similar to the conventional EMS method 2 (C#2), the minimum vehicle speed for engine ON has to be set for the proposed method during smart charging in extra urban (primary) and urban driving (secondary). For the study, the minimum vehicle speed for extra urban smart charging was selected as 22 m/s and that of urban 12 m/s. The extra urban speed limits can vary from 26.67 to 31.1m/s in UK. These threshold values have to be calibrated based on speed limits and real world driving data observation in UK in order to strike the balance of using engine at higher speed and for enough duration without frequent engine ON/OFF. If the threshold speed is higher than the natural driving speeds then adequate smart charging may not happen in extra urban driving and the system may be forced to charge at lower speed of 12m/s in urban driving which reduces the vehicle efficiency due to higher energy conversion losses. Hence these threshold values may need calibration based on vehicle, driver style and country or region to find the natural driving speed to strike the balance between higher speed and duration. This can be part of future work based on driver styles and region. Delta energy and local delta energy threshold values are same as – 300 kJ. Delta energy is the difference between the available battery energy and the estimated trip energy.

The rules of the proposed blended rule based EMS developed for real world driving is as set below,

- Primary and secondary smart charge when the respective delta energy and vehicle speed threshold limits are met.
- Base control strategy: Engine operates at OOL when SOC ≤ 0.4.
- Otherwise EMS operates only in the electric vehicle (EV) mode (default mode).

So the engine when switched ON always operates at OOL. Delta energy threshold for smart charge activation, sampling rate and all other rules remain the same as in the previous study (Table 8-1). The proposed EMS is referred as 'Prop' in this study.

In all three methods during CD (conventional EMS) or EV mode (proposed EMS), the electric motor meets the demand unless the peak motor power or battery discharge current is above the vehicle demand power. Otherwise the engine is switched ON above the peak threshold.

9.3 Study method

In this chapter vehicle performances of the proposed and conventional rule based EMS are compared over the NEDC in two studies: varied trip distance and initial SOC. Vehicle performance such as the fuel economy, number of engine stop-starts and final SOC of all EMS methods are compared in this study.

In the first study all three EMS methods were simulated over the NEDC for varying trip distance to study vehicle performance for a given initial SOC. The NEDC was considered one time (1x), two times (2x) and three times (3x) to simulate the varied trip distance. Following this the best conventional EMS method is considered in the second comparison study with the proposed EMS. In the second study the initial SOC was varied from 0.8 to 0.5 in steps of 0.1 over the NEDC 3x and vehicle performance is compared.

For the proposed EMS, the vehicle trip energy estimation for the NEDC was discussed in previous chapter, section 8.2.2. Similarly, the vehicle trip energy is estimated for the NEDC

2x and 3x using the respective trips driving information such as road types and its sequences and distance.

In the hybrid vehicle study, to compare the fuel economy results of different EMS methods the final SOC which can be different has to be corrected for fair comparison. Some of the techniques used in the literature are reviewed and a technique is selected for studies in this research in the following section.

9.3.1.1 State of charge (SOC) correction

For a fair comparison, the hybrid vehicle fuel economy results at the end of the driving cycle need to be corrected to a common SOC. This is done by estimating the fuel required to correct SOC (Opila, 2010, Adhikari, 2010).

$$\Delta fuel = Battery\ capacity\ .\Delta SoC \frac{BSFC_{min}}{\eta_{max}^{regen}} \tag{9-1}$$

where, $\Delta fuel$ is the adjustment to the fuel required, ΔSoC is the difference between the actual and minimum SOC, $BSFC_{min}$ is the best brake specific fuel consumption (BSFC) of the vehicle engine (OOP), and η_{max}^{regen} is the best charging efficiency of the vehicle system.

Other method includes, neglecting the battery energy consumption and considering only the fuel consumption over many repetitive legislative driving cycles considered 10 to 15 times (Freyermuth et al., 2007, He et al., 2012b). In this method the contribution of battery energy is small in comparison to the fuel energy, as the total distance is in few hundreds to thousand kilometres.

In another method fuel equivalent value for electric energy is considered like in (O'Keefe and Markel, 2006) to calculate equivalent fuel economy in miles per gallon called as miles per gallon equivalent. In couple of studies, cumulative spent fuel and electric energy was considered for comparison (Sharer et al., 2008, Karbowski, 2006) without correcting the final SOC. However this method was normally used to compare among various vehicle types like electric vehicle (EV), HEV and PHEV and architectures like series, parallel and series-parallel.

First method, Opila et al was considered in this research, as it is appropriate for a limited trip distance (of maximum about 42 km), comparison studies are for a given PHEV and also one of the commonly used. In the study the fuel economy was corrected to minimum SOC of 0.4, which is the target SOC. Hence in the thesis all comparison and discussion are done considering the corrected fuel economy.

9.4 Results and analysis

In the first study all three EMS methods are studied over varied trip distance of the NEDC for a given initial SOC of 0.5. Results of two conventional EMS are compared and studied both at the vehicle level and engine level. Next the performance of the proposed EMS is illustrated for the NEDC with respect to delta energy. Followed by, vehicle performance comparison of all three EMS. After the first study for varied trip distance the proposed EMS comparison results with conventional is also compared with a similar comparison study results from the literature with an optimisation based EMS.

Similarly results of the second study with best conventional and proposed EMS for varied initial SOC over the NEDC 3x are considered. Also adaptability of the proposed EMS for varied deficit trip conditions is analysed.

9.4.1 Comparison study of all EMS methods over varied trip distance

Two conventional EMS methods and the proposed EMS method were simulated over varied distance of the NEDC. The initial SOC was set at 0.5 and the NEDC was considered multiple times continually to vary the trip distance like one time (NEDC 1x), two times (NEDC 2x) and three times (NEDC 3x).

9.4.1.1 Comparison of two conventional EMS operation over the NEDC 3X

The engine operation and SOC profile of both conventional EMS methods for NEDC 3x is shown in Figure 9-1. The CD-CS strategy of the conventional EMS is shown in the figure. The engine is operated only in CS strategy for both conventional EMS.

Figure 9-1: Engine performance and SOC profile of conventional EMS methods, C#1 and C#2 over the NEDC 3x with initial SOC of 0.5

The number engine stop-starts are almost same for both EMS C#1 and C#2. In C#2 as the engine operates always at OOL, the excess engine torque is used to charge the battery and thus the charge sustaining (CS) was achieved. In the case of C#1, no battery charging occurred during CS unless the regenerative braking happens.

The engine operating points of C#1 and C#2 over the NEDC 3x with initial SOC of 0.5 is shown in Figure 9-2.

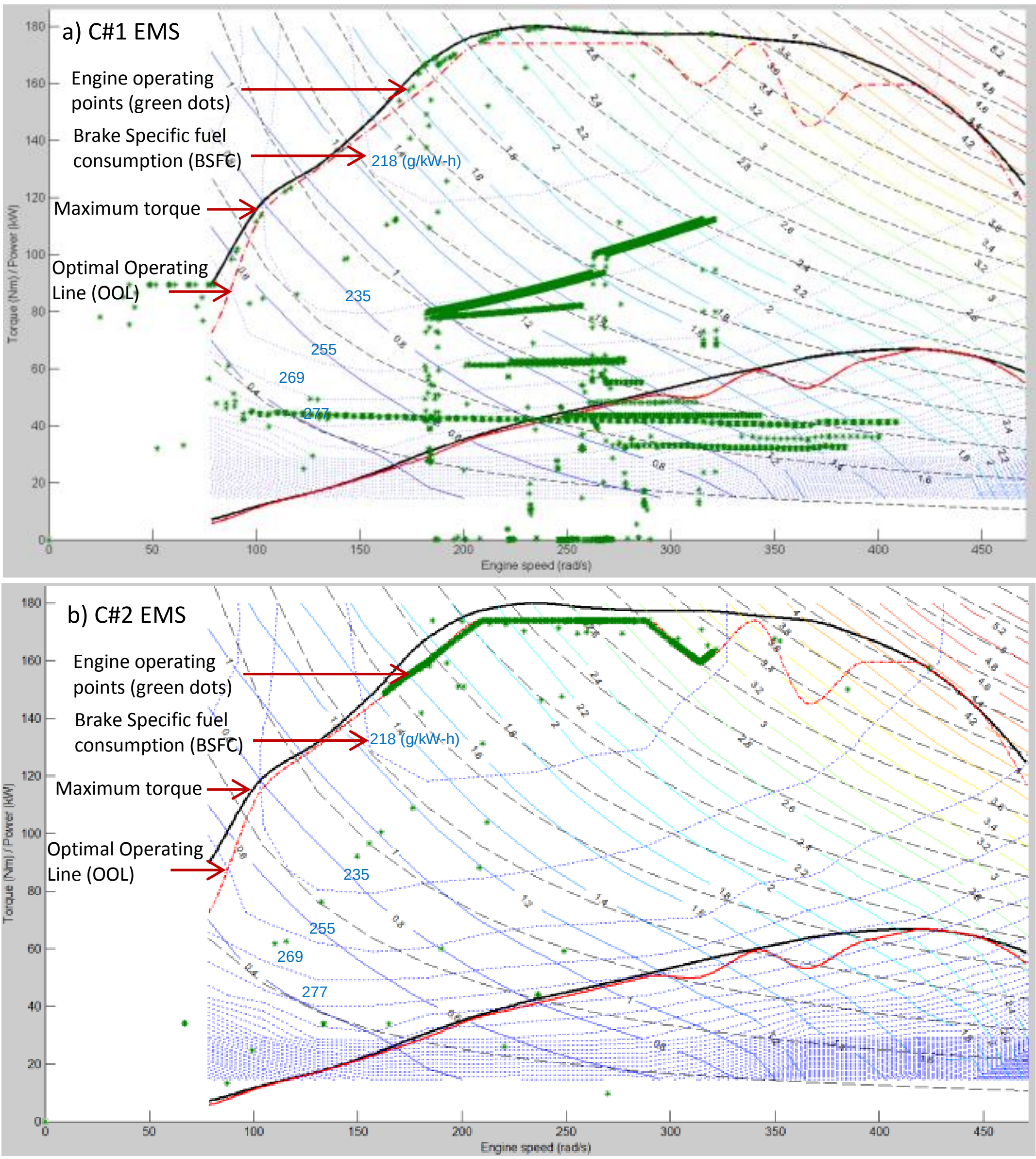

Figure 9-2: Engine operating point comparison of conventional EMS methods over the NEDC 3x with initial SOC of 0.5

In Figure 9-2 the engine operating points of C#1 are away from the most efficient region as the engine output is directly controlled by the vehicle demand. Whereas in the case of C#2 the engine operating points are not dictated by the vehicle demand and always operates at OOL. Also it happened that most of the time the engine operating speed is between 170 to 320 rad/s where the fuel efficiency is higher. Due to OOL operation and its efficient engine speed C#2 engine fuel efficiency is better than C#1. However hybrid vehicle fuel economy also depends on energy conversion losses as discussed in previous chapter. In C#1 there is no energy conversion loss as the engine is not charging the battery.

9.4.1.2 Proposed and conventional EMS operation comparison over the NEDC 3x

The proposed EMS operation is explained and then compared with that of conventional EMS. The proposed EMS performance over the NEDC 3x with initial SOC 0.5 is shown in Figure 9-3.

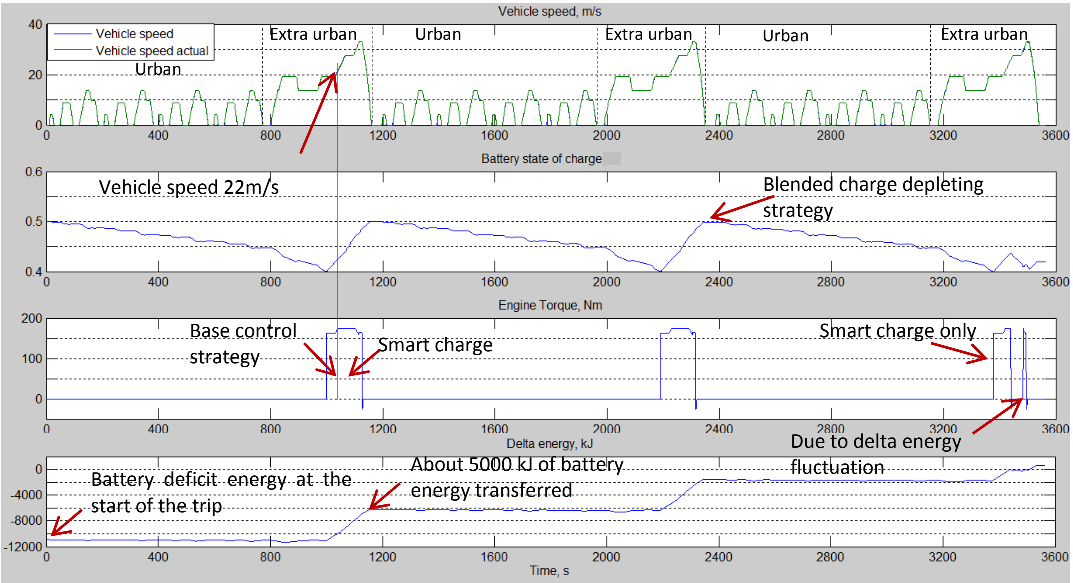

Figure 9-3: Performance of the proposed EMS method over the NEDC 3x with initial SOC of 0.5

Considering the estimated vehicle trip energy for the NEDC 3x and the initial SOC of 0.5, delta energy (ΔE_t) is calculated using equation 7.5. As shown in figure, the delta energy is in deficit of around -11000 kJ at the start of the trip (For the NEDC 1x it was about -1500 kJ). In this study, the base control strategy of the proposed EMS was initially triggered (around 1000 s) as the SOC reaches minimum of 0.4. Later in the journey, smart charge gets activated when the vehicle speed crosses the speed threshold of 22m/s. The energy transferred during both the base control strategy and smart charge is accounted as shown in the delta energy profile. In the first engine operation, about 5000 kJ of energy is transferred to the battery, as reflected in delta engine profile. Similarly energy was transferred to the battery in the followed engine operations during the extra urban road types.

In this study the base control strategy was directed by two factors. First is, the low initial SOC of 0.5 and hence not enough battery energy to wait until the smart charge happens. The other factor is due to the drive cycle. In the NEDC, vehicle speed is less than 20m/s in extra urban driving for more than half of the driving distance. Hence when the vehicle speed is above smart charge threshold, the duration of smart charging is not sufficient to charge the battery in this case. Therefore the split charge due to the base control strategy and smart charge is happening periodically in this study.

The engine operating points of the proposed EMS over the NEDC with initial SOC of 0.5 is shown in Figure 9-4. Like in C#2, the engine operating points are controlled to operate at OOL. In comparison to Figure 9-3/b, the engine operating speed is marginally narrower with about 190 to 320 rad/s in the proposed EMS. However there is no much difference in engine efficiency operating points between the proposed and C#2 EMS.

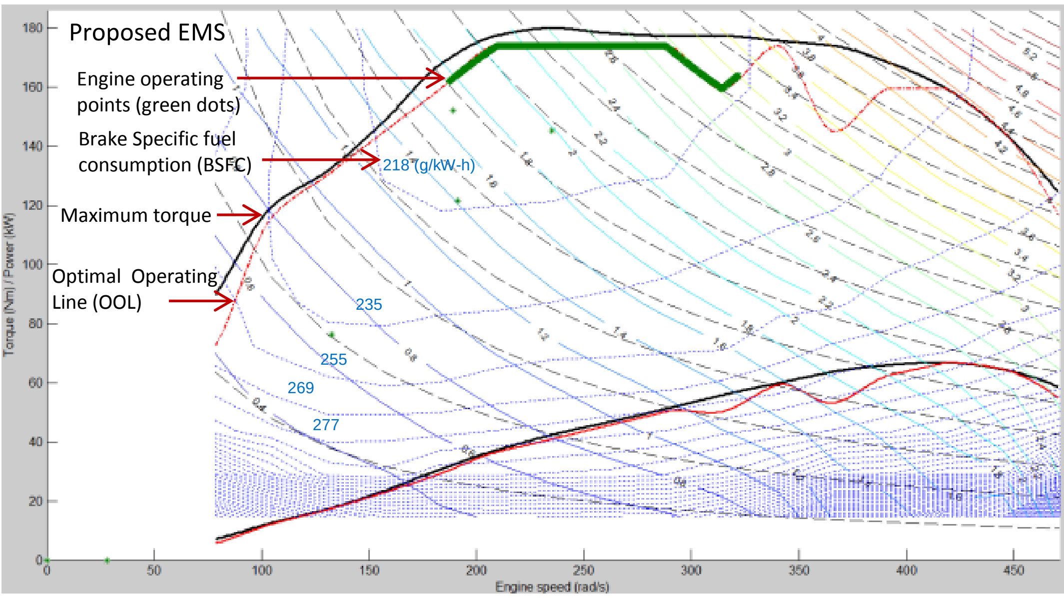

Figure 9-4: Engine operating points of the proposed EMS method over the NEDC 3x with initial SOC of 0.5

For vehicle level comparison of the proposed and conventional EMS Figure 9-3 and Figure 9-1 are compared. In the proposed EMS the engine operation is controlled with respect to road types and trip deficit energy through delta energy. Hence the numbers of engine stop-start are fewer with 4 as against 20 in C#2. Even though the engine is operated at OOL in both C#2 and the proposed EMS, the engine use is preferred at higher vehicle speeds in the proposed EMS. This is to reduce energy conversion losses. Hence the vehicle level efficiency of the proposed EMS should be better than C#2 EMS. In other words the key difference is the engine operation is engineered in the proposed EMS to reduce the energy conversion losses and controlled with respect to the road types and deficit trip energy. Results for all three EMS are summarised and analysed in the next section.

9.4.1.3 Analysis of results for varied trip distance over the NEDC with initial SOC of 0.5

In Table 9-1, the fuel economy (FE), number of engine stop-starts and final SOC are tabulated for all three EMS methods over varied trip distance of the NEDC. The fuel economy figures are decreasing in the table with increased distance for all methods. This is due to the contribution of the limited battery energy is inversely proportional to the distance and the actual fuel economy is calculated based on fuel spent over the entire trip distance.

Table 9-1: Three EMS methods vehicle performance over varied trip distance of the NEDC with initial SOC of 0.5

Driving cycle	NEDC 1x			NEDC 2x			NEDC 3x		
EMS method	C#1	C#2	Prop	C#1	C#2	Prop	C#1	C#2	Prop
Final SOC	0.414	0.455	0.421	0.414	0.455	0.421	0.414	0.455	0.419
Actual FE, MPG	164.5	107.4	159.8	91.0	88.8	109.3	79.3	84.2	99.4
Corrected FE, MPG	207.3	223	228.4	96.3	112.8	121.8	81.9	97.3	105.4
Number of engine stop-start	1	4	2	12	12	3	22	20	4

9.4.1.3.1 Final SOC comparison

Lower final SOC at the end of the trip is desired for better overall vehicle efficiency. In the case of conventional EMS methods, the final SOC of the respective EMS is same for all three NEDC trip distances. 0.414 and 0.455 for C#1 and C#2 respectively. This was due to the identical engine operation towards the end of each trip. For C#1, the final SOC was marginally higher than minimum SOC due to regenerative braking towards the end of the trip. For C#2 it was 0.455 due to engine charging the battery during CS between SOC of 0.4 to 0.45. Further SOC was 0.455 instead of 0.45 or less due to regenerative braking towards the end of the trips.

In the case of the proposed EMS, the final SOC lies in between that of C#1 and C#2 EMS.

9.4.1.3.2 Fuel economy comparison

Between the conventional EMS methods, C#2 (corrected) fuel economy is better up to 18.8% than C#1 due to the controlled engine operation at OOL. This result is consistent with the vehicle efficient modes study in the chapter 8. Even though there is no energy conversion loss in C#1, the fuel consumption was very high in comparison to C#2.

The fuel economy improvement in percentage of the proposed EMS over the conventional EMS methods, C#1 and C#2 are shown in Figure 9-5.

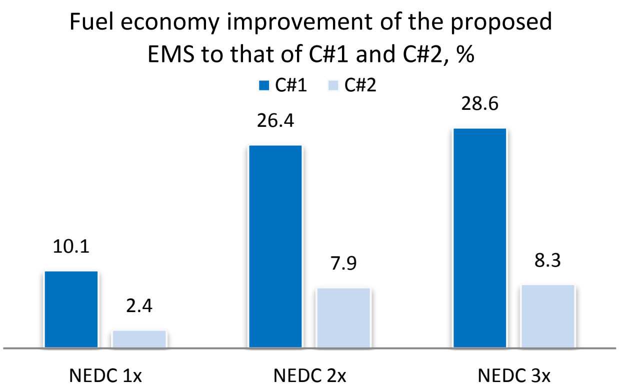

Figure 9-5: The proposed EMS fuel economy improvement (in percentage) over conventional EMS methods C#1 and C#2 over varied distance of the NEDC with initial SOC of 0.5

The proposed EMS method fuel economy improvements over both C#1 and C#2 (CD-CS strategy) increases with trip distance over the NEDC. This is due to the extended period of CS mode in conventional EMS methods which is not efficient due to the narrow SOC constraint. This leads to the frequent engine stop-starts and higher energy conversion losses during engine operation at lower vehicle speed in comparison to the proposed EMS method.

Another perspective is the fuel economy improvement of the BCD strategy (proposed EMS) to that of CD-CS strategy (Conventional EMS) is increasing with distance. Considering a legislative driving cycle multiple times and fuel economy improvement with distance observation is in concurrence to a similar study results in the literature (He et al., 2012a). In the literature the optimisation based equivalent consumption minimisation strategy (ECMS) was used on a power-split architecture pursuing BCD strategy was compared with CD-CS strategy.

9.4.1.3.3 Number of engine stop – start comparison

Fewer numbers of engine stop – start are desired. Between the conventional EMS methods, the numbers of engine stop-start for C#2 are marginally superior with 20 as against 22 for C#1 over the NEDC 3x. In the case of NEDC 2x they were same at 12. But in the case of NEDC 1x the number of engine stop-starts for C#1 is 1 as against 4 for C#2.

The numbers of engine stop-start for the proposed EMS are far fewer than both conventional EMS. It is varying 2 to 4 for the proposed EMS over the NEDC 1x to NEDC 3x in that order. Exception is in the case of NEDC 1x where for C#1 the number of engine stop-start is better with 1 in comparison to 2 in the proposed EMS. In the case of C#2 it was 4. Overall the numbers of engine stop-start for the proposed EMS are fewer.

The numbers of engine stop – start are increasing with trip distance. This is due to increase in deficit battery trip energy leading to higher frequency and duration of engine operation.

9.4.1.4 Summary of study over varied trip distance of the NEDC

Overall the conventional EMS C#2 which was found better in terms of fuel economy than C#1 was considered in all future comparison studies.

In general the proposed EMS vehicle performance is better than conventional EMS over varied trip distance of the NEDC. The proposed EMS fuel economy is better than conventional EMS methods. The final SOC is marginally higher for the proposed EMS in comparison to C#1 but better than C#2. Also the numbers of engine stop-start are better almost in all cases.

The fuel economy comparative improvement trend of the proposed and conventional EMS with trip distance using multiples of legislative drive cycle in the study is in concurrence with a similar comparison study from the literature using optimisation based EMS.

The proposed EMS adapted to varied trip distance of the NEDC with initial SOC of 0.5. Delta energy varied from -11000 to -1500 kJ for NEDC 3x to 1x respectively. This is similar to the adaptability of the proposed EMS for varied initial SOC over the NEDC 3x which is illustrated in the next study in the following sections.

9.4.2 Comparison study over the NEDC 3x with varied initial SOC

The conventional C#2 and proposed EMS were further compared for varied initial SOC, from 0.8 to 0.5 over the NEDC considered three times consecutively (3x).

9.4.2.1 Proposed EMS adaptability to varied initial SOC over the NEDC 3x

The proposed EMS operation is explained again with initial SOC of 0.8 over the NEDC 3x. This is to analyse about the adaptability of the proposed EMS to varied deficit trip energy. Delta energy is calculated based on the estimated trip and initial SOC. As shown in Figure 9-6, the delta energy is in deficit of around -2000 kJ at the start of the trip. Unlike in the

NEDC 3x with initial SOC of 0.5 (Figure 9-3), in this case the battery energy is sufficient to wait till smart charge in extra urban road type when the vehicle speed is above 22 m/s.

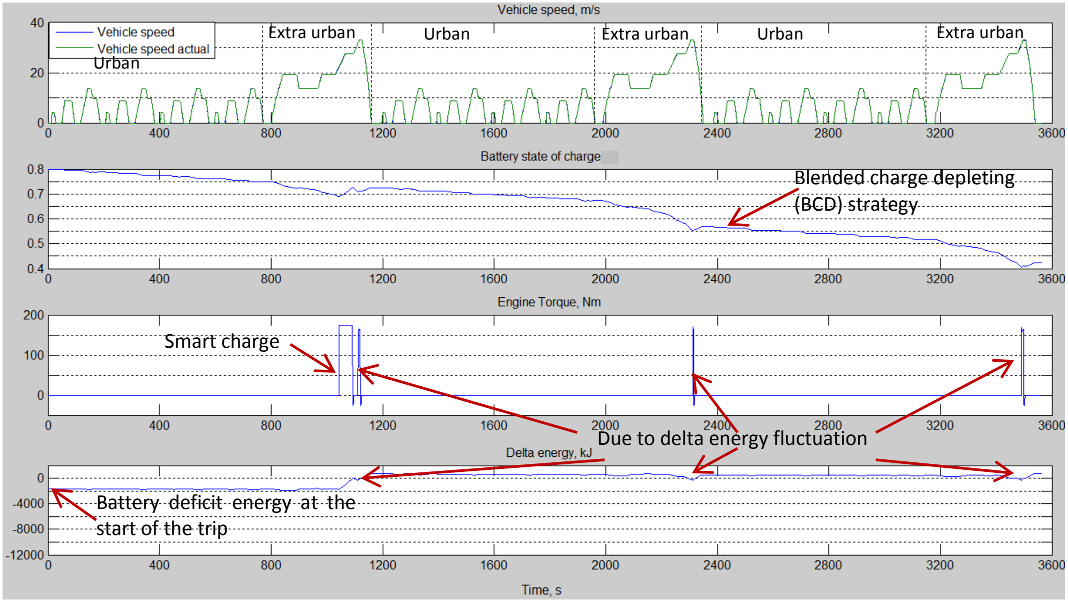

Figure 9-6: Performance of the proposed EMS method over the NEDC 3x with initial SOC of 0.8

Further in Figure 9-6 (at 1100 s) it can be observed that, after the first engine start all the trip energy required to drive the remaining trip in EV mode is made available. This is reflected in the delta energy profile. The remaining three engine starts (smart charge) were all triggered due to momentary delta energy falling below the threshold. This was due to the local variation and the way vehicle energy estimation was done as discussed earlier in section 8.2.2 shown earlier in Figure 8-1/b. At these trigger points; locally the actual vehicle energy was higher than the estimated followed by higher actual regenerative energy than the estimated. Also, higher actual regenerative energy towards the end of the NEDC trip is not helping the EMS to adapt leading to a marginally higher final SOC of 0.42. In future the numbers of engine stop – start can be improved after studying appropriate sampling rate study in the next chapter. At lower sampling frequency (say 10 second) than from the current 0.01 second can reduce the EMS sensitivity to fluctuation.

Also except with initial SOC of 0.5, in all other cases of higher initial SOC (like with initial SOC of 0.8), smart charge is the only mode needed to charge the battery over the NEDC 3x.

In Figure 9-6, the initial trip deficit energy (delta energy), when the initial SOC is of 0.8 is lower (-2000 kJ) than with the initial SOC of 0.5 (-1100kJ) as shown in Figure 9-3. Correspondingly it can be observed the duration of engine operation is varying; lower with the initial SOC of 0.8 and higher with the initial SOC of 0.5. Thus the proposed EMS is adapting according to the deficit trip energy.

9.4.2.2 Analysis of results for varied initial SOC over the NEDC 3x

Vehicle performances of the conventional EMS C#2 and proposed EMS for varied initial SOC over the NEDC 3x are tabulated in Table 9-2.

Table 9-2: Performance comparison over varied initial SOC

EMS Method	Conventional EMS (C#2)				Proposed EMS			
Initial SOC	0.8	0.7	0.6	0.5	0.8	0.7	0.6	0.5
Final SOC	0.455	0.455	0.455	0.455	0.421	0.423	0.421	0.419
Actual FE, MPG	271.3	158.5	107.4	84.2	375.5	191.9	132.6	99.4
Corrected FE, MPG	479.8	212.3	129.7	97.27	492.9	220.2	144.5	105.4
Number of engine stop - starts	6	9	17	20	4	4	4	4

9.4.2.2.1 Final SOC comparison

Like in the previous study with varied trip distance, the proposed EMS final SOC is better with final SOC of about 0.421 in comparison to 0.455 of conventional EMS.

9.4.2.2.2 Fuel economy comparison

The fuel economy improvement of the proposed EMS in percentage over the conventional EMS (C#2) is plotted in Figure 9-7. In the proposed EMS method when the initial SOC was set as 0.5, battery charging due to base control strategy and smart charge was happening as discussed earlier. In all other cases of higher initial SOC, smart charge was the only mode needed to charge the battery. With higher initial SOC, the percentage of fuel economy improvement over conventional EMS method is reduced due to reduced engine operation in both conventional and the proposed EMS method. However at initial SOC of 0.5 the percentage fuel economy improvement over conventional EMS is lower in comparison to an initial SOC of 0.6. This is due to higher energy conversion losses as the engine was required to operate at vehicle speed less than 22 m/s through the base control strategy.

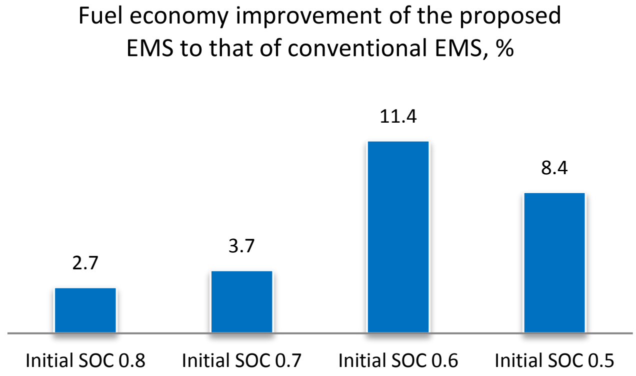

Figure 9-7: The proposed EMS fuel economy improvement (in percentage) over conventional EMS (C#2) method over varied initial SOC

9.4.2.2.3 Number of engine stop – start comparison

The numbers of engine stop-starts for conventional EMS is high, varying from 6 to 20 as against the proposed EMS method of 4 times.

In the proposed EMS the numbers of engine stop-start remains 4 irrespective of the initial SOC in this study. Even at higher initial SOC of 0.8 as discussed with Figure 9-6 in earlier section 9.4.2.1 the total numbers of engine stop-start was 4. Some of these engine stop-starts are contributed due to delta energy fluctuation. The engine stop – starts due to delta energy fluctuation was 1 with initial SOC 0.5 increased to 3 with initial SOC of 0.8.

9.4.2.3 Summary of study for varied initial SOC over the NEDC 3x

The proposed vehicle performance such as fuel economy, the number of engine stop – starts and final SOC are superior to the conventional EMS, C#2 for varied initial SOC over the NEDC 3x.

Adaptability of the proposed EMS for varied initial SOC (0.8, 0.7, 0.6 and 0.5) and its effect on delta energy was illustrated. Delta energy which represents the deficit trip electric energy varied from about -11000 to -2000 kJ for initial SOC of 0.5 to 0.8 respectively.

Correspondingly it can be observed the duration of engine operation is varying; lower with the initial SOC of 0.8 and higher with the initial SOC of 0.5. This was similar in the first study with varied trip distance of the NEDC.

9.5 Comparison summary

Overall, the proposed acausal and blended rule based EMS performance was found superior in comparison to the conventional rule based EMS over the NEDC. The use of driving information and estimated trip energy in the proposed EMS method helps to judiciously manage the battery energy and use engine. The engine operating conditions are predetermined (OOL), but the duration of engine use is controlled by the estimated deficit trip energy (delta energy). The most efficient time to use the engine is decided considering driving information over the whole trip to achieve high vehicle efficiency with fewer numbers of engine stop-start. A comparison summary of conventional and the proposed EMS are listed in Table 9-3. Finally the proposed acausal EMS is formulated over vehicle trip energy and not over vehicle speed profile as usually seen.

Table 9-3: Comparison summary of conventional and the proposed EMS methods

EMS	Conventional rule based	Proposed rule based
Trip demand	Causal	Acausal
Formulation	Instantaneous vehicle demand and battery SOC	Vehicle trip energy, driving information and battery SOC
Control strategy	CD-CS	BCD
Engine operation	Limited control over energy conversion losses	Reduces energy conversion losses

9.6 Conclusion

The proposed blended rule based EMS (Blended charge depleting (BCD) strategy) was simulated as a complete system over the NEDC. Vehicle performances of conventional rule based EMS (Charge depleting – charge sustaining (CD-CS) strategy) and the proposed blended rule based EMS were compared over the NEDC for varied trip conditions.

