ENERGY AND POWER MANAGEMENT IN SERIES HYBRID VEHICLES

by

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ENERGY AND POWER MANAGEMENT IN SERIES HYBRID VEHICLES

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ABSTRACT

Hybrid electric vehicles are characterized by the existence of an electric energy buffer in the powertrain. Compared to a conventional vehicle the existence of the buffer means an extra degree of freedom in the powertrain. The driver's request for a specific power demand can thus be met by a combination of power from the primary power unit (internal combustion engines or fuel cells) and power from the electric buffer (batteries or ultracapacitors).

The subject of this thesis is the control of the load distribution between the power sources in the hybrid electric powertrain. The control problem is to choose the distribution of power from the electric buffer and primary power unit that minimizes the fuel consumption in the long run.

To solve this problem the efficiency characteristics of the components in the powertrain must be considered. It is the advantage of hybrids to have the extra degree of freedom because of the buffer so that the primary power unit can be driven independent of the transient traction demand of the vehicle powertrain.

The improvement in the fuel consumption is obtained by the operation of the engine in a more efficient region. Furthermore, when the vehicle is braking, the electric energy generated by the traction system can be stored back in the buffer. In conventional vehicles this braking energy is dissipated into the atmosphere.

The problem is complicated due to the fact that the future driving demands are largely unknown. This uncertainty of the future driving makes it difficult, from a fuel efficiency viewpoint, to compare the cost of supplying the energy demand from the buffer or the fuel tank. In this thesis this problem is handled by using a prediction based information perspective. It allows utilization of a policy derived by Dynamic Programming. Using a simple model of the power flows, energy levels and a regression model of the future driving, the resulting policy minimizes the expected fuel consumption with respect to the prediction model of the future driving conditions.

Additional information from GPS and digital maps or cooperation with the traffic infrastructure further enhances the optimization in terms of improved predictions and constraints and can be used to better schedule the use of the buffer so that further fuel consumption reductions are achieved.

SERİ HİBRİD ARAÇLARDA
ENERJİ VE GÜÇ YÖNETİMİ

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ÖZET

Hibrid elektrikli araçlar güç aktarma sistemindeki elektrik enerji deposu sayesinde farklılık yaratırlar. Mevcut güç aktarma sistemleriyle kıyaslandığında ekstra enerji deposu ekstra serbestlik derecesi anlamına gelmektedir. Bu sayede sürücünün güç ihtiyacı ana güç sağlayıcının (içten yanmalı motor veya yakıt pili) yanında elektrik enerji deposuyla da sağlanabilir.

Bu tezin konusu aracın güç ihtiyacını içten yanmalı motor ve elektrik depolama ünitesi gibi farklı kaynaklardan karşılayarak uzun vadede yakıt tüketimini en düşük seviyeye indirmektir.

Bu problemi çözmek için sistemdeki elemanların verim karakteristiklerinin bilinmesi ve kullanılması gerekmektedir. Hibridlerin avantajı ise elektrik depolama ünitesinin ekstra serbestlik derecesi sayesinde tahrik sistemi elemanlarının verimliliklerinin yüksek olduğu işletim bölgelerinde çalıştırılabilmeleridir.

Yakıt sarfiyatındaki iyileştirme içten yanmalı motorun daha verimli bölgede çalışmasıyla sağlanabilir. Bunun yanında aracın frenlemesi esnasında oluşan mekanik güç tekrar elektrik enerji deposunda depolanabilir. Mevcut ticari araçlarda bu enerji ısıya dönüşerek atmosfere iletilmektedir.

Sürücü tarafından gelecekte talep edilecek güç değerlerinin tahmininin zor olması eniyileştirme problemini güçleştirmektedir. Bu tezde hesaplamalarında kullanılmak üzere gelecek tahminleri yapılmaktadır. Güç akışlarının kontrolü ve gelecek hız tahminleri ve verimli işletim bölgelerinin kullanımı yakıt tüketiminin azaltılmasına yardımcı olmuştur.

Trafik altyapısı, yükseklik haritaları ve GPS sayesinde elde edilen bilgilerin de eniyileştirmeye olan katkıları incelenmiş, eniyileştirmede tanımlanan kısıtları daha etkin hale getirdiği ve yakıt sarfiyetının iyileştirmesine katkıda bulunduğu görülmüştür.

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LIST OF ABBREVIATIONS

ECU	Engine Control Unit
HEV	Hybrid Electric Vehicles
CVT	Continuously Variable Transmission
ECU	Engine Control Unit
TCU	Transmission Control Unit
BSFC	Brake Specific Fuel Consumption
ZEV	Zero Emission Vehicles
ICE	Internal Combustion Engine
CNG	Compressed Natural Gas
EV	Electric Vehicle
UITP	International Association of Public Transport
NYC	New York City
SoC	State Of Charge
APU	Engine/Generator Set
DP	Dynamic Programming
LP	Linear Programming
NP	Nonlinear Programming
QP	Quadratic Programming
Pbmax	Battery Maximum Power
FIS	Fuzzy Inference Surface
BR	Brake Resistor
KKT	Karush-Kuhn-Tucker
SQP	Sequential Quadratic Programming

CHAPTER 1

INTRODUCTION

The high level of air pollution caused by the increasing number of vehicles on the roads have generated a need for alternative power sources in transportation offering better fuel efficiency and lower exhaust emissions. Governments have designed regulations to keep the emissions of the vehicles on the public roads low. This forces vehicle manufacturers to develop new propulsion technologies. Also decreasing crude oil supplies require the development of alternative fuel vehicles and better fuel economy from present conventional vehicles.

Electric vehicles seem to be an obvious solution for the problem when semiconductors became usual in power electronics. It is not obvious yet that what will be the energy source of these vehicles. It can be solar, wind, geothermal energy. One thing is for sure: electric vehicles will have energy storage on board. At this point batteries fulfill this task but they have low weight to capacity ratio. Customers do not tolerate this limitation.

Hybrid Electric Vehicles (HEV) have emerged as the leading technology to solve this problem. HEVs use less fuel and produce less emission than the conventional vehicles and do not have to be recharged from an off-board electrical source unlike the Electric Vehicles.

The two main configurations of hybrids are the series hybrid, which shows excellent fuel consumption in case of more transient driving in city traffic and the parallel hybrid, which consumes significantly less than a conventional vehicle in highway driving (less transient). Both designs have an internal combustion engine on board as well as an electric motor with an electrical energy storage device (battery or ultracapacitors).

1.1 Conventional Vehicles

Although everybody is familiar with conventional vehicles, their features are summarized here to form a basis of comparison. Figure 1.1 shows the layout of a conventional vehicle drivetrain.

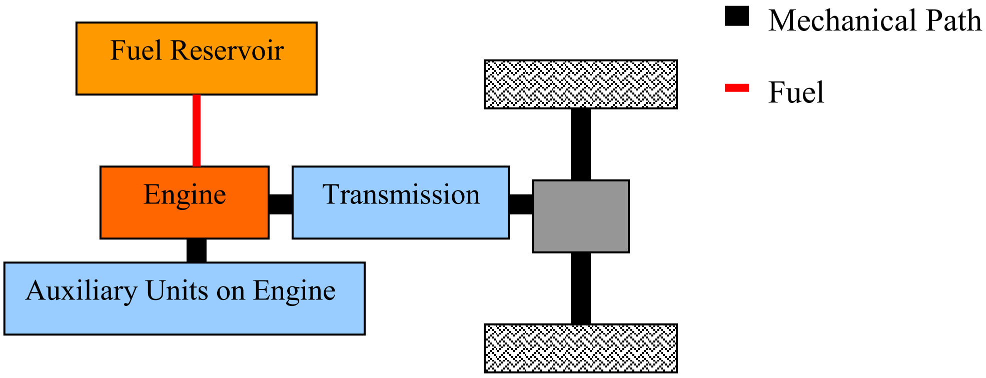

Figure 1.1. A conventional vehicle driveline

In a conventional vehicle an internal combustion engine drives a transmission that drives the differential that drives the wheels. The internal combustion engine (ICE) can be diesel or gasoline. The transmission can be manual, automatic or continuously variable transmission (CVT). A conventional vehicle is relatively cheap and easy to control. It does not require extra control besides the engine control unit (ECU) and the automatic transmission control unit (TCU) if an automatic transmission is applied.

In conventional vehicles, operating points of the engine are concentrated in the inefficient regions of the brake specific fuel consumption (BSFC) maps. This is due to the mechanical coupling between the engine and the final drive and it is inevitable.

To identify the engine optimal operating points, it is common to use an engine efficiency map which is illustrated in Figure 1.2. It is a projection of a 3D surface onto the speed-torque plane. Contours indicate the boundaries of the efficiency regions.

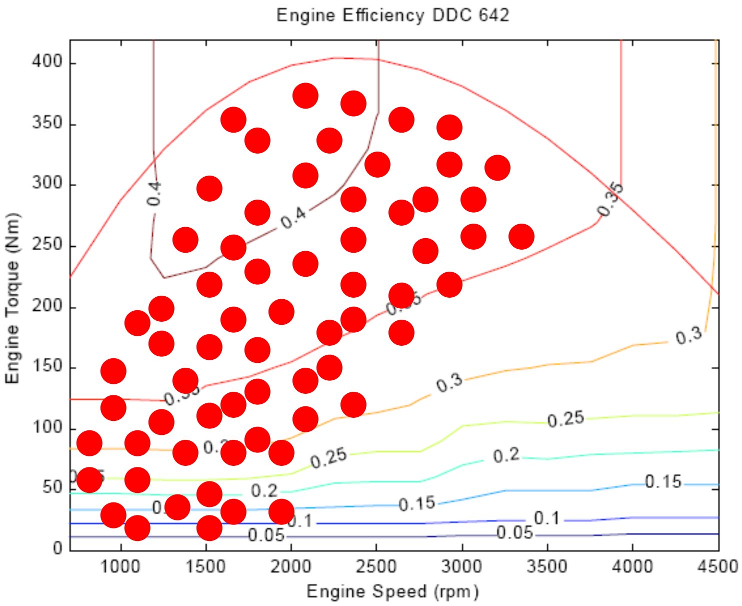

Figure 1.2. Conventional Vehicle Engine Operating Points [1]

Engine efficiency maps are presented using contours indicating either efficiency or fuel consumption in terms of mass per unit energy. The red curve at the top is the maximum torque limit. The red dots in Figure 1.2 indicate the periodically recorded operating points of a conventional vehicle [1]. It should be noted that more than half of the points lie under the contour of 35% efficiency. The operating range mostly lies within the part of the graph where efficiency is low.

In a conventional vehicles the braking torque is generated via friction which dissipates the energy as heat. There is no storage mechanism to recuperate the brake energy.

1.2 Electric Vehicles

An electric vehicle (EV) has a powertrain consists of an electric motor, an energy storage device and a controller. The electric motor provides the power required to propel the vehicle. The energy storage device stores the electrical energy and supplies it to the electric motor. Although the energy storage device could be a an ultra-capacitor system as well as a battery pack or a combination of both. Figure 1.3 shows the layout of a typical electric vehicle.

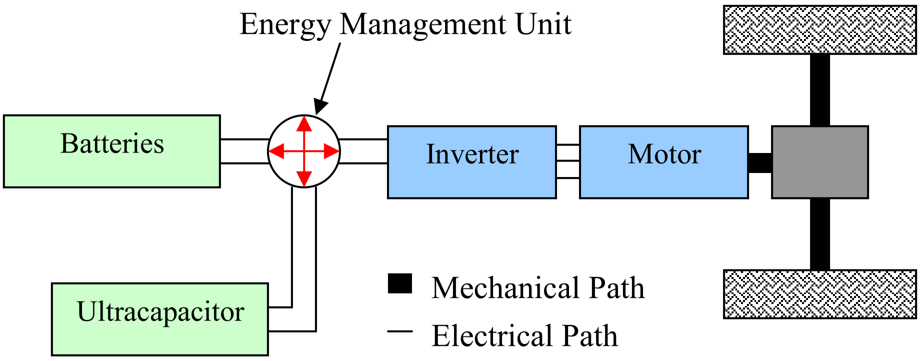

Figure 1.3. An electric vehicle drivetrain

The main advantage of EV is that they don't emit exhaust gases. They are called zero emission vehicles (ZEVs), but it is important to mention that the generation of electrical power may not be free of emissions. According the "wells to wheels" concept, the emissions of the vehicle must be increased by the emissions of any kind related to the vehicle such as production and transportation.

The other advantage of EVs is their noiseless operation. EVs would decrease the noise level in cities significantly. EVs are competitive with conventional vehicles in complexity and price and even less complicated to control.

On the other hand, the disadvantage of the electric vehicle is its short range. It is limited by the capacity of the battery pack. Present battery technology may provide up to a certain mileage on a single charge depending on vehicle size, battery size and capacity and driving conditions.

The short range of EVs is not actually the main problem. While conventional vehicles can be refilled in few minutes, batteries of EVs need several hours of charging once they were fully discharged. Consumers are not used to being without their vehicles for hours every day. As a conclusion it may take a lot more to recharge the batteries as it takes to fill up the fuel tank for the same trip.

1.3 Hybrid Vehicles

The concept of a hybrid vehicle, one which operates from two distinct energy sources, was developed in the early twentieth century with a patent being issued to H.

Pieper in 1905. In these early hybrids, the electric motor augmented the power of the relatively weak ICE during acceleration. However, before these hybrids went into commercial production, ICE technology had progressed to the point that the assistance of the electric motor was no longer needed [2].

Hybrid vehicles provide an alternative to present automotive designs while research to develop advanced energy storage continues. They offer higher efficiency and reduced emissions when compared with conventional automobiles, but they can also be designed to overcome the range limitations of an electric vehicle.

Hybrid vehicles utilize two different energy sources, usually an electric motor and an ICE to power the vehicle systems. The electric motor is used to improve the energy efficiency and vehicular emissions while the engine provides extended range capability.

Although the widespread use of electric vehicles would require an investment in new infrastructure, current facilities can accommodate hybrid vehicles since the engine runs on gasoline, diesel, or Compressed Natural Gas (CNG), which are widely available. The batteries used to power the electric motor can be either charged by the engine or the electric machine, during regenerative braking.

Although many different configurations of power sources and converters are possible in a hybrid electric power plant, there are two generally accepted classifications, series and parallel.

In a series hybrid, only one traction source provides torque to the wheels while the other is used to recharge an energy accumulator, usually a battery pack. The series configuration represents a typical design where the engine generator combination charges the batteries and only the motor actually provides propulsion.

A disadvantage of the series hybrid arrangement is that three distinct energy converters for generation, storage and motoring are required, increasing the vehicle weight and cost decreasing the overall efficiency due to excessive energy conversions.

In series hybrid vehicles, if the energy stored in the baterries/ultracapacitors is high enough to supply the tractive power than it is possible to shut down the engine to save fuel (or to stop injection). However frequent start/stops may cause discomfort by ride and stop the auxiallary units on the engine (Steering Unit, Air compressor to fill the braking tanks, hydraulic engine cooling fans are all drived through the engine crankshaft) which may lead to safety critic situations. Therefore the start/stop strategy is eliminated in this project.

One solution may be to drive the the engine continuously with the auxillary units on it through the generator which may be controlled in motoring mode. Controlling the generator in motoring mode is a possible solution which can consume the excessive brake energy and at the same time stop the fuel injection of the engine (saving fuel). This sounds logical if the energy in the ultracapacitors is generated more efficiently than in a conventional powertrain.

This operation can be depicted graphically, as shown Figure 1.4, wherein the operating points of the engine are moved to a higher efficiency region, due to the basic operating principle of hybrid electric vehicles.

The figure gives examples of the engine BSFC maps where the efficiency is shown by the contour lines similar to Figure 1.4 and the central part of closed curves is the more efficient operating region of the engine.

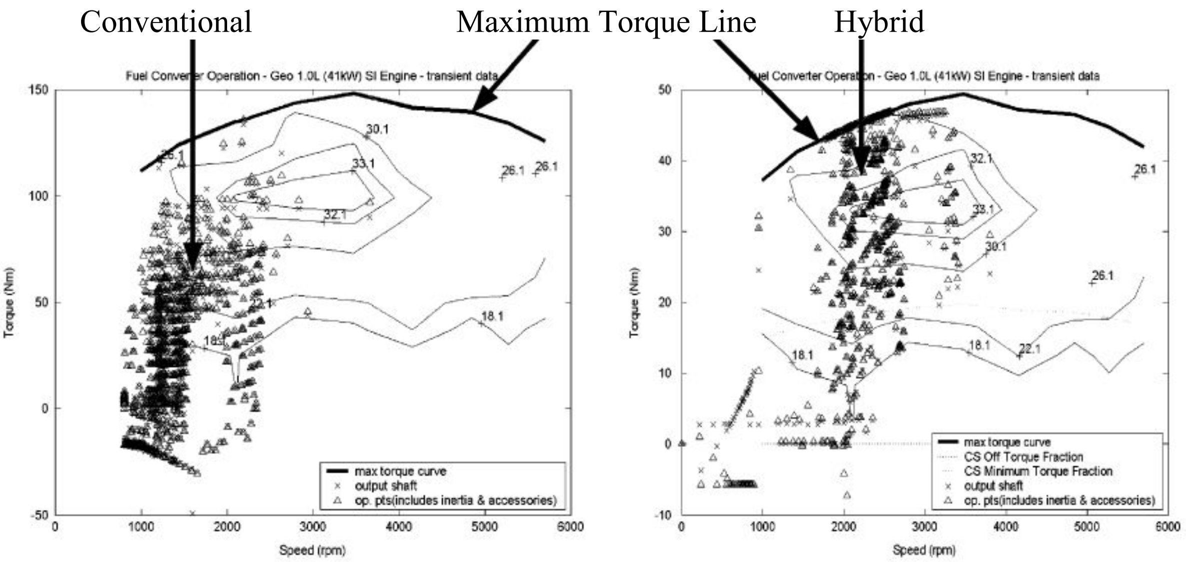

Figure 1.4. Operating region for engines of conventional(left) and hybrid(right) vehicle [3]

These maps are the tools to calculate the fuel consumption per unit energy. For Hybrid vehicles it is always desirable to run the engine within the most efficient regions as long as possible to minimize the overall fuel consumption. In order to do so, the amount of energy and the time period in which this amount of energy will be consumed should be decided.

Another point to mention about hybrid vehicles is the fact that ultracapacitors have limited energy storage and can not store all of the brake energy if the highest allowable voltage limit is reached. Therefore there exists brake resistors to draw the excessive kinetic energy.

However not to being able to convert mechanical energy back into electrical energy but to dissipate it into atmosphere is a source of inefficiency. The energy and power management unit should be designed to minimize or cancel the deployment of resistive units during brake assistance.

1.3.1 Parallel Hybrid Vehicles

Parallel Hybrid Electric Vehicles have both the engine and the electric motor coupled directly to the wheels through some type of mechanical transmission. This direct coupling dictates that the internal combustion engine undergoes significant transients in speed but not in torque as it can be assisted by the electric motor.

From the vehicle's emissions standpoint the speed transients are a drawback compared to the series setup.

On the other hand the motor can be used to level the torque load that the hybrid is subjected to operate in a more efficient range. Typically engines operate more efficiently at higher loads. When a low load is required by the vehicle the engine can either be shut off while the motor alone drives the vehicle (not desirable since auxillary units should then be electrcially driven) or the engine load can be increased by the motor as it acts as a generator.

In parallel hybrids, the engine is typically not allowed to operate in an inefficient range at low load as it does in a conventional vehicle. In turn it supplies an extra energy to the batteries to be stored for later use. The greatest advantage of a parallel hybrids over series hybrids with the same size components is in its performance. Parallel hybrid vehicles have the potential to use both their electric motor and engine as power sources, simultaneously powering up the vehicle.

The parallel configuration is a typical design, where both the engine and the electric motor can provide torque to drive the wheels where this mechanical coupling leads to another disadvantage of the parallel design: the lack of efficiency while recuperating energy during braking.

There are two basic types of parallel hybrid vehicle. One is when the main power source is the engine and the electric motor assists it. The other one is when the electric motor is the main power source and the engine assists it.

Figure 1.5 shows the Power Flow Diagram for Parallel HEV when the electric motor assists the ICE through a mechanical coupled clutch.

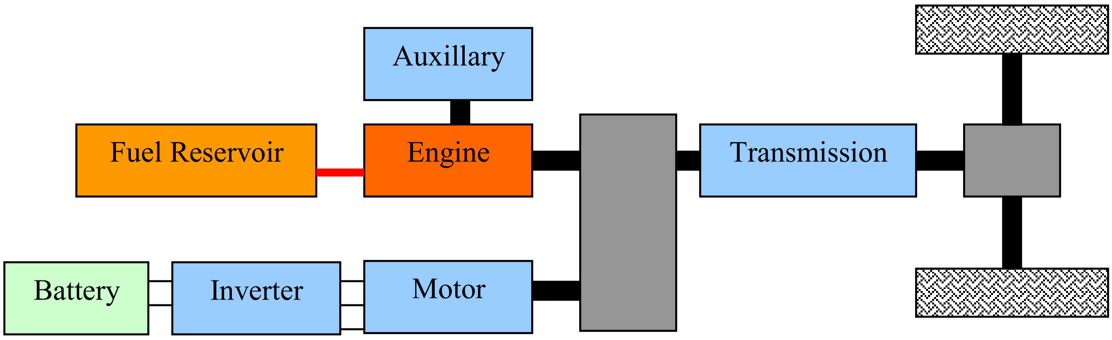

Figure 1.5. Electric Motor and engine coupled before the transmission

Another version of parallel HEVs is when the electric motor is after the transmission. Figure 1.6 shows the Power Flow Diagram for Parallel HEV when the engine assists the electric motor. In that case the inefficiency of the transmission during the regenerative braking does not affect the power generated from the electric motor since the clutch system is a part of the transmission.