- Two conventional rule based EMS C#1 and C#2 were studied for varied trip distance with multiples of the NEDC. C#2 was found to have better fuel economy of up to 18.8% due to controlled engine operation at OOL. C#2 will be used in all future comparison studies.
- The proposed EMS fuel economy improvement is up to 11.4% with fewer number of engine stop-starts in comparison to conventional rule based EMS C#2 over the NEDC.
- Adaptability of the proposed EMS was demonstrated for varied trip distance and initial battery state of charge (SOC) over the NEDC with better vehicle performance than conventional rule based EMS.
- The fuel economy comparative improvement trend with trip distance of the proposed EMS with BCD strategy over the CD-CS strategy is in concurrence with a similar comparison study in the literature but with optimisation based EMS.

Chapter 10 – Real Time Capability and Sampling Rate Study of the Proposed EMS

10.1 Introduction

To address the inherent trip demand uncertainty of real world driving, monitoring and adaptive features of EMS in real time is imperative for effective and efficient vehicle performance. In the proposed EMS, delta energy, road type and distance travelled are sampled at periodic times to revise the control strategy if required. Instantaneous vehicle speed and battery state of charge (SOC) are sampled in real time like in any conventional EMS. In the previous proposed EMS studies to start with the sampling rate was set as 0.01 second. In this study real time capabilities are studied for various sampling rate by comparing with that of conventional rule based EMS. Also the proposed EMS vehicle performance is studied for various sampling rates to arrive at the most effective sampling frequency. It is known that reducing sampling rate may reduce computational time and at the same time this may also deteriorate the vehicle performance such as fuel economy (Adhikari, 2010, Guzzella and Sciarretta, 2007).

In the study method section, a real world vehicle speed profile and sample rates considered for the study are discussed. Later in section 10.3 the performances such as fuel economy, the number of engine stop – starts, final SOC and simulation duration were analysed and compared to performance of the conventional EMS.

10.2 Study method

For a given driving condition (real world vehicle speed profile and battery SOC) the simulation duration of the proposed EMS for various sampling rates of 30, 10, 1 and 0.01 second is compared across and with the conventional rule based EMS. Also the effect of various sampling rates over vehicle performances such as fuel economy, the number of engine stop – starts and final SOC are studied. The same conventional rule based EMS C#2 discussed in the previous chapter is considered for comparison. Initial SOC is set as 0.7 to simulate the deficit trip energy condition for the vehicle speed profile considered and the minimum SOC is set as 0.4.

10.2.1 Vehicle speed profile and vehicle trip energy estimation

One of the real world vehicle speed profiles collected as part of the WMG SAVE project was used. As in the previous studies over the NEDC (chapter 8 and 9), the vehicle speed profile is considered as known in advance. Hence the vehicle trip energy is estimated in the same way as discussed in section 8.2.2. The vehicle model was simulated in electric only mode to determine the total electric energy required for all urban road types of the trip considered. The total electric energy was divided by the total urban road type distance to determine the specific energy for the urban road type (361 kJ/km). Similarly the specific energy for the extra urban was determined (471 kJ/km). Using these specific energy values, the vehicle trip energy is estimated for the considered trip as discussed in chapter 7 and illustrated with the NEDC in chapter 8. The vehicle speed profile considered and vehicle trip energy estimated and actual is as shown in Figure 10-1. In the figure, locally in extra urban road types of the trip noticeably higher actual trip energy than the estimation can be observed. In the case of urban road types of the trip the estimated and actual trip energy are in agreement.

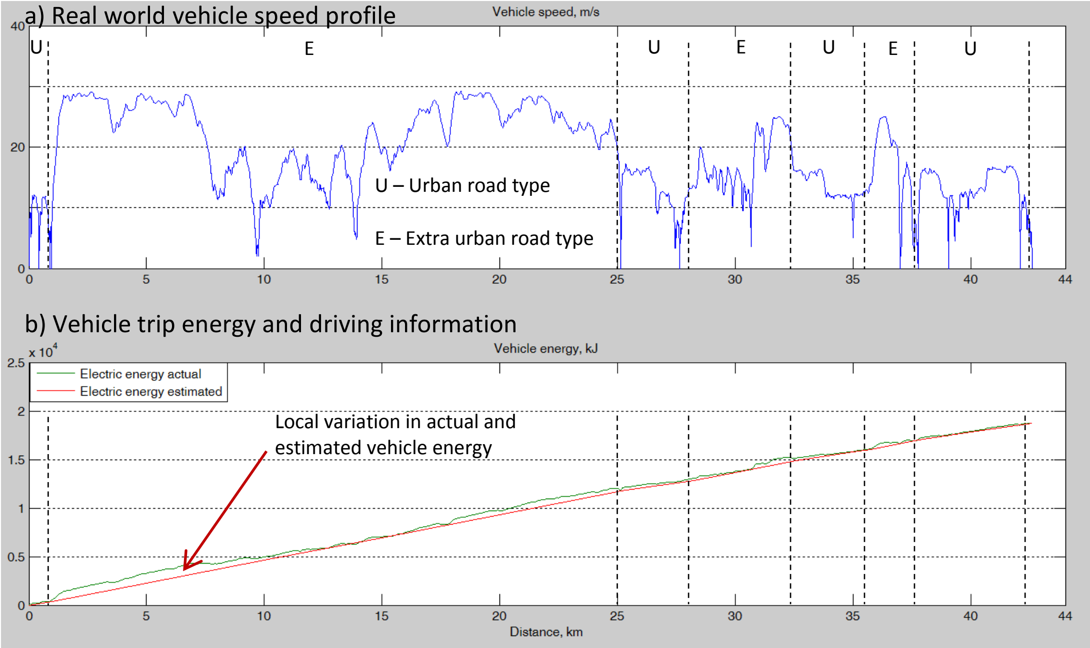

Figure 10-1: Real world vehicle speed profile and vehicle trip energy estimated and actual comparison

10.3 Results and analysis

The proposed EMS was simulated over a prior known real world vehicle speed profile for varied sampling rates as shown in Figure 10-2. The proposed EMS is applied to real world driving data. In comparison to previous studies with the NEDC, the vehicle speed profile is not repetitive even for a trip distance of about 43 km. Also compare to the NEDC, for the considered real world driving data, the vehicle speeds are higher for longer durations and highly transient. These are typical of real world driving.

As in the previous chapter with the NEDC the proposed EMS operation with respect to delta energy is similar. Based on the estimated vehicle trip energy and the initial SOC, delta energy (ΔE_t) is calculated using equation 7.5. At the start of the trip, delta energy is found to be about -10000 kJ as shown in the figure. In the study only the smart charge at extra urban was activated to transfer the deficit energy required to the battery.

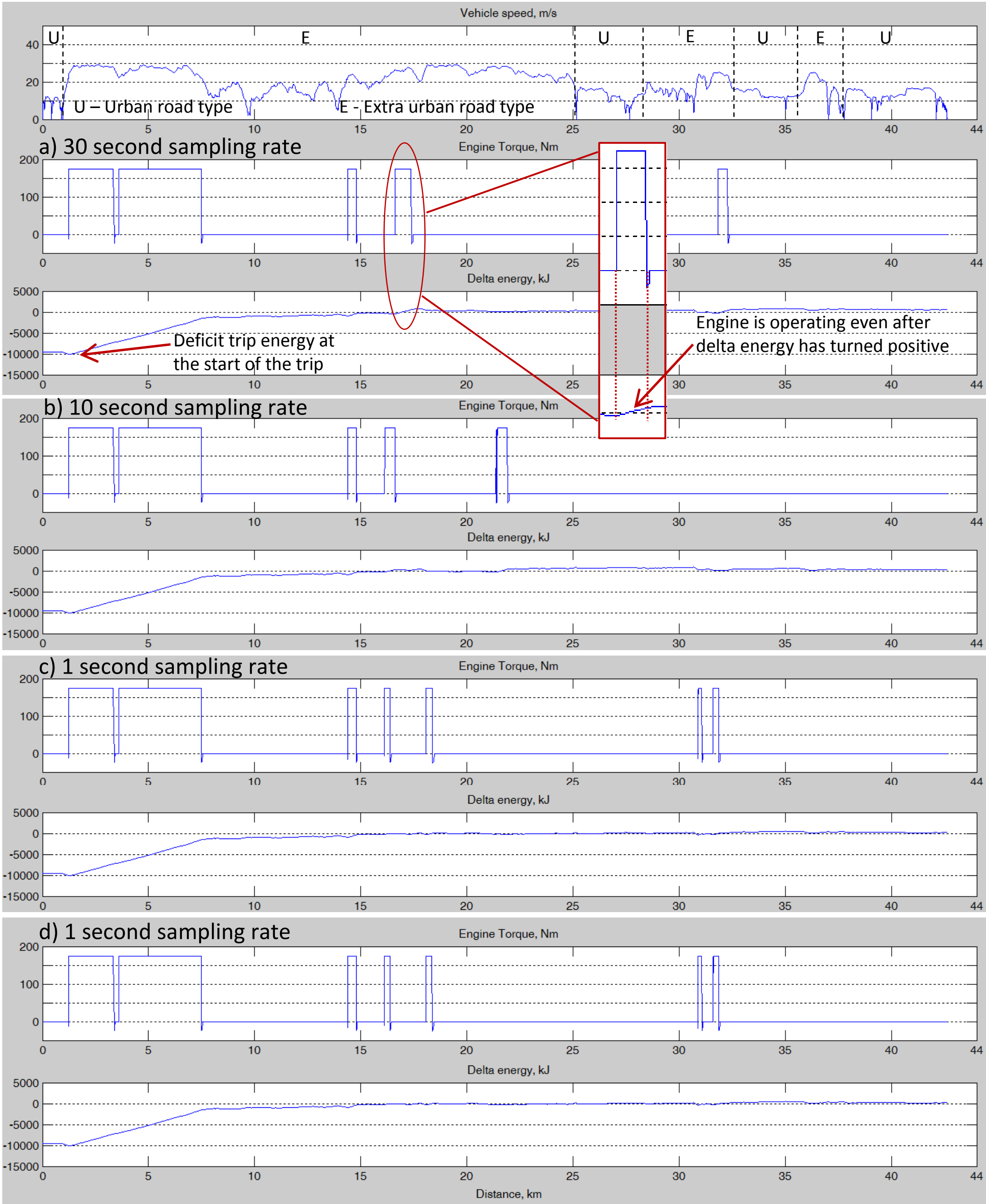

Figure 10-2: The proposed EMS engine performance and delta energy for various sampling rates with initial SOC of 0.7

For all sampling rate trial the vital observation is when the engine is switched ON, it remains ON till the next sampling irrespective of the change in delta energy between the successive samplings as shown in Figure 10-2 (with in zoom window for 30 second sampling rate). In the figure, due to high negative delta energy value of -10000 kJ at the start of the trip, sampling rates has no influence in the initial smart charge engine operation of about distance of 7.5 km. During this time most of the deficit energy required is transferred to the battery. In the later part of the journey after about 15 km, the engine operations are influenced by delta energy fluctuation and sampling rates.

10.3.1 Comparison of results

Vehicle performances of the conventional rule based EMS and the proposed EMS for varied sampling rates are tabulated in Table 10-1.

Table 10-1: The conventional and proposed EMS vehicle performance comparison for varied sampling rates

EMS method	Conventional EMS	Proposed EMS			
Sampling rate, sec	Not applicable	30	10	1	0.01
Final SOC	0.445	0.419	0.409	0.407	0.407
Actual FE, MPG	117.5	133.3	137.9	137.2	137.8
Corrected FE, MPG	133.1	141.3	142.1	140.2	140.8
Number of engine stop-starts	44	5	5	7	7
Simulation duration, sec	341	303	304	305	320

Vehicle performances of the conventional and proposed EMS across sampling rates are compared and discussed in following sections.

10.3.1.1 Final SOC comparison

The final SOC of the proposed EMS for all sampling rates are lower than the conventional EMS. The final SOC of the proposed EMS across sampling rates, there were only subtle differences as shown in Figure 10-3. The final SOC is varying from 0.419 to 0.407 for the sampling rates of 30 to 0.01 second respectively. The increase of final SOC with reduction in sampling was expected but the differences are small. With lower sampling, the engine when switched ON remains so for longer duration irrespective of the delta energy transition as shown earlier.

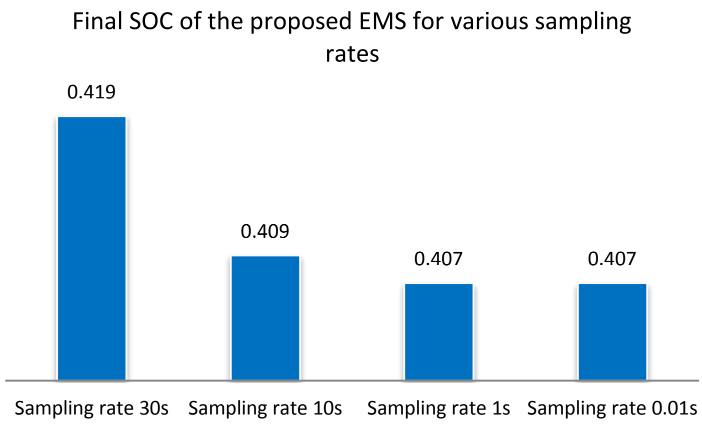

Figure 10-3: The proposed EMS final SOC comparison for various sampling rate

10.3.1.2 Fuel economy comparison

The fuel economy of the proposed EMS is better than the conventional EMS for all sampling rates. The proposed EMS fuel economy on average across the sampling rates is better by 6% than conventional EMS. For various sampling rates, the proposed EMS fuel economy is close to each other varying from 140.2 to 142.1 MPG. No increasing or decreasing fuel economy trend was observed across sampling rates.

10.3.1.3 Number of engine stop – starts

The conventional EMS number of engine stop – starts is high with 44. For the proposed EMS across sampling it varied from 5 to 7. The number of engine stop – start is 5 with 10 and 30 second sampling rates and 7 with remaining two higher sampling rates (Table 10-1). This is due to increase in EMS sensitivity to local variation in delta energy at higher sampling rates. With higher sampling rates the chance of activating the engine smart charge for small changes in delta energy is higher. This can be observed in Figure 10-2 for sampling rate of 0.01 and 1 second.

10.3.1.4 Simulation duration comparison

Conventional rule based EMS are known to be real time capable. Real time capability of the proposed EMS is measured based on the simulation duration of the proposed and conventional EMS. Between the conventional and proposed EMS, the simulation duration is the same in terms of applicability to real time operation as shown in Table 10-1. Surprisingly the proposed EMS is marginally faster than the conventional EMS. The faster performance of the proposed EMS may be due to system structure than the sampling rate. Further for the considered drive cycle of 2700 second, the simulation durations of the proposed EMS is about 320 second. Therefore the proposed EMS is about 8 times faster than real time requirement. Overall based on the simulation duration results it is concluded that the proposed EMS is potentially real time capable.

Further the simulation duration of the proposed EMS across sampling rates from 30 to 1 second is almost same with 303 to 305 second respectively. With sampling rate of 0.01 second the simulation duration was marginally higher with 320 second. As expected the simulation duration decreases with the reducing sampling rate but only marginally. When sampling rate is reduced, the computational load decreases due to fewer calculations.

10.4 Conclusion

For all sampling rates trial of the proposed blended rule based EMS over the considered real world driving data, the vehicle performances such as the fuel economy, number of engine stop – starts and final SOC are better than the conventional rule based EMS. The proposed EMS vehicle performance across sampling rate varied only with subtle differences.

The simulation duration across sampling rate for the proposed EMS is almost the same. The simulation duration of the proposed EMS and the conventional rule base EMS are also the same. For the considered drive cycle, the simulation durations in all these cases are faster than real time. However in this study real time capability was not demonstrated on the vehicle hardware. Therefore the proposed EMS is concluded as potentially real time capable.

Overall, considering the uncertainty of real world driving which calls for a higher sampling rate to bridge the gap between the actual and anticipated trip demand and also to minimise the number of engine stop-starts, the 10 second sampling rate was selected for future studies. Whenever the engine is switched ON, 10 second sampling ensures that the engine operation is for minimum of 10 seconds unless the instantaneous vehicle speed falls below the threshold speed (22 m/s for extra urban and 12 m/s for urban smart charge). This makes EMS insensitive to small and frequent variations in trip demand and system parameters (such as delta energy).

In summary,

- Simulation duration of the proposed and conventional rule based EMS are same. The proposed EMS method is potentially real time capable.
- The proposed EMS vehicle performances such as the fuel economy, number of engine stop – starts and final battery state of charge (SOC) across sampling rates of 30 to 0.01 second are almost same.
- The proposed EMS vehicle performance across sampling rates is better than conventional rule based EMS over the considered real world vehicle speed profile.
- Considering uncertainty of real world driving and to minimise the number of engine stop-starts a 10 second sampling rate for the proposed EMS was considered for future studies.

Chapter 11 – Adaptability Study of the Proposed EMS

11.1 Introduction

As part of the requirement to address the trip demand uncertainty of real world driving, the vehicle performance of the proposed EMS for under and over estimation of vehicle trip energy is studied in this chapter. In real world driving, due to the uncertainty, it is not possible to estimate the exact vehicle trip energy required in advance. Over and under estimation scenarios in real world driving can be caused by a change in actual driving condition or limitation in trip energy estimation due to the uncertainty. This study is designed to investigate the adaptability of the proposed EMS to variation in trip energy estimation along with varied initial battery state of charge (SOC). Also in the process the proposed EMS vehicle performance such as fuel economy and number of engine stop – start will be compared with the conventional rule base EMS.

The study method is explained in the next section. This is followed by in section 11.3 a real world repetitive driving data study for given destination, vehicle, driver and similar journey start time to understand the realistic real world trip energy variations. Based on which, over and under estimation limits for varied trip energy estimation are considered for the adaptability study of the proposed EMS in section 11.4. In addition to varied under and over trip energy estimations, the vehicle performance of the proposed EMS is studied for varied initial SOC. Next these performances are compared with that of conventional rule based EMS. This comparison is to study the proposed EMS vehicle performance even when the trip demand estimation is not exact. Later in section 11.5, trip energy recovery called energy surplus at the end of the trip due to the adaptive principles of the proposed EMS is discussed. The proposed EMS adaptability principle was discussed in section 5.2.4.1. The proposed EMS adaptability to varied trip distance and initial SOC was demonstrated in chapter 9. In this section the proposed EMS adaptability to varied trip energy estimation is discussed. Next in section 11.6, the impact of this adaptability study of the proposed EMS and real world application are discussed. Also in this section, the target region to aim for estimating the vehicle trip energy is explained.

11.2 Study method

The purpose of this study is to demonstrate adaptability of the proposed EMS for varied trip energy estimation and initial SOC. Before undertaking the adaptability study to variation in trip energy, it is required to understand the actual variation in trip energy in real world driving for a given conditions. Later the vehicle performance study of the proposed EMS for varied trip energy estimation and conventional EMS is carried out at various initial SOC of 0.9, 0.7 and 0.5 with the minimum SOC as 0.4.

11.3 Real world vehicle trip energy variation study and simulation method & set up for the proposed EMS adaptability study

Real world repetitive driving data (from the WMG SAVE project), for a driver, route, vehicle and at similar times of the weekdays are considered to investigate the realistic variation in actual vehicle trip energy. Based on which later in section 11.3.2 over and under estimation of vehicle trip energy and simulation conditions for the proposed EMS adaptability study are determined.

11.3.1 Real world vehicle trip energy variation study

The repetitive trips vehicle speed profiles, along with vehicle energy are shown in Figure 11-1. In the figure, the legend H2W refers to Home to Work and the number followed refers to trip start time. The start time of the trip varied from 7.10, 7.14, 7.26 and 7.33 AM.

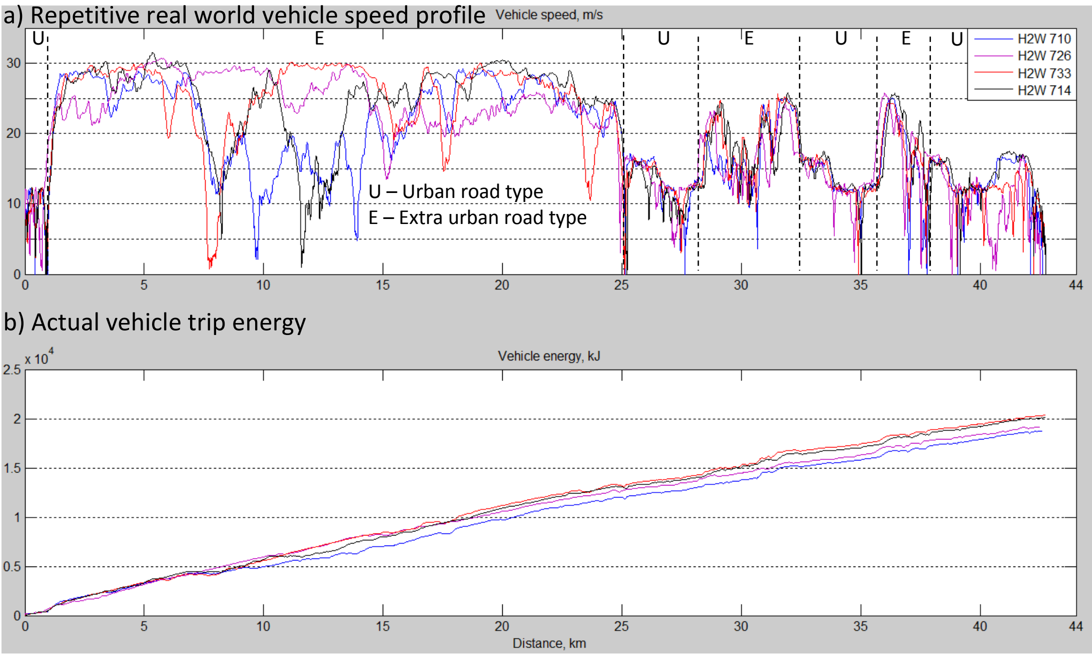

Figure 11-1: Repetitive trip vehicle speed profiles for a given driver, route, vehicle and at similar time along with corresponding actual vehicle (electric) trip energy

The total vehicle trip energy of the four repetitive real world trips and its corresponding specific energy value for urban and extra urban driving are shown in Table 11-1. For each trip, the specific energy is determined for urban and extra urban road types as illustrated with the NEDC in section 8.2.2.

Table 11-1: Total trip energy and the corresponding specific energy of the real world repetitive driving data study.

Vehicle speed profile	H2W 710 (E_{min})	H2W 726	H2W 714	H2W 733 (E_{max})	Percentage of maximum to minimum variation
Urban specific energy, kJ/km	361	370*	364	356*	3.9
Extra urban specific energy, kJ/km	470	484	514	525	11.7
Total trip energy, kJ	18737	19171	20106	20329	8.5

*Maximum and minimum values are in red and blue font respectively

The vehicle speed profile of the lowest (H2W 710) and highest (H2W 733) total vehicle trip energy are called as E_{min} and E_{max} respectively. In Table 11-1 the percentage total trip energy variation of E_{max} to E_{min} is 8.5%. The total trip energy variation of E_{min} and E_{max} over the average of the four trips is only about 5% even though a large variation in vehicle speed is observed in Figure 11-1. This figure is similar to Figure 5-5 shown to compare the dynamic nature of real world vehicle speed profile and gradual variation in vehicle trip energy in chapter 5. The range of urban specific energy is narrow at 3.9% variation. Extra urban specific energy variation is relatively wide at 11.7%. This may be due to higher speed limits and higher variation in external driving conditions in extra urban than in urban road type. Also higher extra urban specific energy variation may be due to higher variation in vehicle energy for small variation at higher vehicle speed. The minimum and maximum specific energy value observed for urban and extra urban road types among the four repetitive trips are shown in blue and red font respectively in Table 11-1.

11.3.2 Over and under estimation of the vehicle trip energy for the adaptability study

As the vehicle trip energy is estimated using specific energy, realistic limits of specific energy values for urban and extra urban road types are observed in the repetitive trip study are used to simulate the variation in total vehicle trip energy such as under and over estimation.

For over and under estimation the vehicle trip energy, the minimum (blue) and maximum (red) specific energy value for urban and extra urban road types among the four repetitive trips shown in Table 11-1 are used. To simulate the worst condition of maximum difference between the estimated and actual vehicle trip energy:

- For over estimation, E_{min} (H2W 710) vehicle speed profile is used as the actual trip demand and the maximum specific energy values (red) observed in the repetitive study are used for vehicle trip energy estimation. The maximum specific energy for urban and extra urban is 370 and 525 kJ/km respectively.
- For under estimation, E_{max} (H2W 733) vehicle speed profile is used as the actual trip demand and minimum specific energy values (blue) observed in the repetitive study are used for vehicle trip energy estimation. The minimum specific energy for urban and extra urban is 356 and 470 kJ/km respectively.

In addition to over and under estimation, using the actual (or respective) specific energy observed for E_{min} and E_{max}, the vehicle trip energy is estimated. This is called actual estimation in the study. This vehicle trip energy estimation is similar to previous studies where the trip demand (or vehicle speed profile) is considered as known in advance.

Use of limit (minimum and maximum) specific energy values lead to 9% of over and under estimation to the corresponding actual total vehicle trip energy of E_{min} and E_{max} respectively. It is interesting to know that 9% variation in estimated vehicle trip energy with respect to actual for both cases are sheer coincidence. In both over and under estimation conditions, the trip driving information such as road type, sequence of road type and its distance are the same. Only the specific energy values used in the vehicle trip energy estimation are different. To extend the study further up to 15% variation in estimation to that of the actual total vehicle trip energy, the specific energy values were adjusted accordingly. This led to over and under estimation of vehicle trip energy by 9 and 15% along with estimation with actual specific energy as shown in Figure 11-2 and Figure 11-3 respectively.

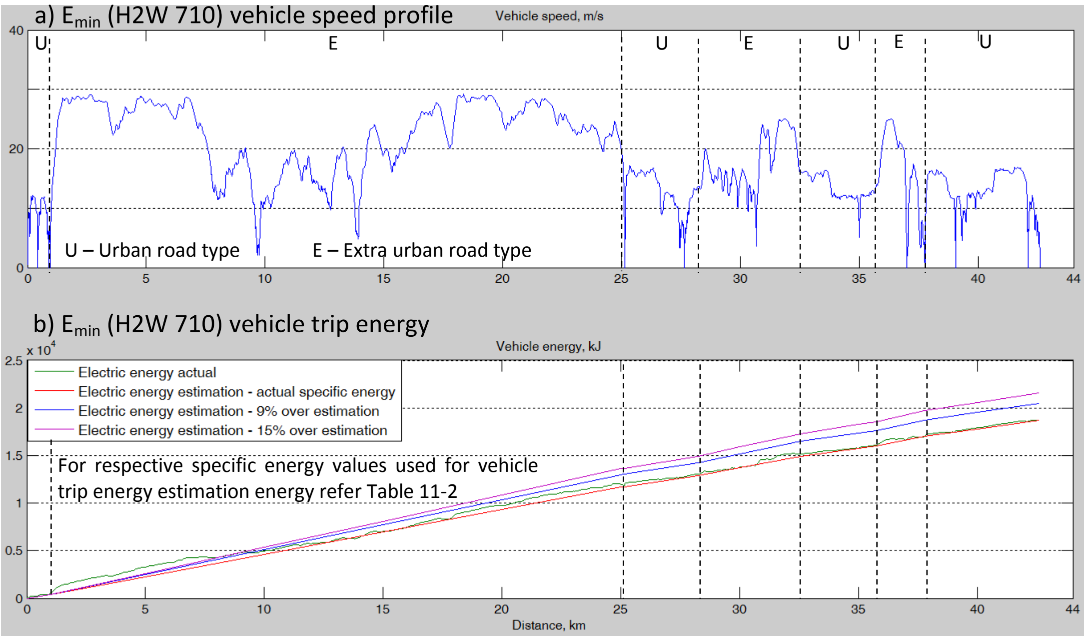

Figure 11-2: E_{min} (H2W 710) vehicle speed profile with over estimation of the vehicle trip energy in comparison to actual (green)

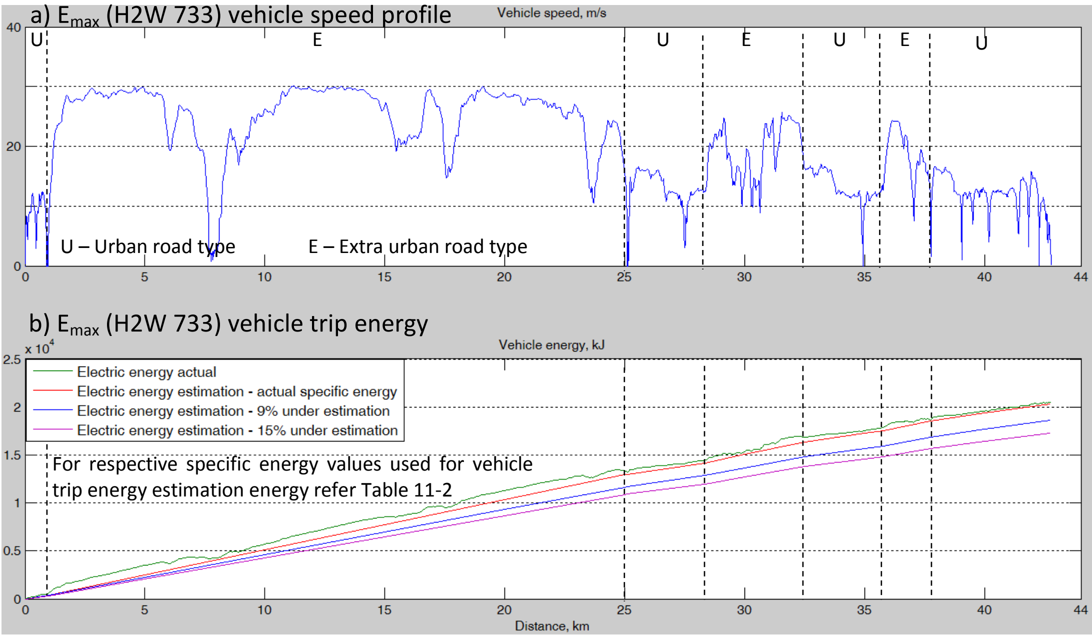

Figure 11-3: E_{max} (H2W 733) vehicle speed profile with under estimation of the vehicle trip energy in comparison to actual (green)

In both Figure 11-2 and Figure 11-3, the actual vehicle energy (green) is different to electric energy estimation with actual specific energy (red) as in the previous studies. This is so as the specific energy of the respective road type is linearly extrapolated over distance to estimate the vehicle trip energy (as discussed in section 7.2.3). Hence the vehicle energy estimation even with actual specific energy (red) is not same as actual vehicle energy (green). But the vehicle energy estimation with the actual specific energy is the closest possible to consider. In Table 11-2 the actual and estimated total vehicle trip energy with their corresponding specific energy values are tabulated.

Table 11-2: Actual and estimated total vehicle trip energy with their corresponding specific energy values are tabulated for the proposed EMS adaptability study.

Vehicle speed profile	E_{min} (H2W 710)			E_{max} (H2W 733)		
Vehicle energy estimation	Actual	9% over estimation	15% over estimation	Actual	9% under estimation	15% under estimation
Urban specific energy, kJ/km	361	370*	400	356	356*	320
Extra urban specific energy, kJ/km	470	525	550	525	470	440
Total trip energy, kJ	18737	20494	21619	20329	18665	17308

*The specific energy values in red and blue font are the maximum and minimum specific energy values respectively observed in the repetitive trip study.

Beyond 15% variation was not considered due to couple of reasons. Based on the limit specific energy values, the total trip energy variation with respect to E_{min} and E_{max} was only 9%. In the repetitive study the total trip energy variation of E_{min} and E_{max} over the average of the four trips was only about 5%. Hence ±15% variation considered represents a wide variation in terms of trip demand (vehicle speeds) and may be beyond realistic possible variation.

11.3.3 Summary of variation in vehicle trip energy considered

The E_{min} and E_{max} vehicle speed profiles are considered as actual trip demand for over and under estimation simulation of the proposed EMS respectively. Using their respective actual specific energy values, the vehicle trip energy is estimated as in previous studies referred as actual estimation. The vehicle trip energy is over and under estimated each by 9 % and 15% as shown in Table 11-2. After deciding the over and under estimation simulation trips and conditions, the proposed EMS is studied for its effect on vehicle performance in the next section and compared with the conventional rule based EMS.

11.4 Results of the adaptability study of the proposed EMS for variation in the vehicle trip energy

In this section the vehicle performance for over and under estimation of the trip energy as defined in section 11.3 is studied for the proposed EMS. The proposed EMS vehicle performance for over and under estimation is compared to respective vehicle energy estimation with actual specific energy. Vehicle performance results of the proposed EMS for over and under estimation and conventional EMS are presented in section 11.4.1 to 11.4.2.2. Vehicle performance of the proposed EMS is also compared across varied trip energy estimation and to that of conventional rule based EMS in section 11.4.3.

11.4.1 Conventional rule based EMS performance

Varied trip energy estimation is not applicable to the conventional rule based EMS as they are causal systems. However it is studied here to compare the vehicle performance with what is currently possible in real world (or production) vehicle. The conventional EMS was studied for performance such as the fuel economy (FE), number of engine stop – starts and final SOC over the two separate E_{min} and E_{max} vehicle speed profiles. The performance was studied for initial SOC of 0.9, 0.7 and 0.5. These vehicle performances are compared to that of the proposed EMS for the respective E_{min} and E_{max} vehicle speed profiles considered for over and under estimation respectively later in section 11.4.3. Conventional rule based EMS operation over E_{min} is shown in Figure 11-4.