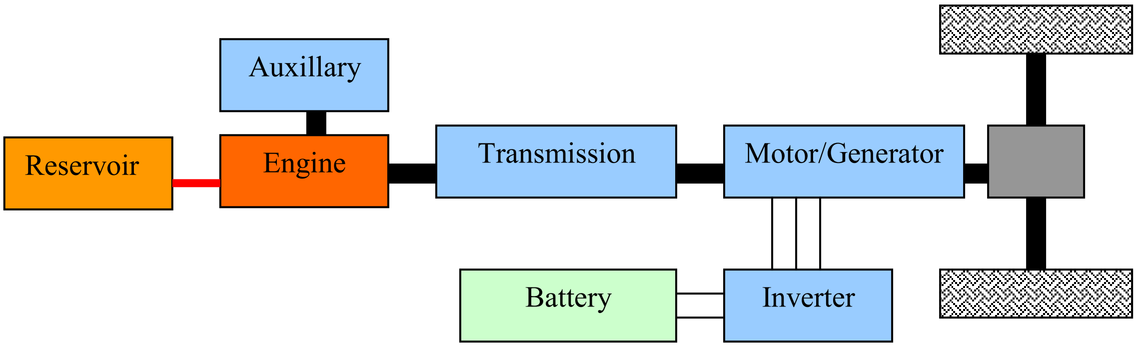

Figure 1.6. Electric motor is coupled after the transmission

The hardware of a parallel hybrid electric vehicle is less expensive than a series type because one electric motor is enough (motoring and generating). The control, on the other hand, is much more complicated since the torque is coupled because of physical coupling between the engine and the motor so the torque is coupled.

1.3.2 Series Hybrid Vehicles

Series HEVs have the motor coupled either straight to the differential through a gear or chain drive while the internal combustion engine is coupled to the electric generator. Figure 1.7 illustrates the typical layout of a series hybrid electric vehicle.

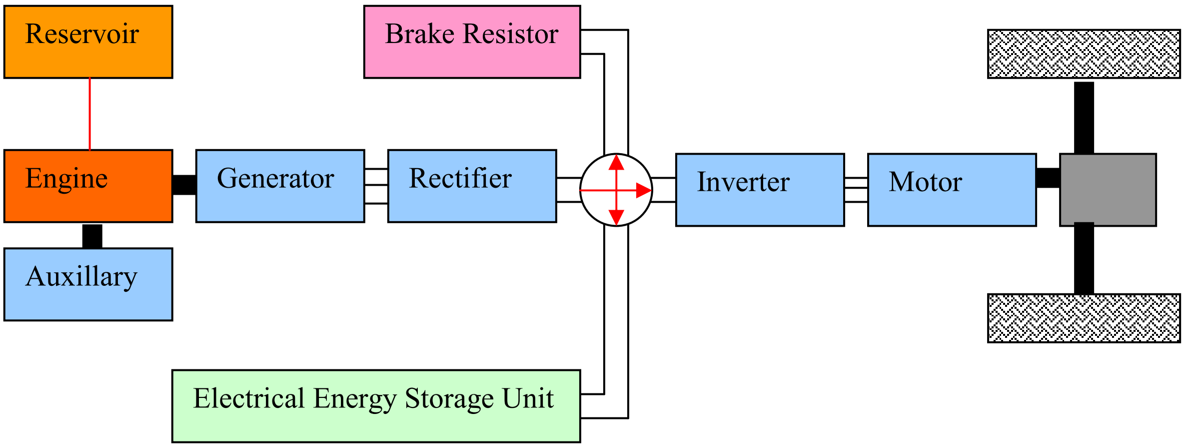

Figure 1.7. Series Hybrid Vehicle Architecture

In a series hybrid vehicle, the combustion engine drives an electric generator instead of a mechanical coupling (directly driving the wheels). The generator charges an electrical energy storage unit which is then deployed to power an electric motor that moves the vehicle. Absence of a physical coupling between the engine and the transaxle can reduce the transient operation of the engine that is especially helpful from an emissions standpoint allowing optimal fueling and ignition control. Under heavy acceleration often an engine will fuel heavily to prevent a misfire situation due to an instantaneously high air to fuel ratio.

The drawback to a series hybrid electric vehicle is the mechanical to electrical and again back to mechanical prolonged energy conversion losses. However absence of a mechanical coupling makes it possible for the engine to operate in its most efficient region [1].

A series hybrid vehicle engine operating points on an efficiency map is illustrated in the Figure 1.8.

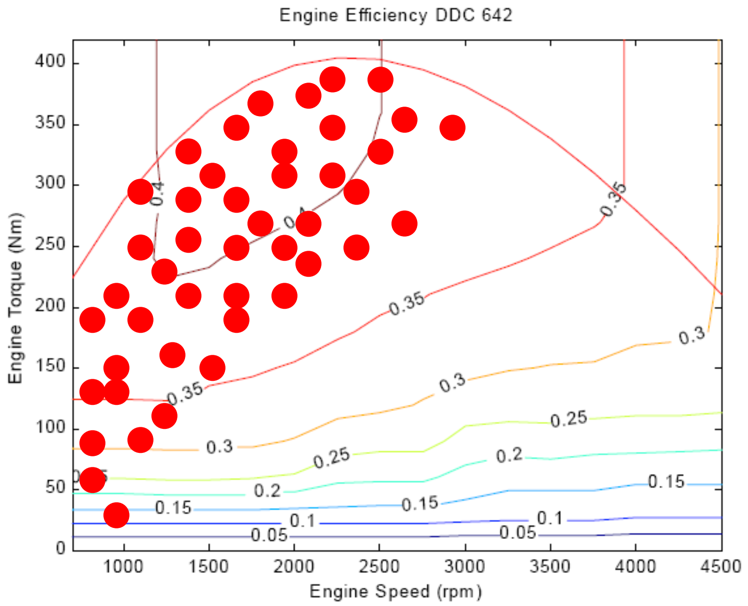

Figure 1.8. Series hybrid vehicle engine operating region [1]

The fact that the engine can operate in its most efficient region compensates the energy conversion losses and results fuel economy improvement that is significant in the city and moderate on the highway. The design also offers regenerative braking to capture the braking energy and store it in the battery instead of wasting it on the brake disks in the form of heat.

The hardware of the series hybrids is more expensive than the hardware of EV or conventional vehicles because it requires two electric machines and an engine. In addition to that its control of it is more complicated than the control of electric and conventional vehicles.

The control strategy is developed in such a fashion that the battery is always charged on board, and thus the driving distance is never limited by the life of the battery. As mentioned previously, the capacity of the battery is the biggest disadvantage of the electric vehicle, and by charging the batteries on board, this disadvantage is eliminated. The control strategy, which causes the engine to run at a desired torque and speed condition, is also supposed to ensure that the battery remains charged to a certain level at all time.

When large amounts of power are required, the motor draws electricity from both the electrical energy storage and the generator. A transmission is not needed at all. Some vehicle designs have separate electric motors for each wheel. Series hybrids can also be fitted with an ultracapacitor to store regenerative braking energy, which can improve efficiency by minimizing the losses due to high power transmission.

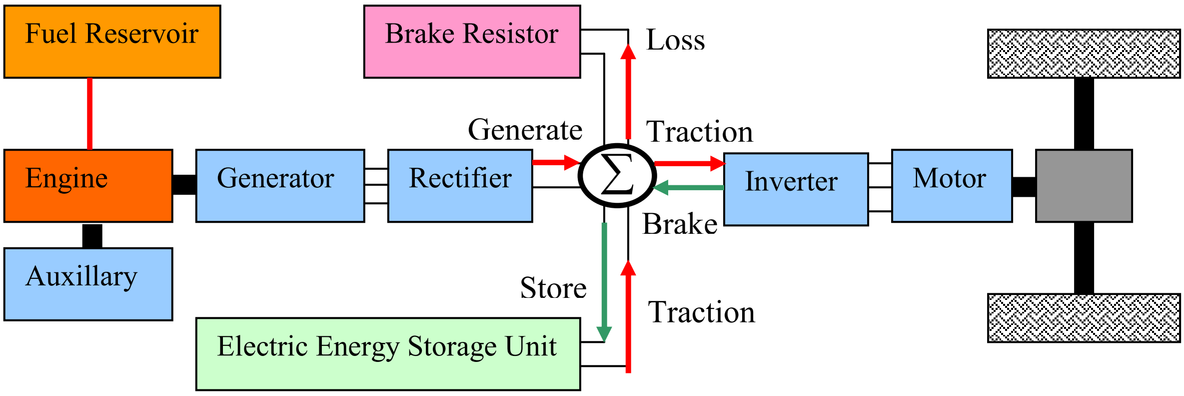

Figure 1.9. Power flow in series hybrid vehicles

During long-distance highway driving, the combustion engine will need to supply all of the energy, in which case a series hybrid will be less efficient than a conventional system because the power from the combustion engine must run through both the generator and electric motor, so due to the prolonged conversion path the engine-to-transmission efficiency becomes 70% - 80%, which is less than a conventional mechanical drivetrain having an engine-to-wheel efficiency of 90%.

It is clear that the real advantage of hybridization lies within the ability to recuperate the kinetic energy of the vehicle back to electrical energy during braking and in supplying transient peak energy requirements where the engine operates in an inefficient region.

1.4 Drive Cycles

In urban areas, a vehicle can be driven on the road for different types of roadways (e.g. local roadways, arterial and freeway). A drive cycle is a series of data points representing the speed of a vehicle versus time. It is a trip defined as a driving path from an origin to a destination with a predefined travel speed, time, acceleration and deceleration. Drive cycles are produced by different countries and organizations to assess the performance of vehicles in various ways, as for example fuel consumption and emissions.

For this project, the energy and power management methods developed will be tested for different drive cycles in simulation environment.

SORT1 drive cycle of International Association of Public Transport (UITP) which is 1 km long and takes approximately 160 seconds to complete. This cycle is composed of three accelerations with maximum speeds of 20km/h, 30km/h and 50km/h each.

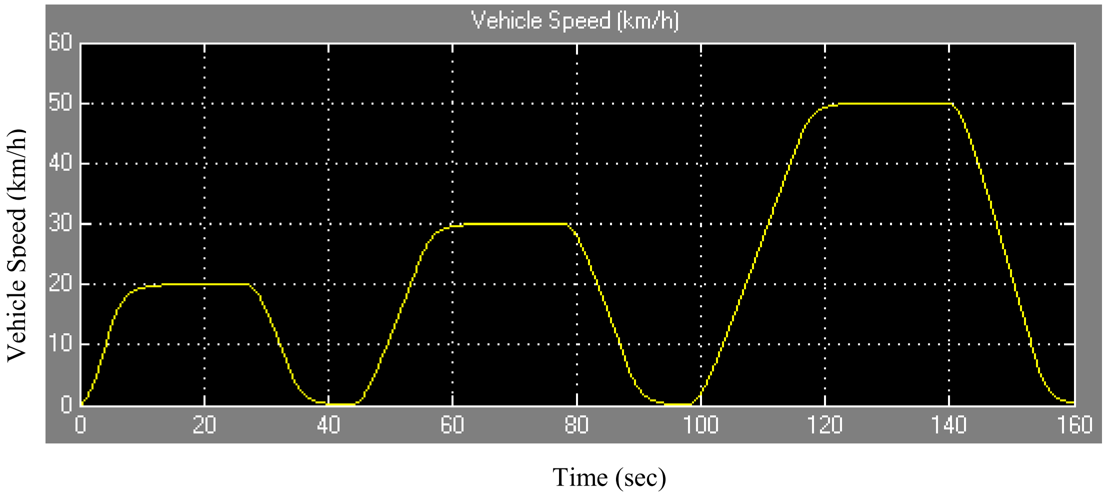

Figure 1.10 SORT 1 Drive Cycle

The New York City (NYC) drive cycle is representative of actual observed driving patterns of transit buses in New York City. It is a short test cycle characterized by frequent stops, fast average acceleration, and low speed. NYC drive cycle is 1 km long and takes approximately 600 seconds to complete. Eleven accelerations of NYC are structured to simulate the real traffic conditions.

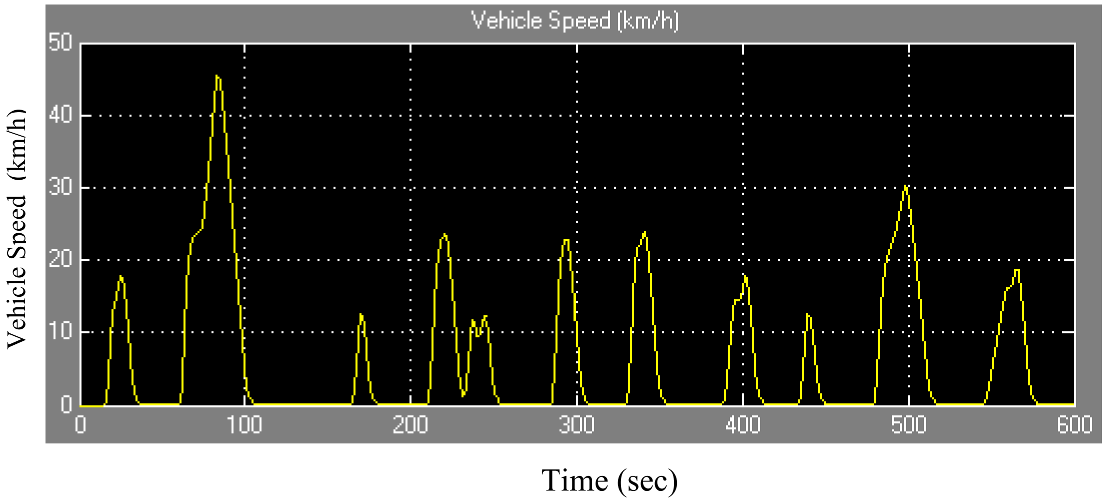

Figure 1.11. NYC Drive Cycle

Both Drive Cycles are independent of the traffic condition or the grade of the road and therefore frequently used as a reference for new vehicle testing.

CHAPTER 2

BACKGROUND

Because of the variations in Hybrid Electrical configurations, different power control strategies are necessary to regulate the power flow to and from different components. These control strategies aim to satisfy a number of goals. The major ones are to achieve:

- maximum fuel economy
- minimum emissions
- minimum system costs
- good driving performance

The design of power control strategies for HEVs involves different considerations. Some key considerations can be summarized as in [2]:

Optimal engine operating point: The optimal operating point on the torque speed map of the engine can be based on the maximization of fuel economy, the minimization of emissions, or even a compromise between fuel economy and emissions.

Optimal engine operating curve: In case the engine needs to deliver different power demands, the corresponding optimal operating points constitute an optimal operating curve. A typical optimal operating line of an engine, in which the optimization is based on the minimum fuel consumption, which is equivalent to maximum fuel economy.

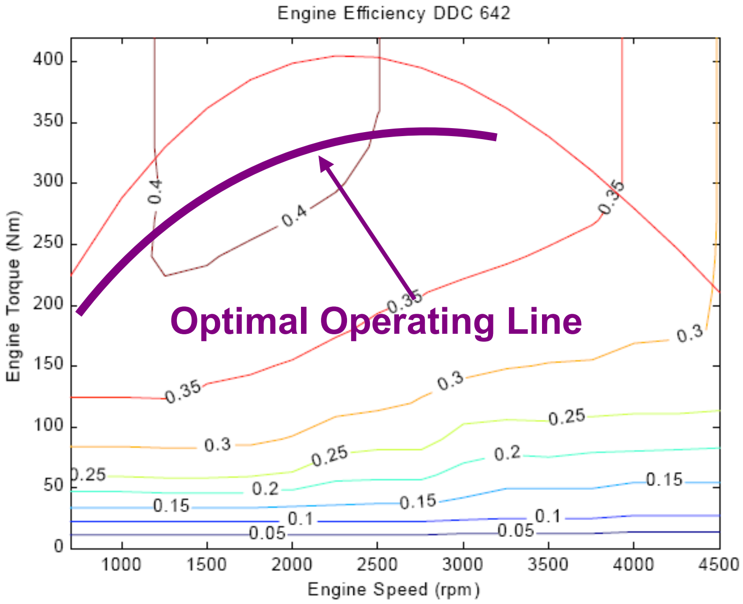

Figure 2.1. An optimal operating line based on minimum fuel consumption [2]

Optimal engine operating region: The engine can have a preferred operating region on the torque speed map, in which the fuel efficiency remains optimum. It is different from optimal engine operating curve due to the fact that there are infinite number of curves within a region but only one of them is optimal, however it may not be possible to track a single curve to implement an algorithm (i.e. in parallel hybrid vehicles) but may be possible to stay within a region instead.

Minimum engine dynamics: The engine operating speed needs to be regulated in such a way that transients are avoided, hence minimizing the engine dynamics.

Minimum engine speed: When the engine operates at low speeds, the fuel efficiency is very low. The engine should be cut off when its speed is below a threshold value.

Minimum engine turn-on time: The engine should not be turned on and off frequently; otherwise, it results in additional fuel consumption and emissions. A minimum turn-on time should be set to avoid such draw backs.

Proper battery capacity: The battery capacity needs to be kept at a proper level so that it can provide sufficient power for acceleration and can accept regenerative power during braking or going downhill. When the battery capacity is too high, the engine should be turned off or operated idly. When this capacity is too low, the engine should increase its output to charge the battery.

Safety battery voltage: The battery voltage may be significantly altered during discharging, generator charging or regenerative charging. This battery voltage should not be over-voltage or under-voltage; otherwise, the battery may be permanently damaged.

Relative distribution: The distribution of power demand between the engine and battery should be proportionally divided during the driving cycle.

Geographical policy: In certain cities or areas, the HEV needs to be operated in the pure electric mode. The changeover should be controlled manually or automatically.

When compared, most of the power management strategies or algorithms for HEVs could be summarized in three categories, namely static or rule based algorithms, dynamic programming or optimization strategies and algorithms using fuzzy logic and neural network control techniques.

2.1 Static Optimization Methods (Rule Based Algorithms)

Static optimization methods or rule based algorithms are utilizing point-wise optimizations which decide the proper power flow between different power sources according to the optimization made for fuel efficiency and vehicle performance.

2.1.1 The rule-based energy management strategy for Parallel Hybrids

The design process starts from interpreting the driver pedal signal as a power request. According to the power request, an energy management controller determines the power flow in the hybrid powertrain. The operation of this controller can be divided into three modes [7].

2.1.1.1 Normal Mode

Based on the engine efficiency map shown in the Figure 2.2, a pre-selected “motor only” power line and “power assist” power line, are chosen. If the total power request is less than the “motor only” power level, the electric motor will supply the requested power. Beyond “motor only” power line, the engine replaces the motor to provide the total power request. Once the power request exceeds what the engine can efficiently generate, “power assist” power line, the motor is activated to supply the additional power. In this mode, the engine always operates within the high efficiency region.

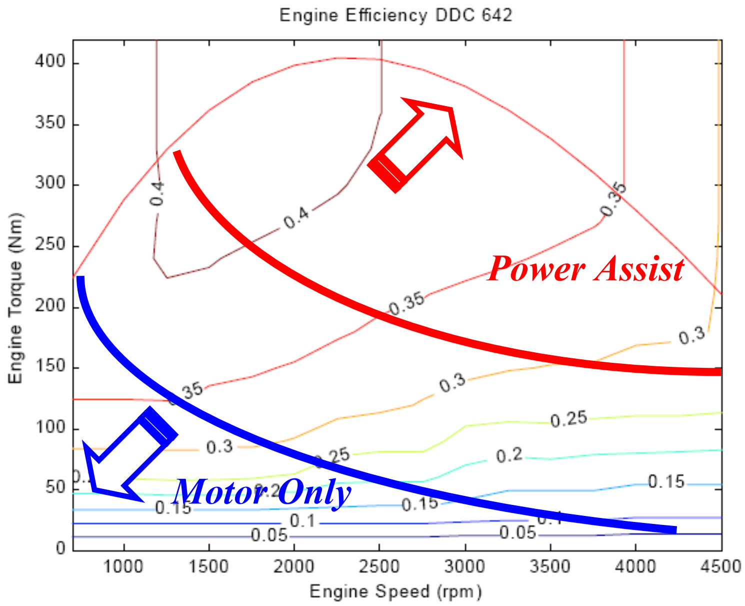

Figure 2.2. Rule based energy management strategy

2.1.1.2 Charging Mode

A charge-sustaining strategy is implemented to assure that the battery State Of Charge (SoC) stays within preset upper and lower bounds. The 55-60% SoC range is chosen for efficient battery operation. When the SoC drops below the low limit min $SoC_{\min}$, the energy management controller will switch to the battery recharge mode. A preselected recharge power level is added to the driver power request, and the motor power command is forced to become negative to recharge the battery. One exception is that when the total power request is less than the “motor only” power level, the motor will still propel the vehicle to avoid the engine operating in this inefficient region. The battery recharge mode will not stop until the SoC hits the upper bound maximum SoC (60%).