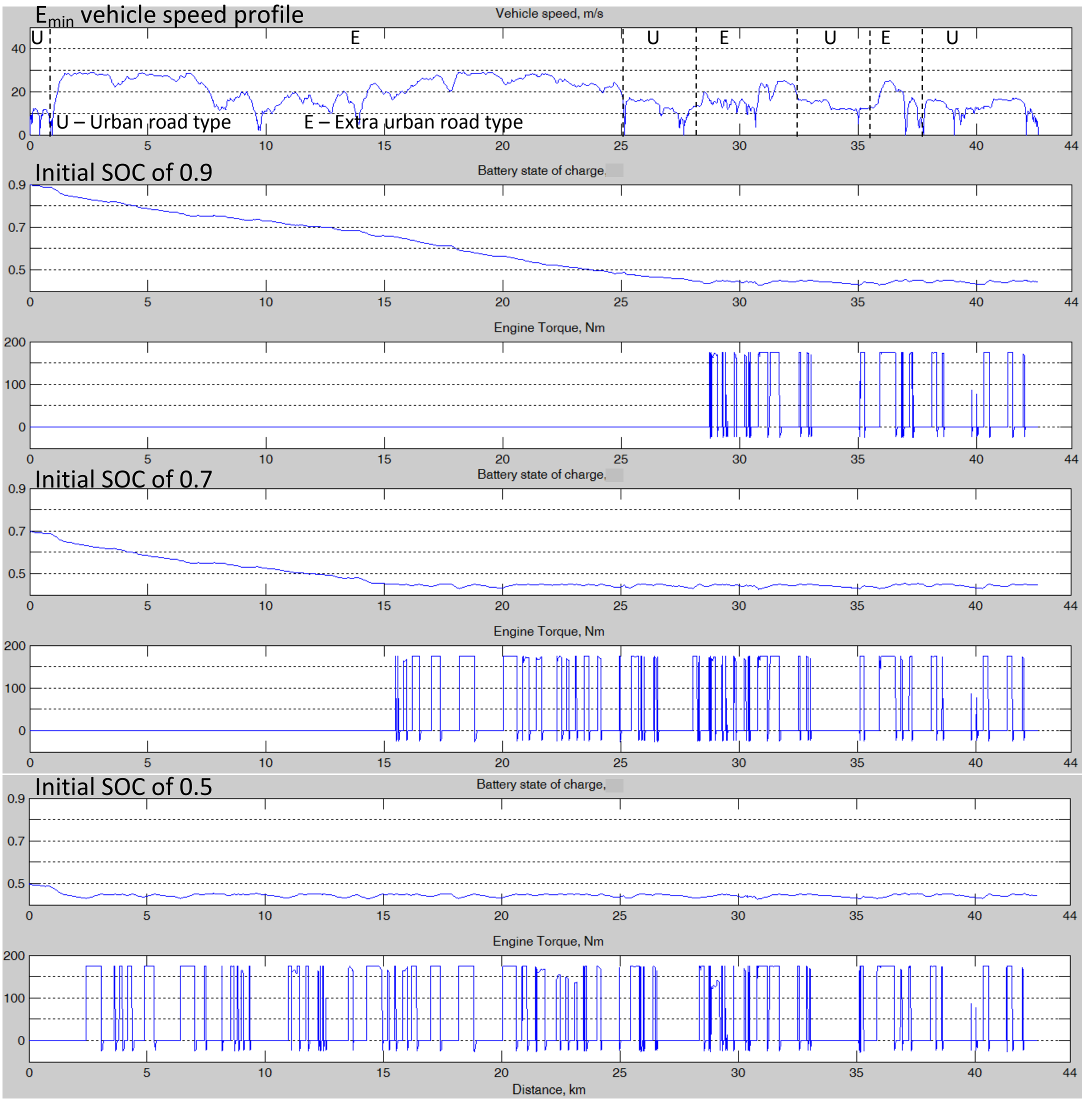

Figure 11-4: Conventional EMS performance over E_{min} at various initial SOC

As discussed with studies in previous chapters, conventional rule based EMS is following charge depleting – charge sustaining (CD-CS) strategy. As expected, the duration of CS strategy and engine operation is increasing with decrease in the initial SOC. Also in the figure the number of engine stop-start is more which is a typical of this EMS. In the figure the engine operation across various initial SOC at the same trip distance when in CS strategy is identical and hence leading to similar or same final SOC. The conventional EMS operation over E_{max} was similar to E_{min}.

The vehicle performance results of the conventional EMS for E_{min} and E_{max} at various initial SOC are shown in Table 11-3.

Table 11-3: The vehicle performance of the conventional rule based EMS over the E_{min} and E_{max} at various initial SOC

Vehicle speed profile	E_{min}			E_{max}		
Initial SOC	0.9	0.7	0.5	0.9	0.7	0.5
Final SOC	0.444	0.445	0.443	0.441	0.441	0.441
Actual FE, MPG	230	117.5	79.26	188.4	104.5	73.4
Corrected FE, MPG	296.1	133.1	85.79	227.2	115.4	78.6
Number of engine stop-starts	28	44	73	39	52	67

The vehicle performances of the conventional EMS for E_{min} and E_{max} are compared in the following sections.

11.4.1.1 Final SOC comparison

Due to identical engine operation at the corresponding trip distance when in CS strategy the final SOC across various initial SOC is similar or same for the respective vehicle speed profile. Also for both E_{min} and E_{max} the final SOC happens to be similar.

11.4.1.2 Fuel economy comparison

The E_{min} (corrected) fuel economy is higher than E_{max} as the vehicle speeds and hence the trip demand is lower for E_{min} in comparison to E_{max} vehicle speed profile. Therefore for a given initial SOC, the deficit energy required to be met by the engine operation is lower with E_{min} in comparison to E_{max} vehicle speed profile. Across initial SOC, expectedly the fuel economy is decreasing with a decrease in the initial SOC. This is due to the increased duration of engine operation with decrease in the initial SOC.

11.4.1.3 Number of engine stop – starts

Similar to fuel economy, the number of engine stop –starts increases with decrease in the initial SOC due to increase in the engine operation duration. As the trip demand is lower for E_{min} in comparison to E_{max}, the duration of engine operation and hence the number of engine stop – starts is lower most of the time.

11.4.2 The proposed EMS performance study for over and under estimation of the vehicle trip energy

The proposed EMS vehicle performance was studied for over estimation of the vehicle trip energy followed by under estimation along with varied initial SOC. Vehicle trip energy for the proposed EMS was estimated using trip driving information and specific energy from Table 11-2. Actual, over and under estimation of the vehicle trip with respect to E_{min} and E_{max} are shown in Figure 11-2 and Figure 11-3 respectively.

11.4.2.1 Over estimation of the vehicle trip energy

The proposed EMS vehicle performance for over estimation of the vehicle trip energy by 9% and 15% along with actual vehicle trip energy is compared and studied over the E_{min} vehicle speed profile. The proposed EMS performance for 9% over estimation of the vehicle trip energy over the E_{min} for varied initial SOC is shown in Figure 11-5. The proposed EMS operation based on the deficit trip energy and driving information is as discussed in previous chapters. In the figure expectedly the duration of engine operation and the number of engine stop – starts are increasing with decrease in the initial SOC to meet the increase in deficit trip energy.

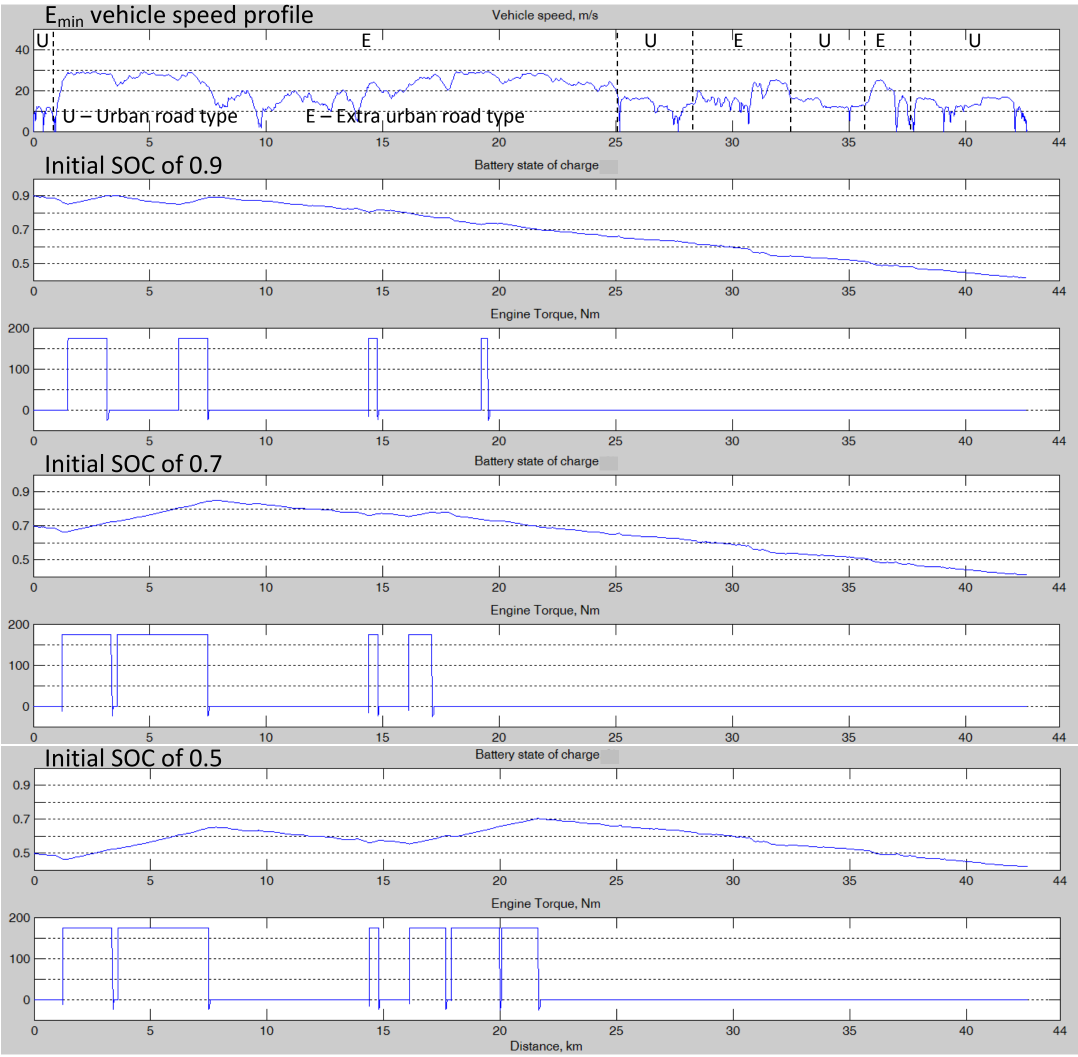

Figure 11-5: The proposed EMS performance over E_{min} for 9% over estimation of the trip energy and for various initial SOC

During over estimation of vehicle trip energy study of both 9% and 15%, smart charging was triggered only due to delta energy and only during extra urban road type. No base control strategy engine operation was observed which may reduce the fuel economy due to no control over energy conversion losses.

As the proposed EMS is pursuing blended charge depleting (BCD) strategy, the engine operation for the proposed EMS is distinctly different pattern in comparison to conventional rule based EMS (Figure 11-4). The number of engine stop – starts is fewer and the engine when switched on operates for relatively longer in comparison to frequent and short duration in the conventional EMS. Also the engine operation in the proposed EMS is ensured to operate at higher vehicle speeds to reduce energy conversion losses. As seen in Figure 11-5 the engine smart charge in extra urban is switching OFF whenever the vehicle speed is less than the threshold of 22 m/s. These are very similar to previous comparison studies of the proposed and conventional rule based EMS.

The proposed EMS vehicle performances for over and actual estimation of the vehicle trip energy over the E_{min} for varied initial SOC are as shown in Table 11-4.

Table 11-4: The proposed EMS vehicle performance for over estimation and varied initial SOC over E_{min}

Vehicle trip energy estimation	Actual estimation			9% over estimation			15% over estimation		
Initial SOC	0.9	0.7	0.5	0.9	0.7	0.5	0.9	0.7	0.5
Final SOC	0.407	0.409	0.404	0.416	0.411	0.420	0.428	0.432	0.440
Actual FE, MPG	295.2	137.9	90.2	282.5	137.9	88.0	267.3	128.9	84
Corrected FE, MPG	309.9	142.1	91.1	315.4	142.7	91.7	321.8	142.0	91.7
Number of engine stop-starts	4	5	6	4	4	6	4	4	6

In the following sections the proposed EMS performance across varied vehicle trip energy estimation and initial SOC are compared.

11.4.2.1.1 Final SOC comparison

In Table 11-4, the final SOC is at increasing trend with increase in over estimation of the trip energy. This is expected as the proposed EMS operates the engine to meet the deficit trip energy as per the vehicle trip energy estimated. As the vehicle trip energy estimation is higher than the actual, a part of this over estimation led to energy surplus at the end of the trip. The point to note is only a relatively small part of the over estimation is left as energy surplus at the end of the trip. More about the energy surplus of the proposed EMS is discussed later in section 11.5. Coming back to the table, there is no relation between initial and final SOC with respect to trip energy estimation.

11.4.2.1.2 Fuel economy comparison

The fuel economy is almost same across vehicle trip energy estimation most of the time. When the initial SOC is 0.9 the fuel economy increases with increase in over estimation of the vehicle trip energy. This may be due to comparatively short duration of engine operation and fuel economy is calculated over the entire trip distance leading to higher fuel economy numbers. In effect this leads to a significant change in fuel economy numbers for a small change in the engine operation duration as shown in Figure 11-6. Hence under the circumstances of high fuel economy numbers and small change in engine operation, the fuel economy with initial SOC of 0.9 can be considered similar for varied trip energy estimation. In other cases of initial SOC the fuel economy is almost same across vehicle trip energy estimation. For a given vehicle trip energy estimation, the fuel economy is decreasing with decrease in the initial SOC as expected.

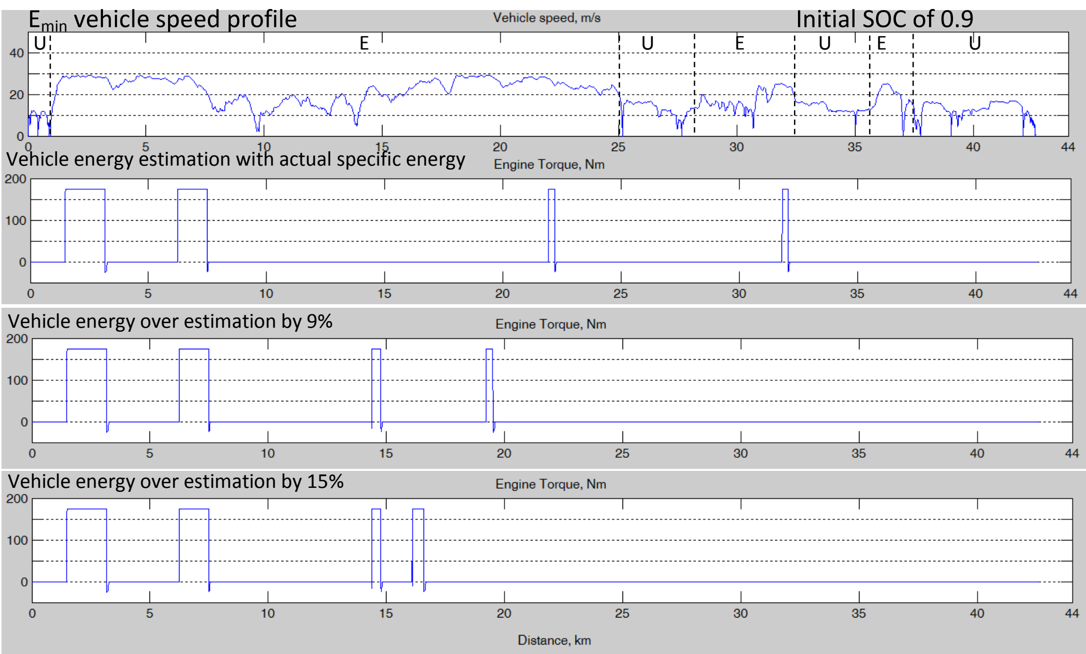

Figure 11-6: The proposed EMS performance over E_{min} for various estimation of vehicle trip energy with initial SOC of 0.9

11.4.2.1.3 Number of engine stop – starts comparison

The number of engine stop – starts of the proposed EMS is similar or same across varied trip energy estimation. Also expectedly the number of engine stop – starts is marginally increasing with decrease in the initial SOC.

11.4.2.2 Under estimation of the vehicle trip energy

The proposed EMS vehicle performance for under estimation of the vehicle trip energy by 9% and 15% along with actual vehicle trip energy estimation is compared and studied over the E_{max} vehicle speed profile as shown in Figure 11-7. The proposed EMS operation is similar to previous studies.

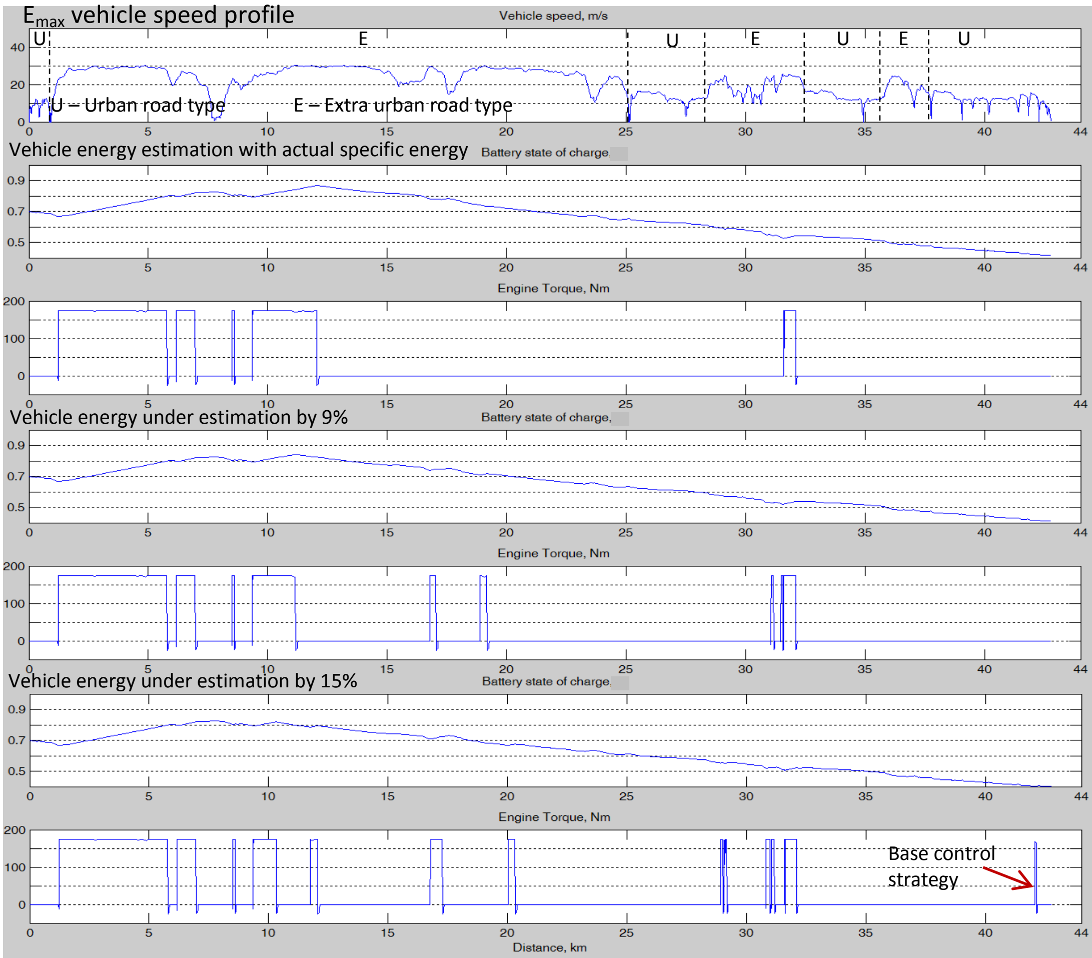

Figure 11-7: The proposed EMS performance comparison across under estimation of the vehicle trip energy at initial SOC of 0.7

As the vehicle trip energy is under estimated compared to the actual, the base control strategy activation is expected for cases beyond the proposed EMS ability to adapt. The proposed EMS was able to adapt and recover from 9% under estimation of the trip energy during the journey even with the initial SOC of 0.5. The base control strategy activation was observed towards the end of the trip only with 15% under estimation and initial SOC of 0.7 as shown in Figure 11-7. This was so for all three cases of initial SOC with 15% under estimation. The base control strategy is activated when the battery SOC reach minimum value, 0.4 and irrespective of the vehicle speed. Hence during the operation of base control strategy, there is no control over the energy conversion losses which may decrease the fuel economy. With 15% under estimation the base control strategy was activated during urban road type where the vehicle speeds are lower which decrease fuel economy. In all cases of vehicle trip under estimation studies, the engine smart charge was activated only during extra urban and not during urban road type.

In comparison to the over estimation study, the number of engine stop – starts is higher for under estimation. This was expected as the proposed EMS realises the under estimation during the journey and hence activates the smart charge due to its adaptive principles. The adaptive principles of the proposed EMS are discussed in section 7.2.4.1. However in comparison to the number of engine stop – start for the conventional EMS which varies from 39 to 67, the proposed EMS number varies from 6 to 13. They are still significantly fewer for the proposed EMS.

The proposed EMS performances for actual and under estimation of the vehicle trip energy along with varied initial SOC is shown in Table 11-5.

Table 11-5: The proposed EMS performance during under estimation over the E_{max}

Vehicle trip energy estimation	Actual estimation			9% under estimation			15% under estimation		
Initial SOC	0.9	0.7	0.5	0.9	0.7	0.5	0.9	0.7	0.5
Final SOC	0.415	0.416	0.417	0.412	0.411	0.412	0.401	0.400	0.401
Actual FE, MPG	216.9	117.8	80.2	217.6	119.3	80.6	225.4	118	81.2
Corrected FE, MPG	234.4	122.8	82.7	231.8	123.0	82.5	227.5	118.1	81.5
Number of engine stop-starts	6	5	7	10	9	7	11	13	12
Activation of base control strategy	No	No	No	No	No	No	Yes	Yes	Yes

In the following sections the above table is discussed.

11.4.2.2.1 Final SOC comparison

Expectedly the final SOC incremental decrease with an increase in under estimation of the vehicle trip energy was observed. Similar to over estimation there is no relation between initial and final SOC with respect to variation in trip energy estimation.

11.4.2.2.2 Fuel economy comparison

With 9% under estimation and actual trip energy estimation, fuel economy is same or similar. Fuel economy with 15% under estimation of the vehicle trip energy is lower in comparison to other two cases of trip energy estimation.

11.4.2.2.3 Number of engine stop – starts comparison

The number of engine stop-starts increases with increase in percentage of under estimation of the vehicle trip energy. There is no obvious trend between the initial SOC and the number of engine stop-starts which was not expected. The number of engine stop – starts for 9% under estimation with initial SOC of 0.9 and 0.5 is 10 and 7 respectively as shown in Figure 11-8.

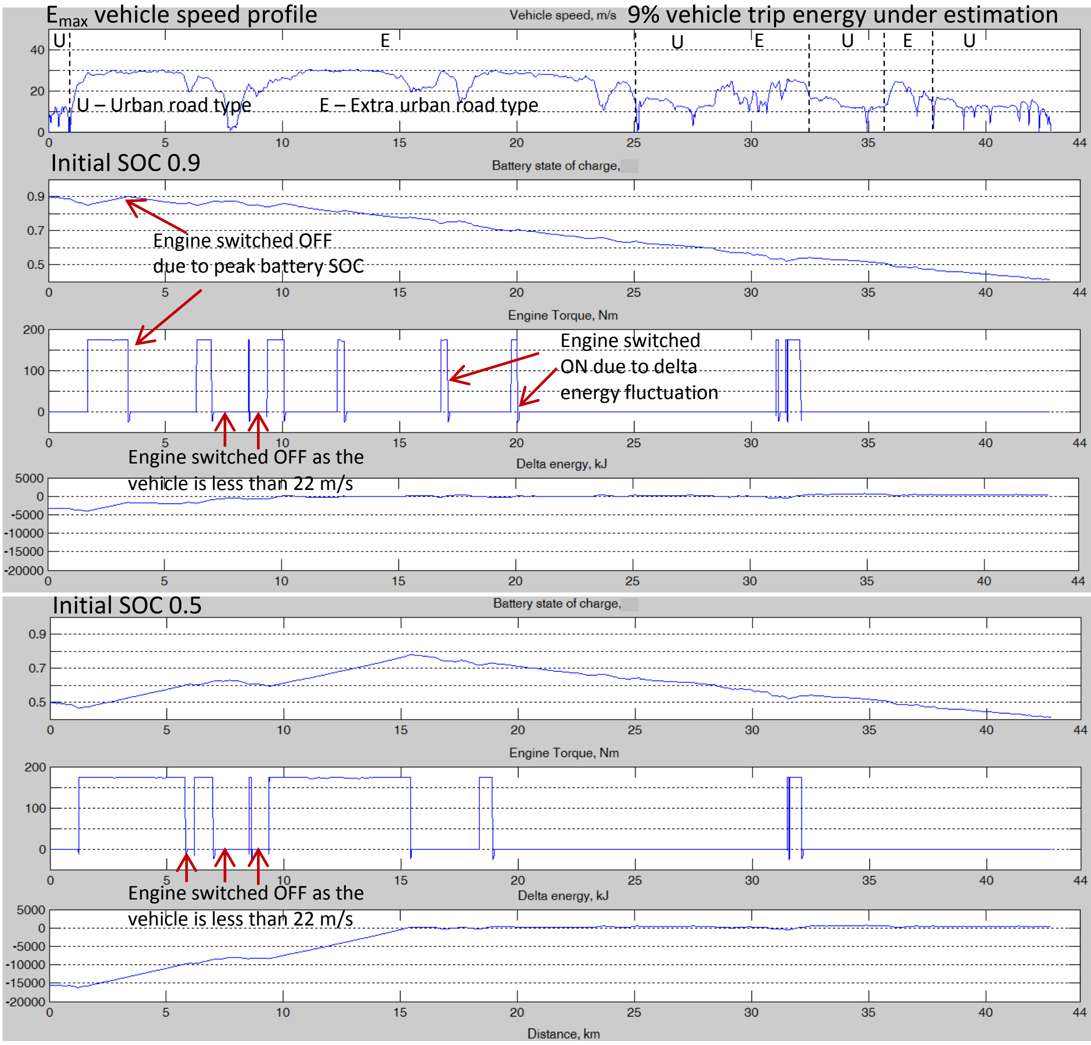

Figure 11-8: The proposed EMS number of engine stop – starts performance with varied initial SOC for 9% under estimation of the vehicle trip energy

It can be observed that some engine stop – starts are due to delta energy fluctuation as shown in Figure 11-8. Delta energy fluctuations are due to local variation in vehicle energy estimation as discussed in the NEDC study (chapter 8). As in this case, it is part of the EMS adaptability in recovering from under estimation during the journey. Also some engine stop – starts are due to vehicle speed decreasing less than 22 m/s when the engine was on. In the case of initial SOC of 0.9 some engine stops are triggered by maximum battery SOC of 0.9 when the engine was smart charging. Hence the number of engine stop – starts is a function of vehicle trip energy estimation, local variation in energy estimation, initial SOC and also the trip vehicle speed profile. All these factors can make the number of engine stop – starts correlation with the initial SOC for a given trip non – linear.

11.4.2.2.4 Base control strategy activation comparison

The base control strategy was activated only with 15% of under estimation of vehicle trip energy for all three initial SOC.

11.4.3 Discussion

In this section the proposed EMS performance for over and under estimation are compared and studied with respect to conventional rule based EMS performance.

11.4.3.1 Final SOC comparison

The final SOC for both over and under estimation of the vehicle trip energy for the proposed EMS is lower than the conventional EMS.

With 9% over and under estimation of the vehicle trip energy, the final SOC of the proposed EMS is similar and close to minimum SOC (around 0.41). With 15% under estimation, the proposed EMS final SOC is at minimum battery SOC of 0.4 and that of 15% over estimation is relatively higher around 0.43 to 0.44.

11.4.3.2 Fuel economy comparison

The fuel economy improvement of the proposed EMS and average benefit across initial SOC for vehicle trip energy over and under estimation to conventional EMS is shown in Table 11-6. The proposed EMS fuel economy is higher than that of conventional EMS for both over and under estimation of the vehicle trip energy considered across varied initial SOC.

Table 11-6: Fuel economy (FE) benefit comparison of the proposed EMS across vehicle trip energy estimation with conventional EMS

Vehicle trip energy estimation	**15% over estimation**			**9% over estimation**			**9% under estimation**			**15% under estimation**		
Initial SOC	0.9	0.7	0.5	0.9	0.7	0.5	0.9	0.7	0.5	0.9	0.7	0.5
FE improvement over conventional EMS, %	8.7	6.7	6.9	6.5	7.2	6.9	1.9	6.6	5.0	0.1	2.3	3.7
Average percentage FE benefit over conventional EMS across initial SOC, %	7.4			6.9			4.5			2.1		

In the table the fuel economy of the proposed EMS for 15% under estimation of the vehicle trip energy to conventional EMS with initial SOC of 0.9 is small with 0.1% benefit. The vehicle performances for the same are shown in Figure 11-9.

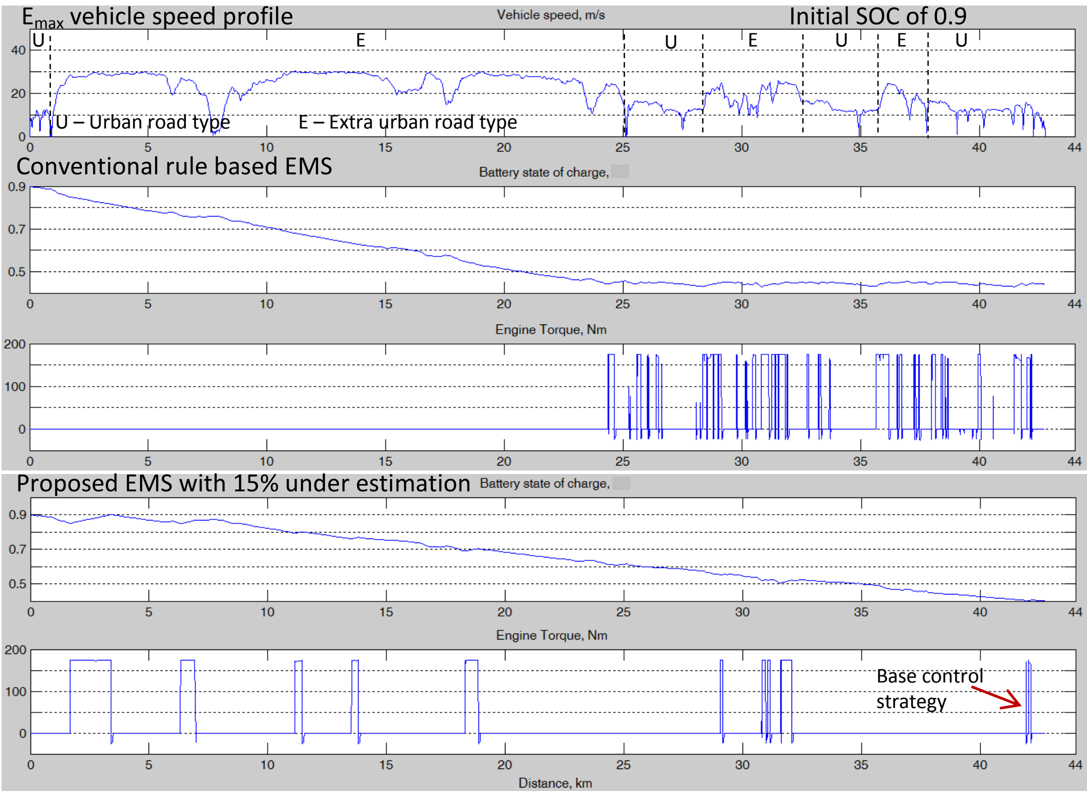

Figure 11-9: The proposed EMS performance for 15% under estimation of the vehicle trip energy and the conventional rule based EMS performance comparison over E_{max}

In Figure 11-9, the proposed EMS engine operation is better controlled in the proposed EMS by operating at higher vehicle speed most of the time. As discussed earlier the base control strategy is activated towards the end of the trip which is operating at lower vehicle speed at urban road type. This increases energy conversion losses for the proposed EMS. On the other hand for the conventional rule based EMS the engine operation is partially at lower vehicle speeds and partially at transient vehicle speeds (higher acceleration) which increase and decrease energy conversion losses respectively. However the net difference in energy conversion losses and hence the fuel economy between the proposed and conventional rule based EMS happens to be almost the same.

The averaged percentage fuel economy benefit across three levels of initial SOC for varied vehicle trip energy estimation to conventional EMS is shown in Figure 11-10.