2.1.1.3 Braking Mode:

When the driver steps on the brake pedal, it is interpreted as a negative power request. The regenerative braking is activated to absorb the braking power. However, when the braking power request exceeds the regenerative braking capacity, the hydraulic braking will be activated to assist the vehicle deceleration.

The algorithm of the rule-based energy management strategy defined above is summarized in equations 2.1-2.4:

$$\begin{array}{l}
\text{IF } \; SoC < SoC_{\min} \\
Flag_{charge} = True, \quad P_{total} = P_{request} + P_{charge} \\
\text{IF } \; SoC > SoC_{\max} \\
Flag_{charge} = False, \quad P_{total} = P_{request}
\end{array} \tag{2.1}$$

where

$Flag_{charge}$ is the flag for charging enable

P_{total} is the total power generated

$P_{request}$ is the demanded power of the vehicle

P_{charge} is the charging power to the battery

$$\begin{array}{l}
\text{IF } \; Flag_{charge} = False \text{ and } P_{request} > 0 \text{ (Normal Mode) THEN} \\
\quad \text{IF } \; P_{total} \le P_{motor\_only} \\
\quad\quad P_{engine} = 0, \; P_{motor} = P_{total} \\
\quad \text{IF } \; P_{motor\_only} \le P_{total} \le P_{power\_assist} \\
\quad\quad P_{engine} = P_{total}, \; P_{motor} = 0 \\
\quad \text{IF } \; P_{power\_assist} < P_{total} \le P_{power\_assist} + P_{motor\_\max} \\
\quad\quad P_{engine} = P_{power\_assist}, \; P_{motor} = P_{total} - P_{power\_assist} \\
\quad \text{IF } \; P_{total} > P_{power\_assist} + P_{motor\_\max} \\
\quad\quad P_{engine} = P_{total} - P_{motor\_\max}, \; P_{motor} = P_{motor\_\max}
\end{array} \tag{2.2}$$

where

P_{motor_only} is the power level for motor only power line in Fig. 2.2

P_{engine} is the power generated by the engine

P_{power_assist} is the power level for power assist line in Fig 2.2

P_{motor} is the electric motor power

$P_{motor\_\max}$ is the maximum available electric motor power

IF $Flag_{charge} = True$ and $P_{request} > 0$ (Charging Mode) THEN

$$\begin{aligned}
&\text{IF } P_{total} \le P_{motor\_only} \\
&\quad P_{engine} = 0,\ P_{motor} = P_{request} \\
&\text{IF } P_{motor\_only} < P_{total} \le P_{engine\_\max} \\
&\quad P_{engine} = P_{total},\ P_{motor} = -P_{charge} \\
&\text{IF } P_{total} > P_{engine\_\max} \\
&\quad P_{engine} = P_{engine\_\max},\ P_{motor} = P_{request} - P_{engine\_\max}
\end{aligned} \tag{2.3}$$

where

$P_{engine\_\max}$ is the maximum engine power

IF $P_{request} < 0$ (Braking Mode) THEN

$$\begin{aligned}
&\text{IF } P_{request} \ge P_{motor\_\min} \\
&\quad P_{engine} = 0,\ P_{motor} = P_{request},\ P_{brake} = 0 \\
&\text{IF } P_{request} < P_{motor\_\min} \\
&\quad P_{engine} = 0,\ P_{motor} = P_{motor\_\min},\ P_{brake} = P_{request} - P_{motor\_\min}
\end{aligned} \tag{2.4}$$

where

P_{brake} is the brake power demanded by the vehicle

$P_{motor\_\min}$ is the minimum electric motor power to recuperate energy

2.1.2 The rule-based energy management strategy for Series Hybrids

Based on the status of the SoC and the power demand, the power will be assigned to the Engine/Generator set (APU), to the battery, or to a combination of both. The strategy uses a "Thermostat" in the background. This has been used mainly to charge the battery in a consistent way. Based on the status of the Thermostat, the assignment of power is determined as follows; For the engine, a curve that connects the most efficient speed/torque operating points is defined. This gives a range of powers, bounded by a minimum $P_{\min}$ and a maximum $P_{\max}$ values, which can be delivered by the engine when it is operated efficiently.

If the lower SoC is reached, then the APU will be on and the default output power of the APU is the optimal operating point (maximum efficiency) power. However, if more power than $P_{\min}$ is needed, then the APU will supply it. If the power demand exceeds $P_{\max}$ then both sources (APU and the battery) will supply power to satisfy the demand.

IF $SoC \le SoC_{low}$ THEN

$$\begin{aligned} &P_{APU} = \max(P_{opt}, P_{demand}) \\ &P_{APU} \le P_{\max} \\ &P_{Battery} = P_{demand} - P_{APU} \end{aligned} \tag{2.5}$$

where

P_{APU} is the power generated by the engine generator set

P_{opt} is the optimal operating point power

P_{demand} is driver's power demand

On the other hand, if the higher SOC is reached, then the default output power from the APU is zero (engine is idle). However, if the power demand exceeds the $P_{\min}$ limit, at any moment, then the APU will start delivering power. The battery will satisfy the power demand if the latter is less than $P_{\min}$, in addition, the battery will help the APU if the power demand is more than $P_{\max}$.

IF $SoC \ge SoC_{high}$ THEN

IF $P_{demand} \le P_{\min}$ THEN

$$\begin{aligned} &P_{APU} = 0 \\ &P_{Battery} = P_{demand} \end{aligned} \tag{2.6}$$

IF $\mathrm{P}_{\min} \le P_{demand} \le P_{\max}$ THEN

$$\begin{aligned} &P_{APU} = P_{demand} \\ &P_{Battery} = 0 \end{aligned} \tag{2.7}$$

IF $P_{demand} \ge P_{\max}$ THEN

$$\begin{aligned} &P_{APU} = P_{\max} \\ &P_{Battery} = P_{demand} - P_{APU} \end{aligned} \tag{2.8}$$

In any case regenerative braking is active if power demand is negative. The engine will not be shut off under this strategy, it will be idle if no APU power is needed. This causes some extra fuel consumption, but there are advantages of this by limiting engine cycling on and *0%* moreover, the engine will be warm all the time which is better for emissions [8].

2.2 Dynamic Optimization Methods

In dynamic programming (DP) strategies, the optimizations could be made for dynamic system parameters changing with time. Under transient conditions, these dynamic optimizations give more accurate results when compared with the fixed point optimization of steady-state parameters [3-6].

2.2.1 Optimization Theory Overview

Optimization techniques are used to find a set of design parameters, $x = \{x_1, x_1, ..., x_n\}$ for a given system, that can in some way be defined as optimal. In a simple case this might be the minimization or maximization of some system characteristic, called a cost/objective function that is dependent on x.

In a more advanced formulation the objective function, $f(x)$, to be minimized or maximized, might be subject to constraints in the form of equality constraints, $G_i(x) = 0$ ($i = 1,...,m_e$); inequality constraints, $G_i(x) \leq 0$ ($i = m_e + 1,...,m$); and/or parameter bounds, x_l, x_u. A General Optimization Problem description is stated as

$$\min_x f(x) \tag{2.9}$$

Subject to the following constraints:

$$\begin{aligned} &G_i(x) = 0 \quad i = 1,...,m_e \\ &G_i(x) \leq 0 \quad i = m_e + 1,...,m \end{aligned} \tag{2.10}$$

where

x is the vector of dimension n design parameters,
$f(x)$ is the objective function, which returns a scalar value,
and the vector function $G(x)$

It returns a vector of length m containing the values of the equality and inequality constraints evaluated at x [9].

2.2.2 Dynamic Programming Based Algorithm

The DP based algorithms mentioned in references [3] and [6] usually depend on a model with an optimization schemes aiming to minimize an objective function in order to compute the best control strategy. For a given drive cycle, the optimal operating strategy to minimize fuel consumption, or combined fuel consumption/ emissions can be obtained.

$$J = \sum_{k=0}^{N-1} W_{f,k} \tag{2.11}$$

where
J is the total fuel consumption
N is the total number of steps of the driving cycle.
k is the time index,
$W_{f,k}$ is the engine fuel flow rate.

With the proper inequality constraints, the engine speed, SoC, fuel consumption and motor torque are bounded within predetermined limits and with the equality constraints, the vehicle is guaranteed to follow the specified driving cycle with the suitable speed and acceleration values.

There can be numerous choices of objective function in HEVs. In reference [6], the aim of the dynamic optimization is to minimize a cost function, whose sum is the fuel consumption of the Parallel HEV for a defined driving cycle in order by utilizing a sequence of control decisions for the engine torque, Electric Motor torque, and gear selection of the Parallel Hybrid Electric Vehicle:

$$\min J = \min_{k=0,1,\ldots,N-1} \sum_{k=0}^{N-1} W_{f,k} \tag{2.12}$$

The torque balance equation to be satisfied is:

$$T_{w,k}(T_{e,k} + T_{m,k}, g_k, \omega_{wr,k}) + T_{b,k} = T_{wr,k} \tag{2.13}$$

where

$T_{w,k}$ is the wheel torque,

$T_{e,k}$ is engine torque,

$T_{m,k}$ is the motor torque,

g_k is the transmission gear number,

$T_{b,k}$ is the friction braking torque,

$\omega_{wr,k}$ is the requested wheel speed,

$T_{wr,k}$ is the requested wheel torque

The SoC of the battery is computed as follows:

$$SoC_{k+1} = SoC_k + f(SoC_k, T_{m,k}, \omega_{m,k}) \tag{2.14}$$

With the proper inequality constraints; the engine speed, SoC, fuel consumption and motor torque are bounded within predetermined limits. The augmented cost function to be minimized for fuel efficiency improvement then becomes:

$$\min J = \min_{k=0,1,\ldots,N-1} \left\{ \sum_{k=0}^{N-1} (W_{f,k} + L_k + G_N) \right\} \tag{2.15}$$

where

L_k is the gear change penalty function,

G_N is the SoC terminal penalty

An efficient and accurate solution to this problem depends not only on the size of the problem in terms of the number of constraints and design variables but also on characteristics of the objective function and constraints. When both the objective function and the constraints are linear functions of the design variable, the problem is known as a Linear Programming (LP) problem. Quadratic Programming (QP) concerns the minimization or maximization of a quadratic objective function that is linearly constrained.

For both the LP and QP problems, reliable solution procedures are readily available. More difficult to solve is the Nonlinear Programming (NP) problem in which the objective function and constraints can be nonlinear functions of the design variables. A solution of the NP problem generally requires an iterative procedure to establish a direction of search in every major iteration. This is usually achieved by the solution of an LP, a QP, or an unconstrained sub-problem [9].

2.3 Fuzzy Logic Algorithms

Fuzzy Logic can be seen as an extension of conventional boolean logic. Fuzzy Logic can handle the concept of partial truth, i.e. truthvalues between "completely true" and "completely false". Linguistic variables instead of numerical or Boolean values are used in Fuzzy Logic. Such variables are combined to express rules, i.e. linguistic input/output associations. Fuzzy Logic is suitable to solve many types of "real-world" problems, especially where a system is difficult to model, is controlled by a human operator or where vagueness is common [5].

In automotive engineering, Fuzzy Logic has for example been used in anti lock braking systems. The point of ABS is to monitor the braking system of the vehicle and release the brakes just before the wheels would lock.

The intention of using fuzzy logic control technique for HEV power management is to utilize the concept of “load-leveling”, which attempts to run the irreversible energy machines like ICE only in an efficient region while compensating the power demanded from the reversible energy device, i.e. Electric Machine is used during peak demands for leveling the load. Due to the unknown nature of future power demand, a charge sustaining strategy is also needed to keep the SoC level between preset bounds [6].

A fuzzy logic controller application for parallel hybrids is presented in reference [9] in order to display the potential of an operation strategy for HEVs. The controller utilizes the Electric Machine in a parallel HEV to force the ICE to operate at or near its peak point of efficiency or at or near its best fuel economy.

In the reference, two control strategies, which optimize the efficiency of the ICE and the fuel consumption respectively, are investigated. Efficient load leveling in an HEV where the ICE is the prime mover aims to move the actual operating point of the ICE as close to the point of best efficiency for every time step in the driving cycle. The resulting power difference will be leveled by the electrical machine and when the SoC capacity of the battery is filled up to the upper bound, the electric machine dominates the automobile's operation. Four different scenarios of the controller for locating actual operating point of ICE relative to the best efficiency point which is represented in Table 2.1 are as follows:

CASE	ω_ICE	T_ICE	Δα	T_EM
I	LOW	LOW	>0	<0
II	LOW	HIGH	<0	>0
III	HIGH	LOW	>0	<0
IV	HIGH	HIGH	<0	>0

Table 2.1. Four scenarios for best efficiency point operation

where

ω_ICE is the engine speed,

T_ICE is the engine torque,

Δα is the change in throttle command

T_EM is the torque of the electric machine

CASE 1: When engine speed and engine torque output are too low, until the ICE reach the best efficiency point, throttle command is increased while EM is operated as generator in order to maintain the overall powertrain output at a constant level and to prevent undesirable acceleration.

CASE II: When engine speed is too low while the engine output torque is too high, the throttle command is decreased to have the ICE approach the point of best efficiency while EM is utilized to adjust for the decrease in the ICE power output and maintain the overall powertrain output at a constant level.

CASE III: When engine speed is too high while the engine torque is too low, increasing the throttle command make the ICE approach the point of best efficiency and the excessive ICE power output is leveled by EM running as a generator.

CASE IV: When both engine speed and engine torque outputs are too high, the throttle command is decreased. The EM must operate to compensate for the reduction in ICE power output and maintain the overall powertrain output at a constant level.

A fuzzy logic controller application for series hybrids is presented in [13]. The controller utilizes ultracapacitors in a series HEV and a battery to operate at or near its best fuel economy. A strategy is considered to maintain the vehicle kinetic to electric energy balance correlation by regulating the SoC of the ultracapacitor bank as a function of the vehicle velocity, such that the sum of the energy stored in the ultracapacitor and the vehicle kinetic energy is kept constant.

$$E_{UC} + E_{KINETIC} = E\{K\} \tag{2.16}$$

It is subject to the constraints that battery and the ultracapacitor SoC ranges between the limits:

$$SoC_{batt,UC}\min \leq SoC_{batt,UC}(k) \leq SoC_{batt,UC}\max \tag{2.17}$$

The strategy is to ensure that the ultracapacitors are held at an acceptable state of charge such that the ultracapacitors are both capable of delivering peak power requests and receptive to regenerative power conditions.

In this strategy, only maximum battery power is varied throughout the decision with all other outputs held at constant values determined by design. As the strategy decision mechanism, fuzzy logic control is employed. As fuzzy logic permits systems to be controlled by heuristic representation of how the system behaves, this feature to generate the battery maximum power (Pbmax) reference output of the EMS. Pbmax is then fed forward to the Power Management System.

Dictated by the energy balance equation of vehicle kinetic energy to ultracapacitor potential energy, a fuzzy inference system is employed.

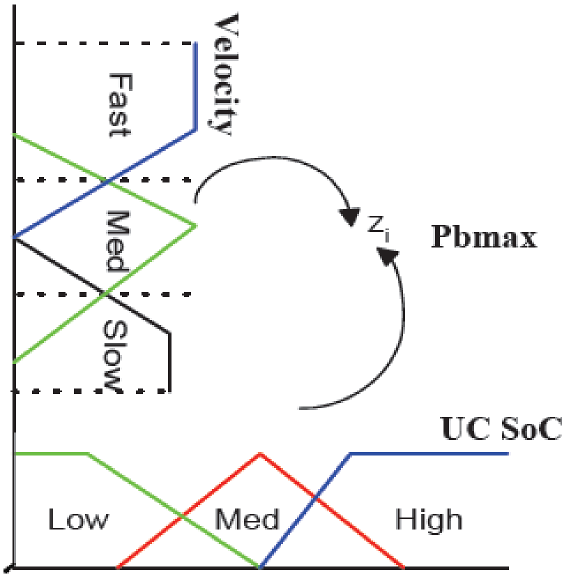

Figure 2.3. Fuzzy Logic Membership Functions

Rule1: The higher the vehicle speed, the lower the ultracapacitor SoC reference.

Rule2: The greater the ultracapacitor actual SoC deviation from the reference SoC, the higher or lower the battery maximum power.

The vehicle speed input is defined by three membership functions, I{Slow, Medium, Fast). Similarly, the ultracapacitor SoC membership function is defined by (Low, Medium, High}. With x1 and x2 as the state variables and z representing the output variable, the Fuzzy Inference Surface (FIS) is represented as a two input one output system in a FIS Surface as follows;

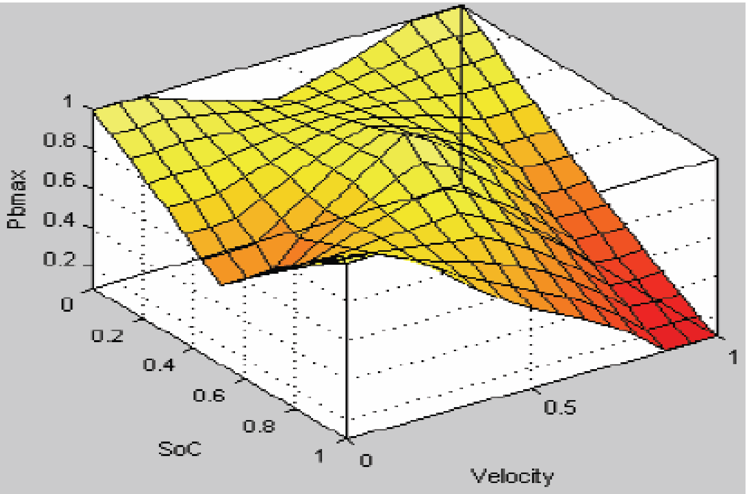

Figure 2.4. Fuzzy Inference Surface

A finite state machine with selectable regulation modes in each state is illustrated in Fig. 2.5. The operating states can transit between seven normal operating states. The additional state Brake Resistor (BR) only occurs when the ultracapacitors are fully charged and the batteries are unreceptive to regenerative power. In such an event, the DC bus voltage rise is limited by the activation of the dynamic brake resistor.

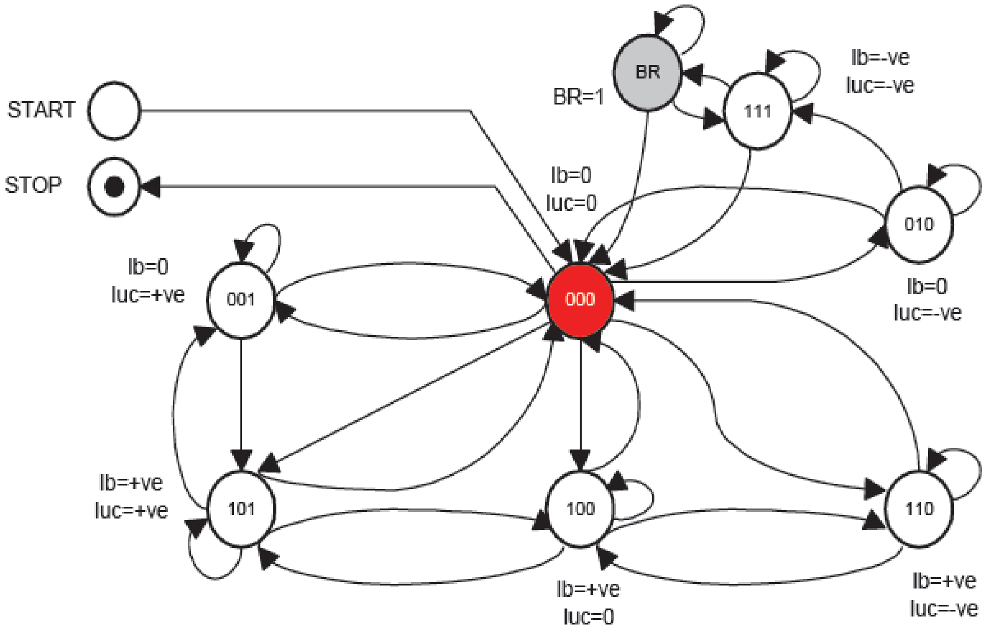

Figure 2.5. Finite States

The following table describes the possible states the vehicle experiences during acceleration and deceleration cycle.

Case	Battery	Ultracaps	Operating condition
0	Transition	Transition	Zero load condition or zero crossing to next state
1	Stillstate	Discharging	Conditions require only the ultracapacitors to service the load
2	Discharging	Stillstate	Battery is generating within operating constraints and ultracapacitors are at constant level
3	Discharging	Discharging	Both Battery and Ultracapacitors are discharging within the specified discharge rate and power levels
4	Discharging	Charging	Battery is servicing all load demands and charging the ultracapacitors
5	Stillstate	Charging	Ultracapacitors are charging via regenerative DC Bus Power
6	Charging	Stillstate	Ultracapacitors are fully charged and surplus power is diverted to battery to charge.
BR	Stillstate	Stillstate	Activation of the dissipative brake resistors for failsafe operation

Table 2.2. Description of Finite States

2.4 Summary of the Existing Methods

In summary, when compared, most of the power management strategies or algorithms for HEVs could be summarized in three categories, static or rule based algorithms, dynamic programming or optimization strategies and algorithms using fuzzy logic control techniques.

Static optimization methods or rule based algorithms are utilizing point-wise optimizations which decide the proper power flow between different propulsion sources according to the optimization made for fuel efficiency and vehicle performance whereas in dynamic programming strategies, the optimizations could be made for dynamic system parameters changing with time. Under transient conditions, these dynamic optimizations give more accurate results when compared with the fixed point optimization of steady-state parameters. Algorithms using fuzzy logic control strategies are also investigated for HEV applications, however these are rather rare due to their complex nature and hard implementability to the vehicles.

CHAPTER 3

PROBLEM DEFINITION

Contrary to static rule-based algorithms, the dynamic optimization approach relies on a dynamic model to compute the best control strategy. In general, algorithms resulting from dynamic optimization approaches are more accurate under transient conditions, but are computationally more intensive and not implementable in real driving conditions because it requires knowledge of future speed and load profile. [16].

Nonetheless, analyzing the dynamic optimization approach provides an useful insight into possible improvement. Therefore, in this chapter, modelling and optimization approach for energy and power management problem in series hybrid vehicles is further investigated.

3.1 Modelling the Vehicle Dynamics in Series Hybrid System

Energy management requires the knowledge of power flows between the hybrid electric vehicle components. The overall power flow can be described by:

$$P_{ICE} = P_{UC} + P_{TR} + P_{AUX} + P_{BR} \tag{3.1}$$

where:

P_{ICE} is power generated by the internal combustion engine

P_{UC} is the power flow into/out of the energy storage (ultracapacitor)

P_{TR} is the tractive power demanded by the driver

P_{AUX} is the auxillary units on the engine to run safety critical systems

P_{BR} is the dissipated energy through resistors if E_{UC} is maximum

Then the generator power can be defined as the net power available to generate electricity:

$$P_G = P_{ICE} - P_{AUX} \tag{3.2}$$

The instantaneous tractive power required to cruise the hybrid electric vehicle at velocity ν is defined in [14]:

$$F_{TR} = m\frac{dv}{dt} + (F_{gxT} + F_{AD} + F_{roll}) \tag{3.3}$$

$$P_{TR}(t) = F_{TR}(t)v(t) \tag{3.4}$$

where:

m is the vehicle mass

F_{gxT}	is the gravitational force
F_{AD}	is the aerodynamic drag force
F_{roll}	is the resistive rolling force
$\sin\beta$	is the grade

The above mentioned resistive vehicular dynamical forces are also defined in [14]:

$$F_{gxT} = mg\sin\beta \tag{3.5}$$

$$F_{AD} = [mgC_1 + \frac{P}{2}A_F D_D]v^2 \tag{3.6}$$

$$F_{roll} = mgC_0 \tag{3.7}$$

The power loss due to resistive dynamical forces can be expressed as:

$$P_{LOSS\_MECHANICAL} = v(F_{AD} + F_{roll}) \tag{3.8}$$

Auxiallary Power Consumption can be modelled as a function of the engine speed as follows:

$$P_{AUX}(w) = P_{motoring}(w) + P_{hydraulics}(w) + P_{pneumatics}(w) + P_{A/C}(w) + P_{alternator}(w) \tag{3.9}$$

where:

$P_{motoring}(w)$ is the power consumption due to dynamics of the engine

$P_{pneumatics}(w)$ is the power consumption of the suspension and brake systems

$P_{A/C}(w)$ is the power consumption of the air conditioner unit

$P_{alternator}(w)$ is the 24V alternator power demand

$P_{hydraulics}(w)$ is the power consumption of the hydraulic steering system and the hydraulic cooling system for the engine and powertrain

The auxillary units exhibit mostly linear behaviour and it is advantageous that the power consumptions appear to be a function of the engine speed. An example power consumption curve of the auxillary units can be given as follows.

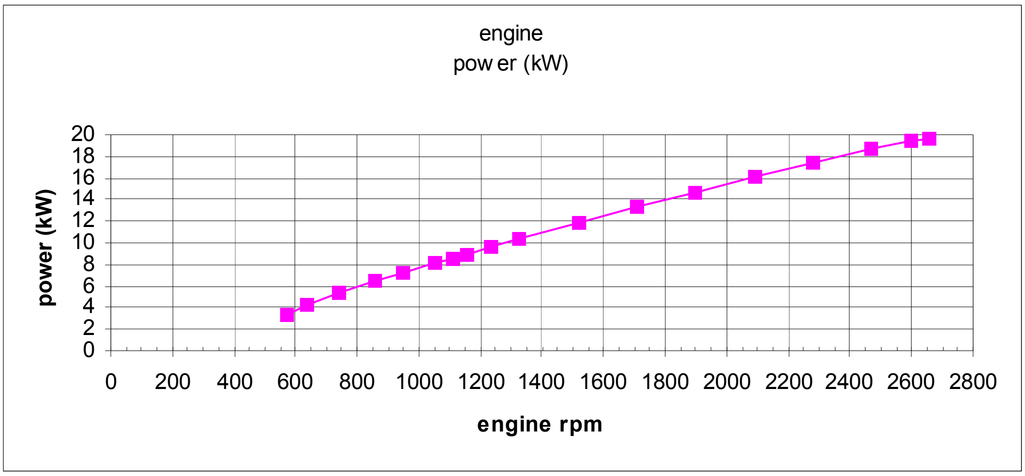

Figure 3.1. A typical $P_{AUX}(w)$ curve

Since an engine on/off strategy is not considered for this project it is important to understand the behaviour of the auxillary units. Excessive power should not be spend to drive the auxillary units. Therefore it is advantageous to drive engine in low speeds as much as possible. The idea is further discussed in the following section.

3.2 Obtaining an Optimal Engine Power Generation Curve

The Brake Specific Fuel Consumption (BSFC) map of an engine can be represented as a three dimensional surface in which torque, speed and correspoding fuel consumption rate in terms of mass per unit energy can be graphed. However, to be more practical, engine manufacturers provide two dimensional maps characterized by isolines of constant fuel consumption as in the following figure.

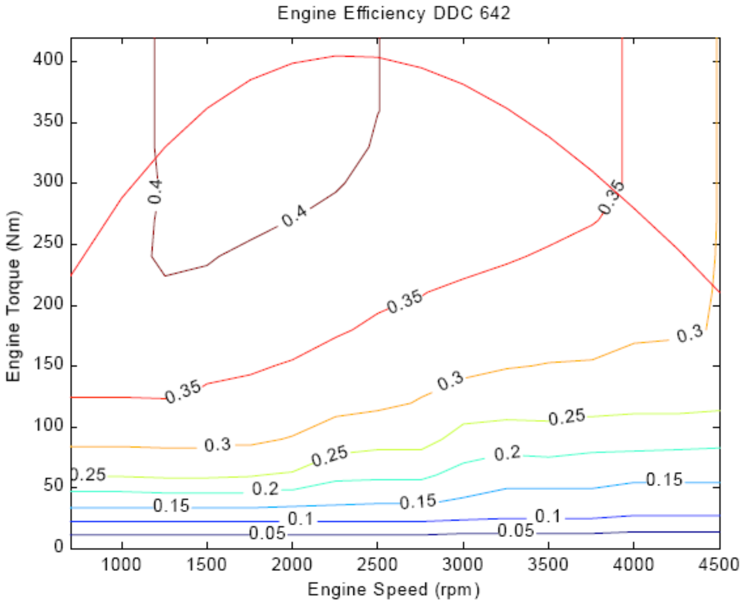

Figure 3.2. BSFC map of an engine

The BSFC maps can be further developed to involve constant power lines to understand at which point a certain power level can be optimally achieved. In the following figure, the dashed lines represent the constant power levels (the product of torque and speed). The red line is composed of splines connecting the points of power levels in terms of minimum fuel consumption.

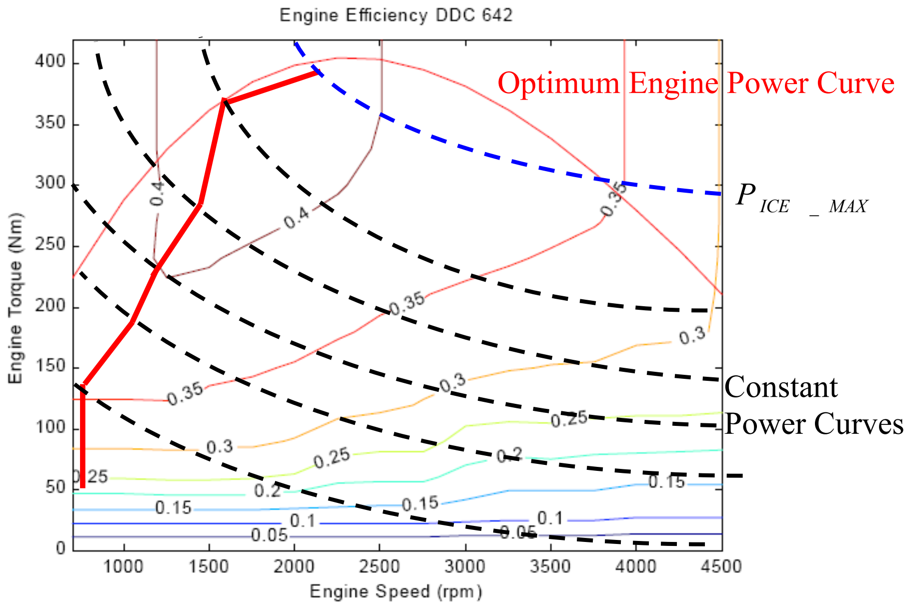

Figure 3.3. Optimum Engine Power Curve

However, power generated by the engine P_{ICE} is not consumed by the electric generator only. Auxillary units also demand power P_{AUX}. Eq. (3.2) can be rewritten in terms of engine speed:

$$P_G(\omega) = P_{ICE}(\omega) - P_{AUX}(\omega) \tag{3.10}$$

Depending on the type of vehicle the power loss due to auxillary units may become decisive in obtaining the $P_G(\omega)$ curve. When $P_{AUX}(\omega)$ values are also calculated on the same map with $P_{ICE\_OPTIMUM}$ it becomes easier to understand that the loss due to auxillaries can be more disadvantageous than the advantage of using $P_{ICE\_OPTIMAL}$ curve since a certain amount of decrease in engine speed may end up with an overall increase in fuel consumption economy.

The best efficiency curve defines the optimal engine operating points that implies the minimum fuel consumption of the engine under certain speeds. For this project Eq.(3.10) is calculated for a number of P_G's on each constant power curve. Optimal P_G's are then fitted into a differentiable form as in the following figure.

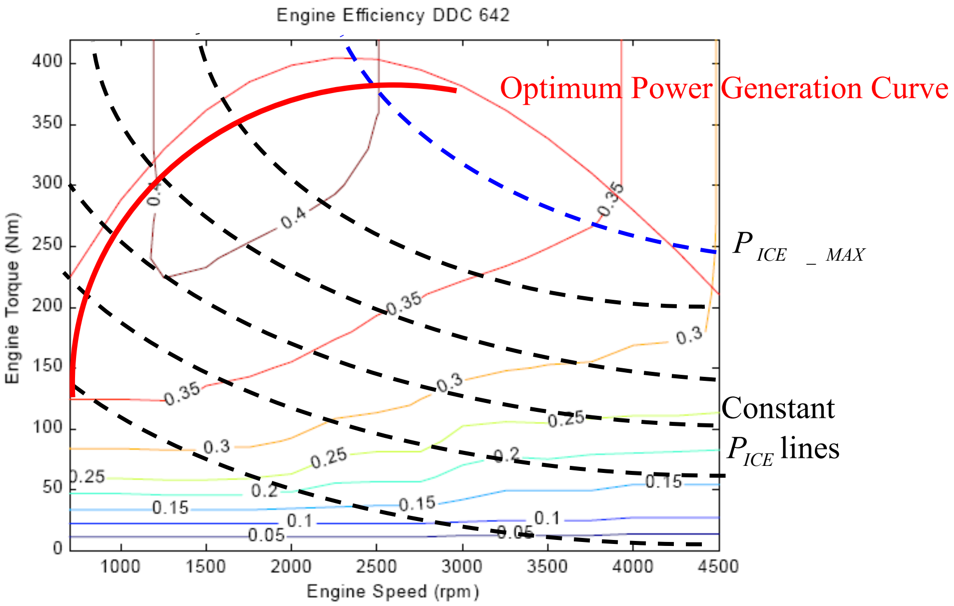

Figure 3.4. Optimum Power Generation Curve

The optimum power generation curve can finally be written as a function in polynomial form:

$$f_{BSFC}(P_{ICE}) = f_{BSFC}(P_G + P_{AUX}) \tag{3.11}$$

3.3 Power Flow Model of Series Hybrid System

The fundamental dynamical relations discussed so far can be depicted in a power flow model. The power flows are demonstrated with arrows where energy storage as levels. The losses due to auxillaries, efficiencies, friction and power conversion are illustrated as dashed lines. The part of the model in red color represents the vehicle dynamics to fulfill a given driver task. The doube sided arrows represent a reversible power flow (i.e.Regeneration creates a power flow into the system).

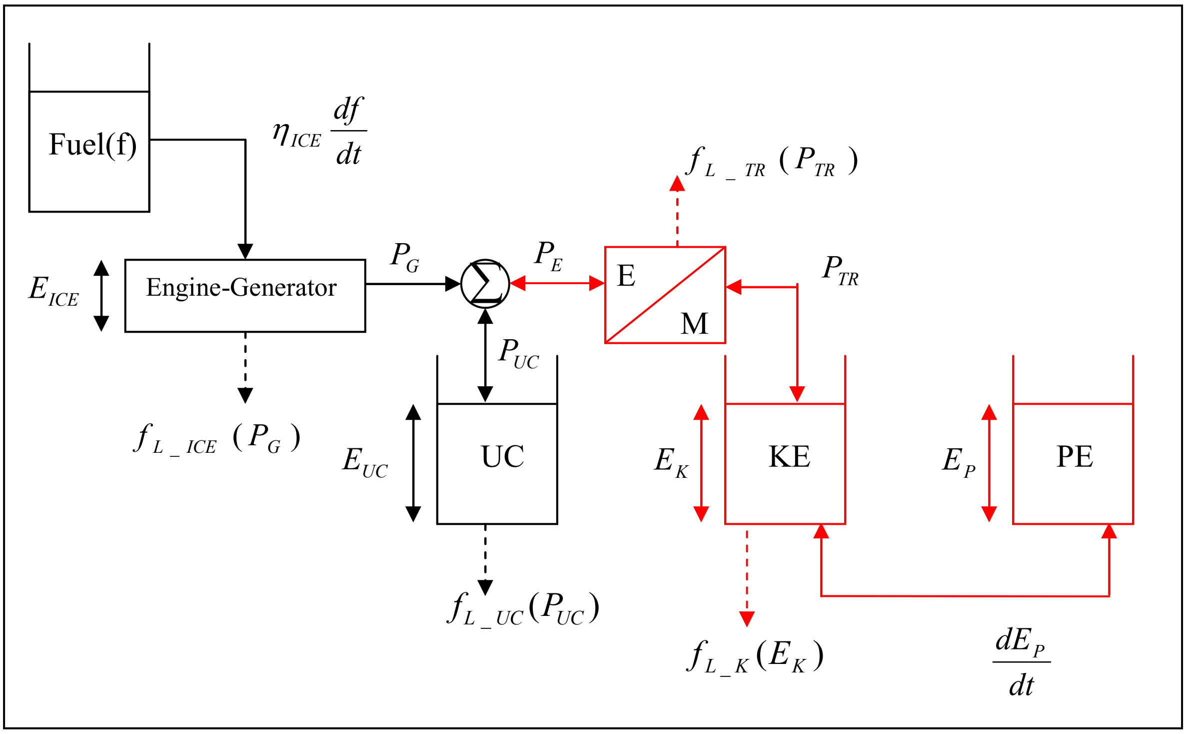

Figure 3.5. Power Flow Model of the Hybrid System

where

f is the amount of fuel in the tank

$\frac{df}{dt}$ is the fuel consumption rate

η_{ICE} is the Efficiency of the engine (g/kWh)

E_{ICE} is the mechanical energy stored in Engine-Generator set

P_G is Power generated by the generator

$f_{L\_ICE}(P_G)$ is the power lost in the engine (a function of the generator power)

E_{UC} is energy of the ultracapacitor

P_{UC} is the power of the ultracapacitor

$f_{L\_UC}(P_{UC})$ Power lost in the ultracapacitor (a function of ultracapacitor power)

P_E is the power of the electric machines on the driveline

$f_{L\_TR}(P_{TR})$ Power lost during energy conversion in electric machines

P_{TR} is the traction power of the vehicle to track the desired drive cycle

E_P is the potential energy of the vehicle

$\frac{dE_P}{dt}$ is the rate of change in Potential Energy

E_K is the kinetic energy of the vehicle

$f_{L\_K}(E_K)$ is the Power lost due to vehicle dynamics

The governing equations are described as: The energy stored in the engine can be defined by a differential equation as:

$$\frac{dE_{ICE}}{dt} = \eta_{ICE}\frac{df}{dt} - P_G - f_{L\_ICE}(P_G) \tag{3.12}$$

At the junction of fig. 3.5 the power flow can be defined as:

$$P_G = P_{UC} + P_E \tag{3.13}$$

Drivetrain Efficiency can be defined as a loss function in which the electrical side is less than the mechanical side in case of regenerative braking but greater in case of traction.

$$f_{L\_TR}(P_{TR}) = (1-\eta_{TR})\left|P_{TR}\right| \tag{3.14}$$

$$P_E = P_{TR} \pm f_{L\_TR}(P_{TR}) \tag{3.15}$$

Ultracapacitor is defined by the following differential equation and It should noted that the power loss $f_{L\_UC}(P_{UC})$ is always positive.

$$\frac{dE_{UC}}{dt} = P_{UC} - f_{L\_UC}(P_{UC}) \tag{3.16}$$

$$f_{L\_UC}(P_{UC}) = (1-\eta_{UC})\left|P_{UC}\right| \tag{3.17}$$

In order to simplfy the rest of the derivations, k_{UC} is defined such that $k_{UC} = 1-\eta_{UC}$

Mechanical Energy is also represented by a differential equation as:

$$\frac{dE_K}{dt} = P_{TR} + \frac{dE_P}{dt} - f_{L\_K}(E_K) \tag{3.18}$$

The power loss due to vehicle $f_{L\_K}(E_K)$ was already defined.

$$f_{L\_K}(E_K) = P_{LOSS\_MECHANICAL} \tag{3.19}$$

3.4 Determining the Objective Function

In a series hybrid configuration the power flow should be managed in such a way to minimize the fuel consumption for a given drive cycle of the vehicle in a predetermined period of time. Before determining the objective functions some assumptions are required to realize the power flow model mentioned previously.

1- The part of the model in red color in Fig 3.5 is assumed to be predicted for a short period of time (the prediction method will be described in next chapter) which means P_E is calculated beforehand.