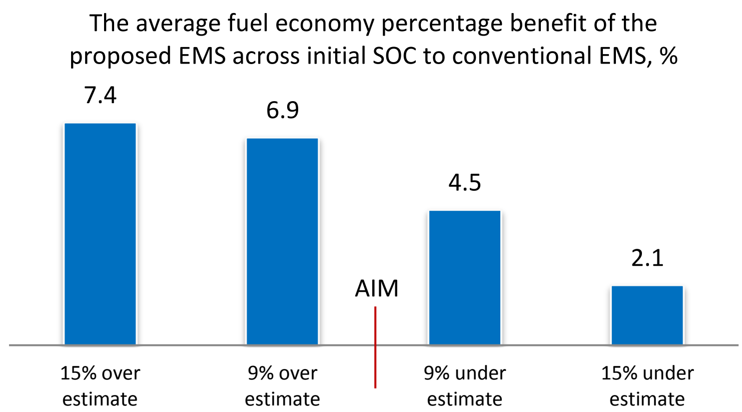

Figure 11-10: The average fuel economy percentage benefit across initial SOC of the proposed EMS for over and under estimation of the trip energy to conventional EMS is plotted.

The average fuel economy benefit for vehicle trip energy over estimation by 9% and 15% to conventional EMS is comparatively close to each other. In the case of under estimation of the vehicle trip energy, the fuel economy benefit to conventional EMS is noticeably decreased with 15% under estimation. For 15% under estimation the fuel economy decreased due to the base controls strategy activation. However in all cases the fuel economy of the proposed EMS is above the conventional EMS.

11.4.3.3 Number of engine stop - starts

The average number of engine stop starts across initial SOC of the proposed EMS for over and under estimation of the vehicle trip energy and that of conventional EMS is shown in Figure 11-11.

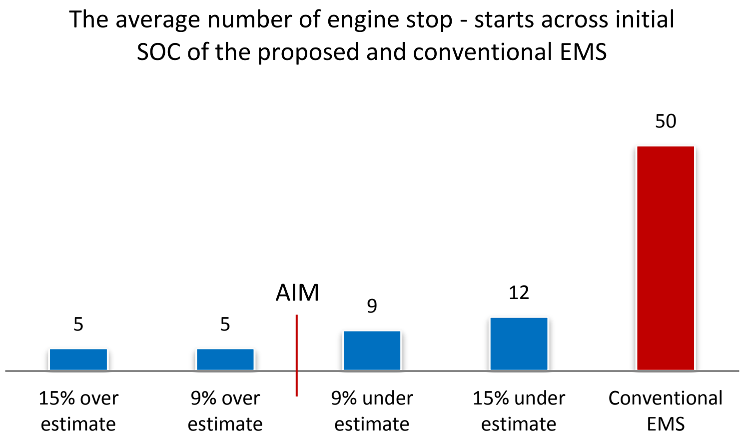

Figure 11-11: The average number of engine stop – starts across initial SOC of the proposed EMS for over and under estimation of the vehicle trip energy and that of conventional EMS is plotted.

In both under and over estimation of the vehicle trip energy, the proposed EMS number of engine stop – starts is much fewer than that of conventional EMS. The number of engine stop – starts is comparatively fewer with over estimation in comparison to under estimation of the proposed EMS.

11.5 Surplus battery energy analysis for over and under estimation of the vehicle trip energy

The adaptability of the proposed EMS in terms of the battery energy left at the end of the trip called energy surplus is studied in this section. This analyses the proposed EMS adaptability for over and under estimation of the vehicle trip energy by the end of the trip.

The total vehicle battery capacity (B) is 30960 kJ. Using the final SOC observed during actual, under and over estimation of the trip energy, the battery energy left above minimum SOC of 0.4 is determined as shown in Table 11-7. Also in the table the difference between the actual and estimated vehicle trip energy is shown for both E_{min} and E_{max}. During both under and over estimation of the trip energy, the proposed EMS was able to recover the gap during the journey for varied initial SOC.

Table 11-7: Battery energy above minimum SOC at the end of the trip for the proposed EMS with varied initial SOC

Parameters	Estimated vehicle trip energy, kJ	Difference from the actual vehicle trip energy, kJ	Energy surplus at the end of the trip, kJ (Final battery SOC)		
Initial SOC	-	-	0.9	0.7	0.5
E_{min} actual	18737	0	217 (0.407)	279 (0.409)	124 (0.404)
With 9% over estimation	20494	1757	495 (0.416)	340 (0.411)	619 (0.420)
With 15% over estimation	21619	2882	867 (0.428)	991 (0.432)	1238 (0.440)
E_{max} actual	20329	0	464 (0.415)	495 (0.416)	526 (0.417)
With 9% under estimation	18665	-1664	371 (0.412)	340 (0.411)	371 (0.412)
With 15% under estimation	17308	-3021	31 (0.401)	0 (0.400)	31 (0.401)

As the vehicle trip energy is linearly estimated using specific energy over driving distance and due to regenerative braking, the energy surplus at the end of the trip even with actual specific energy is not zero. Hence the final SOC or energy surplus is also a function of vehicle speed profile towards the end of the trip. This was discussed in previous study over the NEDC in section 8.3. Next the energy surplus is higher with over estimation and lower with under estimation of the vehicle trip energy. During over estimation of the vehicle trip energy, the proposed EMS ability to adapt to keep the energy surplus minimum at lower initial SOC of 0.5 is relatively restricted. In other cases there is no relation between the proposed EMS ability to keep the energy surplus minimum and the initial SOC for a given trip energy estimation.

For over estimation study, the proposed EMS is able to adapt and reduce higher initial trip energy estimation (15%) of 2882 kJ to a third of this by the end of the trip with initial SOC of 0.9. Similarly with initial SOC of 0.5 the EMS was able to reduce by more than half of the initial trip energy estimate.

For under estimation study, the proposed EMS is able to adapt and recover lower initial trip energy estimation (15%) of -3021 kJ by the end of the trip for all three levels of initial SOC.

The adaptive principle of the proposed EMS for both over and under estimation of the vehicle trip energy is demonstrated.

11.6 Discussion

The impact on the proposed EMS with respect to real world driving and conventional acausal EMS is discussed. The proposed EMS vehicle performance for over and under estimation of the vehicle trip energy across varied initial SOC are compared. Based on this the target region to aim for vehicle trip energy estimation in maximising the vehicle performance for the propose EMS is discussed.

11.6.1 The proposed EMS impact

In the repetitive real world driving data study in this chapter the actual minimum and maximum vehicle trip energy variation over the average mean was only about 5%. However the proposed EMS was studied up to 15% of over and under estimation of the vehicle trip energy. It can be said the proposed EMS was studied beyond the realistically possible variation in the vehicle trip energy in real world driving. It was found the proposed EMS can accept a reasonable variation (±15%) in trip energy estimation and still deliver better vehicle performance than the conventional EMS for all varied initial SOC. Hence the propose EMS need not require exact estimation of the vehicle trip energy.

Given the vehicle performance sensitivity to the vehicle speed profile base EMS as discussed in the literature (Qiuming and Yaoyu, 2009, Serrao et al., 2011), overall results of the proposed EMS is a revelation. Due to formulation on vehicle trip energy and driving information and also due to adaptive principles (discussed in previous section) the proposed EMS can handle the dynamic and uncertain nature of trip demand to deliver efficient performance for varied trip energy estimation and initial SOC. The proposed EMS does not require exact estimation of the trip demand like in optimisation based EMS.

11.6.2 Vehicle trip energy estimation implication

In this section the vehicle performance of the proposed EMS for over and under estimation with actual vehicle trip energy estimation are compared with and across to infer the favourable target estimation region. In Table 11-8, the proposed EMS performance for over and under estimation of the vehicle trip energy are compared to the actual estimation across three levels of initial SOC.

Table 11-8: The proposed EMS performance comparison for over and under estimation of the vehicle trip energy across initial SOC

Vehicle trip energy estimation	Over estimation		Under estimation	
	9%	15%	9%	15%
Final SOC	Low (about 0.41)	Relatively higher (0.44)	Low (about 0.41)	Minimum (0.4)
Fuel economy	Similar as with actual estimation	Similar as with actual estimation	Similar as with actual estimation	Relatively lower
Number of engine stop - starts	Similar or same as with actual estimation	Similar or same as with actual estimation	Marginally higher than with actual estimation	Relatively higher than with actual estimation

The table is discussed in the following sub-sections

11.6.2.1 Final SOC comparison

With respect to final SOC comparison across vehicle trip energy estimation, with 15% of over estimation the final SOC is relatively high. However as long as the final SOC is around 0.45 (5% above minimum SOC) it should be acceptable. In the current CD-CS strategy used in industry this is considered acceptable as the CS strategy is designed to operate up to 5% above minimum SOC (O'Keefe and Markel, 2006). In all other cases of trip energy estimation final SOC is low or minimum.

11.6.2.2 Fuel economy comparison

Except with 15% under estimation, the fuel economy for all other vehicle trip energy estimation to actual estimation is similar. With 15% under estimation the decrease in fuel economy is relatively higher. Hence there is a fuel economy penalty with severe under estimation of the vehicle trip energy.

11.6.2.3 Number of engine stop - starts

With both over estimation of the vehicle trip energy cases, the number of engine stop – starts are similar. With 9% under estimation the number of engine stop – starts is marginally higher in comparison to the actual estimation. Further it is relatively higher with 15% under estimation.

11.6.2.4 Summary of vehicle performance for varied vehicle trip energy estimation

The advantage of over estimation is it gives a chance for the EMS to smart charge to meet the deficit trip energy at the most efficient manner which serves well for any eventuality. In the case of under estimation which EMS realises the deficit in estimation during the journey and hence smart charge is activated along the way which may not always be the most efficient conditions leading to compromise in fuel economy. This can be either due to the base control strategy activation at lower vehicle speeds (as observed with 15% under estimation) or the EMS realised the deficit in estimation after the vehicle has crossed the last extra urban road type. Also in this process the number of engine stop – starts are increasing.

Overall, higher vehicle trip energy over estimation after a limit (above 15% over estimation in the study) leads to higher final SOC. Higher final SOC is not acceptable after a limit (above 5% from minimum SOC). On the other hand higher vehicle trip energy under estimation after a limit (with 15% under estimation) leads to decrease in fuel economy and higher number of engine stop – starts. Hence considering the overall vehicle performance there is benefit in getting the vehicle trip energy estimation close to the actual vehicle trip energy. This should be the primary aim. Up to 9% of over and under estimation of the vehicle trip energy no compromise in performance is observed and hence can be considered as the target region. With a higher vehicle trip energy estimation of 15% only issue observed is higher final SOC and hence considering uncertain and dynamic real world driving this can be acceptable. However it is recommended to avoid higher under estimation of 15% which decreases the potential fuel economy and increase the number of engine stop – starts. The desired (target region) and avoidable (not recommended) vehicle trip energy estimation region to maximise the proposed EMS potential vehicle performance is summarised in Figure 11-12.

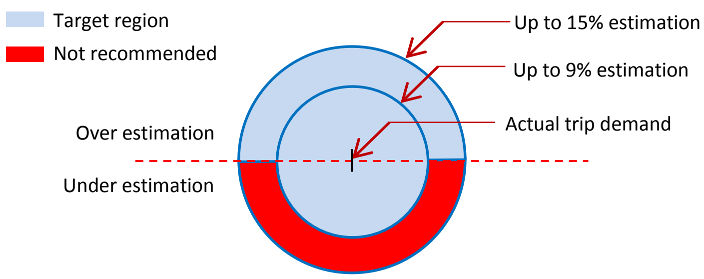

Figure 11-12: Vehicle trip energy target estimation region to maximise the proposed EMS potential vehicle performance

11.7 Conclusion

- For the proposed EMS, the trip demand estimation need not be exact. The proposed blended rule based EMS can accept reasonable (±15% in the study) variation in vehicle trip energy estimation and still perform better than the conventional EMS.
- For all cases of over and under estimation and varied initial battery state of charge (SOC), vehicle performances such as the final SOC, number of engine stop-starts and fuel economy of the proposed EMS are superior to conventional rule based EMS. The proposed EMS performance for varied estimation with respect to conventional rule based EMS is as follows:

- For 9% over estimation - The average fuel economy benefit to conventional EMS across initial SOC was 6.9% with 10 times lesser number of engine stop – starts.
- For 15% over estimation - The average fuel economy benefit to conventional EMS across initial SOC was 7.4% with 10 times fewer number of engine stop – starts.
- For 9% under estimation - The average fuel economy benefit to conventional EMS across initial SOC was 4.5% with over 5 times fewer number of engine stop – starts.
- For 15% under estimation – The average fuel economy benefit to conventional EMS across initial SOC was 2.1% with over 4 times fewer number of engine stop – starts.

- The proposed EMS vehicle performance across respective over and under estimation (±15%) to actual vehicle energy and with varied initial SOC is similar except with 15% under estimation.
- It is recommended to avoid sever under estimation of the vehicle trip energy to maximise the potential vehicle performance.
- The proposed EMS is expected to adapt to the uncertain trip demand conditions of real world driving and deliver vehicle efficient performance.

Chapter 12 – Validation of the Proposed EMS for Real World Driving

12.1 Introduction

In this chapter the proposed blended rule based EMS working is demonstrated and studied for uncertain trip demand as is the case in real world driving.

In acausal EMS studies in the literature, prior knowledge of trip demand specific to the destination considered such as historic vehicle speed profiles (Kessels, 2007, Johannesson, 2009) or intelligent transport system (ITS) data (Qiuming et al., 2007, Qiuming and Yaoyu, 2009) are required to make the trip demand prediction. In this study the trip demand is estimated for multiple (four) real world destinations based on historic trip demand knowledge of two different destinations. These estimations are used in the proposed EMS validation study as a complete system.

The validation study over real world driving involves two parts. The first is to determine the specific energy matrix based on real world driving data. This is followed by the validation study.

In section 12.3 using two real world destination data which are not part of the validation study are considered to determine specific energy values for urban and extra urban road types, for a driver. This is known as specific energy matrix. Two specific energy matrixes determined using two different methods but using the same two real world destination data are considered.

In the next section 12.4, the proposed EMS validation study is covered using these specific energy matrixes. The proposed EMS working is studied for four real world destinations with varied sequence of road types and trip distance. Also in one of these four real world destination validation studies, the initial battery state of charge (SOC) is varied. In the validation study the vehicle performance such as fuel economy, final SOC and the number of engine stop – starts of the proposed EMS is compared to that of conventional rule based EMS. Based on the vehicle performance, the two specific energy matrixes considered are analysed and recommended in section 12.5. Next in section 12.6 the implication of the proposed EMS based on the validation study with respect to real world application and differentiation from other acausal EMS studies are discussed. Followed by in section 12.7, the fuel economy improvement of the proposed EMS to conventional rule based EMS which follows blended charge depleting (BCD) and charge depleting – charge sustaining (CD-CS) strategies respectively with respect to trip demand are analysed.

12.2 Study method

For real world application as in this study, only the driving information to the destination such as road type, distance and driver style are known in advance. The actual trip demand remains uncertain. Using driving information for the destination planned and specific energy matrix the vehicle trip demand is estimated and the proposed EMS is studied for vehicle performance. This study is carried out for a given vehicle and driver style. Effect of traffic was not considered for simplicity.

12.2.1 To determine the specific energy matrix

For real world application of the proposed EMS, the specific energy matrix is determined using real world driving data for the given vehicle and driver style considered. To ensure the specific energy matrix determined is free from any biases specific to a destination, real world driving data for two destinations is considered.

From the WMG SAVE project for a driver two destination vehicle speed profile data are considered to determine the specific energy matrix. They are:

a) Repetitive driving data for a given destination used in previous chapter, and

b) A new individual trip data (Leamington Spa – Coventry)

The specific energy values are determined for urban and extra urban road types of a trip by simulating the vehicle in electric vehicle (EV) mode as discussed in previous studies for both destination data.

The specific energy matrix is determined using two different methods for the two destination data as mentioned below:

- Method 1 (S1): The highest specific energy value for each road type in an individual destination data out of the two is considered.
- Method 2 (S2): The specific energy values of both destination data is averaged over the total distance of the respective road types. In other words, the specific energy values are distance weighted.

In the previous adaptability study, over estimation of the vehicle trip energy in comparison to under estimation led to relatively better vehicle performance. S1 was considered based on this learning. S2 reflects the average demand exhibited by the driver over two destinations.

12.2.2 Study set up for the validation of the proposed EMS

In the validation study, vehicle trip energy is estimated using the above two specific energy matrixes separately. The validation study is carried out for the same driver and vehicle of which specific energy matrix is determined. Real world driving data from the SAVE data that was not part of the specific energy matrix determination is used for this validation study. In total, four destinations of varied sequence of road types and trip distances are considered. The sequences of road types considered are:

- Trip A: Urban - Extra urban - Urban,

- Trip B: Urban - Extra urban,
- Trip C: Extra urban - Urban, and
- Trip D: Urban

The proposed EMS and conventional rule based EMS method remain the same as in previous chapter. In the study vehicle performance such as the final SOC, fuel economy (FE) and number of engine stop-starts are compared and studied. The vehicle performances are compared between the proposed and conventional rule based EMS. Also the proposed EMS vehicle performance considering two specific energy matrixes in trip energy estimation is also analysed.

12.3 Specific energy matrix determination using real world data

Real world vehicle speed profile data of two different destinations from the WMG-SAVE project for a driver is shown in Figure 12-1.

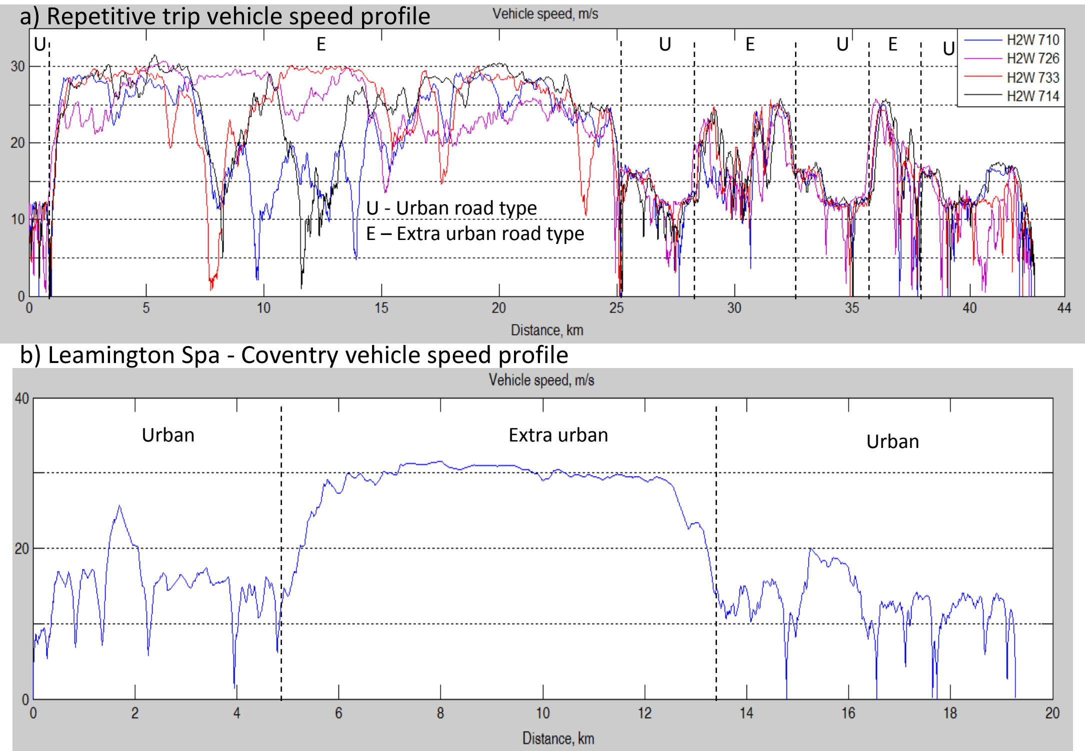

Figure 12-1: Real world vehicle speed profile data from SAVE project for a driver used for developing specific energy matrix

One of these (Figure 12-1/a) is the same set of repetitive trip vehicle speed profiles used in the previous chapter. The Leamington Spa – Coventry vehicle speed profile is the new individual trip data considered (Figure 12-1/b).

In the case of repetitive trip, the specific energy for urban and extra urban road types of four trips for a given destination considered are averaged to determine the respective specific energy values for urban and extra urban road types. The total distance and specific energy values for urban and extra urban road types of two destinations are shown in Table 12-1.

Table 12-1: Destination specific energy observed for two real world driving destination

Type of data	**Repetitive data (Averaged)**		**Leamington Spa - Coventry**		**Difference in destination specific energy, %**
Road type	Distance, km	Specific energy, kJ/km	Distance, km	Specific energy, kJ/km	-
Urban	12.0	363	10.9	397	9.3
Extra urban	30.2	505	8.5	587	16.2

In Table 12-1, the destination distance for urban and extra urban road types are comparatively longer for repetitive trip data. The specific energy values for Leamington Spa – Coventry are comparatively higher for both urban and extra urban road types. The difference in specific energy values across two destinations is wider for extra urban than urban road type. This trend is same as seen in Table 11-1 for the same destination but repetitive trips in the previous chapter.

As the study is for a driver, the specific matrix is reduced to just road types. Two methods are considered to determine the specific energy matrix out of two real world destinations.

Specific energy matrix - Method 1 (S1): In Table 12-1, out of two destinations, the Leamington Spa – Coventry destination, has the highest specific energy values for both urban and extra urban road types. These values are considered.

Specific energy matrix – Method 2 (S2): In this case, for each road type, the specific energy values and its respective total distance of both trips are averaged over total distance of both destinations. From Table 12-1, say for urban road type it is,

= (12x363+10.91x397) / (12+10.91) = 379 kJ/km

Similarly for extra urban it is 523 kJ/km.

Specific energy matrix of both methods S1 and S2 are shown in Table 12-2. In the table the difference in specific energy value for urban road type across two methods is narrower in comparison to extra urban. Also the S2 specific energy matrix values for urban and extra urban are lower than in S1. Therefore vehicle trip energy estimation using S1 will be higher than S2.

Table 12-2: Specific energy matrix by two methods

Road type	Method 1 (S1)	Method 2 (S2)
Urban, kJ/km	397	379
Extra urban, kJ/km	587	523
Remarks	Highest value observed in an individual trip	Specific energy calculated over total distance of both destinations

Using the above table, vehicle trip energy is estimated for all four real world destinations of varied sequence of road types to validate the proposed EMS in the next section. To reiterate, the real world driving data considered in determining the specific energy matrix is not part of four destinations considered for the validation study.

12.4 Validation and performance comparison study

The proposed blended rule based EMS working principle illustrating vehicle trip energy estimation and devising control strategy was covered earlier in section 5.2.2. Vehicle trip energy is estimated using known driving information of a planned destination and specific energy matrix. Based on the estimated vehicle trip energy and the available battery energy, delta energy (ΔE_t) is calculated using equation 7.5. Delta energy polarity and value controls the engine operation with respect to the destination driving information to reduce the energy conversion losses. The destination vehicle speed profile is not an input to the proposed EMS. In this section the proposed EMS is validated for real world destinations.

In the first validation study road type sequence of Urban - Extra urban - Urban is considered called trip A. First and last two consecutive road types of trip A is considered for trip B (Urban - Extra urban) and C (Extra urban - Urban) respectively. For the last only urban road type validation study, a new urban trip data was considered to have a longer trip distance. This is trip D.

12.4.1 Trip A – Urban - Extra urban - Urban study

In this section vehicle performance over real world trip A for the proposed and conventional EMS is studied. Vehicle trip energy estimation for the proposed EMS using driving information and specific energy matrix is explained for trip A. Next the vehicle performance are compared with conventional and the proposed EMS with vehicle trip energy estimation using S1 and S2 matrix. Later in section 12.4.1.4, the local delta energy operation of the proposed EMS is illustrated.

12.4.1.1 Vehicle trip energy estimation for trip A

In the first validation trip with sequence of urban - extra urban - urban road type was studied at initial SOC of 0.75, 0.6 and 0.45. Compared to previous studies, the initial SOC is lowered to demonstrate the local delta or secondary smart charge operation of the proposed EMS (discussed in section 8.3.7) when initial SOC is 0.45. For trips B – D studies, the initial SOC of 0.6 is considered.

As discussed in the proposed EMS working principle (section 7.2.3), vehicle trip energy is estimated using driving information and specific energy matrix (Table 12-2). The driving information for trip A, road types and distance used for vehicle energy estimation is shown in Figure 12-2. Note that the trip vehicle speed profile is not part of the energy estimation.

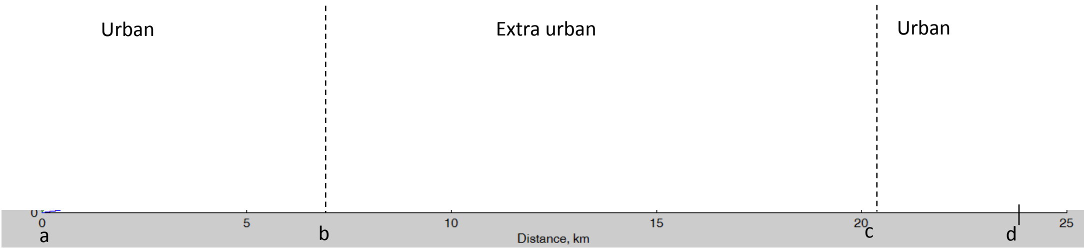

Figure 12-2: Trip A driving information to estimate the vehicle trip energy for the proposed EMS

In Figure 12-3, the actual and estimated vehicle trip energy using both specific energy matrix of method 1 (S1) and 2 (S2) are shown.

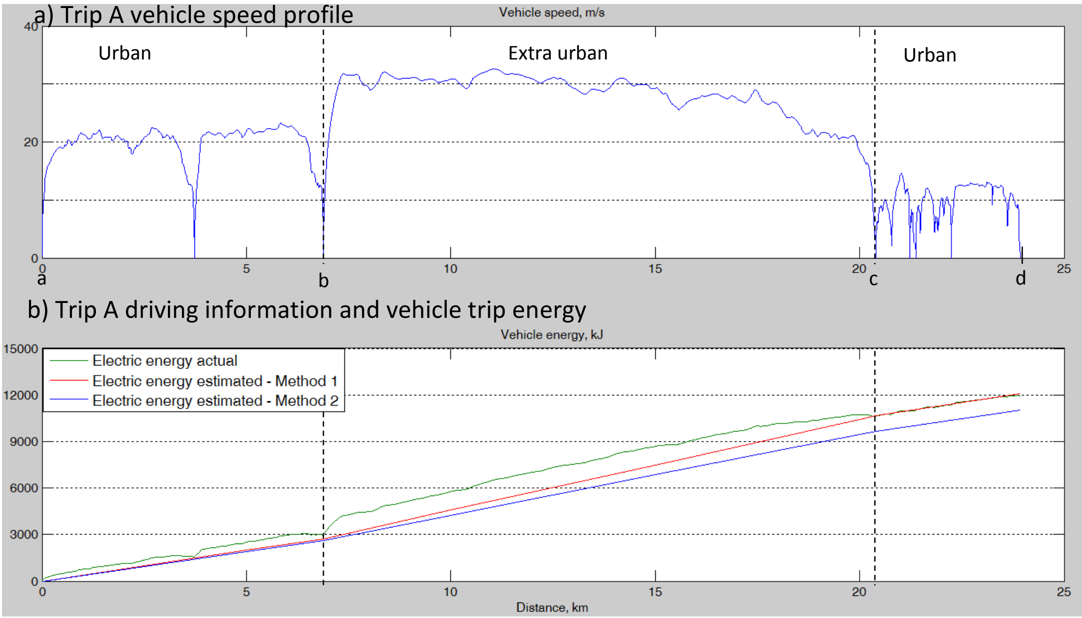

Figure 12-3: Trip A vehicle speed profile along with the actual and estimated vehicle trip energy using method 1 (S1) and 2 (S2) specific energy matrix.

For each road type, the respective specific energy is linearly extrapolated over distance. There is a variation in vehicle energy estimation locally and globally for each road type in Figure 12-3 with S1 and S2. In the first urban road type, the actual vehicle energy is higher than both S1 and S2 estimations. For extra urban road type the gap between actual and S1 is wider most of the time before the actual energy converges at the end of extra urban. For

S2 the gap with the actual vehicle energy in extra urban is initially diverging towards under estimation. For the second urban road type the vehicle energy estimations with S1 and S2 are similar to the actual vehicle energy. Estimations using S1 and S2 for urban road type are almost the same, as their specific energy values in the matrix are close to each other. The vehicle energy estimation is not so good for extra urban due to higher speed limits and higher variation in external driving conditions in extra urban than in urban road type. This is in concurrence with high variation in extra urban vehicle energy observed in the repetitive study in the previous chapter.

Variation in vehicle trip energy between the actual and estimated using both specific energy matrixes is shown in Table 12-3. It so happened that the total trip energy of S1 is almost the same as the actual vehicle energy. For S2 vehicle trip energy is under estimated by about 8 % of the actual.

Table 12-3: Actual and estimated vehicle trip energy comparison for real world trip A

Trip name	Actual total vehicle energy, kJ	Vehicle trip energy estimated using S1, kJ	Vehicle trip energy estimation using S2, kJ	Difference in vehicle trip energy estimation using S1 and actual energy, %	Difference in vehicle trip energy estimation using S2 and actual energy, %
Trip A	11943	12073	11020	1.1	-7.7

12.4.1.2 Vehicle performance comparison for trip A

Vehicle performance data for both EMS are shown in Table 12-4 for trip A.

Table 12-4: Vehicle performance data of the proposed and conventional EMS for trip A

EMS and vehicle trip energy estimation method	Proposed EMS using specific energy matrix – Method 1 (S1)			Proposed EMS using specific energy matrix – Method 2 (S2)			Conventional rule based EMS		
Initial SOC	0.75	0.60	0.45	0.75	0.60	0.45	0.75	0.60	0.45
Final SOC	0.440	0.440	0.439	0.423	0.425	0.424	0.443	0.443	0.443
Actual FE, MPG	269.0	110.8	71.0	314.3	117.6	73.1	224.7	100.1	65.8
Corrected FE, MPG	471.0	134.5	79.9	444.4	133.3	78.6	363.3	120.6	74.0
Number of engine stop-starts	2	2	3	3	2	4	14	19	30

12.4.1.2.1 Final SOC comparison

Consistent with the adaptability study in the previous chapter, the final SOC is lower during under estimation (S2). Also the final SOC of conventional EMS is higher in comparison to the proposed EMS with both S1 and S2 vehicle energy estimation. The total vehicle trip energy estimated using S1 is similar to the actual value (Figure 12-3/b). At the same time the final SOC for the proposed with S1 estimation is higher even though there is no high speed regenerative braking at the end of the trip. The proposed EMS operation with S1 vehicle energy estimation for initial SOC of 0.75 is shown in Figure 12-4.

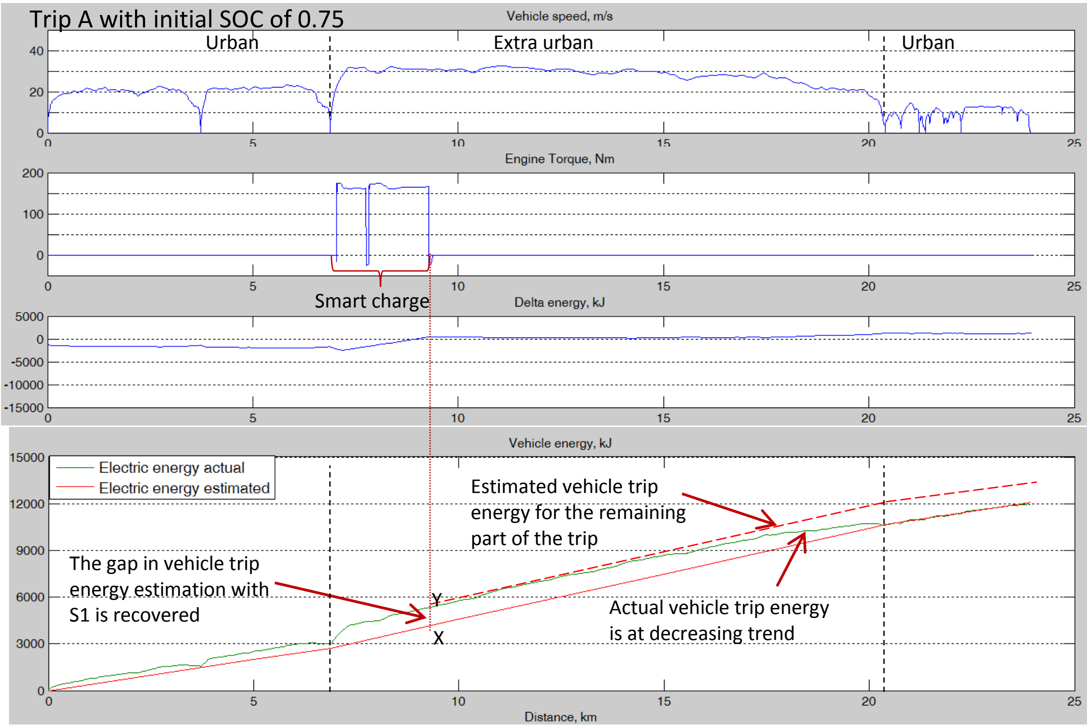

Figure 12-4: The proposed EMS performance for Trip A with estimation of vehicle trip energy using S1 and initial SOC is 0.75

In Figure 12-4 at the end of smart charge, the difference in the estimated and actual vehicle trip energy is recovered due to the proposed EMS adaptability (explained earlier in section 7.2.4.1). Hence from that point the estimated vehicle trip energy for the remaining trip shifts from X to Y as shown in Figure 12-4 by a red - dash line. This leads to over estimation of the vehicle trip energy in comparison to the actual (green line). The actual vehicle energy is at decreasing trend after the journey distance of 15 km. Thus the vehicle trip energy estimated with S1 which was similar to actual at the start of the trip became over estimation. This led to higher final SOC.