2- The structural or the rotational parts of the engine are assumed to have no capability to store mechanical energy which means:

$$\frac{dE_{ICE}}{dt} = 0 \tag{3.20}$$

3-For each unit of power produced in the engine there exists a corresponding efficiency. It can be represented using the curve generated in section 3.2:

$$\eta_{ICE} = \left[f_{BSFC}(P_G + f_{L\_ICE}(P_G)) \right]^{-1} \tag{3.21}$$

4- The power loss of the ultracapacitor can be expressed in terms of P_G and P_E using equation (3.13) and the ultracapacitor efficiency η_{UC}:

$$f_{L\_UC}(P_{UC}) = k_{UC}\left| P_G - P_E \right| \tag{3.22}$$

The optimization problem is to minimize the fuel consumption, f in a predetermined period of the time interval $[t_0, t_1]$ and can be defined by:

$$\min \int_{t_0}^{t_1} \frac{df}{dt} dt \tag{3.23}$$

where $\frac{df}{dt}$ can be defined by $\eta_{ICE}^{-1}(P_G + f_{L\_ICE}(P_G))$ using the equations (3.12) and (3.20)

$$\min \int_{t_0}^{t_1} f_{BSFC}(P_G + f_{L\_ICE}(P_G))(P_G + f_{L\_ICE}(P_G))dt \tag{3.24}$$

The minimization problem is subject to the constraints:

Constraint 1-

The strategy is to ensure that the ultracapacitors are held at an acceptable state of charge such that the ultracapacitors are both capable of delivering peak power requests and adaptive to regenerative power conditions. The ultracapacitor energy is limited:

$$0 \le E_{UC} \le E_{UC\_\max} \tag{3.25}$$

This constraint can be written in terms of P_{UC} using Eq. (3.16) :

$$0 \le \int_{t_0}^{t_1} \frac{dE_{UC}}{dt} dt \le E_{UC\_\max} \tag{3.26}$$

$$0 \le \int_{t_0}^{t_1} P_{UC} - f_{L\_UC}(P_{UC})dt + E_{UC}^{initial} \le E_{UC\_\max} \tag{3.27}$$

The power loss $f_{L\_UC}(P_{UC})$ in the ultracapacitor is defined to be always positive:

$$0 \le \int_{t_0}^{t_1} (P_G - P_E) - k_{UC}\left|P_G - P_E\right| dt + E_{UC}^{initial} \le E_{UC\_\max} \tag{3.28}$$

If $k_{UC}= 0$;

$$\int_{t_0}^{t_1} P_E dt - E_{UC}^{initial} \le \int_{t_0}^{t_1} P_G dt \le \int_{t_0}^{t_1} P_E dt + E_{UC\_\max} - E_{UC}^{initial} \tag{3.29}$$

If $k_{UC} \ne 0$; then $\left|P_G - P_E\right|$ can be either positive or negative;

If $\left|P_G - P_E\right| > 0$

$$0 \le \int_{t_0}^{t_1} (1-k_{UC})P_G - (1-k_{UC})P_E dt + E_{UC}^{initial} \le E_{UC\_\max} \tag{3.30}$$

Or in extended form

$$\frac{\int_{t_0}^{t_1} (1-k_{UC})P_E dt - E_{UC}^{initial}}{(1-k_{UC})} \le \int_{t_0}^{t_1} P_G dt \le \frac{\int_{t_0}^{t_1} (1-k_{UC})P_E dt - E_{UC}^{initial} + E_{UC\_\max}}{(1-k_{UC})} \tag{3.31}$$

Else If $\left|P_G - P_E\right| < 0$

$$0 \le \int_{t_0}^{t_1} (1+k_{UC})P_G - (1+k_{UC})P_E dt + E_{UC}^{initial} \le E_{UC\_\max} \tag{3.32}$$

Or in extended form

$$\frac{\int_{t_0}^{t_1} (1+k_{UC})P_E dt - E_{UC}^{initial}}{(1+k_{UC})} \le \int_{t_0}^{t_1} P_G dt \le \frac{\int_{t_0}^{t_1} (1+k_{UC})P_E dt - E_{UC}^{initial} + E_{UC\_\max}}{(1+k_{UC})} \tag{3.33}$$

Constraint 2-

The power created in the engine is bounded. In case the driver is asking for high power the engine will operate at its maximum rated power in order to satisfy the demand. Furthermore, the power to be charged or discharged from the battery, at any moment, will not exceed the maximum allowable value:

$$f_{L\_ICE}(P_G) \le P_G + f_{L\_ICE}(P_G) \le P_{ENGINE\_MAX} \tag{3.34}$$

$$0 \le P_G \le P_{ENGINE\_MAX} - f_{L\_ICE}(P_G) \tag{3.35}$$

The solution to this continuous type optimization problem is a continous function P_G which minimizes the objective function defined eq. (3.24). This may lead to a solution space with infinite dimensional solutions. Therefore discretization is necessary.

3.5 Optimization Problem in Discrete Form

The optimization problem can also be defined in discrete form:

$$\min \sum_{i=1}^{n} h(P_G^i)\Delta t \tag{3.36}$$

where Δt is the sampling time between ith and $i+1$th step and h is the discrete form of fuel rate, $\frac{df}{dt}$, which was defined in equation (3.12)

$$h(P_G^i) = f_{BSFC}(P_G^i + f_{L\_ICE}(P_G^i))(P_G^i + f_{L\_ICE}(P_G^i)) \tag{3.37}$$

The constraints should also be defined in discrete form:

Constraint 1- In discrete form

If $k_{UC} = 0$;

$$\sum_{i=1}^{n} P_E^i - E_{UC}^{initial} \leq \sum_{i=1}^{n} P_G^i \leq \sum_{i=1}^{n} P_E^i + E_{UC\_\max} - E_{UC}^{initial} \tag{3.38}$$

Else If $k_{UC} \neq 0$; then $|P_G - P_E|$ can be either positive or negative;

If $|P_G - P_E| > 0$

$$\frac{(1-k_{UC})\sum_{i=1}^{n} P_E^i - E_{UC}^{initial}}{(1-k_{UC})} \leq \sum_{i=1}^{n} P_G^i \leq \frac{(1-k_{UC})\sum_{i=1}^{n} P_E^i + E_{UC\_\max} - E_{UC}^{initial}}{(1-k_{UC})} \tag{3.39}$$

Else If $|P_G - P_E| < 0$

$$\frac{(1+k_{UC})\sum_{i=1}^{n} P_E^i - E_{UC}^{initial}}{(1+k_{UC})} \leq \sum_{i=1}^{n} P_G^i \leq \frac{(1+k_{UC})\sum_{i=1}^{n} P_E^i + E_{UC\_\max} - E_{UC}^{initial}}{(1+k_{UC})} \tag{3.40}$$

Constraint 2- (In discrete form)

$$0 \leq P_G^i \leq P_{ENGINE\_MAX} - f_{L\_ICE}(P_G^i) \tag{3.41}$$

CHAPTER 4

SOLUTION METHODS

In chapter 3, optimal energy and power management method in series hybrid vehicles was developed. In this chapter solution methods of the problem formulated in chapter 3 will be given. First a regression method for vehicle speed and traction power prediction will be introduced and the constraints defined for the optimization problem will be further improved to compensate this prediction method.

4.1 Predicting the future speed and traction powers

If the momentary vehicle speed and elevation information in a drive cycle is known, the optimal operating strategy to minimize fuel consumption can be obtained. Although the optimization approach may provide an optimal solution for minimizing fuel consumption, the resulting control policy is not implementable in real driving conditions because the optimal policy requires knowledge of the future speed and load profile of the vehicle [16]. Although average speed values for a given drive cycle can be estimated by a municipal government based on experience for example, instantaneous values depend on many parameters such as traffic conditions, and cannot be accurately predicted at the beginning of the drive cycle.

In this thesis, we have chosen to use a short term prediction of the vehicle velocity. The road gradient can be estimated using estimated position based on estimated velocity. This is a compromise where a tradeoff is made between minimization of fuel consumption and realizability of the method.

The dynamic behavior of the vehicle in terms of the vehicle speed is assumed to have a differentiable profile so that the speed estimate of the vehicle can be calculated through a polynomial curve fitting with a suitable order depending on the number of previous data points. The maximum energy stored in the ultracapacitors can only move the vehicle for a limited time. Therefore the length of the prediction time horizon can be kept short.

An example can be given as a 2nd degree polynomial curve fitting applied using the velocities in the range t = [167, 170] as shown in Fig.4.1

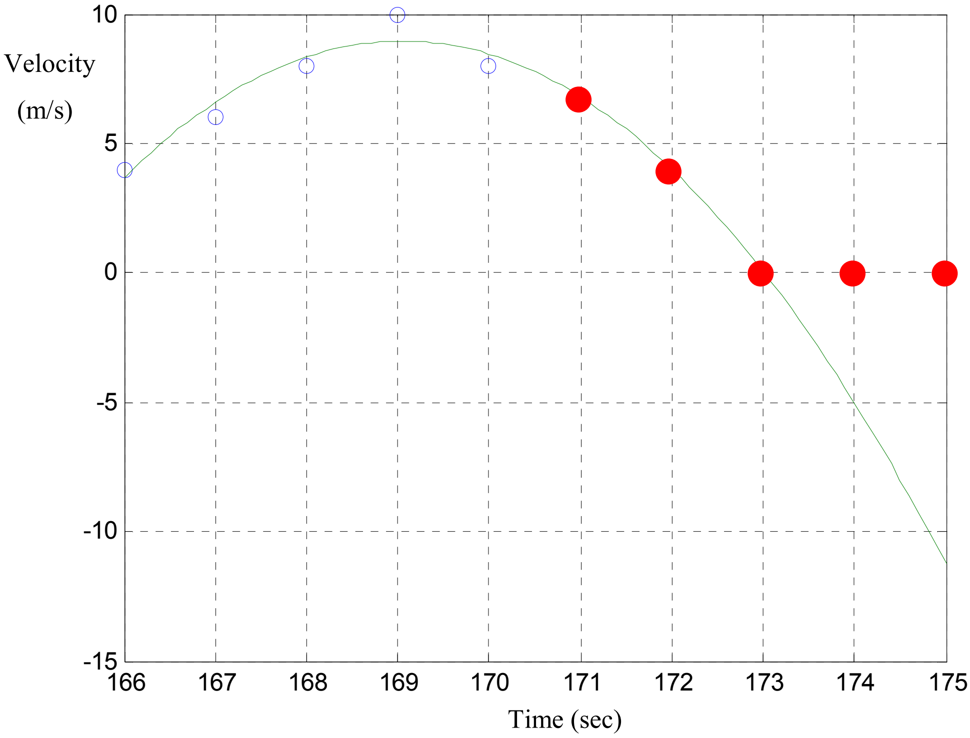

Figure 4.1. An example 2nd degree polynomial fitting for vehicle speed calculated at P_0

The blue points indicate the last 5 recordings of speed. At t = 170 the velocity estimate for the next 5 seconds are calculated. The velocity predictions for the next t = [171,175] can be assumed to be a very short term drive cycle which allows an optimization to be done at t = 170 for the next 5 seconds.

4.2 Improving the Optimization Constraints to Compensate the Prediction Uncertainities

A hybrid vehicle body and powertrain can store two types of energy: electrical energy and mechanical energy (kinetic plus potential energy). The total energy of the vehicle can be defined as:

$$K = E_{UC} + (E_{KINETIC} + E_{POTENTIAL}) \tag{4.1}$$

Ideally if there were no losses due to energy conversion or frictional dynamics, the energy could be conserved at indefinitely into in either form:

$$E_{MECHANICAL\_MAX} \leftrightarrow K \leftrightarrow E_{ELECTRICAL\_MAX} \tag{4.2}$$

A simple strategy that allows for both acceleration and regenerative braking is to keep the current level of stored electrical energy to such a point that all of the energy generated by regenerative braking can be absorbed or all of the energy necessary acceleration to the maximum velocity can be supplied.

During acceleration:

$$K \leq E_{ELECTRICAL\_MAX} \tag{4.3}$$

During deceleration (Regenerative Braking):

$$E_{MECHANICAL\_MAX} \leq K \tag{4.4}$$

This strategy defines the electrical energy in the ultracapacitor as a function of vehicle speed and the road gradient. The basic idea is to keep the sum of the electrically stored energy in the ultracap, the kinetic energy and the potential energy of the vehicle constant.

At low speed, only a small amount of energy can be recovered from braking and further acceleration is probable, thus the ultracapacitor should be kept at a high state of charge.

$$E_{KINETIC\_MAX} - E_{KINETIC} + E_{POTENTIAL\_MAX} - E_{POTENTIAL} \leq E_{UC} \tag{4.5}$$

At high speed, the ultracapacitor voltage should be kept low in order to allow as much energy as possible from the next braking event to be stored in the ultracap module.

$$E_{UC} \leq E_{UC\_\max} - E_{POTENTIAL} - E_{KINETIC} \tag{4.6}$$

The constraint [eq.] should then be redefined as follows:

$$E_{KINETIC\_MAX} - E_{KINETIC} + E_{POTENTIAL\_MAX} - E_{POTENTIAL} \leq E_{UC} \leq E_{UC\_\max} - E_{POTENTIAL} - E_{KINETIC} \tag{4.7}$$

By regulating the parameters the proportioning ratio of powers can be biased towards the ultracapacitors. In effect, this forces ultracapacitor energy to be drawn even though the load power demand trajectory does not explicitly require it or regenerative power can be directed to the generator to ramp up the engine.

In order to calculate the above mentioned $E_{KINETIC\_MAX}$ and $E_{POTENTIAL\_MAX}$ the maximum height and velocity should be gathered using a map (such as using a GPS unit) and infrastructural information system. It is assumed to be possible to define the geographical position and the height profile for a predetermined drive cycle.

In reference [17] an implementation approach was developed that fuel savings of approximately 2% to 4% can be obtained with route based control. It is assumed to be possible to define the geographical position and the height profile.

An example route height profile can be illustrated in Fig. 4.2, $h_{\max}$ is used to calculate the maximum potential energy, $E_{POTENTIAL\_MAX}$:

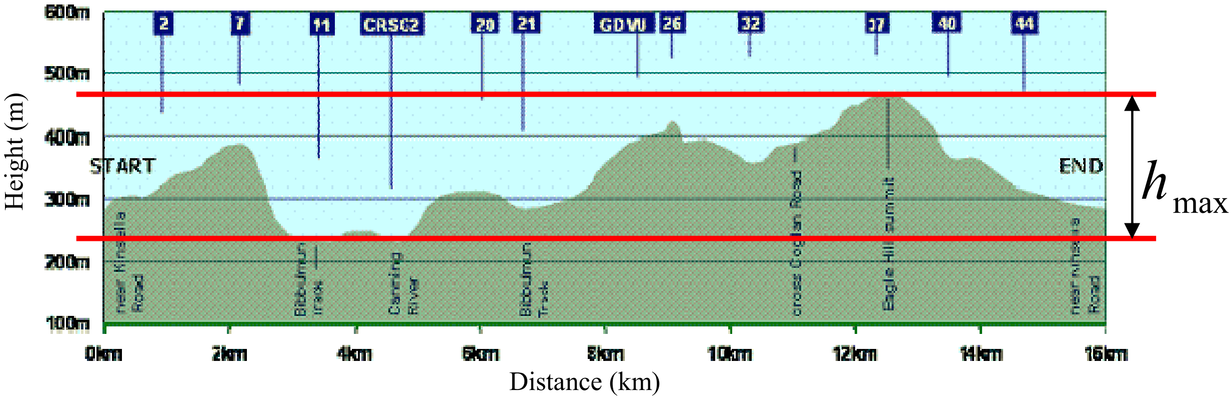

Figure 4.2. Altitude profile of a route

Also maximum required velocity in the vicinity of the vehicle $v_{\max}$ is assumed to be received either from the traffic infrastructure or from other similar vehicles within the same drive cycle in front. The research topic “traffic modelling” [17] and[18] deals with these problems.

Combining all these information will greatly reduce the uncertainity of trip prediction. If the trip becomes predictable to an extent , optimization techniques will then be realizable.

4.3 Solution using Constrained Optimization Method

In constrained optimization, the general aim is to transform the problem into an simpler subproblem that can then be solved and used as the basis of an iterative process. A characteristic of a large class of methods is the translation of the constrained problem to a basic unconstrained problem by using a penalty function for constraints that are near or beyond the constraint boundary. In this way the constrained problem is solved using a sequence of parameterized unconstrained optimizations, which in the limit converge to the constrained problem.

These methods are now considered relatively inefficient and have been replaced by methods that have focused on the solution of the Karush-Kuhn-Tucker (KKT) equations. The KKT equations are necessary conditions for optimality for a constrained optimization problem.

If the problem is a so-called convex programming problem, that is, $f(x)$ and $G_i(x)$, $i = 1,...,m$, are convex functions, then the KKT equations are both necessary and sufficient for a global solution point. Referring to General Problem described in section 2.2.1, KKT equations can be stated as

$$\begin{aligned} &\nabla f(x) + \sum_{i=1}^{m} \lambda_i \nabla G_i(x) = 0 \\ &\lambda_i G_i(x) = 0, \quad i = 1,...,m_e \\ &\lambda_i \geq 0, \qquad\quad i = m_e + 1,...,m \end{aligned} \tag{4.8}$$

The first equation describes a canceling of the gradients between the objective function and the active constraints at the solution point. For the gradients to be canceled, Lagrange multipliers (λ_i, $i = 1,...,m$) are necessary to balance the deviations in magnitude of the objective function and constraint gradients. Because only active constraints are included in this canceling operation, constraints that are not active must not be included in this operation and so are given Lagrange multipliers equal to 0. This is stated implicitly in the last two Kuhn-Tucker equations.

The solution of the KKT equations forms the basis to many nonlinear programming algorithms. These algorithms attempt to compute the Lagrange multipliers directly. These methods are commonly referred to as Sequential Quadratic Programming (SQP) methods, since a QP subproblem is solved at each major iteration (also known as Iterative Quadratic Programming, Recursive Quadratic Programming, and Constrained Variable Metric methods) [9].

CHAPTER 5

RESULTS AND DISCUSSIONS

The power flow and energy management model described in chapters 3 and 4 has been implemented and simulated with Matlab/Simulink for the two drive cycles described in section 1.4. First the parameters used for the simulation are introduced. Results are then presented in the following order: Simulation outputs related to the vehicle dynamics, prediction method outputs and the results of the optimization problem defined in chapter 3.

5.1. Simulation Parameters

The vehicle studied in this project is a commercial 12m long citibus (18 ton maximum weight) with a 6 cyclinder 185kW diesel engine. Regarding the legal non-disclosure agreements the torque-speed-fuel efficiency map is not presented in this thesis. The optimum power generation curve is derived using the method described in section 3.2 to formulate the $f_{BSFC}(P_G)$ function.

The electric propulsion is composed of 2 x 85kW rated (2x150kW maximum) induction machines. The final driveline is assumed to have an efficiency of 0.9. The ultracapacitor system is capable of storing 1kWh energy and assumed to have an initial energy storage of 0.5 kWh. The charge/recharge efficiency is assumed to have an efficiency of 0.9.

To represent the performance of the methodology used in this thesis and produce results that are representative of real life conditions, road gradients were added to the drive cycles. The corresponding grade profile of the route is presented in Figure 5.1. The figure represents a hilly route in public transport systems with a maximum +-5% grade limit.

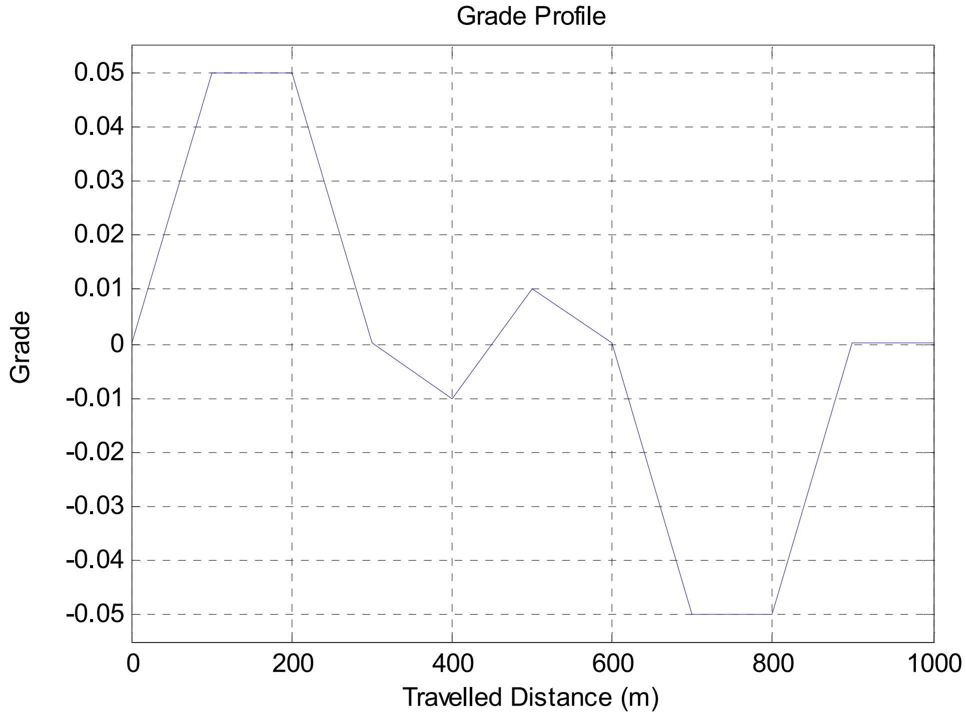

Figure 5.1. Grade Profile used for the drive cycles SORT1 and NYC

The above illustrated profile with a maximum +-5% grade limit is chosen regarding the fact that it represents a frequent hilly route in the public transport system.

5.2. Vehicle Dynamics Results

The concept of traction power was described in chapter 3. In this section the outputs of the simulated commercial citibus regarding the traction power will be presented.

The citibus is assumed to have a weight of 18000kg. The drag coeffcient due to aerodynamic forces is taken as 2.6 which is reasonable for a bus. The rolling resistance is taken as 0.007 which is appropriate for an interaction between asphalt road and a tire with a heavy duty vehicle specification.

For SORT1 and NYC drive cycles the vehicle dynamic perfomance was recorded The speed profile, the total travelled distance and the traction power demanded to complete the cycle is presented in Figure. 5.2.

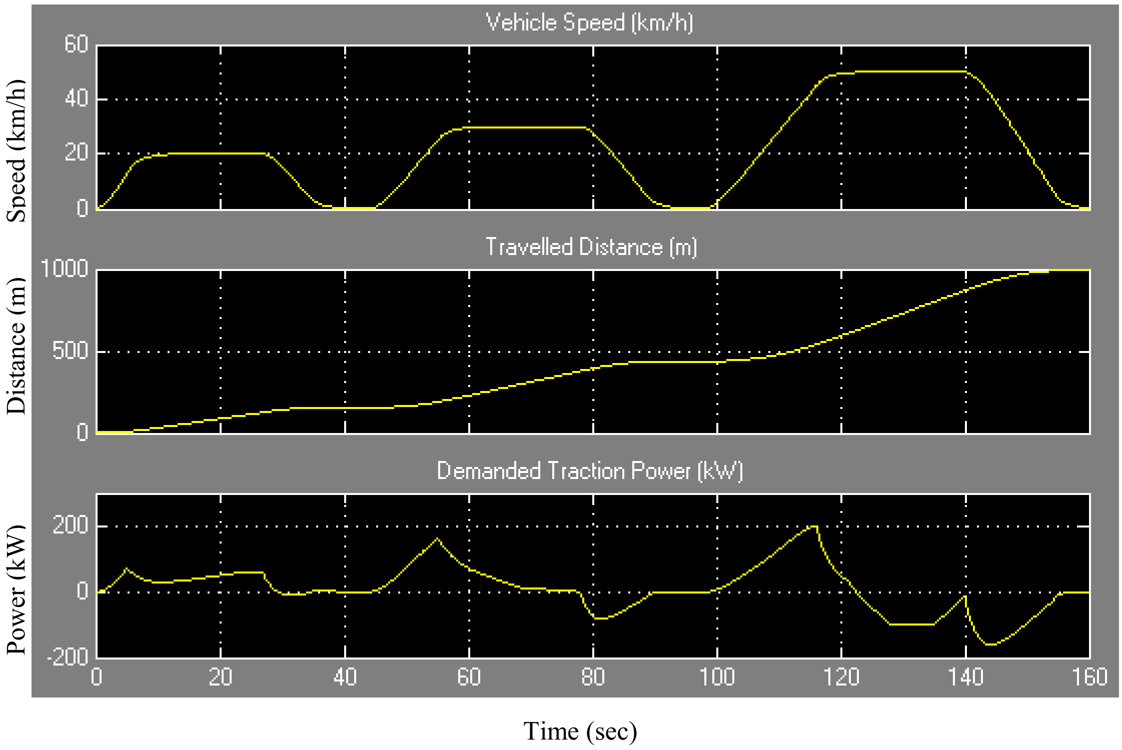

Figure 5.2 Speed, Distance and Demanded Traction Power for SORT 1 drive cycle

It is important to note that the peak traction power demand is observed to be 200kW for SORT1 drive cycle with the given grade profile. It exhibits a good example for the performance of hybrid powertrains. A commercial vehicle would not be capable delivering this amount of propulsion power so the performance would be degraded.

The energy consumption in case of a hybrid powertrain and also in case of a commercial powertrain is graphed in the figure 5.3 to emphasize the difference due to the recuperated braking energy .

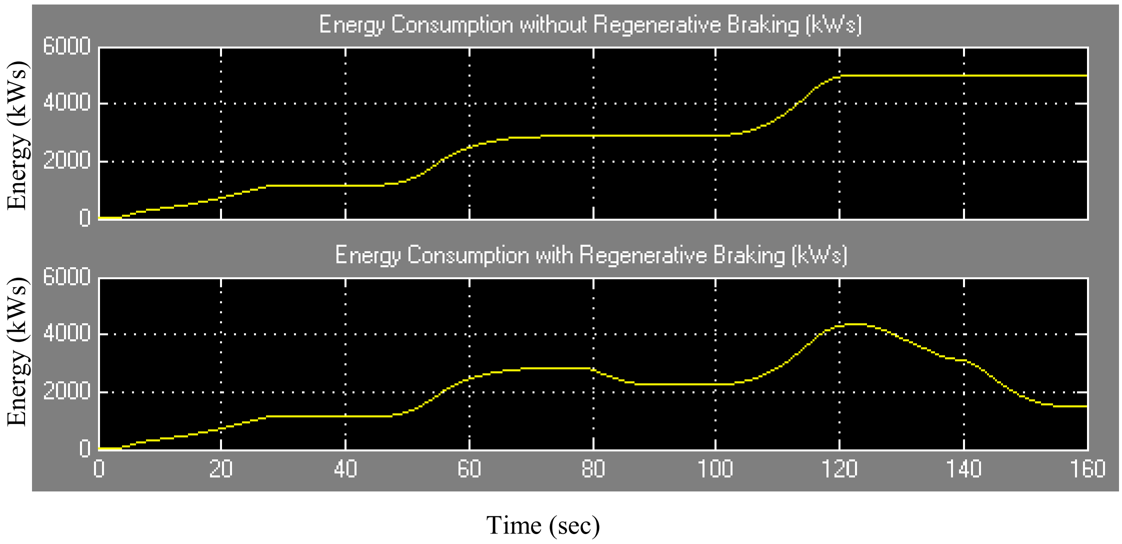

Figure 5.3 Energy Consumption with / without Regenerative Braking

In NYC Drive Cycle the peak demanded traction power (300kW) is even higher due to the fact that the second speed up with 50km/h maximum speed has a relatively high acceleration of 8 m/s.

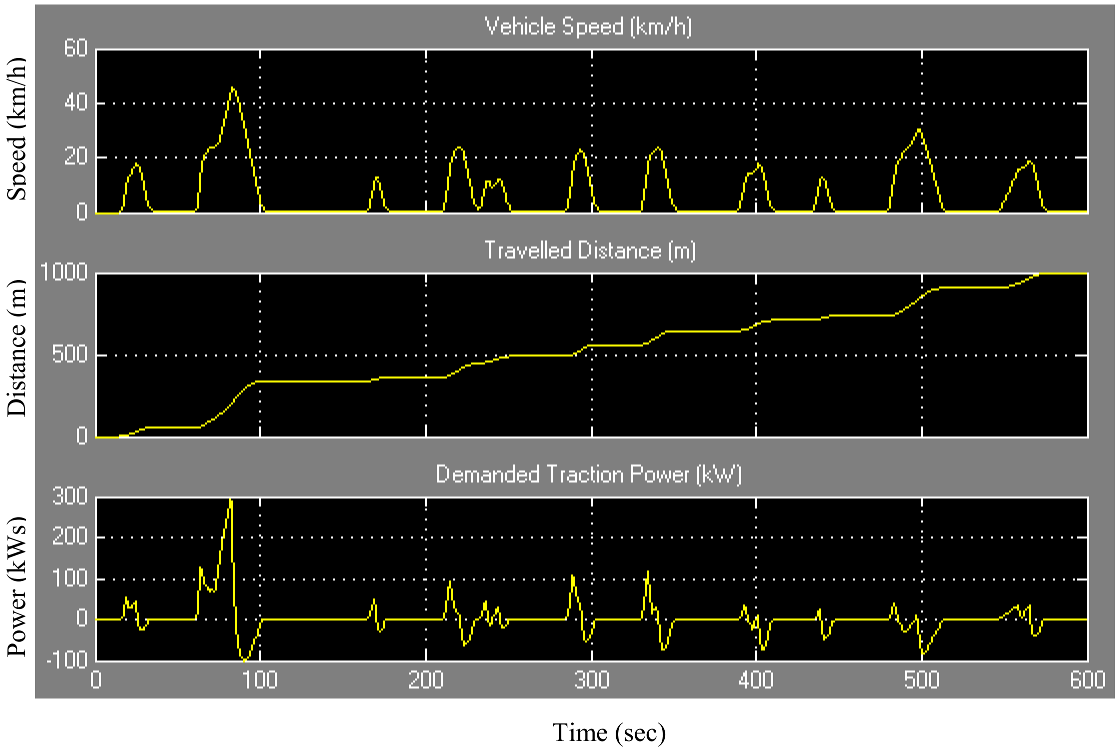

Figure 5.4 Speed, Distance and Demanded Traction Power for NYC drive cycle

After simulating the two cycles with different structural characteristics it should be noted that as the number of ramps within a drive cycle increases the total energy loss due to braking, ultracapacitor inefficiency and road loads increases also.

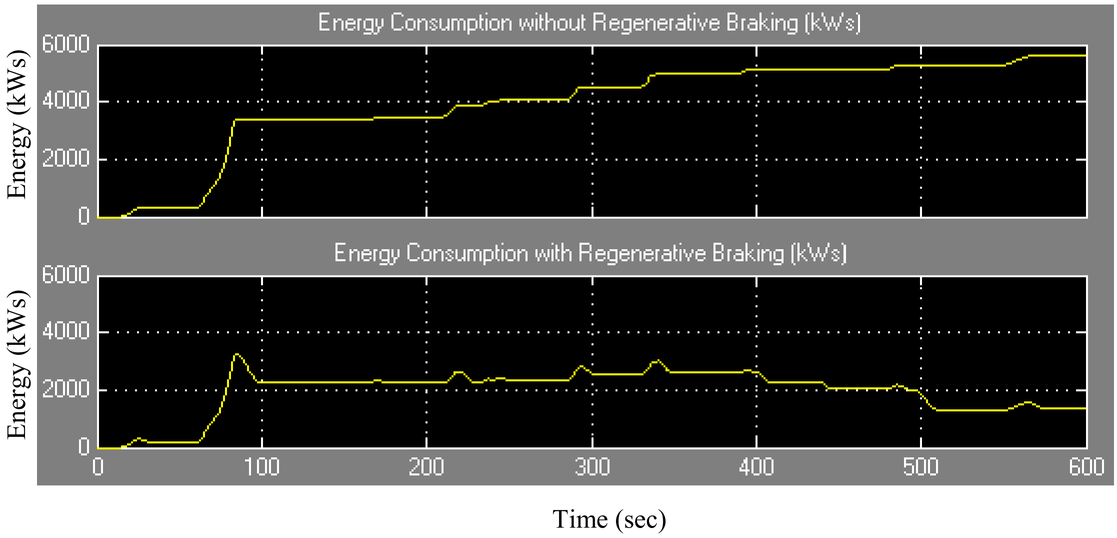

Figure 5.5 Energy Consumption with or without Regenerative Braking

5.3. Prediction Method Results

In section 4.1 the solution method for predicting the future values of the vehicle speed was introduced. Simulation results for linear regression and nonlinear regression are presented in this section for SORT1 drive cycle.

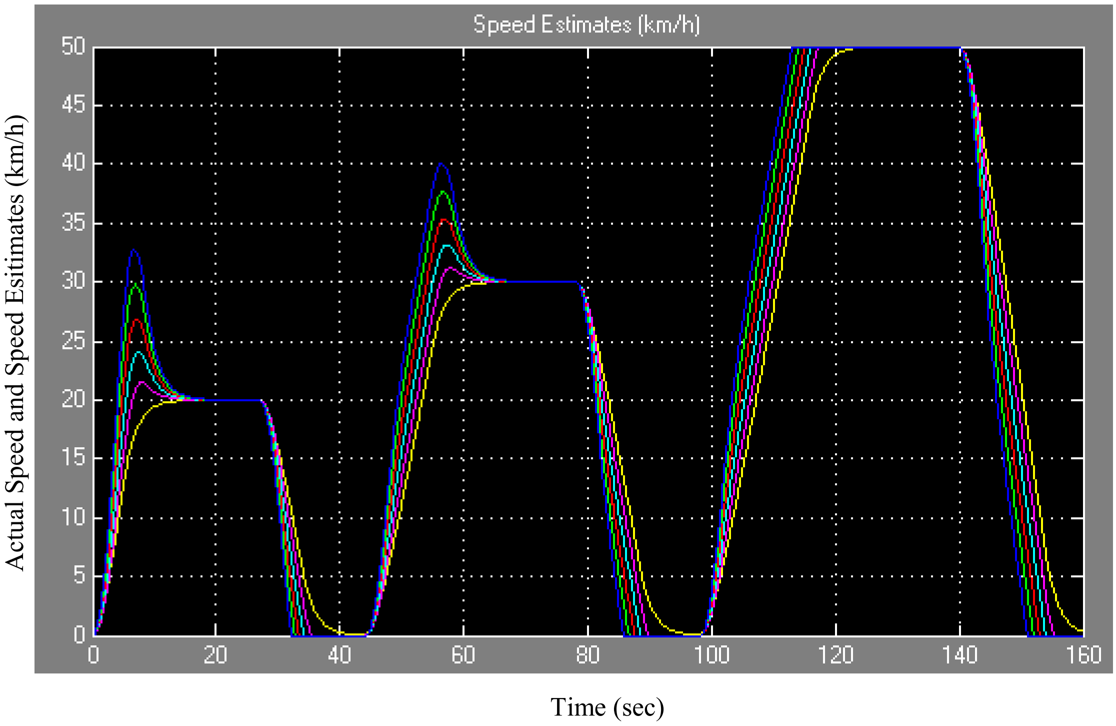

Figure 5.6 Linear Regression results for Speed Prediction for SORT1

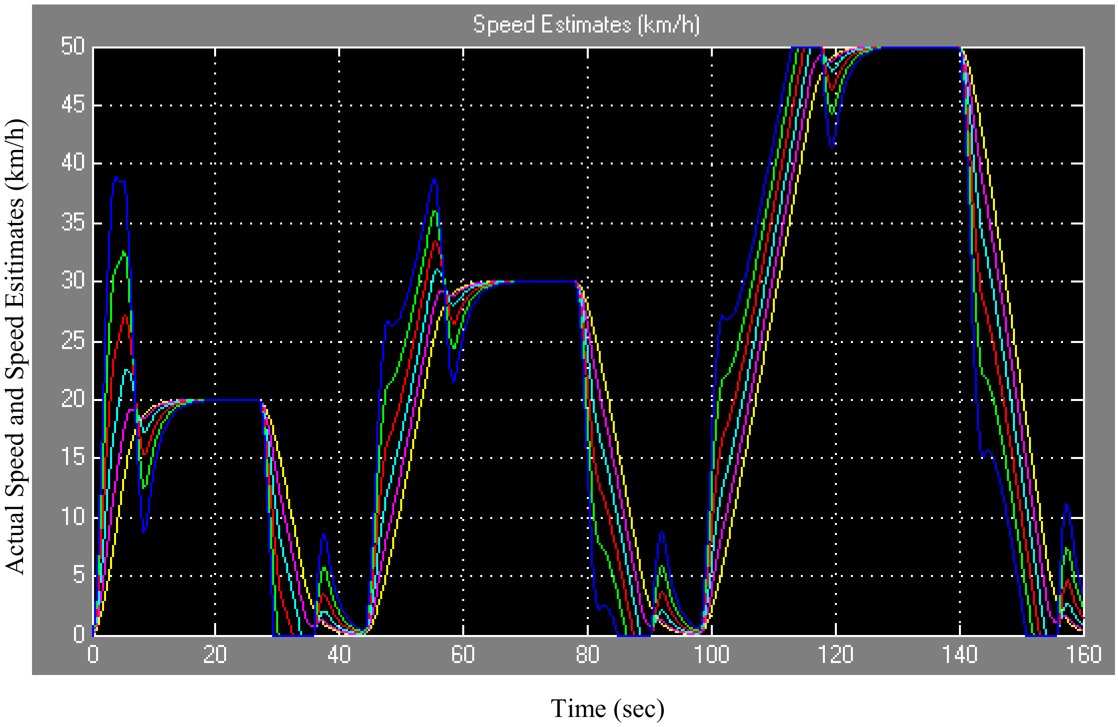

Figure 5.7 Nonlinear Regression results for Speed Prediction for SORT1

Figures 5.6 and 5.7 exhibit the actual speed (yellow curve) and the predicted speed values (Magenta for $t = t + \Delta t$, Light Blue for $t = t + 2\Delta t$, Red for $t = t + 3\Delta t$, Green for $t = t + 4\Delta t$ and Dark Blue for $t = t + 5\Delta t$) according to the method described in section 4.1.

The two regression methods were deployed for all simulations and it was observed that the difference is negligible in terms of the corresponding demanded traction power which leads to the fact that none of them is superior with respect to total fuel consumption.

However, linear regression exhibit a better performance regarding the simulation time. It is observed that nonlinear regression method consumes 50% more time in average compared to linear regression method and therefore linear regression is chosen to be the standard regression method for the rest of the simulations.

5.4. Optimization Method Results

This section presents the main results of this study. The objective function defined in Section 3.4 has an increasing behaviour within the boundaries of the decision variables P_G^i. Therefore within the scope of this project the optimization problem focuses on finding a feasible region, namely the constraints especially related to the ultracapacitor SoC.

The SoC, fuel consumption, the constraints and the output of the dynamic optimization problem was recorded for the two drive cycles.

5.4.1 UITP SORT1 Drive Cycle

5.4.1.1 Case 1-a

Case 1-a investigates the performance of the proposed energy and power management method for the constraint 1 defined in equation 3.25 which is assumed to be in its simplest form $0 \le E_{UC} \le E_{UC\_\max}$. In other words, the ultracapacitor system is assumed to be capable of delivering 100% of its stored energy.

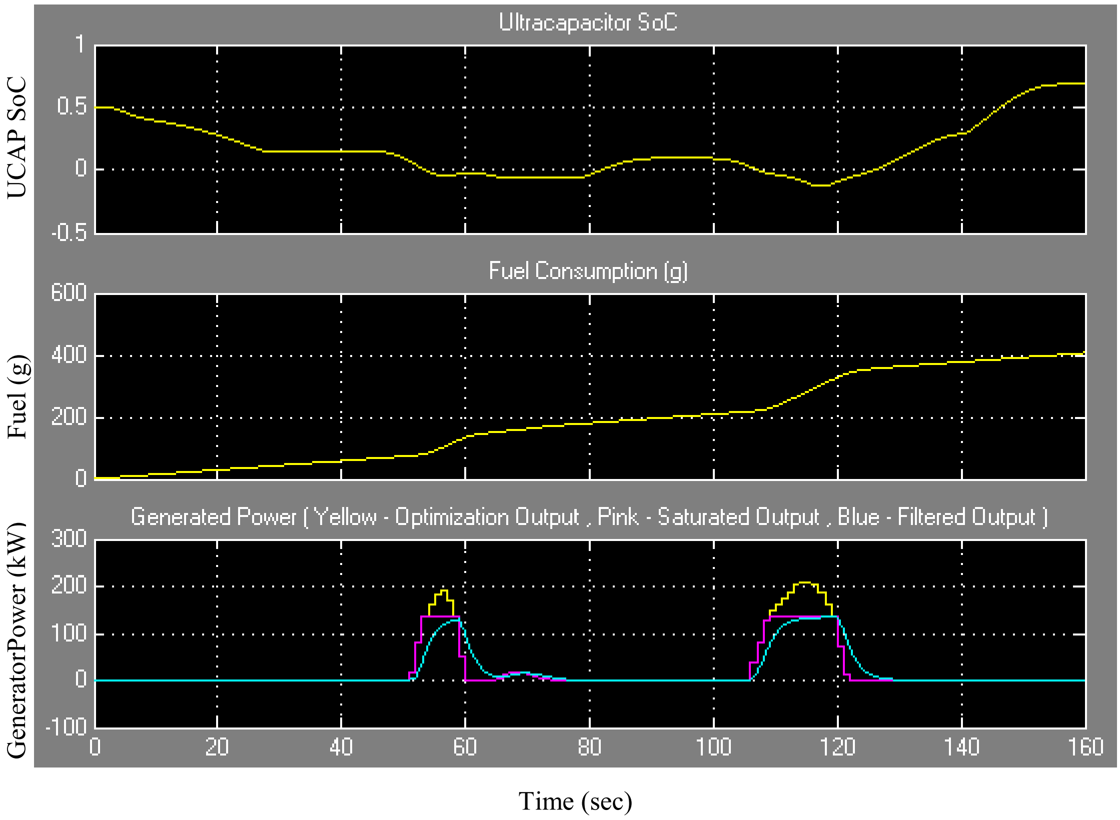

Figure 5.8 SoC, fuel consumption and generator power for SORT1 drive cycle Case 1-a

The first graph presents the ultracapacitor SoC which depletes after 55 seconds due to the second acceleration of the vehicle. The constraint can not fullfill the requirement to follow the demanded speed profile. The second graph presents the fuel consumption of the vehicle calculated via f_{BSFC} function. The yellow curve in the last graph presents the optimization output for P_G. As the ultracapacitor energy depletes, P_G is observed to be increasing exceeding its physical limits. Therefore a saturated signal (magenta) represents the physical limitations of the generator power. The blue curve is both low-pass-filtered and saturated output. It simulates the time lag due to the fuel injection response and the dynamics of the ICE which is named as the ”slew rate”.