Similar X to Y shift happened with S2 vehicle trip energy estimation after smart charge. But the offset of the estimated vehicle trip energy for the remaining part of the trip is lower than S1. This is so, as the S2 vehicle energy profile is lower than S1 throughout the journey as seen in Figure 12-3. Hence the final SOC of the proposed EMS is lower with S2 trip energy estimation.

12.4.1.2.2 Fuel economy comparison

The percentage improvement of (corrected) fuel economy (FE) of the proposed EMS with vehicle energy estimation using S1 and S2 matrixes to conventional EMS for varied initial SOC is plotted in Figure 12-5.

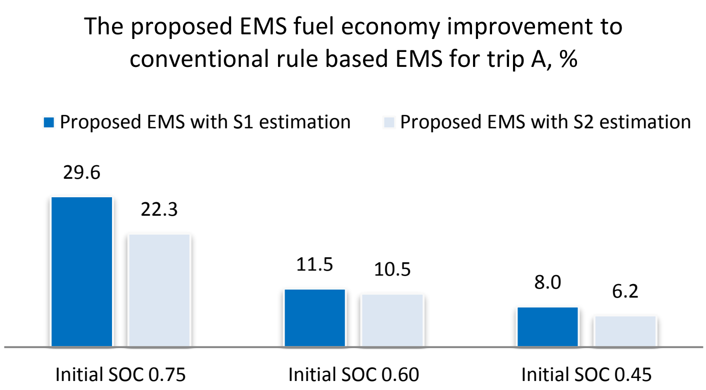

Figure 12-5: The proposed EMS with vehicle trip energy estimation using S1 and S2 specific energy matrix to conventional rule based EMS for trip A with varied initial SOC.

As in the adaptability study in the previous chapter the fuel economy improvement of the proposed EMS to conventional rule based EMS is noticeably higher during higher initial SOC of 0.75. Also as observed and explained in the previous chapters 9 to 11, the reasons are same for the superior fuel economy of the proposed EMS to that of the conventional EMS. The engine operation of the proposed and conventional EMS for trip A when initial SOC is 0.75 with S1 trip energy estimation is shown in Figure 12-6. For the proposed EMS the delta energy determines the duration of the engine operation (as shown in Figure 12-4) with preference to smart charge in the extra urban road type and when the vehicle speed is above threshold (22 m/s) as explained in section 9.4.1.2. Thus the proposed EMS tries to operate the engine at higher vehicle speed to reduce the energy conversion losses as only a minor part of the engine power will be used to charge the battery while pursuing BCD strategy. In other words a major part of the engine power is directly used to drive the vehicle. This was illustrated in section 8.3.6 earlier. In Figure 12-6, for the proposed EMS the engine operation is at higher vehicle speed of about 30 m/s. The conventional EMS has limited control over the engine operation which is determined by instantaneous vehicle speed and battery SOC. In other words due to causal and CD-CS strategy as summarised in section 9.5. In Figure 12-6 the conventional EMS limitations led to the engine operation for the major portion is below the vehicle speed of 30 m/s and reducing up to about 10 m/s. Also the duration of engine operation for the conventional EMS is relatively longer. These two factors lead to a lower energy conversion losses for the proposed EMS to that of conventional EMS which in turn resulted in the fuel economy improvement of 29.6%.

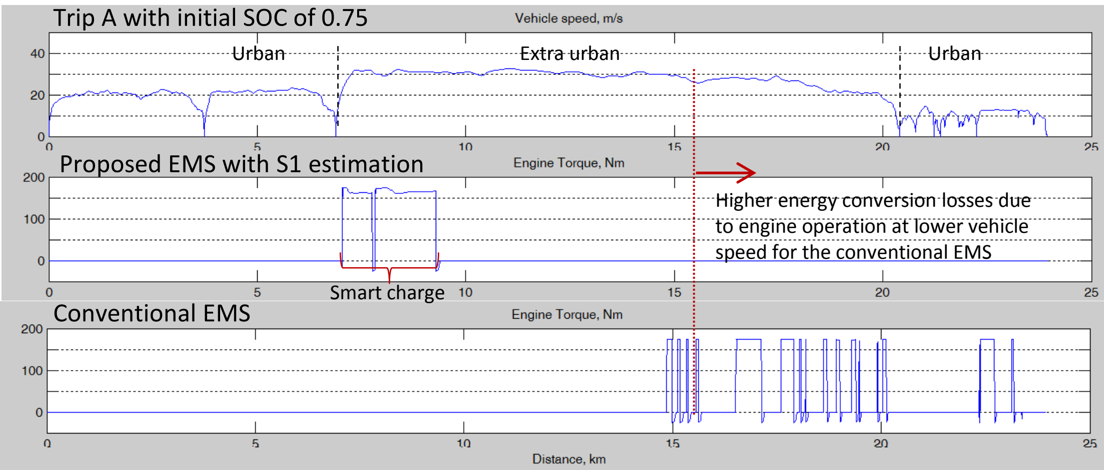

Figure 12-6: The proposed (with S1 estimation) and conventional EMS engine operations for trip A with initial SOC of 0.75

Going back to Figure 12-5, similar to the adaptability study in the previous chapter the difference in fuel economy between the estimated vehicle energy (S1 and S2) is higher for higher initial SOC of 0.75. Likewise influence is less for lower two levels of initial SOC. The fuel economy improvement trend with respect to initial SOC is consistent with that of previous studies; NEDC (chapter 9) and adaptability study (chapter 11).

The fuel economy improvement of the proposed EMS to conventional EMS is better with vehicle trip energy estimation using S1 than S2 for all three initial SOC.

12.4.1.2.3 Number of engine stop - starts

In Figure 12-7, the number of engine stop – starts for the proposed EMS with vehicle energy estimation using S1 and S2 are compared to that of conventional rule based EMS.

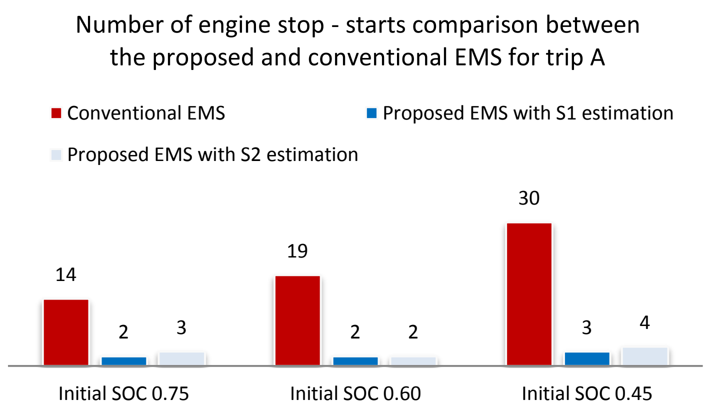

Figure 12-7: Number of engine stop-starts of the proposed EMS with vehicle trip energy estimation using S1 and S2 specific energy matrix and conventional EMS for the trip A is compared.

Between S1 and S2, the proposed EMS number of engine stop - starts are similar for all three initial SOC. Performances of the proposed EMS are superior to conventional EMS for all three initial SOC. The number of engine stop-starts is at gradually increasing trend with lower initial SOC which is in expected line due to increase in deficit trip energy. The numbers are high with conventional EMS due to the CS strategy which does not consider the whole trip demand for engineering the engine operation. Also, the conventional EMS number of engine stop – starts is increasing at higher rate with lower initial SOC.

12.4.1.3 Summary of the vehicle performance over trip A

The fuel economy and number of engine stop - starts are similar or better when the vehicle trip energy estimation is nearer to actual i.e. S1 in comparison to S2. The performance trend of the proposed EMS with vehicle energy estimation is similar to the adaptability study (in chapter 11). Overall results demonstrate robustness of the proposed EMS to variation in vehicle trip energy estimation with superior vehicle performance in comparison to conventional EMS when applied to real world driving conditions.

12.4.1.4 Illustration of the local delta energy operation of the proposed EMS

In the study the initial SOC of 0.45 was deliberately considered to demonstrate local delta energy operation of the proposed EMS. The local delta energy operation was explained earlier in section 8.3.7. The primary and preferred smart charging of the proposed EMS is to smart charge in extra urban road type. This is triggered by delta energy which considers the global trip energy deficit. The secondary smart charge of the proposed EMS is to smart charge in urban road type. This is triggered by the local delta energy which considers the deficit trip energy only for the current urban road type. The secondary smart charge is designed to trigger when there is insufficient available battery energy (above minimum SOC) to wait until the extra urban driving for the battery smart charging. Hence as seen in Figure 12-8, the battery SOC reaches minimum by the end of the first urban road type. However the delta energy which monitors the global or overall deficit trip energy takes into account the deficit energy partially met by the secondary smart charge. In the figure, the delta energy profile is moving towards zero during the secondary smart charge. Later in the journey, the primary smart charge is activated to meet the remaining global or overall deficit trip energy.

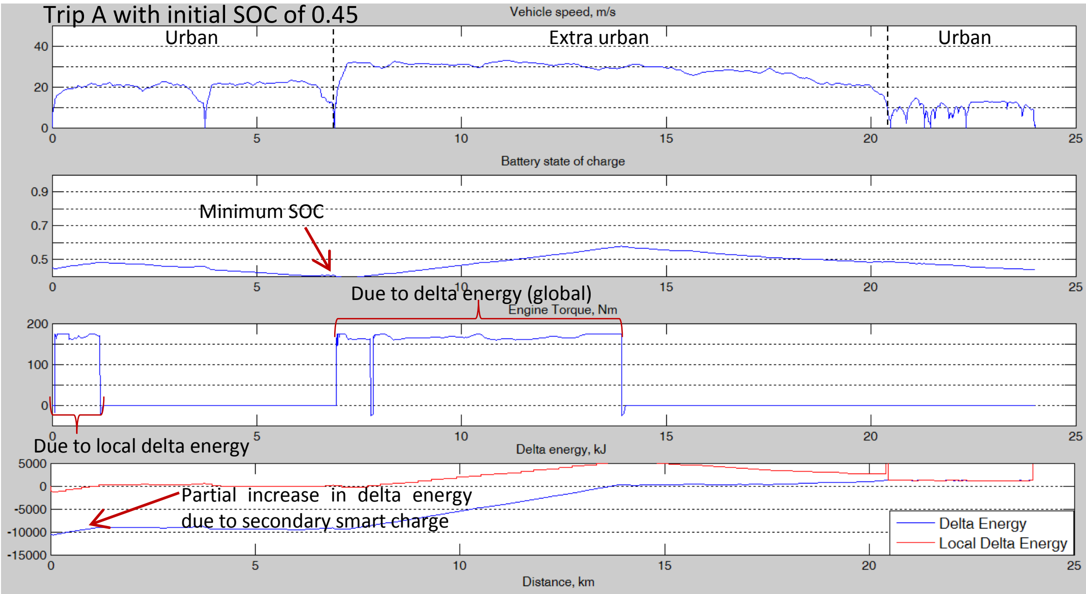

Figure 12-8: Demonstration of the local delta energy operation of the proposed EMS with initial SOC of 0.45 and trip estimation with S1 specific energy matrix over trip A

The local delta energy or secondary smart charge enables the proposed EMS to avoid the SOC reaching the minimum during the urban road type and therefore avoids the base control strategy. This secondary smart charge is included in the proposed EMS design based on learning from performance studies. Thus the proposed EMS adaptability to varied trip conditions is enhanced for improved vehicle performance.

12.4.2 Real world trips with other sequences of road types

Real world trips B, C and D with varied sequences of road types are considered to study with initial SOC of 0.6.

12.4.2.1 Vehicle trip energy estimation for trips B -D

As in previous studies only driving information and specific energy table was used to estimate the vehicle trip energy. The vehicle speed profiles for trips B – D are not part of the vehicle trip energy estimation. For trips B – D the actual speed profiles along with actual vehicle trip energy and estimated trip energy using method 1 (S1) and 2 (S2) specific energy matrix are shown in Figure 12-9 to Figure 12-11.

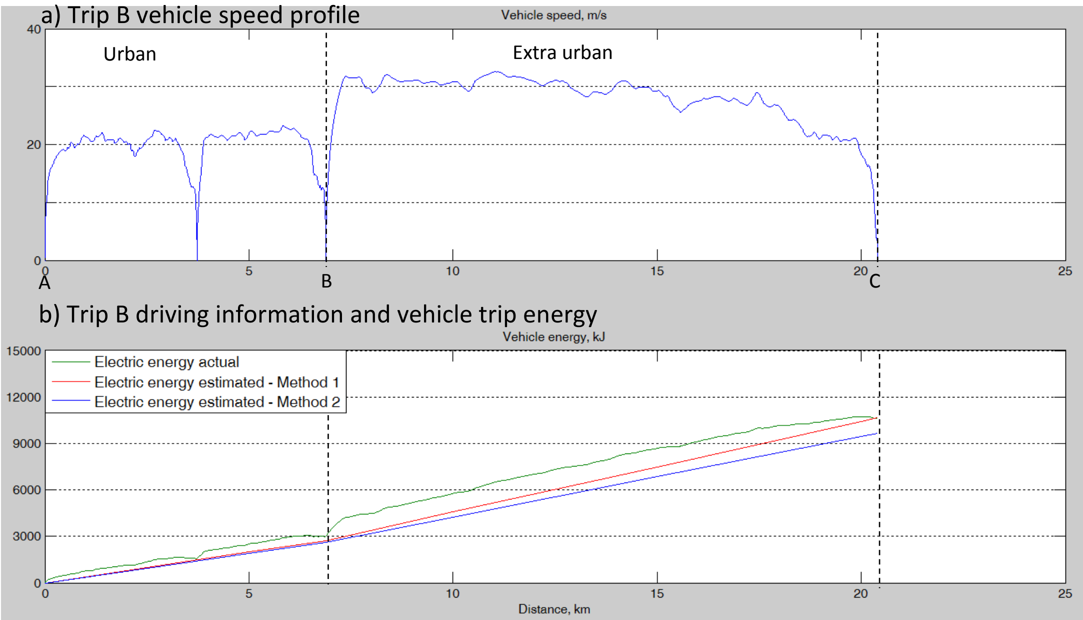

Figure 12-9: Trip B vehicle speed profile along with the actual and estimated vehicle trip energy using method 1 (S1) and 2 (S2) specific energy matrix.

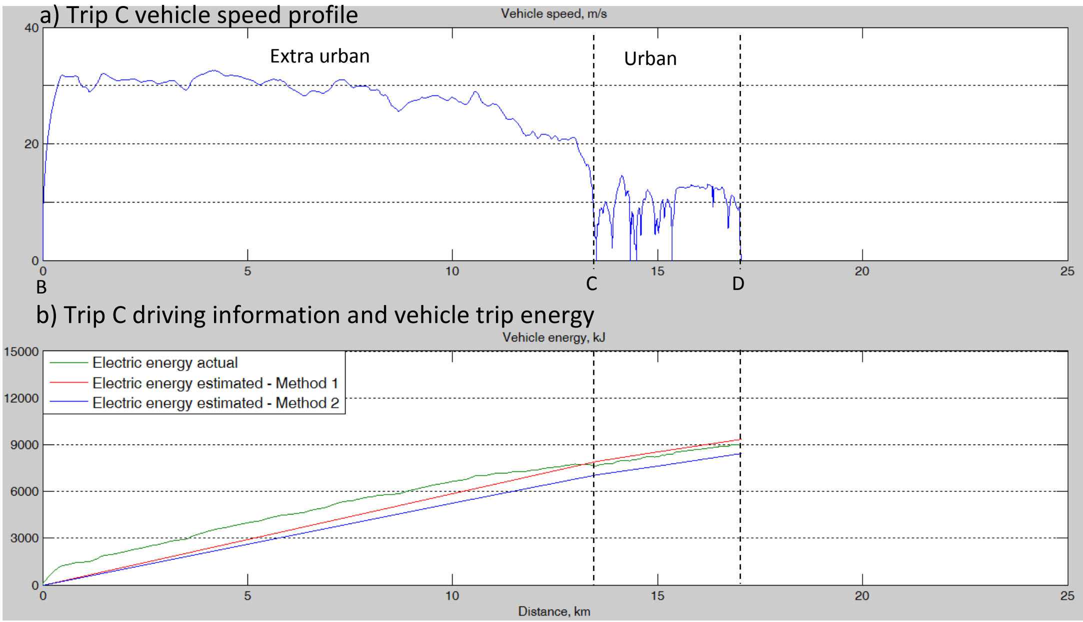

Figure 12-10: Trip C vehicle speed profile along with the actual and estimated vehicle trip energy using method 1 (S1) and 2 (S2) specific energy matrix.

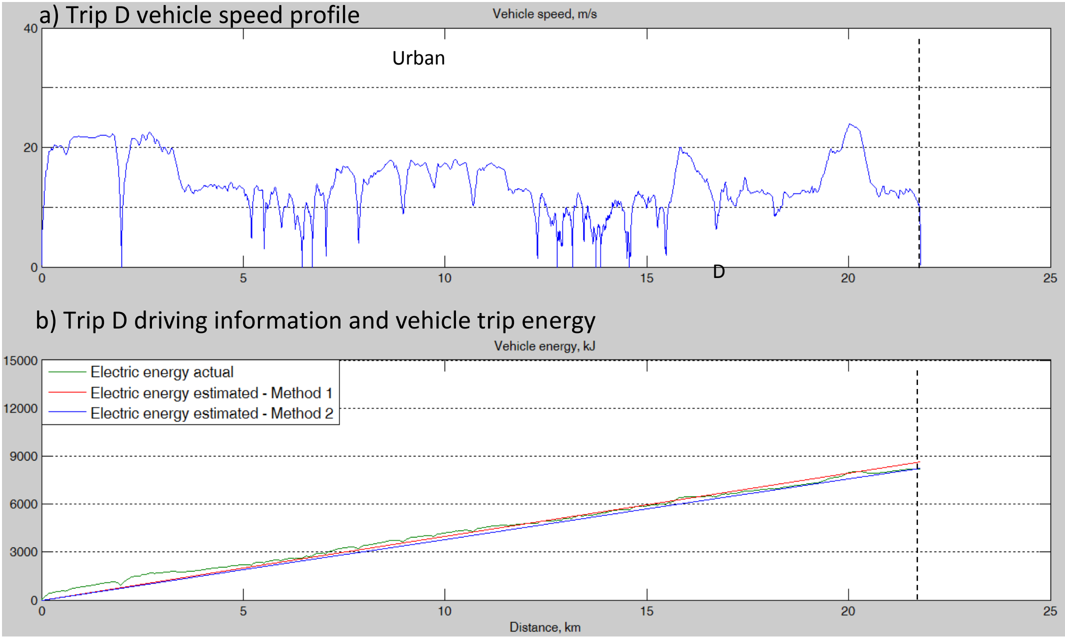

Figure 12-11: Trip D vehicle speed profiles along with the actual and estimated vehicle trip energy using method 1 (S1) and 2 (S2) specific energy matrix.

In trips B – D the vehicle energy estimation is comparatively better in urban road type. This is in agreement with the specific energy values in Table 12-1 (and also Table 11-1). In the table, the urban specific energy values for two different destinations are comparatively close to each other. This indicates the variations are narrower in urban road and hence the estimations are better placed. As in the specific energy values, the variation in estimation are higher for extra urban road type.

In all three trips B – D, the vehicle trip energy estimation using S1 specific energy matrix is similar or higher than the actual vehicle trip energy as shown in Table 12-5. Similarly with S2 estimation is similar or lower than the actual vehicle trip energy.

Table 12-5: Actual and estimation vehicle trip energy comparison for real world trips B - D

Trip name	Actual total vehicle energy, kJ	Vehicle trip energy estimated using S1, kJ	Vehicle trip energy estimation using S2, kJ	Difference in vehicle trip energy estimation using S1 and actual energy, %	Difference in vehicle trip energy estimation using S2 and actual energy, %
Trip B	10597	10668	9678	0.1	-8.7
Trip C	8999	9342	8413	3.8	-6.5
Trip D	8255	8651	8258	4.8	0.0

For trip B, estimation using S1 is almost the same as actual energy. For trip C and D estimation is higher to actual by 3.8 and 4.8% respectively. The vehicle trip energy estimation with S2 is under estimated for trip B and C by 8.7 and 6.5 % respectively. For trip D the actual trip energy is almost the same to the vehicle energy estimation using S2. Vehicle trip energy estimation using both S1 and S2 are close to each other for trip D. This is so, as the specific energy values for urban road types are close to each other (Table 12-2) and the trip D has only urban road type.

12.4.2.2 Vehicle performance study for trips B - D

Vehicle performances for the conventional EMS and the proposed EMS with vehicle energy estimation using method 1 (S1) and 2 (S2) specific energy matrix are shown in Table 12-6 for all three trips B to D.

Table 12-6: Vehicle performance of the proposed and conventional EMS for trips B, C and D with initial SOC of 0.6.

EMS Method and vehicle trip energy estimation	Proposed EMS using specific energy matrix - Method 1 (S1)			Proposed EMS using specific energy matrix - Method 2 (S2)			Conventional rule based EMS		
Trip (Road type sequence)	B (U/E)	C (E/U)	D (U)	B (U/E)	C (E/U)	D (U)	B (U/E)	C (E/U)	D (U)
Final SOC	0.442	0.439	0.418	0.427	0.422	0.418	0.453	0.443	0.451
Actual FE, MPG	114.6	133.0	245	123.6	147.3	238.5	100.6	114.8	171
Corrected FE, MPG	147.9	187.2	305.1	146.6	180.4	293.9	133.3	158.1	273.2
Number of engine stop-starts	2	2	3	2	3	3	19	18	13

Note: U – Urban; E – Extra urban;

12.4.2.2.1 Final SOC comparison

In Table 12-5, the vehicle trip energy estimation using S1 specific energy matrix is over estimated or similar to the actual vehicle trip energy. Similarly vehicle trip energy estimation using S2 specific energy matrix is under estimated or similar to the actual vehicle trip energy. In addition to the vehicle trip energy estimation and local variation to the actual, the regenerative braking towards the end of the trip has major influence on the final SOC.

As discussed with trip A with Figure 12-4, for trip B and C the final SOC of the proposed EMS is higher with S1 estimation due to variation in the actual vehicle trip energy before and after the smart charge. Similarly the final SOC was lower with S2 estimation due to overall under estimation of the vehicle trip energy.

For trip D, the final SOC of the proposed EMS is same for both estimation using S1 and S2. The difference in estimation was narrower for this trip in comparison to other trips.

The final SOC of the conventional EMS for all three trips are higher than the proposed EMS with both estimation methods.

12.4.2.2.2 Fuel economy comparison

The fuel economy of the proposed EMS with both method 1 (S1) and 2 (S2) are superior to conventional EMS (Figure 12-12) for all three varied sequence of road types; trip B, C and D with initial SOC of 0.6.

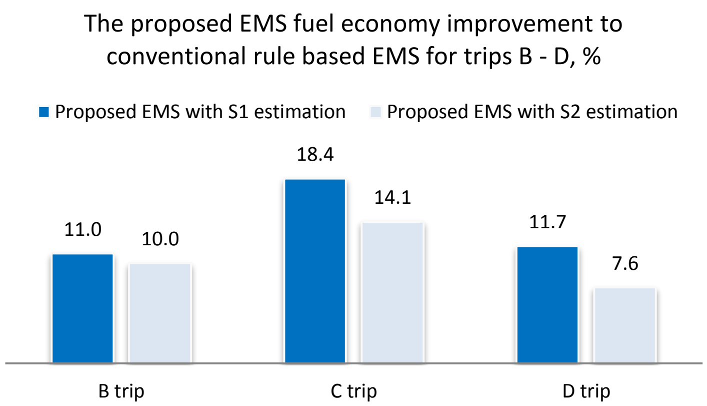

Figure 12-12: Corrected fuel economy improvement in percentage comparison of the conventional EMS and the proposed EMS with S1 and S2 specific energy matrix for A, B and C trips with initial SOC of 0.6.

For trip C, the fuel economy improvement of the proposed EMS is higher in comparison to trip B and D. As the conventional EMS follows CD – CS strategy and has no control over the vehicle efficient engine operation, in trip C, during CS strategy the engine operated at lower vehicle speed during extra urban and urban road type. Due to the engine operation at lower vehicle speed energy conversion losses is higher for the conventional EMS as shown in Figure 12-13. In the proposed EMS, the engine operation is engineered with respect to deficit trip energy and reducing energy conversion losses. Hence in the proposed EMS engine operates in extra urban road type for trip C leading to minimum energy conversion losses. In total this led to maximum difference in energy conversion losses between the proposed and conventional EMS. This in turn results in maximum improvement in the fuel economy of the proposed EMS in comparison to conventional EMS.

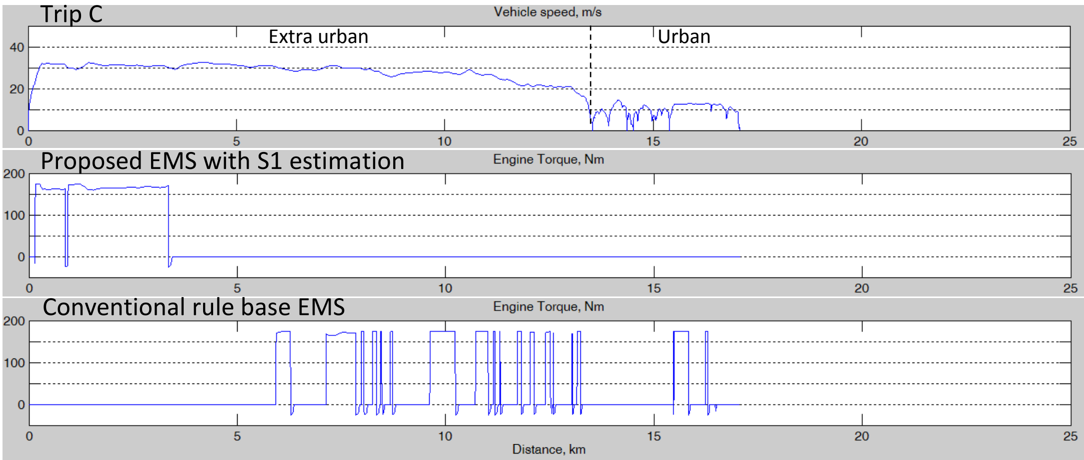

Figure 12-13: Engine operation comparison of the proposed and conventional rule based EMS over trip C

The fuel economy improvement of the proposed EMS to conventional EMS (or BCD to CD-CS strategy) is a function of their difference in energy conversion losses. This is in turn is a function of deficit trip energy and trip demand (or vehicle speed profile).

Now the fuel economy of the proposed EMS between S1 and S2 vehicle energy estimation is compared. Earlier it was observed that the vehicle energy estimation using S1 is similar or overestimated in comparison to actual vehicle trip energy. For that of S2 is similar or under estimated as shown in Table 12-5. Now, in all three trips, the proposed EMS fuel economy with S1 is similar or better than S2 as discussed below.

For trip B, the proposed EMS fuel economy with vehicle trip energy estimation using S1 and S2 are similar as seen in Table 12-6. But for trip C and D the fuel economy with S1 estimation is better than S2.

In trip C, the engine is operated at about 30 m/s for both S1 and S2 estimation as shown in Figure 12-14. In S2 estimation, the engine operated the second time due to under estimation and recovery as part of the adaptability of the proposed EMS. However the engine operation of second time with duration of ‘q’ is similar to earlier at about 30 m/s as shown in the figure. The engine operation duration with S1 estimation after considering the second engine operation duration (q) of S2, is longer than S2 due to higher vehicle energy estimation. This difference in duration led to higher final SOC. Also the vehicle speed during ‘q’ period is not exactly same with S1 which may add to marginal difference in energy conversion losses. The marginal difference in energy conversion losses and higher final SOC may have led to higher corrected fuel economy with S1 estimation.

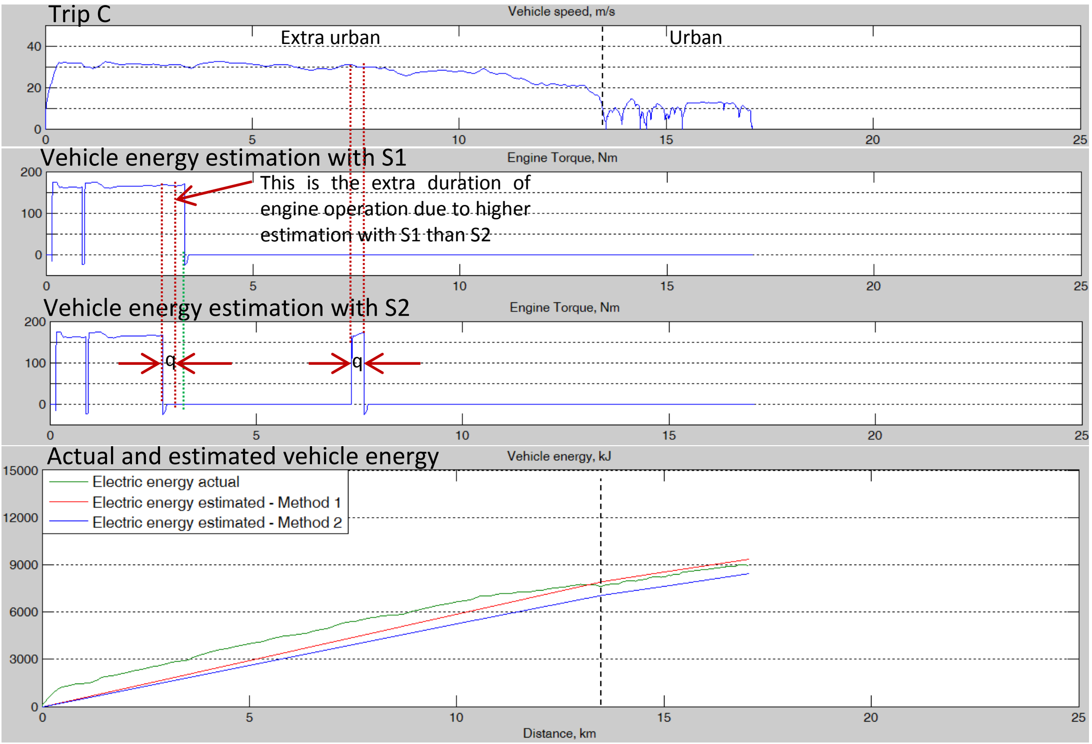

Figure 12-14: Engine operation comparison of the proposed EMS with S1 and S2 estimation for trip C

For trip D, the final SOC was same (0.418) for both vehicle energy estimations. In Figure 12-15, the proposed EMS engine operation with S1 and S2 vehicle energy estimation for trip D is compared. As the trip D has only urban road type, the secondary smart charge is activated for both S1 and S2 estimation. With S2 estimation, the engine operation second time during the trip happened to be at vehicle speed less than 20 m/s (like in trip C during 'q' period). This led to increase in energy conversion losses and hence decrease in fuel economy for vehicle energy estimation with S2 in comparison to S1. This actual trip speed local variation is part of natural variation expected in real world driving and the proposed EMS has no control beyond the binary control (above or below) over the smart charge threshold vehicle speed. In other words this could have happened with S1 also for both trips C and D. The primary (extra urban) and secondary (urban) smart charge threshold vehicle speeds for the proposed EMS are set as 22 and 12 m/s respectively as discussed in section 9.2.2.

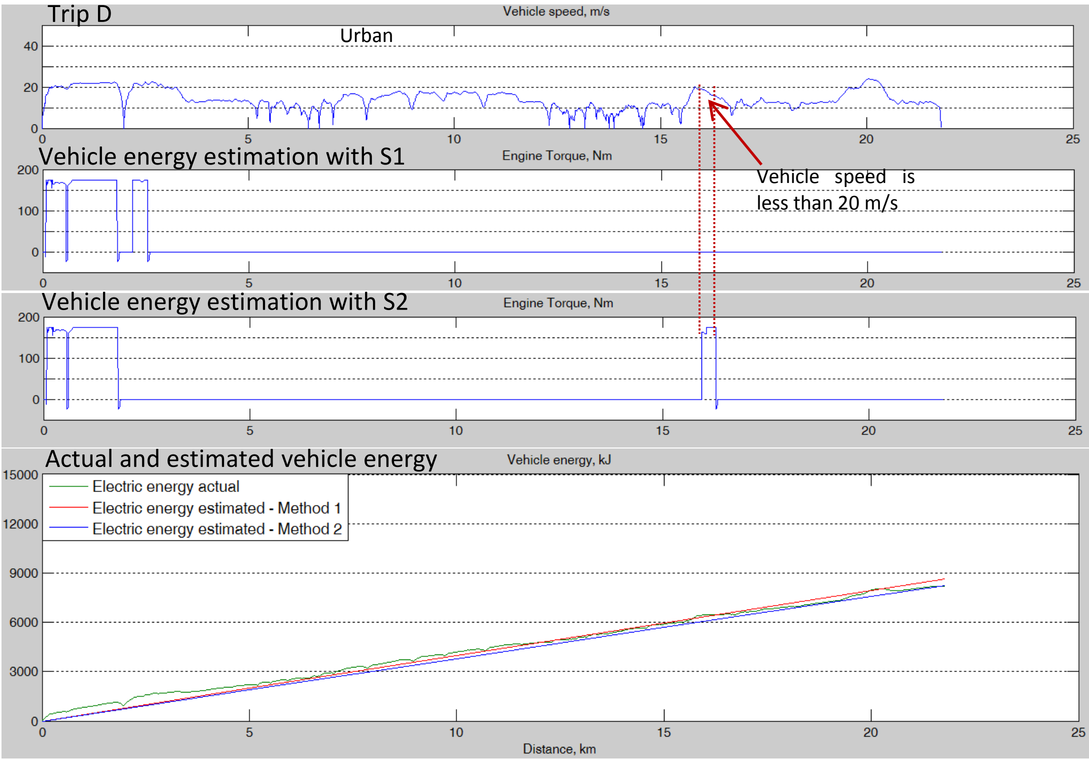

Figure 12-15: Engine operation comparison of the proposed EMS with S1 and S2 estimation for trip D

12.4.2.2.3 Number of engine stop – start comparison

As observed in trip A, the number of engine stop – starts of the proposed EMS are superior to conventional EMS for all real world trips, B, C and D as shown in Figure 12-16. The number of engine stop – starts is similar for the proposed EMS between S1 and S2 vehicle trip energy estimation across trips B – D.