Figure 5.9 exhibits the behaviour of the upper bound (yellow curve) and lower bound (magenta curve) and the total generator power $\sum_{i=1}^{n} P_G^i$ (blue curve) regarding the constraints defined in equations (3.38)-(3.39)

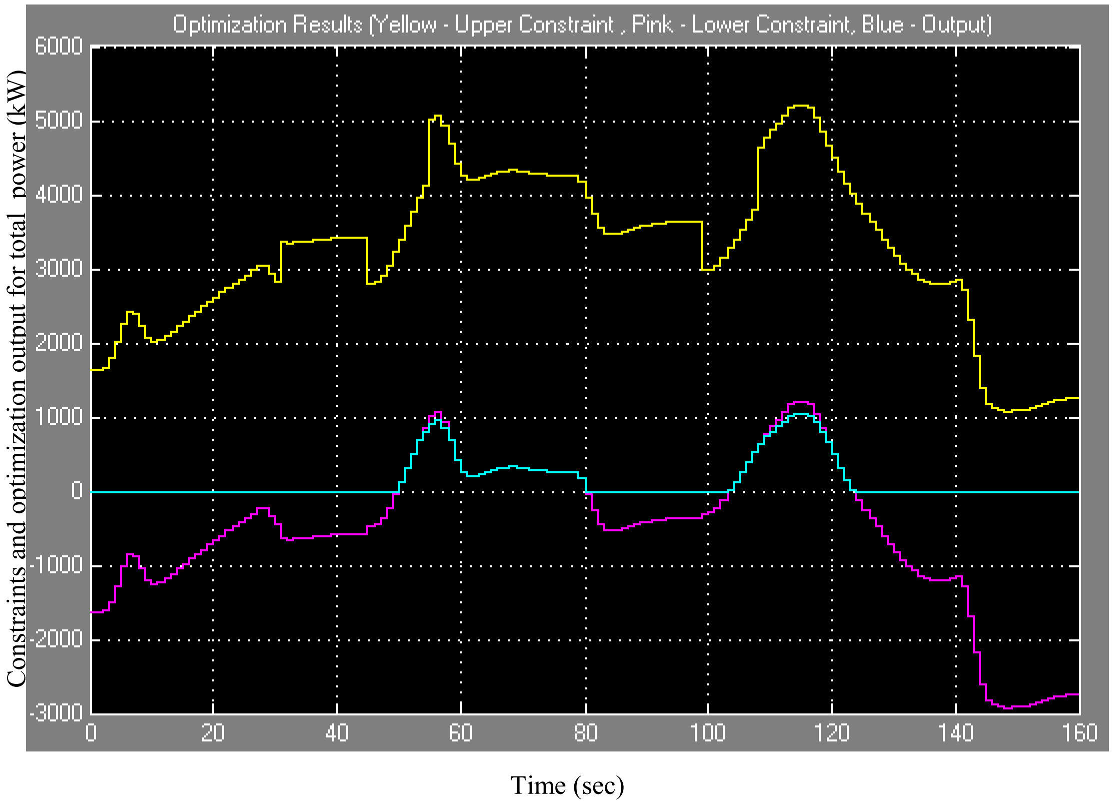

Figure 5.9 Optimization results for SORT1 drive cycle Case 1-a

The inconsistency that can be seen as a separation of curves representing the lower constraint and the output $\sum_{i=1}^{n} P_G^i$ at time t=55 and t =110 is due to the physical limits defined for the decision variables ($0 \leq P_G^i \leq P_{G\_MAX}$) which leads to the insufficiency to fullfill the requirements and consequently depletes of the ultracapacitor SoC.

For the period in which the lower bound takes negative values, the blue line representing the optimization output P_G follows its lower physical limit which is defined as zero.

5.4.1.2 Case 1-b

Because of the pitfalls of the constraint 1 observed in the previous section, it should be further developed to be able to cope with the depletion problem. An enhanced version of Case 1-a is presented here in which the lower bound for ultracapacitor SoC is defined to be greater than zero, namely $0.5E_{UC\_\max} \leq E_{UC} \leq E_{UC\_\max}$.

As in figure 5.8, the three scopes exhibit the resulting SoC, total fuel consumption and the optimization output, the decision variable P_G, for the improved version of constraint 1.

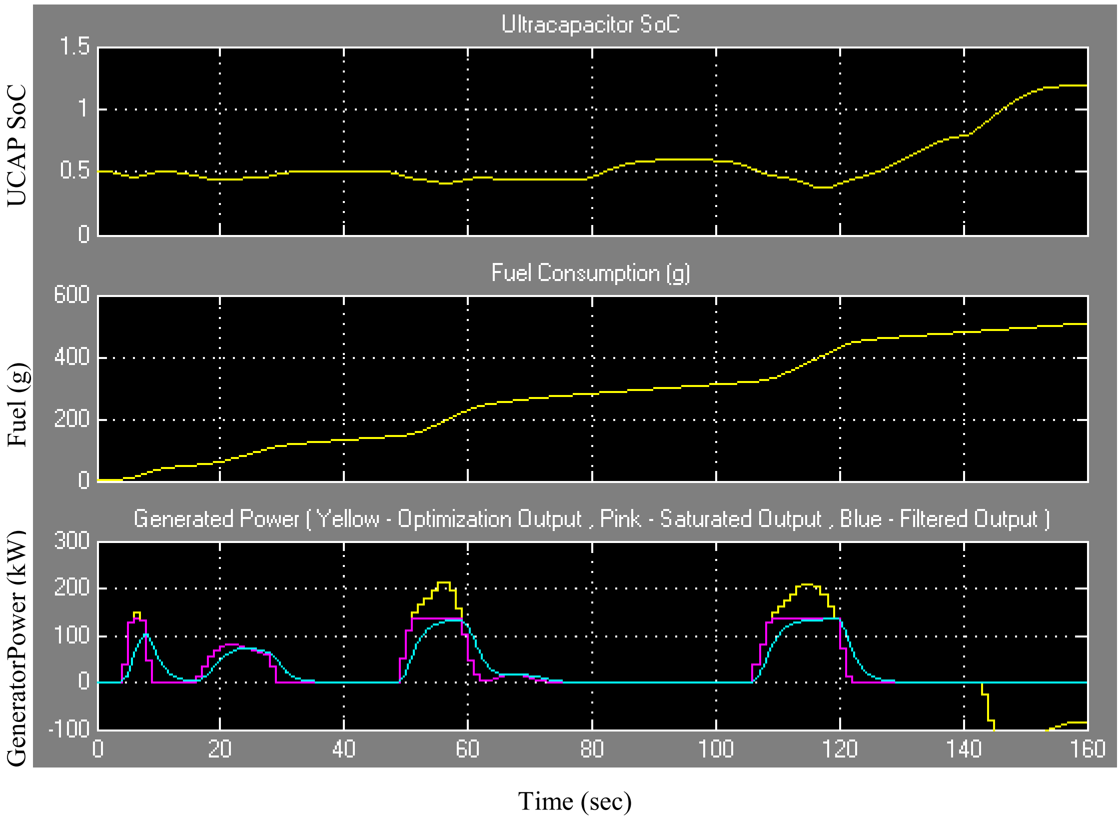

Figure 5.10 SoC, fuel consumption and generator power for SORT1 drive cycle Case 1b

As expected, the SoC of the ultracapacitor does not deplete. Hovever, in case I-b, the SoC output overshoots the upper bound (100%) because of the excessive regenerated energy recuperated during the last deceleration. It can be concluded that due to the fact that the constraint defined is not capable of adaption to changing load conditions. This insufficiency is valid for both case 1-a and case 1-b.

In Figure 5.11, similar to Figure 5.9, an inconsistency between is observed between the curves of the lower constraint (magenta color) and the output $\sum_{i=1}^{n} P_G^i$ (in blue color) at t=55 sec and t =110 sec.

It can be concluded that if the fuel consumption minimization problem is defined with static constraints, it is observed that the electric energy storage unit either depletes or overflows due to the unpredictable nature of the demanded traction power.

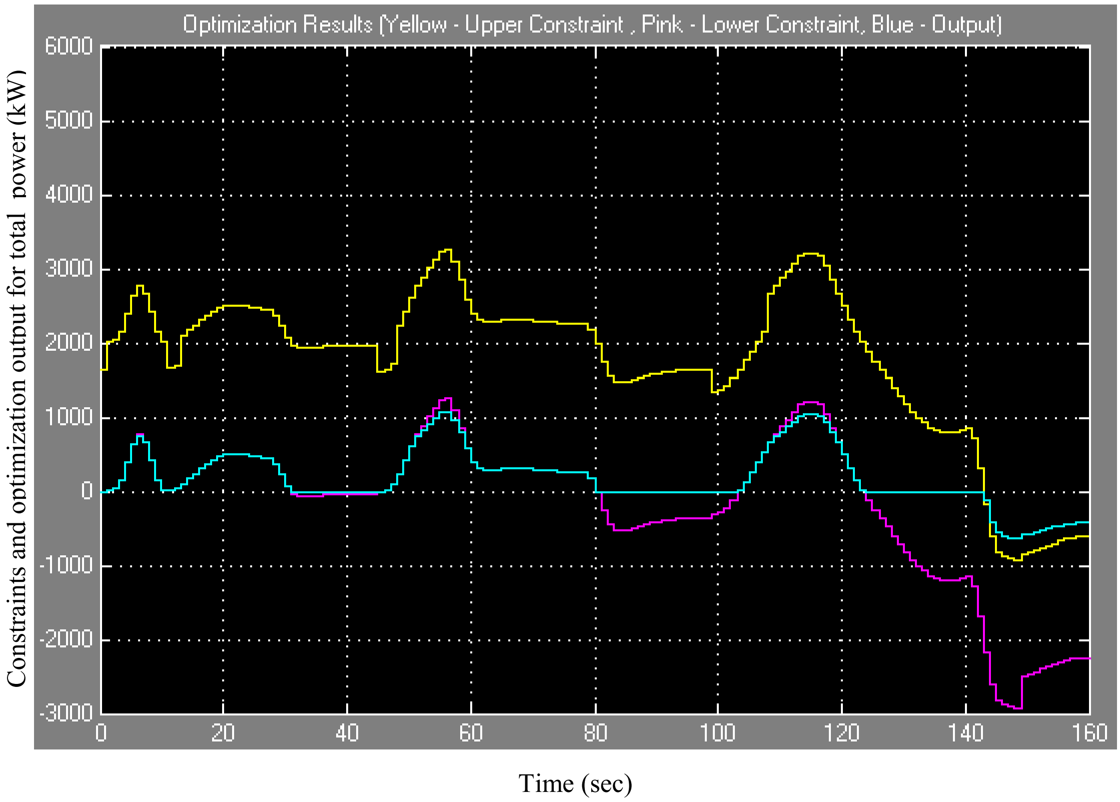

Figure 5.11 Optimization results for SORT1 drive cycle for Case 1-b

5.4.1.3 Case 1-c

Because of the insufficiency of the static constraints, a simple strategy as defined in equation (3.48). is used to compensate the load uncertainties. The electrical energy in the ultracapacitor system can be defined as a function of vehicle speed and the road gradient. The sum of the electrically stored energy in the ultracapacitor, the kinetic and the potential energies of the vehicle is kept constant and is assumed to be less than or equal to the ultracapacitor energy capacity. For this reason, as illustrated in Fig 5.12, the SoC drops down to almost zero at t=115 and rises up to 90% after regeneration. The improvement in SoC output is due to the increase of adaptability against the unpredictable road load conditionas and driver traction demand.

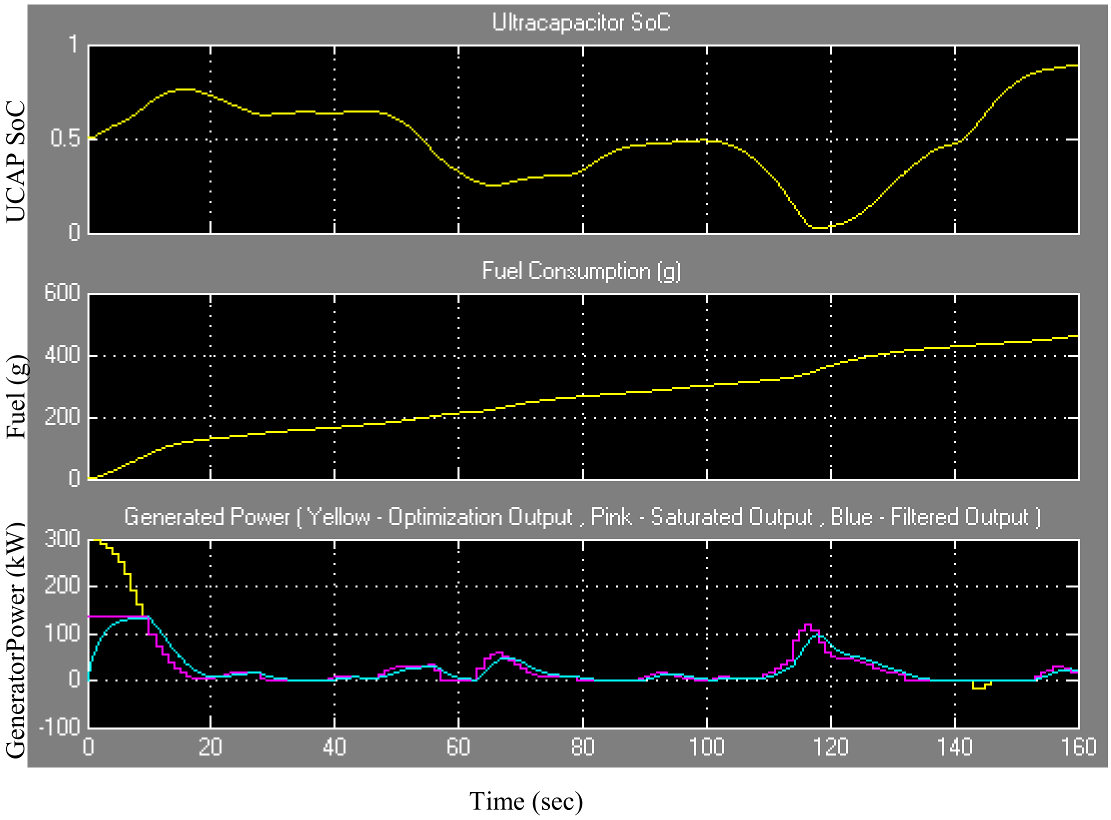

Figure 5.12 SoC, fuel consumption and generator power for SORT1 drive cycle Case 1c

Total fuel consumption is less than the previous case 1-b due to the fact that the storage capacity is fully exploited instead of a percentage (There is no static constraint on E_{UC}). Another improvement to mention is the reduced transients of the ICE. Compared to the previous cases the engine shows a more steady behaviour which is in reality an advancement in terms of decreased transient dynamics due to excessive injection etc.

Figure 5.13 is plotted with the same scale as in case 1-a and case 1-b to emphasize the difference in gap between the upper and lower bounds. This is due to the fact that the dynamic constraints defined is section 4.2 forces a smaller feasible region for the optimization problem.

At the beginning of the simulation, the output $\sum_{i=1}^{n} P_G^i$ falls below the lower constraint due to the saturated power generation. The dynamic constraint dictates to have a full energy storage when the mechanical energy (kinetic and potential) of the vehicle is minimum, but intentionally for the simulation purposes the initial SoC was set to 0.5 to observe its effect.

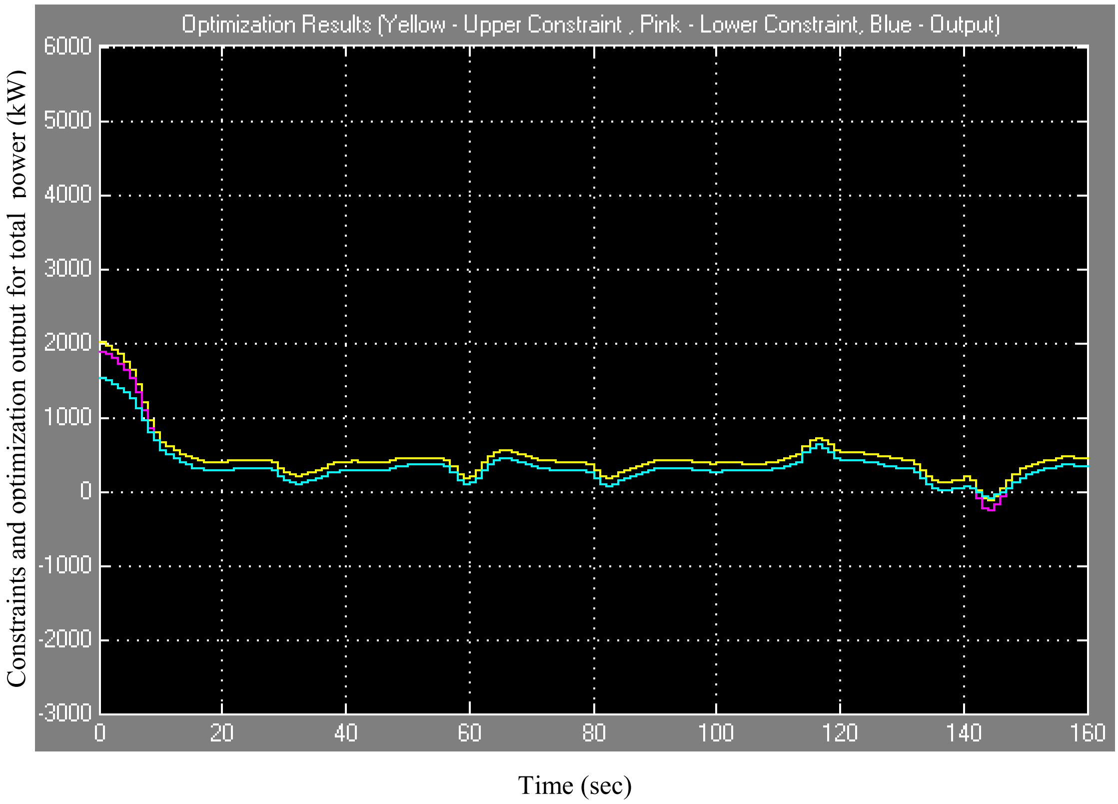

Figure 5.13 Optimization results for SORT1 drive cycle Case 1-c

As stated before the increasing behavior of the objective function forces the output of the optimization to overlap with the lower bounds.

5.4.2 NYC Drive Cycle

The 3 cases simulated with the UITP SORT1 drive cycle are also applied to the NYC cycle to observe the outputs of the optimization method.

5.4.2.1 Case 1-a

Similar to the outputs in UITP SORT1 cycle, with the simple constraint $0 \leq E_{UC} \leq E_{UC\_\max}$ it is not possible to fulfill the requirements of the demaded vehicle propulsion to complete the mission. The SoC drops below zero witin the second acceleration of the cycle.

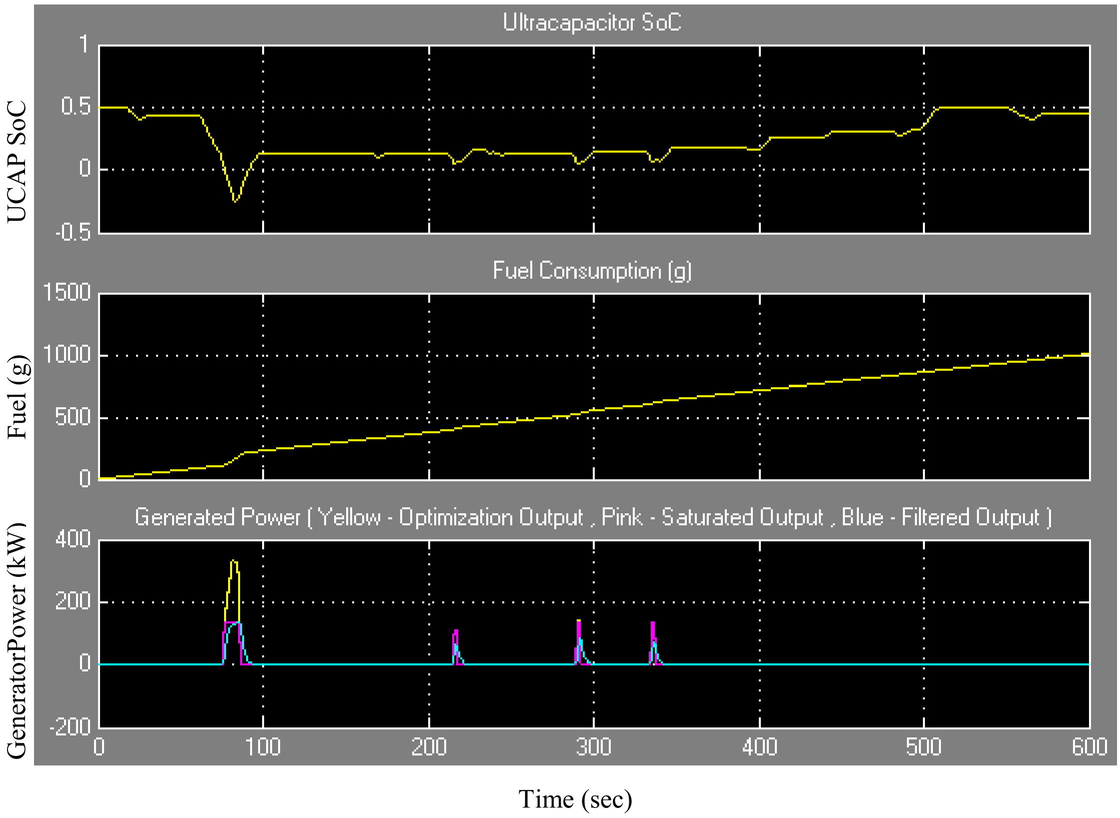

Figure 5.14 SoC, fuel consumption and generator power for NYC drive cycle Case 1-a

Similar to case 1-a of the SORT 1 the problem of SoC depletion is observed again for the 600 sec long NYC drive cycle. Total fuel consumption is observed to be 1000g.

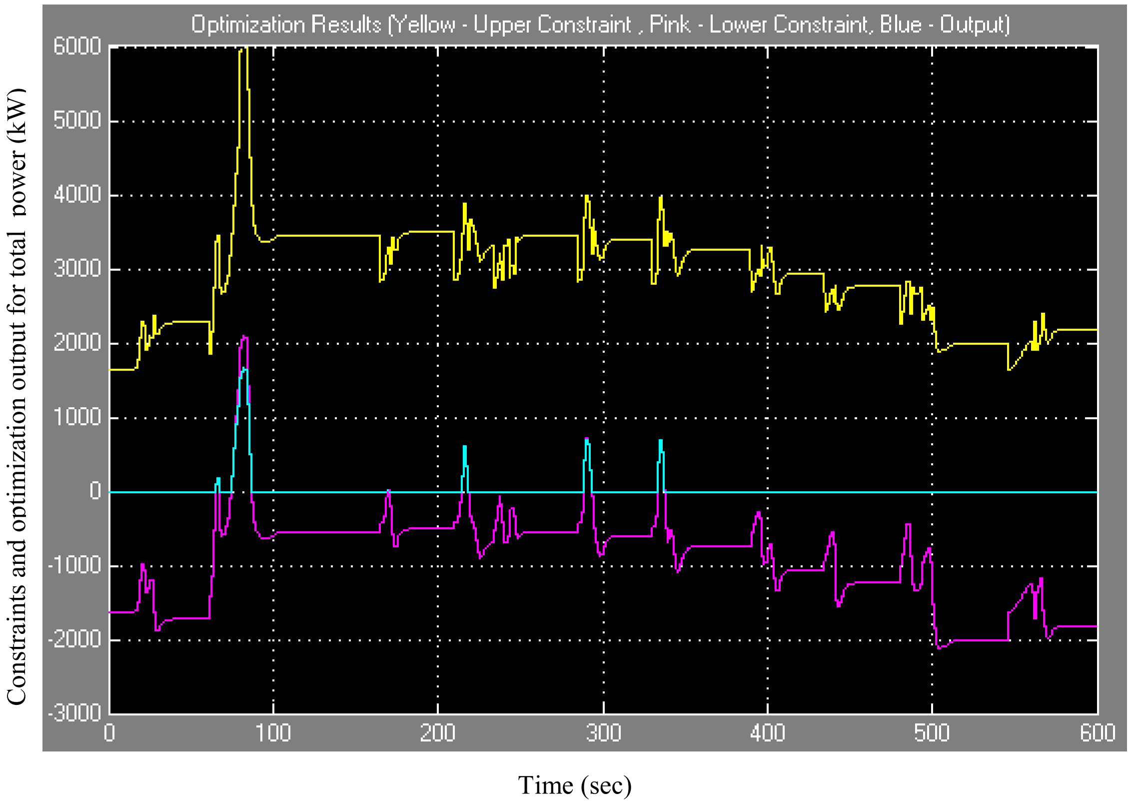

Figure 5.15 Optimization results for NYC drive cycle Case 1-a

5.4.2.2 Case 1-b

The following graph presents the outputs for the constraint 1-b, $0.5E_{UC\_\max} \le E_{UC} \le E_{UC\_\max}$

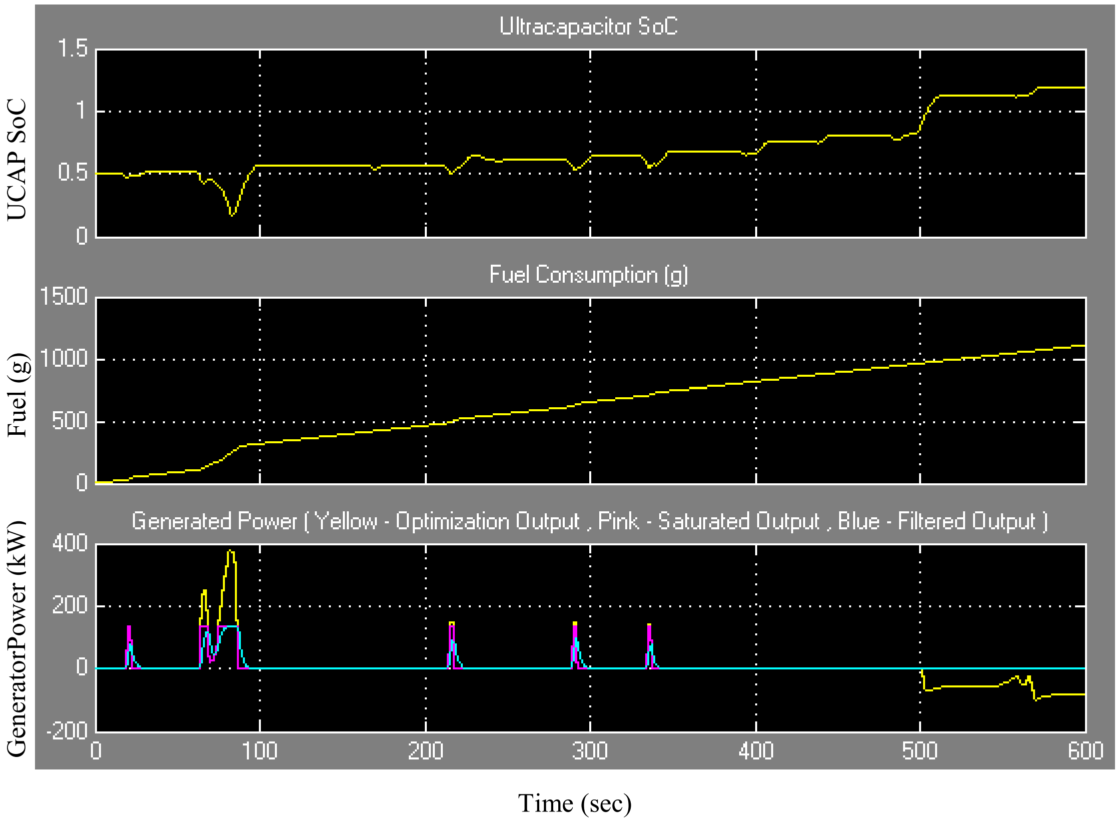

Figure 5.16 SoC, fuel consumption and generator power for NYC drive cycle Case 1-b

The SoC overflow problem is also observed at the end portion of NYC cycle composed of increased number of accelerations and decelerations. The SoC is observed to be exceeding the physical limits which would lead to deploy brake resistors to dissipate the excessive energy. Similar to case 1-a the transients of the engine are observed to be high. High transients would lead to excessive fuel injection in real world scenario.

Figure 5.17 exhibits the inconsistency between the curves of the lower constraint (magenta color) and the output $\sum_{i=1}^{n} P_G^i$ (in blue color) at t=61 sec and t =75 sec.

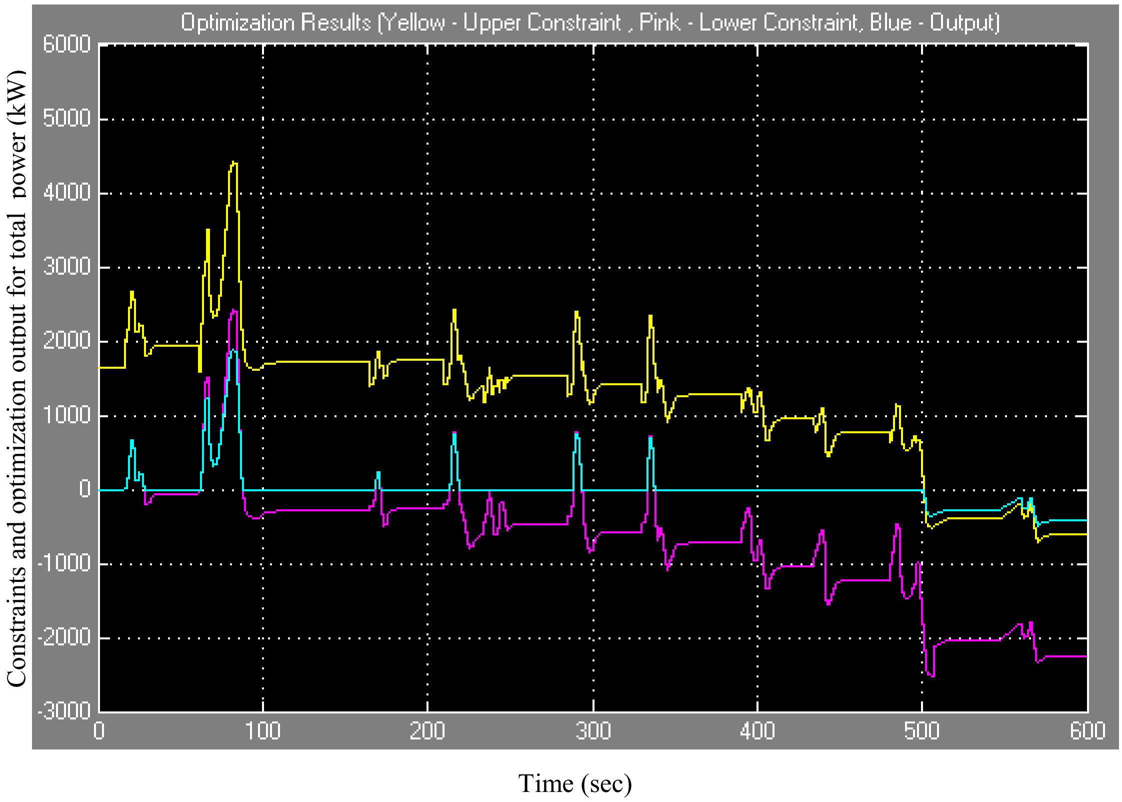

Figure 5.17 Optimization results for NYC drive cycle Case 1-b

5.4.2.3 Case 1-c

The following diagram presents the SoC output, fuel consumption and the generator power required to complete the NYC cycle.

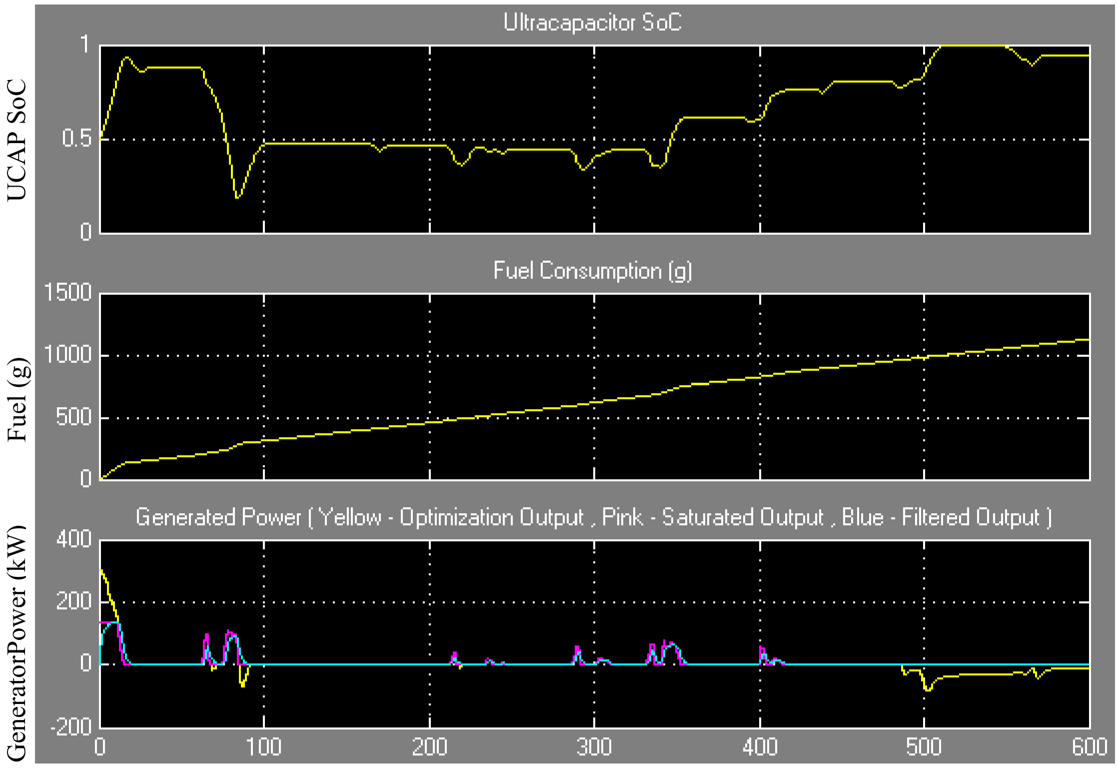

Figure 5.18 SoC, fuel consumption and generator power for NYC drive cycle Case 1-c

Unlike the case I-a and case I-b no overflow or full depletion is observed throughout the mission in terms of SoC. Fuel consumption is comparable to case 1-b (~1000g). The transients of the engine are reduced.

In simulation environment the increasing effect of transients on fuel consumption is another research topic. It is not covered in this thesis but the benefits of reduced transients are welcomed in automotive engineering applications.

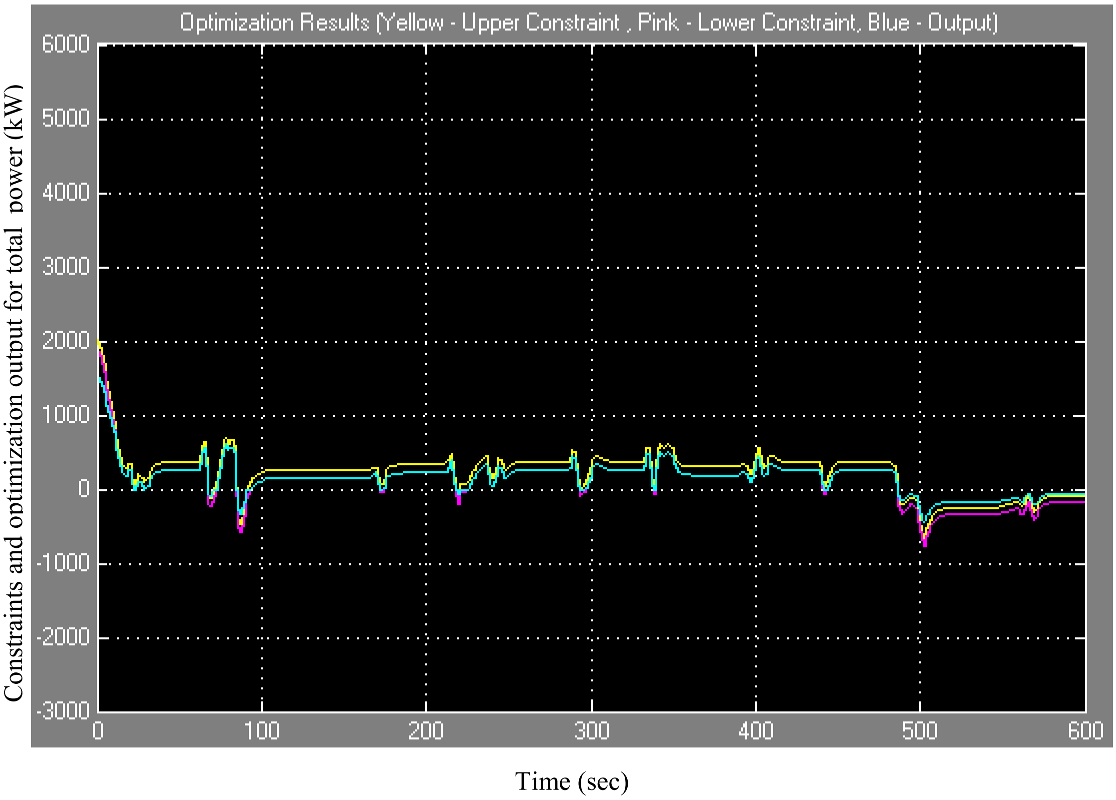

Figure 5.19 Optimization results for NYC drive cycle Case 1-c

In this chapter, a simulation study was conducted to assess the performance of a series hybrid vehicle configuration using two standard driving cycles, UITP's SORT1 and NewYorkCity. Simulation parameters were introduced and the simulated vehicle dynamical outputs were presented.

In order to predict the future values of the vehicle speed, linear and nonlinear regression models (defined in Section 4.1) were compared to each other.

The results indicated that depending on the constraint type chosen, the SoC of the storage unit can be fully or partially used to reduce the fuel consumption of a series HEV in city cruising.

CHAPTER 6

CONCLUSIONS

In this thesis an energy and power management strategy has been proposed which can be applied to series hybrid electric vehicles. The problem is handled by using a prediction based information perspective and utilization of a policy derived by Dynamic Programming.

Since the driver's traction power demand depends the driving environment which makes it difficult to know the driving pattern exactly, the proposed policy minimizes the fuel consumption with respect to the predicted model of the future driving conditions using a simple model of the power flow, energy levels and a regression model of the future driving.

Additional information from GPS and digital maps or cooperation with the traffic infrastructure further enhances the optimization in terms of improved predictions and constraints for the optimization problem and therefore can be used to better schedule the use of the buffer so that further fuel consumption reductions are achieved.

The solution methods were assembled for a detailed assessment of fuel consumption in various drive cycles via Matlab/Simulink. In order to monitor various strategies, a rather simple UITP drive cycle and a well known urban NYC drive cycle were taken into consideration in the fuel efficiency assessment. It can be concluded according to the detailed simulation results including vehicle speed, electric motor power, ultracapacitor SoC and average fuel consumption that HEVs have superior fuel consumption attributes if compared to the conventional vehicle in the urban cycle.

The study also showed that selection of power management strategies in terms of optimization parameters and constraints plays a key role in the fuel consumption dynamics as well as the state of charge of the ultracapacitor. Three different constraint sets were presented for both drive cycles. By analyzing the optimization results, an improved constraint based control strategy was developed.

The simulation system does not only allow to investigate the influence of different energy management strategies, but could also be used to optimize the size of the electric energy storage unit by investigating its influence on optimization and power availability.

REFERENCES

[1] He X, Parten M, Maxwell T, “Energy Management Strategies for a Hybrid Electric Vehicles”, Advanced Vehicle Engineering Laboratory, IEEE 2005

[2] K.T. Chau , Y.S. Wong, “Overview of power management in hybrid electric vehicles”, Energy Conversion and Management Vol.43 (2002) pp1953–1968

[3] Lin, C.C.; Filipi, Z.; Wang, Y.; Louca, L.; Peng, H.; Assanis, D.; Stein, J., “Integrated, Feed-forward Hybrid Electric Vehicle Simulation in SIMULINK and its Use for Power Management Studies”, SAE Technical Paper No. 2001-01- 1334, 2001

[4] Glenn, B.; Washington, G.; Rizzoni, G., “Operation and Control Strategies for Hybrid Electric Automobiles”, SAE Technical Paper No. 2000-01-1537, 2000

[5] Wipke K.; Cuddy M.; Buch S., “ADVISOR 2.1: a user-friendly advanced powertrain simulation using a combined backward/forward approach”, IEEE Transaction on Vehicular Technology, Vol.48, No: 6, pp.1751-1761, 1999.

[6] Lin, C.C.; Peng, H.; Grizzle J.W.; Liu, J.; Busdiecker, M., “Control System Development for an Advanced-Technology Medium-Duty Hybrid Electric Truck”, SAE Technical Paper No. 2003-01-3369, 2003.

[7] Chan-Chiao Lin, Zoran Filipi, Yongsheng Wang, Loucas Louca “Integrated, Feed Forward Hybrid Electric Vehicle Simulation in SIMULINK and its Use for Power Management Studies” , SAE Technical Paper No. 2001-01-1334, 2001.

[8] Nashat J., Naim A.K., Mutasim S., “A Rule-Based Energy Management Strategy for a Series Hybrid Vehicle” Proceedings of the American Control Conference, 1997.

[9] Mathworks Inc.”Optimization Toolbox for use with MATLAB” User’s Guide Version 2.

[10] Johnson, V.H.; Wipke, K.B.; Rausen, D.J., “HEV Control Strategy for Realtime Optimization of Fuel Economy and Emissions”, SAE Technical Paper No. 2000-01-1543, 2000.

[11] Bauman, Bernd M.; Washington, G; Glenn, Bradley C.; Rizzoni, G., “Mechatronic design and control of hybrid electric vehicles”, IEEE/ASME Transactions on Mechatronics, v5 n1 2000. p 58-72, 2000. 156

[12] Rajagopalan A.; Washington, G; Rizzoni, G.; Guezennec Y., “Development of fuzzy logic and neural network control and advanced emissions modeling for parallel hybrid vehicles”, The National Renewable Energy Laboratory (NREL) Report.

[13] Leon C. Rosario, Patrick C.K.Luk “Implementation of a Modular Power and Energy Management Structure for Battery – Ultracapacitor Powered Electric Vehicles” Department of Aerospace Power and Sensors, Cranfield University

[14] Gillespie, T.D., “Fundamentals of Vehicle Dynamics”, Society of Automotive Engineers, Inc., 1992.

[15] McQueen B. and McQueen, J. *Intelligent Transportation Systems Architectures*. Artech House Publishers. 2003.

[16] Chan-Chiao Lin', Jun-Mo Kang', J.W. Grizzle2, and Huei Peng, “Energy management strategy for a parallel hybrid electric truck”, American Control Conference, 2001 Proceedings of the 2001 Volume 4, Page(s):2878 - 2883 vol.4

[17] Jeffrey D. Gonder, “Route-Based Control of Hybrid Electric Vehicles”, National Renewable Energy Laboratory, SAE Technical Paper No. 2008-01-1315, 2008.

[18] M. J. West C. M. Bingham N. Schofield, “Power management for an electric propulsion system using fuel cells”, Proceedings of the 9th WSEAS International Conference on International Conference on Automation and Information, Pages 422-430, 2008.

[19] Q.Gong, Y.Li, ZR Gainesville, “Trip Based Optimal Power Management of Plug-in Hybrid Electric Vehicle with Advanced Traffic Modeling”, SAE Technical Paper No. 2008-01-1316, 2008.