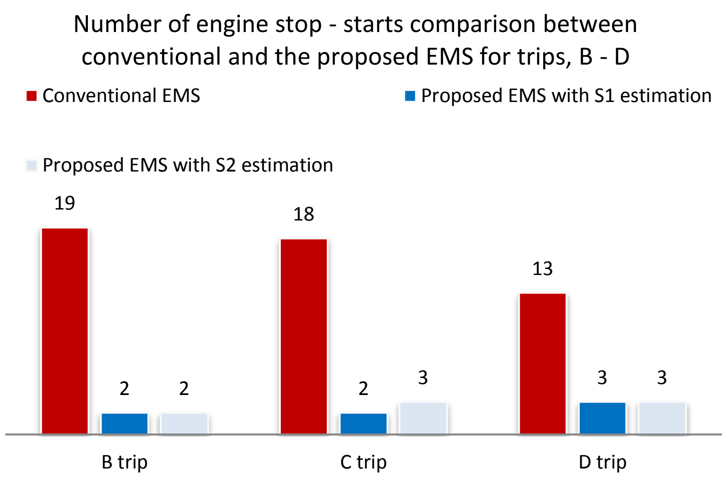

Figure 12-16: Number of engine stop-stats comparison of the conventional and the proposed EMS with method 1 (S1) and 2 (S2) specific energy matrix for trips B, C and D.

12.4.2.3 Summary

The proposed EMS along with vehicle energy estimation matrix has been validated for four real world destinations of varied sequence of road types and trip distance. Vehicle performance of the proposed EMS with vehicle energy estimation using S1 and S2 specific energy matrix, the fuel economy improvement to conventional EMS is up to 29.6 % with 7 times fewer number of engine stop – starts.

12.5 Analysis of effect of specific energy matrix S1 and S2 on vehicle performance

All four real world trips A to D are analysed for vehicle energy estimation and performance to study the effect of specific energy matrix S1 and S2.

12.5.1 Vehicle energy estimation comparison between S1 and S2

Vehicle energy estimation for all four real world trips (A to D) is similar or overestimated (0.1 to 4.8%) with S1 specific energy matrix in comparison to the actual vehicle energy as seen in Table 12-5. For that of S2, the estimated vehicle energy is similar or underestimated

(0 to 8.7%) in comparison to actual. However the difference in estimation to actual with S1 specific energy matrix is narrower across the trips. With S2 specific energy matrix the difference in estimation to actual is almost double.

12.5.2 Vehicle performance comparison between S1 and S2

Vehicle performances of the proposed EMS with vehicle trip energy estimation using S1 and S2 specific energy matrix are analysed for the final SOC, fuel economy and number of engine stop – starts for four real world trips in previous section 12.4. Overall, the vehicle performance of the proposed EMS with vehicle energy estimation using S1 is similar or better than S2.

12.5.3 Summary on specific energy matrix

Vehicle energy estimation is closer to actual vehicle energy with S1 specific energy matrix for four real world destinations (Trips A – D) and vehicle performance of the proposed EMS with vehicle energy estimation using specific energy matrix S1 is similar or better than S2. Hence S1 specific energy matrix method is recommended.

12.6 Implication of the validation study

The proposed EMS performance has been validated for four real world trips of varied sequence of road types and trip distance along with varied initial SOC. The most unique features of this validation is unlike in other acausal EMS studies from literature (Chan-Chiao et al., 2004, Qiuming et al., 2007, Kessels, 2007, Dean et al., 2008, Johannesson, 2009, Qiuming and Yaoyu, 2009, Cairano et al., 2013):

- No prior knowledge of the trip vehicle speed profile is required
- Validated for multiple real world destinations with varied driving conditions such as sequence of road type, trip distance and initial SOC.

Also in almost all acausal EMS studies the predicted trip demand is considered 100% accurate. Only in (Qiuming and Yaoyu, 2009) study, the prediction is validated for a real world trip data by comparing the vehicle performance.

The proposed EMS method can be used for any trip without the prior knowledge of trip demand. The vehicle trip demand is estimated for the proposed EMS using known driving information (such as road type, distance and driver for a given vehicle) and specific energy matrix. Another aspect is only about 62 km of real world driving data for a given vehicle and driver was used at determining the specific energy matrix (Table 12-1). In the literature, destination specific prior knowledge of trip demand is required which becomes data intensive. In real world driving, the proposed EMS vehicle performance is expected better than conventional EMS due to better engine control (reducing energy conversion losses) and adaptability to the uncertain trip demand and to varied driving scenarios.

12.7 Analysis of fuel economy improvement with respect to the trip demand

The purpose of this section is to understand the factors influencing improvement in the fuel economy for the BCD strategy over the CD-CS strategy in real world driving trips for varied trip demand. The proposed EMS which are designed to work on the BCD strategy and the conventional EMS on CD-CS strategy are compared. For this analysis all four real world validation trips results with initial SOC of 0.6 are considered. Also for the proposed EMS performance with the vehicle energy estimation using S1 specific energy matrix are considered.

12.7.1 Background

Earlier in chapter 9 it was observed that the fuel economy improvement of the proposed EMS with the BCD over the conventional EMS with the CD-CS strategy increases with the trip distance. In the study the NEDC was considered multiple times to vary the trip distance.

Considering a legislative driving cycle multiple times and the fuel economy improvement with the trip distance observation was in concurrence to a similar study in the literature (He et al., 2012a). In such studies after the initial CD strategy, energy conversion losses were periodic as the driving cycle was considered multiple times. Therefore the difference in energy conversion losses and hence the fuel economy of the BCD to CD-CS strategy is improving with the trip distance. In the following sections, four real world validation studies are analysed to investigate whether the fuel economy improvement between the BCD and CD-CS strategy increases with the trip distance in real world driving and are there any other factors influencing the fuel economy improvement.

12.7.2 Analysis of real world validation studies

The fuel economy improvement in percentage of the proposed EMS over the conventional EMS for all four validation trips with initial SOC of 0.6 are plotted in Figure 12-17. In the real world study the fuel economy improvement is not increasing with the trip distance. This indicates that the trip distance is not the only factor for fuel economy improvement between the strategies.

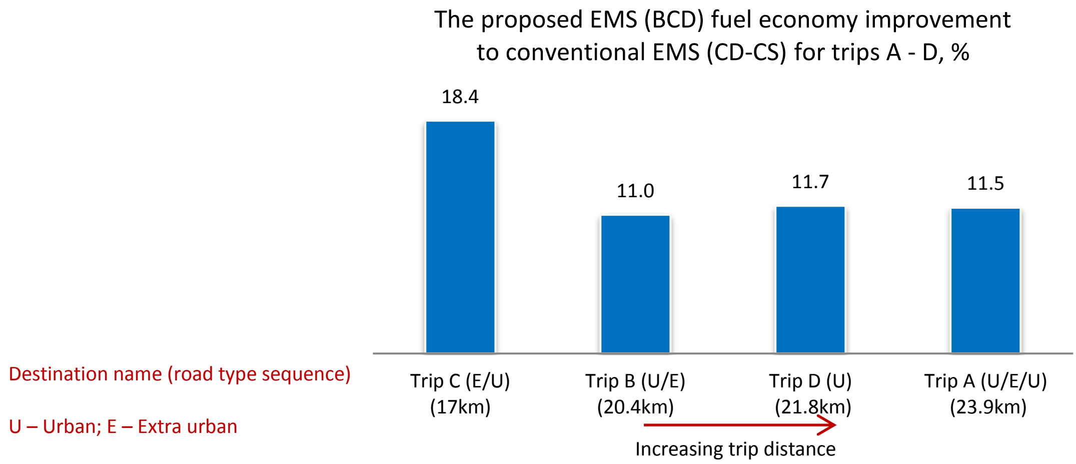

Figure 12-17: The fuel economy improvement in percentage of the proposed EMS (BCD) to conventional EMS (CD-CS) for varied real world trips distance with initial SOC is 0.6

Energy conversion losses vary with the engine operation and vehicle speed (trip demand) as discussed earlier in section 8.3.5. Hence it is not possible to quantify energy conversion losses, especially with the BCD strategy. In the BCD strategy, the engine is operated even before SOC reaches the minimum. Therefore it is not possible to distinguish which part of the battery energy is from the external electric grid and engine smart charge was used to meet the vehicle trip demand. An attempt has been made to explain and analyse factors influencing the fuel economy based on the engine operation and trip demand of all four validation trips.

12.7.2.1 Deficit trip energy

The total trip demand or the actual vehicle energy for four trips is as shown in Table 12-7.

Table 12-7: Actual vehicle trip demand for four real world trips

Trip name	Actual total vehicle energy, kJ
Trip A	11943
Trip B	10597
Trip C	8999
Trip D	8255

The actual trip vehicle energy is highest for trip A and is decreasing with subsequent trips, B, C and D in that order. For a given initial SOC of 0.6 which is in deficit, the deficit trip energy becomes highest for trip A and is decreasing with subsequent trips B, C and D in that order. The deficit trip energy typically decides the duration of engine operation for both the proposed (BCD) and conventional (CD-CS) EMS. Hence typically higher the deficit trip energy, higher the duration of engine operation which in turn decreases the fuel economy for a given trip.

The vehicle speed profiles of four validation trips and the engine operation of the proposed and conventional EMS with initial SOC of 0.6 are shown in Figure 12-18 and Figure 12-19. In these figures it can observed that the duration of engine operation is highest for trip A and lowest for trip D for a given EMS. This trend is same for both the proposed and conventional EMS. In addition to the duration of engine operation other factor effecting fuel economy is energy conversion losses discussed in the next section.

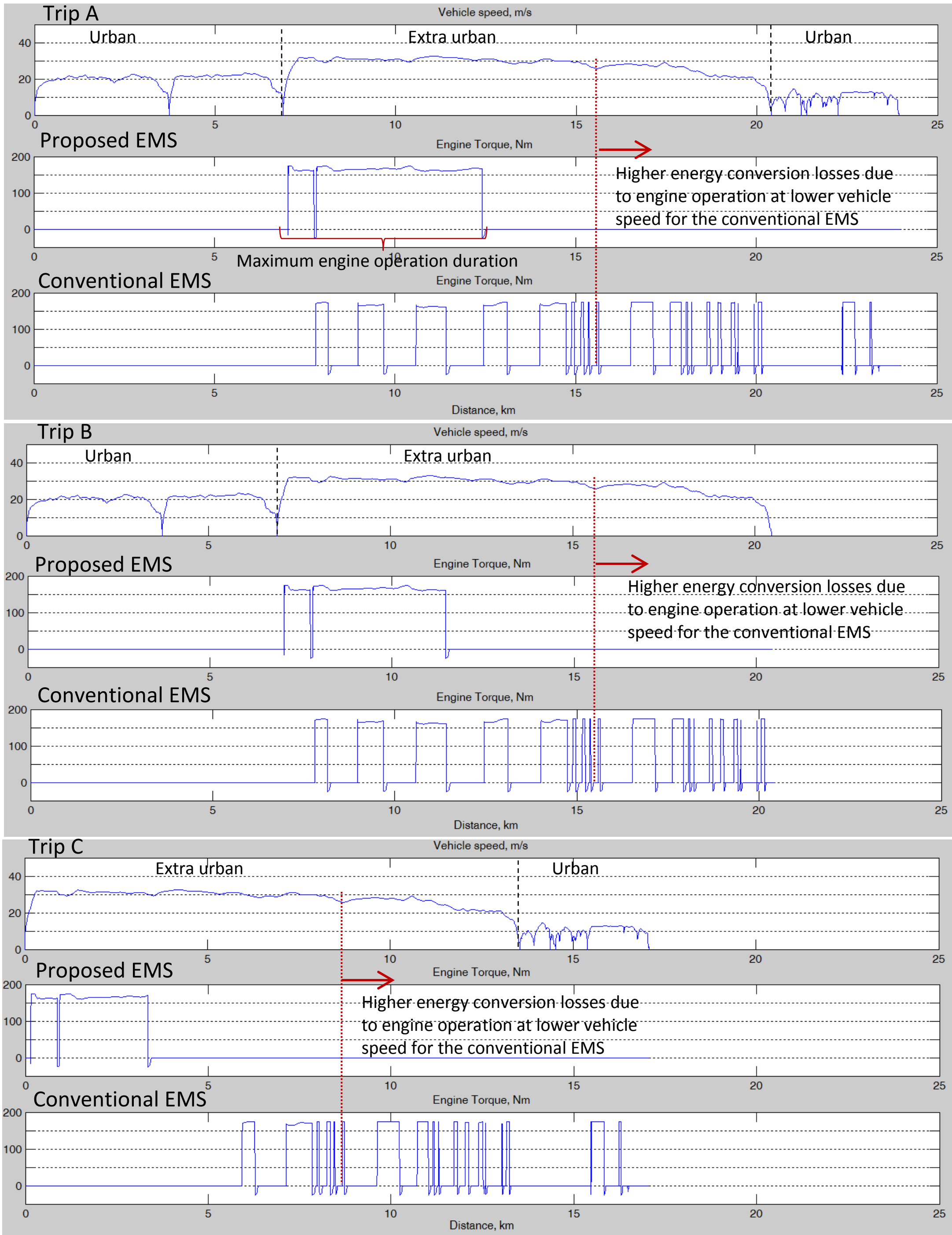

Figure 12-18: Engine performance of the proposed and conventional EMS for trips A to C with initial SOC of 0.6

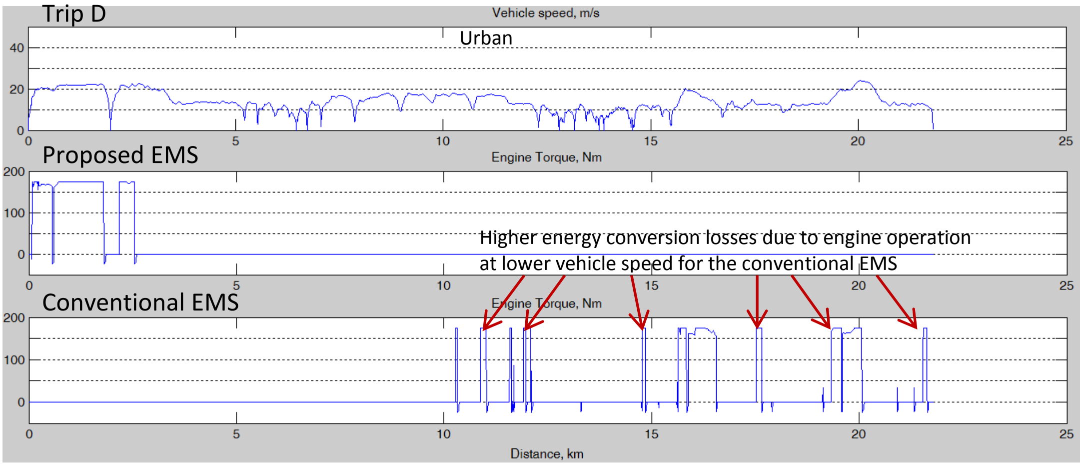

Figure 12-19: Engine performance of the proposed and conventional EMS for trip D with initial SOC of 0.6

12.7.2.2 Sequence of road types (vehicle speed profile)

The engine operation duration with respect to the deficit trip energy was discussed in the previous section. In addition, the energy conversion losses become an important factor for the EMS fuel economy improvement. The higher the vehicle speed (or instantaneous trip demand) when the engine is ON, lower the energy conversion losses as discussed in chapter 8.

The proposed EMS, which works on the BCD strategy, controls the engine operation over the given trip such that energy conversion losses are reduced. The conventional EMS which works on the CD – CS strategy use initially the electric vehicle (EV) mode followed by the engine operation in the CS strategy. This is followed irrespective of the trip demand. Hence the conventional EMS has no control over the engine operation with respect to energy conversion losses.

Therefore during the deficit trip energy condition, and if the trip vehicle speed profile is lower or road type is urban towards the latter part of the trip, then energy conversion losses will be higher for the conventional EMS. Whereas the proposed EMS picks the smart charge in extra urban as the preferred mode to reduce energy conversion losses as observed in Figure 12-18 for trip A to C. In the case of conventional EMS the engine is ON pursuing CS strategy which led to increase in energy conversion losses due to operation at lower vehicle speed. The longer the engine operates at lower vehicle speed, higher the energy conversion losses.

In trip D which has only urban road type as shown in Figure 12-19, it just happened that the vehicle speeds are higher when engine operated for the proposed EMS is higher than that of conventional EMS. Hence energy conversion losses are higher for the conventional EMS.

Out of four real world trips, the difference in energy conversion losses due to the engine operation at lower vehicle speed between the proposed and conventional EMS is higher for trip A and C than other two trips. This is due to the longer duration of engine operation in the conventional EMS at vehicle speed less than 20 m/s as shown in Figure 12-18 for trip A and C. Energy conversion losses are similar for trip A and C as the latter part of the trip is the same with lower vehicle speed profile. However between trip A and C, the trip deficit and hence the duration of engine operation is lower in trip C than trip A. These two factors together led to maximum difference in the fuel economy between the proposed and conventional EMS for trip C. For the other three trips (A, B and D), the combination of these two factors happens to be similar. Hence the fuel economy improvement of the proposed EMS to conventional EMS for these three remaining trips is similar as shown in Figure 12-17.

12.7.3 Summary

Overall in any trip, the improvement of fuel economy of the BCD (the proposed EMS) over CD-CS (conventional EMS) strategy depends on:

- Trip deficit energy which defines the duration of engine operation. Trip deficit energy is in turn is a function of the total trip demand and available battery energy

- The fuel economy improvement will be higher if the latter part of the trip vehicle speed profile is lower or road type is urban. That improvement is a function of the trip vehicle speed profile.

Hence fuel economy improvement need not improve with the trip distance like in the NEDC study in chapter 9.

12.8 Conclusion

- Unlike existing acausal EMS methods, no prior knowledge of trip vehicle speed profile is required for the proposed EMS. The proposed EMS method has been validated (demonstrated the working) for four real world destinations with uncertain (or unknown) trip demand of varied sequence of road types and trip distance along with varied initial battery state of charge (SOC). The vehicle trip demand is estimated for the proposed EMS using known trip driving information and specific energy matrix.
- Other distinct to existing acausal EMS method is the proposed EMS superior performance was demonstrated for multiple real world destinations with varied trip conditions. In the validation study the proposed EMS fuel economy improvement to conventional rule based EMS is up to 29.6 % with 7 times fewer number of engine stop – starts.
- Validation study demonstrates overall robustness of the proposed EMS to the uncertain trip demand and for varied driving conditions to deliver effective vehicle performance.
- Based on the proposed EMS vehicle performance both specific energy matrixes, S1 (highest observed) and S2 (distance weighted) used for vehicle energy estimation are validated. Vehicle energy estimation with S1 is closer to the actual vehicle trip energy for all four real world destinations. Vehicle performance of the proposed

EMS with vehicle energy estimation using specific energy matrix S1 is similar or better than S2. Hence S1 specific energy matrix method is recommended.

- The proposed EMS vehicle performance is superior to conventional EMS with both S1 and S2 estimation for all four destinations. This reiterates again that for the proposed EMS the vehicle trip demand estimation need not be exact.
- The fuel economy improvement of the blended charge depleting (BCD) strategy to charge depleting – charge sustaining (CD-CS) strategy depends on the deficit trip energy and trip vehicle speed profile (or the sequence of road types).

Overall, the proposed EMS is validated for real world driving and demonstrated robustness to the uncertain trip demand and varied driving scenarios with superior vehicle performance.

Chapter 13 – Discussion and Future Work

13.1 Introduction

The proposed blended rule based EMS design for PHEV is a real world applicable acausal EMS. The proposed EMS brings the desired features of both conventional rule based and optimisation based EMS along with its own advantages. Also the proposed EMS evaluation studies are unique in many ways such as mimicking the uncertain trip demand and varied driving scenarios considered as in real world driving. This chapter discuss the significance of the proposed EMS design and evaluation for real world driving and with respect to existing or conventional EMS methods. Followed by in the suggested future work logical and natural extensions of work are discussed.

In the first part of discussion, the proposed EMS design features, formulation and strategy are compared with that of conventional EMS methods, conventional rule based and optimisation based methods. In the second part, the proposed EMS evaluation such as real time capability, adaptability, vehicle performance and validation as in real world driving is discussed. In the final part, end with a suggested future work.

13.2 Significance of the proposed EMS design

There are many methods and techniques considered in literature for hybrid vehicle EMS. However these EMS structure and strategy can be classified into two: Rule based and optimisation based EMS. Irrespective of different methods and techniques applied to these EMS, their fundamental formulation, structure, control strategy and more importantly their limitations remains the same as discussed with respect to the proposed EMS in the following sections.

13.2.1 Rule based acausal EMS

In practice, to design an EMS with blended charge depleting (BCD) strategy, the EMS has to be acausal to know the future vehicle trip demand (Stockar et al., 2011). Hence BCD strategy is used with optimisation based EMS such as Dynamic programming (DP) (Qiuming et al., 2008, Lars et al., 2007) or Equivalent consumption minimisation strategy (ECMS) (He et al., 2012b) in literature. But optimisation based EMS are not suitable for real world application as they are not real time capable (Sciarretta and Guzzella, 2007, Koprubasi, 2008, Çagatay Bayindir et al., 2011) and requires prior knowledge of vehicle speed profile which has limitations in real world driving due to the uncertain and dynamic conditions.

A causal system does not consider the future trip demand. Conventional rule based EMS are causal systems and hence works on the charge depleting - charge sustaining (CD-CS) strategy. However conventional rule based EMS are real time capable (Çagatay Bayindir et al., 2011) and hence often used in industry (Stockar et al., 2011, Serrao, 2009). EMS being causal and pursuing CD-CS strategy both limit the potential benefits of PHEVs.

The proposed EMS is a blended rule based and acausal EMS. This is the *first time a rule based and acausal EMS* has been designed. Also the proposed EMS works on BCD strategy.

13.2.2 EMS formulated over vehicle trip energy

This section explains the basic difference in considering the vehicle trip demand in the formulation of conventional and the proposed EMS.

13.2.2.1 Conventional EMS methods

Existing EMS methods are framed with respect to vehicle speed profile (Figure 13-1/a) as discussed in the EMS review chapter 4. Vehicle speed profile represents the future trip demand. For an acausal EMS the fuel economy depends on the accuracy of the vehicle speed profile prediction (Serrao et al., 2011). For causal EMS the fuel economy depends on the similarity of the set of legislative driving cycle trip demand considered in the formulation, to the actual trip demand.

In real world driving, the trip demand is uncertain and dynamic. Vehicle speed being an exact demand becomes highly dynamic in real world driving. Hence prediction of exact vehicle speed profile in real world driving is not possible (Guzzella and Sciarretta, 2007). Also prior knowledge of vehicle speed profile specific to the destination is required to make any prediction as discussed in section 3.4.3.4. This limits the use of existing EMS to conditions where prior knowledge of vehicle speed profile is known in advance and predictions are accurate. Further such vehicle speed profile prediction becomes data intensive as discussed in trip modelling in chapter 3 and observed in chapter 5.

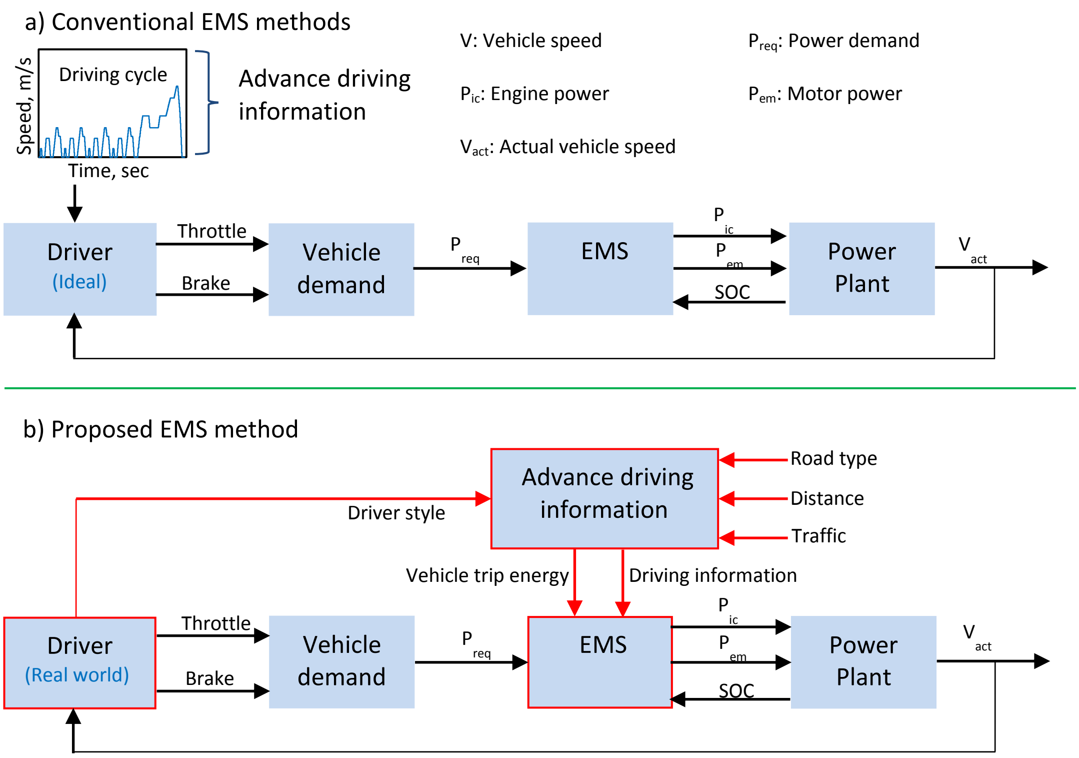

Figure 13-1: A schematic comparison of the existing and proposed EMS formulation

13.2.2.2 Proposed EMS method

The proposed EMS is formulated over vehicle trip energy and driving information as shown in Figure 13-1/b. This is the first time hybrid vehicle EMS is formulated over vehicle trip energy. Driving information that can be considered are driver style, route distance and road types like urban and extra urban with traffic as a sub function.

The limitation of vehicle speed profile and convenience of vehicle trip energy was discussed in preliminary study in chapter 5. This is summarised with Figure 13-2. Real world repetitive driving data (from WMG, Sustainable Action on Vehicle Energy (SAVE) project), for a given driver, route, vehicle and at similar journey starting times of the weekdays and its corresponding actual vehicle trip energy is shown. In the figure, the legend H2W refers to Home to Work and the number followed refers to the journey start time. The start time of the journey varied only from 7.10, 7.14, 7.26 and 7.33 AM.

In Figure 13-2 vehicle speed is dynamic. Vehicle trip energy is less dynamic and change is gradual for wide variation in vehicle speed (or external load). This is due to high electric power train efficiency over wide operating range (Katrašnik, 2011). Hence trip demand when considered in terms of vehicle energy represents a range of loads. Also the total vehicle trip demand can be quantified into a tentative value. This is the key in making *the rule based EMS, acausal and adaptive.*

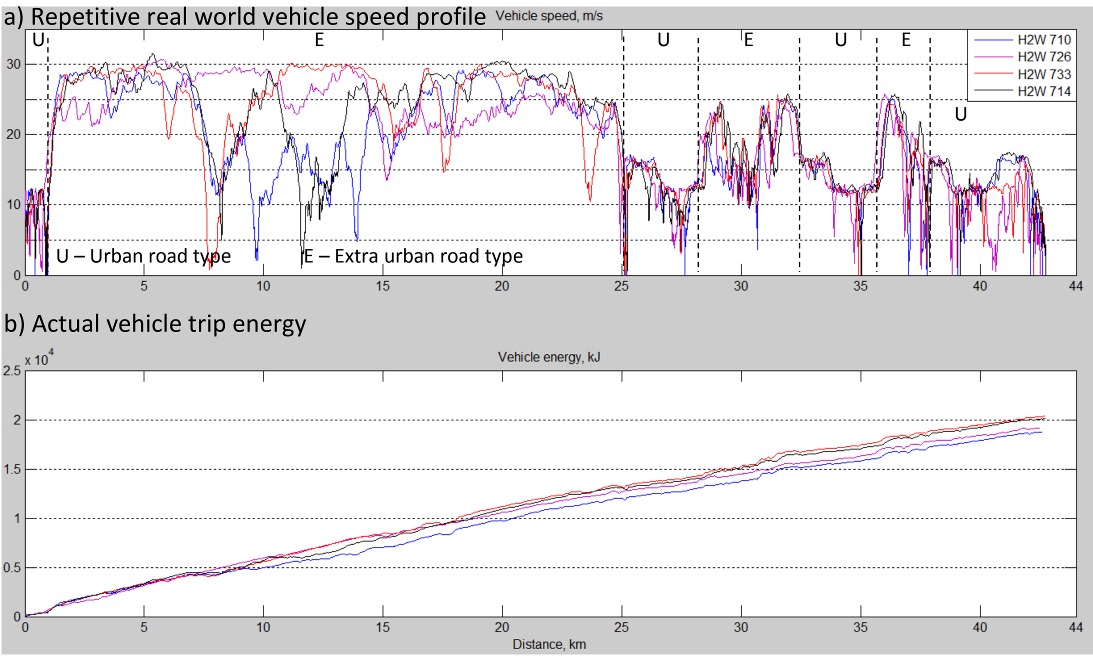

Figure 13-2: The difference between vehicle speed profile and vehicle trip energy in real world driving

For the proposed EMS, real world trip demand is estimated using known driving information of the destination planned and specific energy matrix as discussed in section 7.2.3. Effect of various driving information such as road types, driver style and traffic can be considered through a common parameter, specific energy. Specific energy is the average electric energy required per kilometre. The almost linear relation of the vehicle trip energy to trip distance (as seen in Figure 13-2) is leveraged in the linear estimation of the vehicle trip energy. The specific energy matrix can be determined with limited real world data for the respective driver and road type (In the validation study only 62 km of data was used). Unlike in prediction of vehicle speed profile, no prior knowledge of trip vehicle speed profile is required as demonstrated in the validation study in chapter 12.

13.2.3 Devising control strategy

This section explains the difference in devising control strategy based on the trip demand considered to define the operations of hybrid powertrain for conventional and proposed EMS methods.

13.2.3.1 Conventional EMS methods

Conventional rule based and optimisation based EMS are discussed in this section.

13.2.3.1.1 Conventional rule based EMS

Conventional rule based EMS considers only the instantaneous vehicle demand and battery state of charge (SOC) in determining the power train operation within the system parameters and constraints as shown in Figure 13-3.

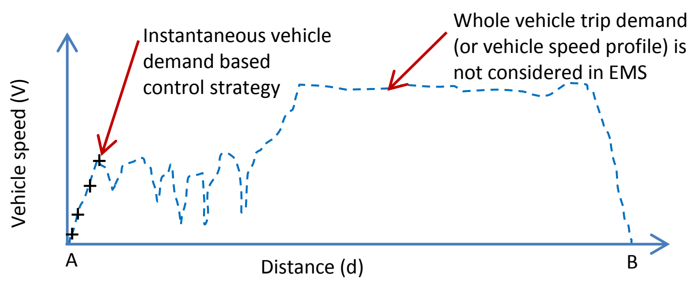

Figure 13-3: A schematic of conventional rule based EMS formulation

Rule based EMS being causal does not consider the whole trip demand in devising control strategy as shown in the figure.

13.2.3.1.2 Optimisation based EMS

In optimisation based EMS (example, DP and ECMS), a series of optimal power split ratio between the engine and electric machine for a given trip vehicle speed profile is determined. Hence both the electric machine and engine operation is predefined specific to each trip vehicle speed profile as shown in Figure 13-4. Therefore for every change in vehicle speed profile, initial SOC and for each destination a new set of power split ratios has to be determined. Also, the optimisation based EMS does not retain any learning about the efficient power train use from the previous optimisations. Both limitations makes EMS data intensive, computationally demanding and optimisation specific to a vehicle speed profile.

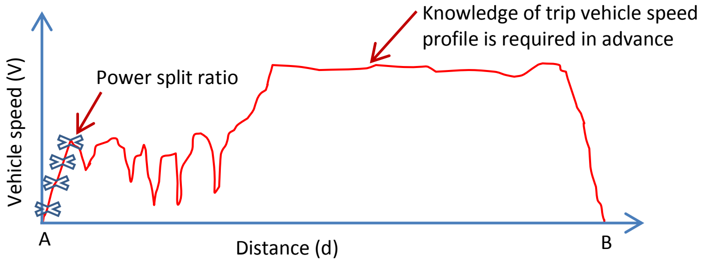

Figure 13-4: A schematic of optimisation based EMS formulation

Also, in general, optimal performance under uncertain trip demand condition is not possible. Optimal performance can be achieved only when the exact trip demand is known in advance. Hence optimal EMS performance is not possible in real world driving by design. However from optimal EMS study knowledge gained can be considered in the design of EMS for efficient performance. It can be used to learn about a generic trend in operating the power train efficiently to implement in real time EMS.

13.2.3.2 Proposed EMS

The Proposed EMS does not guarantee optimum results. However it offers to maximise performance for varied and uncertain driving conditions in real time. The proposed EMS for efficient vehicle performance relies on reducing energy conversion losses when the engine operation is required to meet the deficit battery energy. Due to the higher electric power train efficiency in hybrid vehicle, the motor operation is not controlled for vehicle efficiency. Only the battery energy is monitored with respect to the estimated vehicle trip energy (trip demand) through the system parameter, delta energy. Delta energy is the difference between the available battery energy and estimated vehicle trip energy which is critical in devising control strategy as discussed in section 7.2.4. Vehicle trip energy estimation considers only the electric or battery energy required. To meet the deficit trip energy (Delta energy negative), the engine is operated at pre-determined operating conditions – optimal operating line (OOL) under prioritised road types to reduce energy conversion losses as explained below.

When it comes to hybrid vehicles, operating the engine in efficient regions alone does not guarantee the minimum fuel consumption (Chen et al., 2010) as demonstrated in chapter 8. This is due to energy conversion losses associated with converting mechanical power from the engine to electric power and then again to mechanical power to drive the vehicle (Freyermuth et al., 2007). To identify the vehicle efficient engine use for hybrids, six modes of engine operation over road types – urban and extra urban driving, were studied in chapter 8. It was concluded that the most vehicle efficient and viable mode was the engine operation at OOL in extra urban followed by OOL in urban road type. In the proposed EMS the engine operation at OOL in extra urban and urban road type are used as primary (and preferred) and secondary smart charge respectively. Before this, there was no literature on the efficient engine use for hybrid vehicles to suitably define over driving parameters such as road types.

In the proposed EMS, the vehicle trip energy estimated is considered along with driving information such as road type, road type sequence and distance in devising control strategy as shown in Figure 13-5. When the available battery energy is in surplus (delta energy is positive - Green line in the figure) only the electric vehicle (EV) mode is used. If the available battery energy is in deficit (delta energy is negative – brown line in the figure) the engine is operated in the extra urban part as the preferred and primary smart charge. The delta energy value determines the duration of engine operation. The elevation in delta energy profile (Brown) in the extra urban road type towards zero is due to the primary smart charge. Thus the engine is able to partly able to directly drive the vehicle and meet the deficit. Also the engine is partly able to transfer the excess power produced to the battery. Both these action led to decrease in the deficit trip energy. When the engine is OFF, the EV mode is in operation which is the default mode.

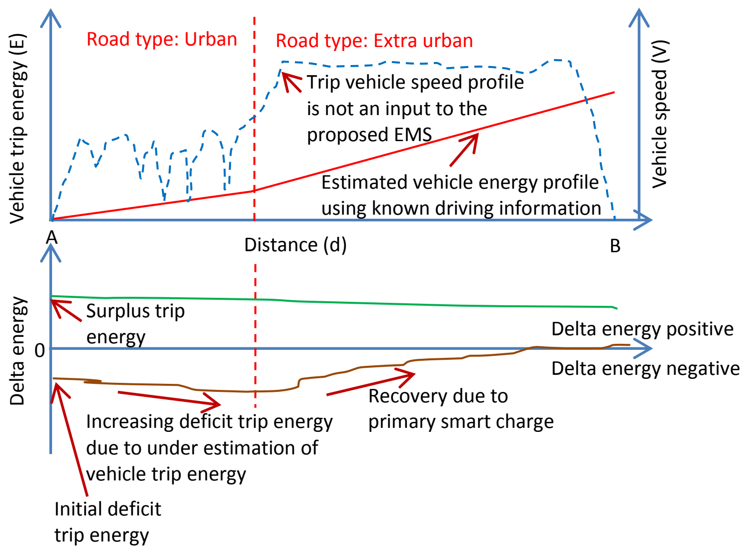

Figure 13-5: A schematic of the proposed EMS

For the proposed EMS the trip vehicle speed profile is not an input. Driving information such as sequence of road type and distance and the estimated vehicle trip energy are input to the proposed EMS. Other inputs are instantaneous vehicle speed and battery SOC as in any conventional EMS. In other words, the proposed EMS considers the total trip demand

and sequence of trip demand in terms of road types in devising the control strategy. In comparison to optimisation based EMS which determines a grid of power split ratio for a given vehicle speed profile and initial SOC, the proposed EMS considers trip demand and devising of control strategy at macro level in terms of sequence of road types.

Again in contrast to the optimisation based EMS, in the proposed EMS once identified efficient powertrain conditions are adapted to a varied driving conditions such as varied sequence of road types, distance and initial SOC, instead of identifying power train efficient conditions each time to a specific condition. In other words, in the proposed EMS, based on driving information of each trip, identified efficient powertrain conditions (such as primary and secondary smart charge) are adapted in devising controls strategy. Also strictly speaking only the engine operation is controlled for vehicle efficient performance and not both the electric machine and engine as in the optimisation based EMS. These two features simplify the proposed EMS structure, making it more adaptive to varied driving conditions under uncertain trip demand and also reduce computational time as discussed in the next section.

13.2.4 Adaptability to varied and uncertain real world driving condition

For causal EMS, real time capability alone is sufficient for real world applicability. But for acausal EMS to be real world applicable, along with real time capability, adaptability is critical for vehicle performance. In real world driving due to dynamic and uncertain trip demand the EMS adaptability is paramount to achieve efficient vehicle performance for varied driving scenarios.

13.2.4.1 Conventional EMS methods

Optimisation based EMS determines optimal operating points of both the engine and motor each time for a given or set of vehicle speed profiles considered for a given destination. Hence knowing the vehicle speed profile in advance is paramount for vehicle performance and adaptability as discussed below.

In a few studies using optimisation based EMS reviewed in chapter 4, Proportional - Integral (PI) controllers are used to address deviation in trip demand based on the current and reference SOC (Kessels et al., 2006, Koot et al., 2005, Johnson et al., 2000, Jeanneret and Markel, 2004). PI controller parameters and the reference SOC are determined specific to a trip reference vehicle speed profile considered.

In a couple of optimisation based EMS studies (Tulpule et al., 2009, He et al., 2012a) the EMS adapts in proportion to deviation in current SOC from reference and the remaining trip distance through a linear equation. In this case, the EMS is constrained to find the optimal power split between the engine and motor at that instance of time or distance (local) without considering the vehicle efficient condition for correction over the remaining trip (global). In other words based on the instantaneous deviation, say the engine is operated with higher power output to recover the deviation at that instance which may not be the vehicle efficient conditions. Hence the EMS does not identify the best condition to execute the change for recovery from deviation which can reduce the fuel economy. This may also make the EMS unstable with a frequent engine stop – starts and require a higher computational requirement.

Another technique is look – ahead or preview window. Preview window is the duration of prediction considered to determine optimal power split ratio. Preview window was considered in some optimisation studies (Adhikari, 2010, He et al., 2012a). They require prior knowledge of the trip demand and likelihood of deviation in trip demand.

In most of the optimisation based EMS studies adaptability feature was not considered and predicted and actual vehicle speed profile is considered true to the actual (Qiuming and Yaoyu, 2009, O'Keefe and Markel, 2006, Qiuming et al., 2007, Musardo et al., 2005).

13.2.4.2 Proposed EMS method

In the proposed EMS adaptability is at two levels:

- Global adaptability: To varied real world driving scenarios such as trip distance, sequence of road type and initial SOC
- Local adaptability: To dynamic and uncertain trip demand

13.2.4.2.1 Global adaptability of the proposed EMS

Once identified vehicle efficient powertrain operation is adapted for varied driving conditions based on delta energy and driving information such as the sequence of road types and trip distance as discussed earlier in section 13.2.3.2.

Delta energy reflects the total deficit of trip energy (global). The parameter delta energy controls the smart charge in extra urban road type which is the preferred and primary mode as discussed earlier Figure 13-5. Smart charge in urban road type is controlled by local delta energy. Local delta energy is determined similar to delta energy but considers energy status for the current urban road type only and not the entire trip. Hence the secondary smart charge triggered by local delta energy meets only the energy deficit of the current road type. Local delta energy (or secondary smart charge) is designed to trigger when there is insufficient battery energy to wait until the extra urban driving part for the battery smart charging as demonstrated in section 12.4.1.4 with Figure 12-8. Or if in a trip the extra urban road type comes later in the trip after a long urban driving or extra urban smart charging was not sufficient. However the delta energy which monitors the global or overall trip deficit trip energy takes into account the deficit energy partially met by the secondary smart charge.

Local delta energy is used to improve vehicle performance under certain specific circumstances to operate in urban road type. This enhanced the proposed EMS adaptability to varied trip conditions. Similarly urban and extra urban road types are predominantly discussed in this thesis, but many more road types and sub function based on the influence and difference in trip demand can be considered (as shown in Table 7-1) such as to ensure the engine is not switched ON in zero emission or noise free zone, etc. Thus the core principles of the proposed EMS could be extended with many more delta energy types or road types introduction to adapt to a specific driving conditions or trip demand.

13.2.4.2.2 Local adaptability of the proposed EMS

In the proposed EMS delta energy is periodically monitored throughout the journey to update controls strategy if required. During the periodic monitoring the adaptive part of the EMS is realised by comparing the estimated vehicle trip energy demand against the total available battery energy through delta energy. The available battery energy (current battery SOC) also reflects any change in the actual vehicle trip demand during the journey. Delta energy in total also reflects any deviation in the estimation to actual vehicle trip energy. The control strategy is updated considering the remaining vehicle trip energy estimated and driving information (Illustrated in section 7.2.4.1). The EMS guides for vehicle efficient power train operation. If there is little deviation in the estimated and actual vehicle trip energy then the delta energy profile is almost horizontal as shown with the delta energy positive green line in Figure 13-5.

Also the remaining estimated vehicle trip energy through delta energy acts like a buffer to control strategy correction in due course as explained here. In Figure 13-5, the brown delta energy profile is moving wider from the initial delta energy value leading to increase in the deficit trip energy in the urban road type. This is due to under estimation of the vehicle trip energy than the actual (deviation in estimation). However for the corrective action (primary smart charge), the EMS is waiting for the extra urban driving part to recover the total deficit in trip energy; including the original (initial deficit) and extra deficit due to under estimation. In other words the EMS is using the available battery energy (local surplus) for the time being in urban road type till the efficient conditions for smart charge in extra urban. However if the local surplus battery energy is not available then the secondary smart in urban is used. Overall, the proposed EMS if possible delays the smart charge till the extra urban road type to recover any deviation either due to initial vehicle trip energy estimation or dynamic change. Thus energy conversion losses are reduced and hence vehicle performance such as the fuel economy and number of engine stop – starts are improved as found in previous chapters. At the same time, the buffer feature and periodic sampling makes the EMS less sensitive to instantaneous and/or trivial changes in trip demand. Overall due to local adaptability, for the proposed EMS the trip demand estimation need not be exact as demonstrated in chapter 11 and 12.

Thus, the global adaptability for varied real world scenarios and local adaptability to address uncertain and dynamic trip demand conditions are designed in the proposed EMS to achieve vehicle efficient performance for varied driving scenarios.

13.2.5 Potentially real time capable acausal EMS

Real time capability is the primary requirement of the EMS and over rules the vehicle performance such as fuel economy. However in the literature real time capability is often over looked for optimal vehicle performance over a deterministic trip demand.

Based on the simulation duration comparison study between the proposed and conventional rule based EMS, the proposed EMS was concluded as potentially real time capable. The formulation over vehicle trip energy and distinctive powertrain operation as discussed in previous two sections led to the proposed EMS being potentially real time capable.

13.2.6 Summary

Irrespective of the techniques employed in conventional EMS methods,

- Typically rule based EMS in literature are real time capable and causal EMS. Similarly, optimisation based EMS are not suitable for real time application.
- Optimisation based EMS are formulated over trip vehicle speed profile. To make any prediction of trip vehicle speed profile, prior knowledge of the trip vehicle speed profile specific to destination is required. This limits the use of such EMS to conditions where prior knowledge of vehicle speed profile is known in advance and predictions are accurate. On the other hand due to dynamic nature of trip demand in real world driving prediction of exact vehicle speed profile is not possible.

These features and limitations are same for the respective EMS method irrespective of methods and techniques applied.

The proposed EMS method structure and strategy is unique. It is different to previous methods both at macro and micro level. At macro level, the proposed EMS is formulated over vehicle energy and driving information. The outcome is potentially a real time capable and acausal EMS. At micro level, the proposed EMS adapts to varied real world scenarios and trip demand estimation need not be exact. No prior knowledge of the trip vehicle speed profile is required, only the trip driving information and specific energy matrix are required. Simulation durations of the proposed and conventional rule based EMS are the same. The proposed acausal EMS potentially meets main requirements for real world application such as,

- Adaptability and
- Real time capability

The Proposed EMS does not guarantee optimum results. However it offers efficient performance for varied and uncertain driving conditions potentially in real time. A schematic of real world applicability and fuel economy comparison for conventional and the proposed EMS is shown in Figure 13-6.

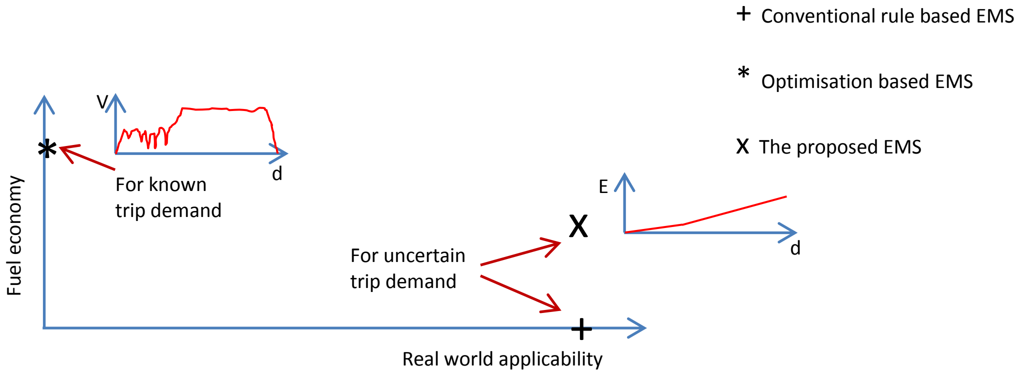

Figure 13-6: A schematic of conventional and proposed EMS real world applicability and fuel economy

For a known trip demand (vehicle speed profile) condition, the proposed EMS vehicle performance such as fuel economy is likely to be less than the optimisation based EMS fuel economy. However optimisation based EMS does not work in real world as the trip demand is dynamic and uncertain and its performances are specific to the vehicle speed profile considered. In the case of the proposed EMS the vehicle performance is not designed to a specific trip demand. The proposed EMS adapts to varied driving scenarios and trip demand estimation need not be exact.

Following features lead the proposed EMS to be potentially real time adaptive and acausal rule based EMS to achieve vehicle efficient performance for varied driving conditions with uncertain trip demand:

- Formulation over vehicle trip energy.
- No monitoring of the electric motor operation for vehicle efficiency but only the battery energy.

- Predetermined engine operating conditions in conjunction with driving information such as road types to reduce energy conversion losses.
- Adaptation of once identified power train efficient conditions to varied trip conditions.
- No prior knowledge of the trip vehicle speed profile is required.
- Multiple factors influencing trip demand such as driver style, road type and traffic can be considered by a common parameter – specific energy.
- Trip demand estimation need not be exact due to the EMS adaptability.

A comparison summary of conventional EMS (conventional rule based and optimisation based) and proposed EMS based on critical parameters is shown in Table 13-1.

Table 13-1: A comparison summary table of existing and the proposed EMS

EMS	Conventional rule based	Optimisation based	Proposed rule based
Trip demand	Causal	Causal or Acausal (predictive)	Acausal (predictive)
Formulation	Instantaneous vehicle demand	Vehicle speed profile and battery SOC	Driving information, vehicle trip energy and battery SOC
Control strategy	CD-CS	CD-CS or BCD	BCD
Computation	Real time capable; used in production vehicles	Cannot be used in real time EMS	Potentially real time capable; same as conventional rule based
Performance	Rule and driving cycle dependent	Vehicle speed profile considered and its prediction accuracy	Adapts to varied driving condition and trip demand estimation need not be exact
Real world applicability	Applicable	Not applicable	Applicable with better vehicle performance than conventional rule based EMS

13.3 EMS Evaluation

The proposed EMS evaluations were designed to demonstrate real world applicability and vehicle performance for the uncertain trip demand and varied driving scenarios. Interdependent performance metrics considered were,

- Potential real time capability (Simulation duration)
- Adaptability

- Vehicle performance - fuel economy and number of engine stop-starts along with final SOC.

Throughout the study the proposed EMS performance metrics were compared with conventional rule based EMS. Conventional rule based EMS was considered for comparison as they are used in industry due to the real time capability. Optimisation based EMS are not suitable for real time application.

13.3.1 Real time capability study (Chapter 10)

The proposed EMS, potential real time capability was demonstrated by comparing the computation duration required to simulate for a given trip demand to that of conventional rule based EMS in chapter 10. Further the proposed EMS performances were studied for various sampling interval.

The simulation duration of the proposed and conventional EMS is same. The simulation duration for the considered trip is faster than real time. Therefore the proposed EMS is concluded as potentially real time capable. Only subtle differences in vehicle performance and simulation duration for various sampling rates in the proposed EMS were observed. No increasing or decreasing fuel economy trend was observed across sampling interval. In optimisation based EMS with increase in sampling interval it was observed that the fuel economy was reducing (Adhikari, 2010, Guzzella and Sciarretta, 2007).

Overall, considering uncertainty of real world driving which calls for a lower sampling interval to bridge the gap between the actual and anticipated trip demand and also to minimise the number of engine stop-starts, the 10 second sampling rate was selected for future studies.

13.3.2 Adaptability study (Chapter 11)

Along with real time capability another requirement to address the uncertainty is adaptability of the EMS.

In chapter 11, the proposed EMS adaptability was demonstrated for a wide variation in trip energy of up to ±15% over real world driving data. However the minimum and maximum actual trip energy variation of the repetitive real world trips considered in the study was only about 5% from the mean. Hence the adaptability study was considered 3 times the actual total vehicle trip energy variation observed. This represents a wide variation in terms of trip demand (vehicle speeds) and may be beyond the realistic possibility in real world driving.

During both under and over estimation of the trip energy, the proposed EMS was able to recover the trip demand gap during the journey for varied initial SOC as shown in Table 11-7. Throughout the study the proposed EMS vehicle performance was superior to conventional rule based EMS. The proposed EMS vehicle performance comparison across varied trip energy estimation to the actual is summarised in Table 11-8. Up to 9% of over and under estimation of the vehicle trip energy, no compromise in performance was observed and hence can be considered as the target or preferred estimation region. With a bit higher vehicle trip energy estimation of 15% the only issue observed is higher final SOC (still lower than conventional rule based EMS) and hence considering uncertain and dynamic real world driving this can be acceptable. However it is recommended to avoid higher under estimation of 15% which decreases the potential fuel economy and increase the number of engine stop – starts. Overall this demonstrates the vehicle trip energy or trip demand estimation for the proposed EMS need not be exact and still deliver better vehicle performance than the conventional rule based EMS across varied initial SOC.

13.3.3 Validation study in real world driving (Chapter 12)

In the study the proposed EMS was validated (for effective working) by simulating over the uncertain trip demand for the considered destinations as is the case in real world driving. The validation study was considered for four real world destinations of varied sequence of road types, trip distance, initial SOC and trip energy estimation. Varied trip energy estimation was determined considering two specific energy matrix methods, S1 and S2. In S1 highest specific energy value out of the two real world destination data considered for each road type was considered. In case of S2, for each road type the specific energy value of the two real world destination data was distance weighted. The two real world destination data used for determining the specific matrix were not part of the real world data used for validation study.

Again throughout the study the proposed EMS performance was superior to conventional rule based EMS. This again demonstrates the robustness of the proposed EMS to various real world scenarios.

In acausal EMS methods in literature (Chan-Chiao et al., 2004, Qiuming et al., 2007, Kessels, 2007, Dean et al., 2008, Johannesson, 2009, Qiuming and Yaoyu, 2009, Cairano et al., 2013) prior knowledge of the trip demand (Vehicle speed profile) is required for the destination considered. Typically in these studies predicted trip demand was considered 100 % accurate. Only in (Qiuming and Yaoyu, 2009) study, prediction is validated for a real world trip data by comparing the fuel economy. This study was reviewed in detail in section 4.4.2.1.2.

In comparison the validation study in this research, the proposed EMS working was demonstrated for four real world destinations of varied sequence of road types, distance and initial SOC. No prior knowledge of the trip vehicle speed profile is required. In fact for the proposed EMS method, the vehicle trip energy (demand) is estimated using the specific energy matrix and known trip driving information, and expected to deliver better vehicle performance than current production vehicles for varied real world driving conditions. Another aspect is to determine specific energy matrix (Table 12-1) for validation study only about 62 km of real world driving data was used. Considering the destination specific prior knowledge requirement for the acausal EMS methods in literature, this is a unique and required feature for application in real world driving.

13.3.4 Vehicle performance

Vehicle performance comparison for known trip demand with the NEDC (chapter 9) and uncertain trip demand (validation study - chapter 12) as in real world driving is discussed in this section. In both studies vehicle performance was studied for varied initial SOC, sequence of road types and trip distance.

13.3.4.1 Vehicle performance for the legislative driving cycle – the NEDC

The vehicle performance for the NEDC was considered as it is commonly used legislative driving cycle. To study for varied trip distance, the NEDC was considered up to three times sequentially (3x) with varied initial SOC. The proposed EMS fuel economy improvement is up to 11.4% with 5 times fewer numbers of engine stop-start and lower final SOC in comparison to conventional rule based EMS for the NEDC 3x.

The closest work from literature (neglecting the effect of power train component size) that can be compared for parallel PHEV over the NEDC is the (Karbowski, 2006) study. In this literature, DP with BCD strategy was compared to a conventional rule based EMS with CD-CS strategy for the NEDC 10x. The total energy used for DP is 60% lower than conventional rule based EMS. The proposed EMS fuel economy improvement over the NEDC 3x to the same rule based EMS considered in the Karbowski study (referred as C#1 in chapter 9) is 28.6%.

As the trip demand is periodic when the NEDC or any driving cycle considered multiple times, the power train operation becomes periodic after initial one or two sequences of driving cycles. Hence the improvement can be expected to be linear with number of times the driving cycle is considered. In that sense the fuel economy improvement for the NEDC 10x is estimated for the proposed EMS as discussed below.

The fuel economy improvement benefits from the NEDC 2x to NEDC 3x was about 2.2% improvement. Hence the fuel economy improvement estimated for the NEDC 10x is,

= (The fuel economy improvement for the NEDC 3x) + ((The fuel economy improvement benefits from the NEDC 2x to NEDC 3x) Multiplied by 7)

= (28.6%) + ((2.2%) x 7) = 44%

Table 13-2: Fuel economy improvement of the dynamic programming and the proposed EMS method to the conventional rule based EMS for the NEDC

EMS method	NEDC 3x	NEDC 10x
Dynamic programming (DP) from literature	-	60%
The proposed EMS	28.6%	44%*

*Estimated value

This fuel economy performance of the proposed and DP EMS methods to conventional rule based EMS is similar to the schematic diagram shown in Figure 13-6.

In the case of DP in Karbowski study, the power split ratios were designed for the NEDC 10x. In the case of the proposed EMS it was not designed specific to the NEDC. Hence the proposed EMS performance for known trip demand can be expected to be lower than optimisation based EMS and higher than conventional rule based EMS. However in real world driving, trip demands are uncertain and hence the optimisation based EMS fuel economy shows only the potential benefit for a given trip demand.

13.3.4.2 Vehicle performance for real world destinations with uncertain trip demand

In the validation study, the proposed EMS fuel economy improvement is up to 29.6% with 7 times fewer numbers of engine stop – start and lower final SOC in comparison to conventional rule based EMS.

Further, vehicle performances between the proposed and conventional rule based EMS were compared in the real time capability and adaptability studies. The fuel economy, number of engine stop-starts and final SOC of the proposed EMS were found to be superior to that of the conventional EMS.

To give a context and significance of these fuel economy improvements, 1% improvement in fuel economy cost on average about 100 euro per light commercial vehicle (IEA, 2012). Three year period range fuel economy improvement is up to 3.7% yearly improvement for new vehicle (IEA, 2012).

The proposed EMS uses existing systems and hardware in vehicle and external transport system such as intelligent transport system (ITS). No new system is required. The proposed EMS method is different only in how the existing set up is used.

13.3.5 Limitation of corrected fuel economy calculation

For a fair comparison throughout the thesis the fuel economy was corrected to the minimum SOC of 0.4 as discussed in section 9.3.1.1. The fuel economy is corrected considering the best brake specific fuel consumption (BSFC) of the engine (optimal operating point – OOP) and maximum vehicle charging efficiency (equation 6.1). Hence the corrected fuel economy is positively biased whenever the final SOC is higher. In the adaptability study (Chapter 11), Figure 11-10, the plot indicates increase in over estimation improves fuel economy. This trend may be misguiding as the increase in over estimation increases the final SOC which in turn leads to higher positive bias in corrected fuel economy. However these biases were small about 0.5% of the fuel economy improvement benefit. This method is used in (Opila, 2010, Adhikari, 2010) and is the only method appropriate for study with limited trip distance as discussed in section 9.3.1.1. In the study maximum trip distance was about 42 km. With longer trip distance (more than 100 km) final SOC is not corrected in literature (Freyermuth et al., 2007, He et al., 2012b) due to the predominant engine operation.

However throughout the study the proposed EMS final SOC is lower than that of the conventional rule based EMS. Hence the correction of fuel economy is biased towards increasing the fuel economy for the conventional rule based EMS. Therefore the proposed EMS fuel economy improvement over conventional EMS is marginally more than the discussed numbers.

13.3.6 Summary

Overall the proposed EMS evaluations comparing interdependent performance metrics to conventional rule based EMS is as follows,

- The proposed EMS is concluded as potentially real time capable.
- Demonstrated trip demand estimation need not be exact and still deliver better vehicle performance than conventional rule based EMS as shown in adaptability and validation study.
- Established robust and superior performance for four real world destinations with various scenarios such varied initial SOC, sequence of road types, trip distance and trip energy estimation.
- Proved the proposed EMS works (validated) for uncertain trip demand and varied driving conditions as would be the case for real world driving.

The proposed EMS performance was demonstrated for a parallel PHEV. However as found in literature (He et al., 2012a), EMS methods demonstrated over parallel architecture is typically applicable to other or derivative hybrid vehicle architectures. Similarly the proposed EMS method can be applicable to hybrid vehicles with different power train such as fuel cells and gas turbines.

13.4 Limitations of the proposed EMS design and evaluation

The main limitations of the proposed EMS design and its evaluation are discussed in this section.

13.4.1 Proposed EMS design

Wrong driving information declarations such as route, final destination and driver style can adversely affect the proposed EMS performance. This may lead to performance inferior to conventional rule based EMS. However this is typical of any EMS method pursuing BCD strategy. This negative effect on the proposed EMS due to the formulation over vehicle trip energy and adaptability is expected to be relatively less in comparison to the existing EMS methods pursuing BCD strategy.

In optimisation based EMS both engine and electric powertrain are optimally controlled based on the prior knowledge of the trip demand (section 13.2.3). In the proposed EMS, the focus is to efficiently use the engine and monitor the battery energy. Hence the proposed EMS fuel economy and emissions performances are expected inherently not optimal as explained with Figure 13-6. This was further illustrated with the NEDC driving cycle study (Table 13-2) showing lower percentage of fuel economy improvement (44%) over the conventional rule based EMS to that of the optimisation based (DP) EMS (60%) (Karbowski, 2006). However for optimised based EMS to deliver optimal performance prior knowledge of the trip vehicle speed profile is required and the proposed EMS do not require this prior knowledge.

Current ECE regulation for fuel economy and emission measurements are designed for hybrid vehicle pursuing CS (HEV) and CD-CS strategy (PHEV) as discussed in section 2.4. ECE regulations to test vehicle for fuel economy and emissions pursuing BCD strategy is work in progress. Therefore currently if the proposed EMS design is used in production, as per the ECE regulations, this may not reflect the true fuel economy and emissions potential of the vehicle.

13.4.2 Proposed EMS evaluation

Commonly used full parallel PHEV model was simulated in studies for a driver (style), and traffic was not considered for simplicity. This evaluation study covered known and unknown trip demand conditions considering the legislative driving cycles, the NEDC and real world trips. However the evaluation studies were carried out for a given vehicle and a driver style. Vehicle, architecture, component size and driver styles are known to effect vehicle performances. Hence change in these factors may change the vehicle performance benefits between the proposed and conventional EMS.

Fuel economy improvement of DP based optimisation based study (Karbowski, 2006) over a conventional rule based EMS is 60%. In the validation study, the proposed EMS fuel economy improvement is up to 29% to that of the conventional rule based EMS. The improvement of the proposed EMS is lower than that of DP. Conventional rule based EMS was considered for comparison as they are used in industry and known for real time capability over other non-real time capable EMS methods. Based on chapter 9 study, the best out of the two commonly used conventional rule based EMS was selected for the comparison study with the proposed EMS (section 9.4.1). For the best conventional EMS so selected and the proposed EMS design, the engine operates at OOL and the lower vehicle threshold speed for the engine operation is the same. The main reason for the propose EMS superior vehicle performance to that of conventional EMS was discussed in section

9.5. In summary, conventional rule based EMS follows first CD and then CS strategy, irrespective of the trip demand. In other words conventional EMS being causal the powertrain operations do not adapt with respect to the trip demand (or vehicle speed profile) to reduce the energy conversion losses. The proposed EMS follows the superior BCD strategy and hence adapt to the trip demand such that the fuel economy is improved by,

- Trying to operate the engine at higher trip demand (or higher vehicle speeds/accelerations) so that the maximum portion of the engine power output is used to drive the vehicle directly and thus reduce energy conversion losses (as explained in section 8.3.6). Hence to meet the deficit trip energy, the engine is primarily operated in extra urban road type and only if required in urban road type at vehicle speeds above their respective thresholds (while pursuing BCD strategy). Whereas the conventional EMS being causal and pursuing CD-CS strategy leading to limited control over energy conversion losses while operating the engine (illustrated in Figure 12-18).
- The duration of the engine operation is defined by the delta energy which avoids any excess engine operation. In the conventional EMS the engine operation is defined purely by only the instantaneous vehicle speed and battery SOC.

In specific to the 29% fuel economy improvement of the proposed EMS to that of conventional EMS observed in a study is due to the engine operation at higher vehicle speed of about 30 m/s and for shorter duration of time as explained in section 12.4.1.2.2 with Figure 12-6.

Next in the conventional EMS based on O'Keefe and Markel (2006), 5% SOC window was selected for the CS strategy. Any change in this SOC window may vary the vehicle performance benefits of the proposed EMS with respect to the conventional EMS.

In a production vehicle, the vehicle performance of the proposed EMS to that of conventional rule based EMS could be better or lower than the numbers discussed in this thesis. As discussed in section 12.7, for a given vehicle, it entirely depends on the initial SOC, trip considered and its characteristics such as road types and vehicle speed profile. However the proposed EMS vehicle performance improvement to conventional rule based EMS is expected to be lower than that of optimisation based EMS improvement when prior knowledge of the trip vehicle speed profile is considered.

13.5 Future work

1. Next the logical work is the implementation of the proposed EMS method over the vehicle controller along with integrated navigation system like GPS will bring the research close to reality. In this research for driving information EMS was not integrated to the navigation system but manually defined for simplicity. Technology for the navigation system inside the vehicle already exists, only the relevant information/signals have to be integrated to the proposed EMS method.
2. Inclusion of the effect of traffic was discussed in the design of the proposed EMS. Traffic was not considered in the evaluations in this research for simplicity. To consider the effect of traffic, traffic density (or grading) has to be characterised in terms of vehicle energy and suitable threshold vehicle speed for smart charging.
    a. Effect on vehicle energy helps in considering traffic in vehicle trip energy estimation.
    b. In the thesis the threshold vehicle speed is fixed at 22 and 12 m/s for primary and secondary smart charge. If the threshold vehicle speed is above the actual driving speed leads to no smart charging, which in turn trigger the base control strategy that may reduce the fuel economy. At the same time keeping the threshold speed too low lead to smart charging at

lower speed which is again reduces fuel efficiency due to higher energy conversion losses. Relation of traffic density to threshold vehicle speed helps in designing the dynamic threshold vehicle speed for the proposed EMS. This can further enhance the proposed EMS fuel economy.

3. In this research study was done for a driver style. Driver style classification based on hybrid vehicle energy sensitivity is required to consider multiple driver styles:
    a. Study variation in hybrid electric energy and specific energy for each road types for individual driver style
    b. Investigate the relation of driver style aspects such as acceleration or jerk or max vehicle speed to its effect on specific energy.
4. The proposed EMS is formulated over vehicle trip energy (only battery energy) to consider the vehicle trip demand as it is found less dynamic to the external driving factors. Therefore, the relation of driver style to the vehicle trip energy for hybrid or electric vehicles is also expected to be relatively less sensitive. Typically driver styles are classified based on the study considering conventional (only engine) vehicle and vehicle speed and acceleration. Hence the relationship of driver style and vehicle trip energy has to be investigated. This may redefine the driver style classification for hybrid or electric vehicles with respect to the vehicle trip energy.
5. Optimal operating line (OOL) for the engine operation was considered based on only the fuel economy. This work can be extended to study emissions. Further the concept of optimal engine operation can be used for optimal use of other components like battery for optimal aging and life.

Chapter 14 – Conclusions

In this chapter the overall conclusions of a proposed blended rule based EMS for a PHEV are presented starting with a gap identified in the literature. This covers both the design and evaluation of a proposed EMS for the uncertain trip demand and varied driving scenarios as expected in real world driving.

To give a perspective to the research done, the gap in literature is summarised here. Owners of hybrid vehicles observed a large deviation between their real-world fuel economy and the certified values in comparison to conventional vehicles (only engine). Also hybrid vehicles are found to be more sensitive to the trip demand variation than a similar conventional vehicle. This is so, as rule based EMS used in production vehicle considers only the instantaneous trip demand (causal system) and not the whole trip demand (acausal system) when devising the control strategy. Also rule based EMS do not adapt to the uncertainties of real world driving. However such causal EMS are used in industry due to their real time capability and design simplicity. Acausal EMS are known to enhance vehicle and component performances. In the literature acausal EMS are optimisation based EMS which are not suitable for real time application and furthermore require prior knowledge of the vehicle speed profile. The vehicle performance using such EMS is sensitive to vehicle speed profile prediction. But prediction of the exact vehicle speed profile in real world driving is not possible due to the dynamic conditions. For efficient performance of EMS in real world driving, a real-time capable EMS must deal and adapt itself to the uncertainties in driving conditions (local) and also consider the whole trip demand (global). In other words, a real time capable acausal EMS that can adapt to the uncertainties of real world driving is required.

The proposed EMS for a PHEV is a blended rule based acausal EMS formulated over driving information and vehicle trip energy and not over dynamic vehicle speed as usually seen. Driving information that can be considered are driver style, route distance and road types like urban and extra urban with traffic as a sub function. Vehicle trip demand is estimated in terms of vehicle trip energy using known driving information and specific energy matrix.

For the proposed EMS evaluation, a commonly used parallel PHEV model was simulated. It was found the proposed EMS real time capability is as good as conventional rule based EMS. The proposed EMS can adapt to a wide variation in vehicle trip energy estimation (± 15% of the actual vehicle trip energy in the study which is beyond the realistically possible variation for the considered trip) and still perform better than the conventional rule based EMS. Hence for the proposed EMS trip energy estimation need not be exact unlike other acausal EMS from the literature. This is due to the local adaptability of the proposed EMS trough periodic sampling. The proposed EMS can globally adapt to varied driving conditions such as sequence of road types, trip distance and initial battery state of charge (SOC) as illustrated in the validation study with four real world destinations. Unlike other acausal EMS studies in literature, no prior knowledge of the trip vehicle speed profile is required in trip demand estimation, and multiple destinations with varied driving conditions were considered. The proposed EMS has real time capability and adaptability which establish its credentials for real world applicability. The proposed EMS vehicle performances are superior to that of conventional rule based EMS throughout the studies. In the study over the NEDC the fuel economy improvement in comparison to conventional EMS is up to 11% with 5 times fewer numbers of engine stop-start and lower final SOC. In the validation study over real world destinations with uncertain trip demand, the proposed EMS fuel economy improvement in comparison to conventional EMS is up to 29% with 7 times fewer numbers of engine stop – start and lower final SOC.

For the proposed EMS, which is formulated on driving information, to pursue the blended charge depleting (BCD) control strategy it was required to define the vehicle efficient engine operation with respect to the road types. Based on an investigation in this thesis, it was found the most vehicle efficient mode was the engine operation at optimal operating line (OOL) over the extra urban road type. Before this study, there was no literature on the efficient engine use for hybrid vehicles to suitably define with respect to trip driving parameters such as road types. This was so, as EMS in the literature are formulated over vehicle speed profile.

Overall, a blended rule based EMS method has been presented that can adapt in real time to the uncertain and varied scenarios of real world driving. For the first time a hybrid vehicle EMS is formulated over vehicle trip energy, which was the key in making rule based EMS, acausal and potentially real time capable. The proposed EMS method could be used in any plug in hybrid architecture. The core principles of the proposed EMS could be extended to address specific conditions such as zero emission or noise free zone and extreme elevation change, either by considering additional delta energy or road types. The breakthrough is that no prior knowledge of the trip vehicle speed profile is required and using known trip driving information the proposed EMS can work out the trip demand and expected to deliver superior vehicle performance.

References

ADHIKARI, S. 2010. *Real-time Power Management of Parallel Full Hybrid Electric Vehicles.* PhD, The University of Melbourne.

ALLGÖWER, F., FINDEISEN, R. & NAGY, Z. K. 2004. Nonlinear Model Predictive Control: From Theory to Application *Journal of the Chinese Institute of Chemical Engineers,* 35**,** 299-315.

ANDRE, M., KELLER, M., SJODIN, A., GADRAT, M., CRAE, I. M. & DILARA, P. The ARTEMIS European tools for estimating the transport pollutant emissions. International conference transport and air pollution, 2008. 10.

AXSEN, J., BURKE, A. & KURANI, K. 2008. Batteries for Plug-in hybrid electric Vehicles (PHEVs): Goals and the state of Technology Institute of Transportation, Studies University of California Davis, CA.

BAUMANN, B. M., WASHINGTON, G., GLENN, B. C. & RIZZONI, G. 2000. Mechatronic design and control of hybrid electric vehicles. *Mechatronics, IEEE/ASME Transactions on,* 5**,** 58-72.

BINGZHAN, Z., ZHIHANG, C., MI, C. & MURPHEY, Y. L. Multi-objective parameter optimization of a series hybrid electric vehicle using evolutionary algorithms. IEEE Vehicle Power and Propulsion Conference, Sept 7-10th 2009. 921-925.

BRAHMA, A., GUEZENNEC, Y. & RIZZONI, G. Optimal energy management in series hybrid electric vehicles. American Control Conference, 2000. Proceedings of the 2000, Sep 2000 2000. 60-64 vol.1.

CACCIABUE, P. C. & CARSTEN, O. 2010. A simple model of driver behaviour to sustain design and safety assessment of automated systems in automotive environments. *Applied Ergonomics,* 41**,** 187-197.

CAIRANO, S. D., BERNARDINI, D., BEMPORAD, A. & KOLMANOVSKY, I. V. 2013. Stochastic MPC With Learning for Driver-Predictive Vehicle Control and its Application to HEV Energy Management. *Control Systems Technology, IEEE Transactions on,* PP**,** 1-1.

CARLSON, T. R. & AUSTIN, T. C. 1997. Development of Speed Correction Cycles. Sierra Research, Inc.

CHAN, C. C. 2002. The state of the art of electric and hybrid vehicles. *Proceedings of the IEEE,* 90**,** 247-275.

CHAN, C. C. 2007. The State of the Art of Electric, Hybrid, and Fuel Cell Vehicles. *Proceedings of the IEEE,* 95**,** 704-718.

CHAN, C. C. & WONG, Y. S. 2004. Electric vehicles charge forward. *Power and Energy Magazine, IEEE,* 2**,** 24-33.

CHAN-CHIAO, L., HUEI, P. & GRIZZLE, J. W. A stochastic control strategy for hybrid electric vehicles. Proceedings of the American Control Conference, June 30-July 2 2004. 4710-4715.

CHAN-CHIAO, L., HUEI, P., GRIZZLE, J. W. & JUN-MO, K. 2003. Power management strategy for a parallel hybrid electric truck. *Control Systems Technology, IEEE Transactions on,* 11**,** 839-849.

CHEN, Z., VAHIDI, A., PISU, P., XIAOPENG, L. & TENNANT, K. 2010. Role of Terrain Preview in Energy Management of Hybrid Electric Vehicles. *Vehicular Technology, IEEE Transactions on,* 59**,** 1139-1147.

CHENG, C., MCGORDON, A., JONES, R. P. & JENNINGS, P. A. Comprehensive Forward Dynamic HEV Powertrain Modelling using Dymola and MATLAB/Simulink. In Proceedings of the Sixth IFAC Symposium on Advances in automotive control, July 12-14th 2010a Munich, Germany,.

CHENG, C., MCGORDON, A., POXON, J. E. W., JONES, R. P. & JENNINGS, P. A. A Model to Investigate the Effects of Driver Behaviour on Hybrid Vehicle Control The 25th

World Battery, Hybrid and Fuel Cell Electric Vehicle Symposium & Exhibition (EVS-25), Nov 5-9th 2010b Shenzhen, China.

CONTESTABILE, M., OFFER, G. J., SLADE, R., JAEGER, F. & THOENNES, M. 2011. Battery electric vehicles, hydrogen fuel cells and biofuels. Which will be the winner? *Energy & Environmental Science,* 4**,** 3754-3772.

DE VLIEGER, I., DE KEUKELEERE, D. & KRETZSCHMAR, J. G. 2000. Environmental effects of driving behaviour and congestion related to passenger cars. *Atmospheric Environment,* 34**,** 4649-4655.

DEAN, E., GRIZZLE, J. W. & PENG, H. 2008. Shortest path stochastic control for hybrid electric vehicles. *International Journal of Robust and Nonlinear Control,* 18**,** 1409-1429.

DEVLIEGER, I. 1997. On-board emission and fuel consumption measurement campaign on petrol-driven passenger cars. *Atmospheric Environment,* 31**,** 3753-3761.

DONGSUK, K., HUEI, P. & BUCKNOR, N. K. 2013. Optimal Energy and Catalyst Temperature Management of Plug-in Hybrid Electric Vehicles for Minimum Fuel Consumption and Tail-Pipe Emissions. *Control Systems Technology, IEEE Transactions on,* 21**,** 14-26.

DUOBA, M. 2011. Engine Design, Sizing and Operation in Hybrid Electric Vehicles. Argonne National Laboratory.

EHSANI, M., GAO, Y., GAY, S. E. & EMADI, A. 2004. *Modern Electric, Hybrid Electric and Fuel Cell Vehicles*, CRC Press.

EHSANI, M., YIMIN, G. & MILLER, J. M. 2007. Hybrid Electric Vehicles: Architecture and Motor Drives. *Proceedings of the IEEE,* 95**,** 719-728.

ELGOWAINY, A., BURNHAM, A., WANG, M., MOLBURG, J. & ROUSSEAU, A. 2009. Well-to-Wheels Energy Use and Greenhouse Gas Emissions Analysis of Plug-in Hybrid Electric Vehicles. Illinois, US: Center for Transportation Research, Energy Systems Division, Argonne National Laboratory.

ERICSSON, E. 2000. Variability in urban driving patterns. *Transportation Research Part D: Transport and Environment,* 5**,** 337-354.

ERICSSON, E. 2001. Independent driving pattern factors and their influence on fuel-use and exhaust emission factors. *Transportation Research Part D: Transport and Environment,* 6**,** 325-345.

FISCHER, M., WERBER, M. & SCHWARTZ, P. V. 2009. Batteries: Higher energy density than gasoline? *Energy Policy,* 37**,** 2639-2641.

FREYERMUTH, V., FALLAS, E. & ROUSSEAU, A. 2007. Comparison of Powertrain Configuration for Plug-in HEVs from a Fuel Economy Perspective. *SAE International*.

GAO, Y. M. & EHSANI, M. 2010. Design and Control Methodology of Plug-in Hybrid Electric Vehicles. *Ieee Transactions on Industrial Electronics,* 57**,** 633-640.

GERRIT, K., MAARTEN, V., RICHARD, S., JORDY, S., ARTUR, P., VAN, R. M., JOHN, N., ANGELA, J., SIMON, O. B., SIMON, W., JULIEN, P., MARTIN, S. & DICK, B. 2012. Supporting Analysis on Test Cycle and Technology Deployment for Reviews of Light Duty Vehicle CO2 Regulations. European Commission – DG CLIMA.

GERSHENSON, C. 2008. *Artificial Neural Networks for Beginners.* University of Sussex.

GRINSTEAD, C. M. & SNELL, J. L. 1997. *Introduction to Probability*, American Mathematical Soc., .

GUZZELLA, L. & SCIARRETTA, A. 2007. Vehicle Propulsion Systems. Second ed.: Springer.

HE, Y., CHOWDHURY, M., PISU, P. & MA, Y. 2012a. An energy optimization strategy for power-split drivetrain plug-in hybrid electric vehicles. *Transportation Research Part C: Emerging Technologies,* 22**,** 29-41.

HE, Y., RIOS, J., CHOWDHURY, M., PISU, P. & BHAVSAR, P. 2012b. Forward power-train energy management modeling for assessing benefits of integrating predictive traffic data into plug-in-hybrid electric vehicles. *Transportation Research Part D: Transport and Environment,* 17**,** 201-207.

HOLMÉN, B. A. & NIEMEIER, D. A. 1998. Characterizing the effects of driver variability on real-world vehicle emissions. *Transportation Research Part D: Transport and Environment,* 3**,** 117-128.

IEA 2012. Technology Roadmap: Fuel Economy of Road Vehicles. INTERNATIONAL ENERGY AGENCY.

JEANNERET, B. & MARKEL, T. Adaptive Energy Management Strategy for Fuel Cell Hybrid Vehicles. SAE World Congress & Exhibition, March 8th 2004 Detroit, Michigan, United SAE.

JINMING, L. & HUEI, P. 2008. Modeling and Control of a Power-Split Hybrid Vehicle. *Control Systems Technology, IEEE Transactions on,* 16**,** 1242-1251.

JOHANNESSON, L. 2009. *Predictive Control of Hybrid Electric Vehicles on Prescribed Routes.* Ph.D Chalmers University of Technology.

JOHNSON, V. H., WIPKE, K. B. & RAUSEN, D. J. 2000. HEV Control Strategy for Real-Time Optimization of Fuel Economy and Emissions. *SAE*.

JONG-SEOB, W. & LANGARI, R. 2005. Intelligent energy management agent for a parallel hybrid vehicle-part II: torque distribution, charge sustenance strategies, and performance results. *Vehicular Technology, IEEE Transactions on,* 54**,** 935-953.

JONG-SEOB, W., LANGARI, R. & EHSANI, M. 2005. An energy management and charge sustaining strategy for a parallel hybrid vehicle with CVT. *Control Systems Technology, IEEE Transactions on,* 13**,** 313-320.

KARBOWSKI, D. Plug-in Vehicle Control Strategy: From Global Optimization to Real-time Application. Electric Vehicle Symposium, EVS22, 2006 Yokohama, Japan.

KATRAŠNIK, T. 2011. Energy conversion phenomena in plug-in hybrid-electric vehicles. *Energy Conversion and Management,* 52**,** 2637-2650.

KELLY, K. J. & RAJAGOPALAN, A. 2001. Benchmarking of OEM Hybrid Electric Vehicles at NREL. Colorado: National Renewable Energy Laboratory.

KESSELS, J., KOOT, M. W. T. & VAN DEN BOSCH, P. P. J. Optimal adaptive solution to powersplit problem in vehicles with Integrated Starter/Generator. IEEE Vehicle Power and Propulsion Conference, 2006. 185-190.

KESSELS, J. & VAN DEN BOSCH, P. P. J. Electronic horizon: Energy management using telematics information. IEEE Vehicle Power and Propulsion Conference, Vols 1 and 2, 2007. 581-586.

KESSELS, J. T. B. A. 2007. *Energy management for automotive power nets.* PhD, Eindhoven University of Technology.

KESSELS, J. T. B. A., KOOT, M. W. T., VAN DEN BOSCH, P. P. J. & KOK, D. B. 2008. Online Energy Management for Hybrid Electric Vehicles. *Vehicular Technology, IEEE Transactions on,* 57**,** 3428-3440.

KIM, N., ROUSSEAU, A. & RASK, E. 2012. Autonomie model validation with test data for 2010 Toyota Prius. *SAE*.

KOOT, M., KESSELS, J. T. B. A., DE JAGER, B., HEEMELS, W. P. M. H., VAN DEN BOSCH, P. P. J. & STEINBUCH, M. 2005. Energy management strategies for vehicular electric power systems. *Vehicular Technology, IEEE Transactions on,* 54**,** 771-782.

KOPRUBASI, K. 2008. *Modeling and control of a HEV for drivability and fuel economy improvements.* Ph.D., The Ohio state university.

KUMAR, L., GUPTA, K. K. & JAIN, S. Architecture and configuration of electrified vehicles: A review. IEEE International Symposium on Industrial Electronics (ISIE), May 28-31st 2013. 1-6.

KUTTER, S. & BAKER, B. Predictive online control for hybrids: Resolving the conflict between global optimality, robustness and real-time capability. IEEE Vehicle Power and Propulsion Conference (VPPC), Sept 1-3rd 2010. 1-7.

LANGARI, R. & JONG-SEOB, W. 2005. Intelligent energy management agent for a parallel hybrid vehicle-part I: system architecture and design of the driving situation identification process. *Vehicular Technology, IEEE Transactions on,* 54**,** 925-934.

LARS, J., MATTIAS, A. & BO, E. 2007. Assessing the Potential of Predictive Control for Hybrid Vehicle Powertrains Using Stochastic Dynamic Programming. *Intelligent Transportation Systems, IEEE Transactions on,* 8**,** 71-83.

LIU, W. 2013. *Introduction to hybrid vehicle system modeling and control* John Wiley & Sons.

M.DUOBA, H.LOHSE-BUSCH & T.BOHN. Investigating vehicle fuel economy robustness of conventional and hybrid electric vehicles. EVS21, April 2004 Monaco.

MACIEJOWSKI, J. 2001. *Predictive Control with Constraints*, Prentice Hall.

MARKEL, T. & SIMPSON, A. Plug-In Hybrid Electric Vehicle Energy Storage System Design. Advanced Automotive Battery Conference, May 17-19 2006 Baltimore, Maryland. 12.

MCGORDON, A., POXON, J. E. W., CHENG, C., JONES, R. P. & JENNINGS, P. A. 2011. Development of a driver model to study the effects of real-world driver behaviour on the fuel consumption. *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering 2011 225: 1518*.

MENDEL, J. M. 1995. Fuzzy logic systems for engineering: a tutorial. *Proceedings of the IEEE,* 83**,** 345-377.

MICHEL, A. 2004. The ARTEMIS European driving cycles for measuring car pollutant emissions. *Science of The Total Environment,* 334-335**,** 73-84.

MILLER, J. M. 2006. Hybrid electric vehicle propulsion system architectures of the e-CVT type. *Power Electronics, IEEE Transactions on,* 21**,** 756-767.

MILLER, J. M., SCHULZ, S. E., CONLON, B., DUVALL, M., KANKAM, M. D. & NAGEL, N. Adjustable speed drives transportation industry needs part I: automotive. Vehicular Technology Conference, IEEE 58th, 6-9 Oct. 2003. 3220-3225.

MONTAZERI-GH, M. & ASADI, M. Application of Vehicle Telematic System in Fuzzy-Based HEV Control. 3rd International Conference on Information and Communication Technologies: From Theory to Applications (ICTTA), April 7-11th 2008. 1-6.

MUSARDO, C., RIZZONI, G. & STACCIA, B. A-ECMS: An Adaptive Algorithm for Hybrid Electric Vehicle Energy Management. 44th IEEE Conference on Decision and Control, and the European Control Conference., Dec 12-15th 2005 Seville, Spain. 1816-1823.

MUSARDO, C., STACCIA, B., BITTANTI, S., GUEZENNEC, Y., GUZZELLA, L. & RIZZONI, G. An Adaptive Algorithm for Hybrid Electric Vehicle Energy Management. FISITA WORLD AUTOMOTIVE CONGRESS, 2004 BARCELONA.

NATIONS, U. 2005. ECE regulation no. 101 revision 2. *Concerning the adoption of uniform technical prescriptions for wheeled vehicles, equipment and parts which can be fitted and/or be used on wheeled vehicles and the conditions for reciprocal recognition of approvals granted on the basis of these prescriptions.* Geneva: United Nation.

NEMRY, F., LEDUC, G. & MUÑOZ, A. 2009. Plug-in Hybrid and Battery-Electric Vehicles: State of the research and development and comparative analysis of energy and cost efficiency. European Commission: Joint Research Centre/Institute for Prospective Technological Studies.

OPILA, D. F. 2010. *Incorporating Drivability Metrics into Optimal Energy Management Strategies for Hybrid Vehicles.* Ph.D., The University of Michigan.

OPPENHEIM, A. V., WILLSKY, A. S. & NAWAB, S. H. 1997. *Signals & systems*, Prentice-Hall.

OVERINGTON, S. & RAJAKARUNA, S. Review of PHEV and HEV operation and control research for future direction. 3rd IEEE International Symposium on Power Electronics for Distributed Generation Systems (PEDG), June 25-28th 2012. 385-392.

O'KEEFE, M. P. & MARKEL, T. Dynamic Programming Applied to Investigate Energy Management Strategies for a Plug-in HEV. Electric Vehicle Symposium, EVS22, October 23–28 2006 Yokohama, Japan. 15.

PARKER, S. T., RUNNELS, M. J., SHAN DI, C. P. & DEMBOWSKI, D. 2007. The WisTransPortal Volume, Speed, and Occupancy Application Suite. Wisconsin Traffic Operations and Safety (TOPS) Laboratory, University of Wisconsin-Madison

PHUC, D. H., RAKSINCHAROENSAK, P., NAGAI, M. & SUZUKI, M. Control Strategy for Hybrid Electric Vehicles Based on Driver Vehicle Following Model. SICE-ICASE International Joint Conference, Oct 18-21st 2006. 555-560.

PISU, P., KOPRUBASI, K. & RIZZONI, G. Energy Management and Drivability Control Problems for Hybrid Electric Vehicles. 44th IEEE Conference on Decision and Control, and the European Control Conference, Dec 12-15th 2005 Seville, Spain. 1824-1830.

PISU, P. & RIZZONI, G. 2007. A Comparative Study Of Supervisory Control Strategies for Hybrid Electric Vehicles. *Control Systems Technology, IEEE Transactions on,* 15**,** 506-518.

POWELL, W. B. 2012. A unified framework for stochastic and dynamic programming. *Informs Computing Society Newsletter*.

QINA, S. J. & BADGWELLB, T. A. 2003. A survey of industrial model predictive control technology. *Control Engineering Practice***,** 733–764.

QIUMING, G. & YAOYU, L. Power Management of Plug-in Hybrid Electric Vehicles Using Neural Network Based Trip Modeling. American Control Conference, 2009 Hyatt Regency Riverfront, St. Louis, MO, USA.

QIUMING, G., YAOYU, L. & ZHONG-REN, P. Optimal power management of plug-in HEV with intelligent transportation system. IEEE/ASME International Conference on Advanced Intelligent Mechatronics, Sept 4-7th 2007. 1-6.

QIUMING, G., YAOYU, L. & ZHONG-REN, P. 2008. Trip-Based Optimal Power Management of Plug-in Hybrid Electric Vehicles. *Vehicular Technology, IEEE Transactions on,* 57**,** 3393-3401.

RE, L. D., ORTNER, P. & ALBERER, D. 2009. Automotive model predictive control: models, methods and applications. *In:* LUIGI DEL RE, P. O., AND DANIEL ALBERER (ed.). Springer.

REPORTS, C. 2004. Surprising facts about gas mileage, hybrids return poorer mileage than expected. Consumer Reports.org.

ROUSSEAU, A. & MOAWAD, A. Impact of Control Strategies on Fuel Efficiency of Different PHEVs using Real World Driving Conditions. IAMF, March 2010 Geneva.

SALMASI, F. R. 2007. Control Strategies for Hybrid Electric Vehicles: Evolution, Classification, Comparison, and Future Trends. *Vehicular Technology, IEEE Transactions on,* 56**,** 2393-2404.

SCHOUTEN, N. J., SALMAN, M. A. & KHEIR, N. A. 2002. Fuzzy logic control for parallel hybrid vehicles. *Control Systems Technology, IEEE Transactions on,* 10**,** 460-468.

SCIARRETTA, A. & GUZZELLA, L. 2007. Control of hybrid electric vehicles. *Control Systems, IEEE,* 27**,** 60-70.

SERRAO, L. 2009. *A Comparative Analysis of Energy Management Strategies for Hybrid Electric Vehicles.* PhD, The Ohio State University.

SERRAO, L., ONORI, S. & RIZZONI, G. 2011. A Comparative Analysis of Energy Management Strategies for Hybrid Electric Vehicles. *Journal of Dynamic Systems Measurement and Control-Transactions of the Asme,* 133.

SHARER, P., LEYDIER, R. & ROUSSEAU, A. 2007. Impact of Drive Cycle Aggressiveness and Speed on HEVs Fuel Consumption Sensitivity. SAE International.

SHARER, P. B., ROUSSEAU, A., KARBOWSKI, D. & PAGERIT, S. 2008. Plug-in Hybrid Electric Vehicle Control Strategy: Comparison between EV and Charge-Depleting Options. *SAE International*.

STOCKAR, S., MARANO, V., CANOVA, M., RIZZONI, G. & GUZZELLA, L. 2011. Energy-Optimal Control of Plug-in Hybrid Electric Vehicles for Real-World Driving Cycles. *Vehicular Technology, IEEE Transactions on,* PP**,** 1-1.

T J BARLOW, S. L., I S MCCRAE AND P G BOULTER 2009. A reference book of driving cycles for use in the measurement of road vehicle emissions. *Published report,* version 3.0**,** 284.

T J. BARLOW, LATHAM, S., MCCRAE, I. S. & BOULTER, P. G. 2009. A reference book of driving cycles for use in the measurement of road vehicle emissions. *Published report,* version 3.0**,** 284.

T. HOFMAN, STEINBUCH, M., SERRARENS, A. F. A. & DRUTEN, R. M. V. Rule-based equivalent consumption minimization strategies for hybrid vehicles. 17th IFAC World Congress, , 2008 Seoul.

TECHNOLOGIES, U. 2009. UQM PowerPhase Select 50 specification. UQM Technologies Inc. 4120 Specialty Pl. Longmont, Colorado 80504: www.uqm.com.

TULPULE, P., MARANO, V. & RIZZONI, G. Effects of Different PHEV Control Strategies on Vehicle Performance. American Control Conference, Vols 1-9, 2009. 3950-3955.

WIPKE, K. B., CUDDY, M. R. & BURCH, S. D. 1999. ADVISOR 2.1: a user-friendly advanced powertrain simulation using a combined backward/forward approach. *Vehicular Technology, IEEE Transactions on,* 48**,** 1751-1761.

WIRASINGHA, S. G. & EMADI, A. 2011. Classification and Review of Control Strategies for Plug-In Hybrid Electric Vehicles. *IEEE Transactions on Vehicular Technology,* 60**,** 111-122.

WU, J., LI, K., JIANG, Y. F., LV, Q., SHANG, L. & SUN, Y. H. 2011. Large-Scale Battery System Development and User-Specific Driving Behavior Analysis for Emerging Electric-Drive Vehicles. *Energies,* 4**,** 758-779.

ÇAGATAY BAYINDIR, K., GÖZÜKÜÇÜK, M. A. & TEKE, A. 2011. A comprehensive overview of hybrid electric vehicle: Powertrain configurations, powertrain control techniques and electronic control units. *Energy Conversion and Management,* 52**,** 1305-1313.

Appendix – Vehicle Model Parameters

a) Chassis data

Air density (ρ): 1.189 kg/m^3

Wheel base: 2.5 m

Height of centre of gravity: 0.6 m

Mass of frontal axle: 900 kg

Mass of rear axle: 600 kg

Unsprung mass: 90 kg

Pitch inertia: 2500 kg.m^2

Wheel inertia: 0.9 kg.m^2

Tyre pressure: 2.1 bar

b) Engine data

Idle speed: 78.5 rad/sec

Maximum speed: 471.2 rad/sec

Flywheel Inertia (around its axis of rotation): 0.25 kg/m^2

Table A.3: Maximum engine torque data

Speed, rad/sec	78.5	130.9	183.3	235.6	288.0	340.3	392.7	445.1	471.2
Max torque, Nm	89.6	131.8	167.8	180.1	177.5	175.7	168.2	145.0	124.0

Table A.4: Engine fuel consumption map (g/s)

Speed, rad/sec / Torque, Nm	**78.5**	**130.9**	**183.3**	**235.6**	**288.0**	**340.3**	**392.7**	**445.1**	**471.2**
14.5	0.23	0.29	0.37	0.47	0.57	0.86	1.31	1.41	2.29
29.0	0.30	0.33	0.49	0.64	0.81	1.10	1.49	1.79	2.41
43.5	0.29	0.44	0.62	0.83	1.05	1.33	1.66	2.17	2.53
58.0	0.35	0.54	0.75	0.99	1.24	1.54	1.93	2.36	2.66
72.5	0.41	0.64	0.90	1.18	1.44	1.79	2.17	2.66	2.98
87.0	0.49	0.73	1.03	1.34	1.67	2.04	2.46	2.93	3.19
101.5	0.56	0.84	1.17	1.51	1.89	2.31	2.76	3.26	3.55
116.0	0.63	0.95	1.30	1.69	2.10	2.57	3.06	3.59	3.90
130.5	0.71	1.07	1.43	1.84	2.29	2.81	3.37	3.98	4.25
145.0	0.81	1.19	1.57	1.98	2.52	3.07	3.69	4.34	4.67
159.5	0.93	1.29	1.71	2.16	2.72	3.35	4.00	4.71	5.01
174.0	1.02	1.41	1.85	2.35	2.94	3.65	4.33	5.12	5.42
179.8	1.05	1.46	1.90	2.42	3.03	3.77	4.47	5.29	5.60

Table A.5: Engine friction and pumping losses torque

Speed, rad/sec	78.5	104.7	157.1	209.4	261.8	314.1	366.5	418.9	471.2
Friction and pumping losses torque, Nm	-22.6	-22.7	-23.6	-23.4	-25.5	-26.0	-26.6	-29.0	-31.1

c) Battery data

Chemistry: Lead acid

Number of modules: 25

Capacity: 28 Ah

Module maximum voltage: 16.5V

Table A.6: Circuit output voltage (V_{oc}) and resistance (charge resistance R_{chg} and discharge resistance R_{dis}) data

SOC	V_{oc} (V)	R_{chg} (ohm)	R_{dis} (ohm)
0	6	0.038	0.038
0.2	8.9	0.024	0.024
0.4	11.8	0.007	0.007
0.6	12	0.007	0.007
0.8	12.3	0.007	0.007
1	12.6	0.011	0.011

d) Electric machine data

Maximum motor/generator power: 50 kW

Maximum motor/generator torque: 395 Nm

Maximum motor/generator speed: 628.3 rad/s

Motor/generator rotor inertia: 0.0226 kg.m^2

Fixed efficiency: 0.8

Table A.7: Motor/generator efficiency map

Torque, Nm \ Speed, rad/sec	**0**	**104.7**	**209.4**	**314.1**	**418.8**	**471.2**	**628.3**
395	0.86	0.68	0.68	0.68	0.68	0.68	0.68
365	0.86	0.68	0.68	0.68	0.68	0.68	0.68
335	0.86	0.68	0.68	0.68	0.68	0.68	0.68
305	0.86	0.68	0.68	0.68	0.68	0.68	0.68
275	0.86	0.70	0.70	0.70	0.70	0.70	0.70
245	0.86	0.72	0.72	0.72	0.72	0.72	0.72
215	0.86	0.74	0.74	0.74	0.74	0.74	0.74
185	0.86	0.77	0.82	0.82	0.82	0.82	0.82
155	0.86	0.79	0.84	0.84	0.84	0.84	0.84
125	0.86	0.82	0.87	0.87	0.87	0.87	0.87
95	0.86	0.85	0.88	0.90	0.90	0.90	0.90
65	0.86	0.86	0.90	0.90	0.90	0.90	0.90
35	0.86	0.89	0.90	0.90	0.90	0.90	0.90
5	0.86	0.81	0.78	0.77	0.76	0.75	0.75
0	0.86	0.86	0.86	0.86	0.86	0.86	0.86

e)Transmission data

Gear switch time: 0.15 s

Transmission efficiency: 0.92

Driveline efficiency: 0.95

Table A.8: Gear up and down shift defined with respect to vehicle speed

Vehicle speed, m/s	Gear number
0 to 5.58	1
5.58 to 9.05	2
9.05 to 13.60	3
13.6 to 18.80	4
Above 18.80	5

f) Auxiliary data

Auxiliary inertia: 0.001 kg.m^2

Auxiliary power load: 500 W