AN ENERGY BASED MODEL FOR OPTIMIZATION OF MOTOR RUNTIME IN PLUG-IN HYBRID ELECTRIC VEHICLES

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ABSTRACT

Plug-in Hybrid Electric Vehicles (PHEVs) presently utilize torque–speed characteristics of the Electric Motor (EM) and Internal Combustion Engine (ICE) together with the stored energy available in the battery to determine the running mode of the motor and engine. This decision is based on the real time information provided by the vehicle sensory system. The motor and engine controllers will try to match the torque-speed characteristic of the load in a reactive mode. This type of control is one of the contributing factors that result in battery drain due to unnecessary drive train acceleration needed to meet the torque-speed requirements. Drive train efficiency maps that emphasize the torque-speed characteristics of PHEVs for highway and city journeys allow for the development of intelligent energy management systems based on a reactive mode of operation. This paper presents a proactive/predictive energy based model and software for a Parallel PHEV drive train that would have the capability to optimize on motor runtime by forecasting on energy demand.

KEYWORDS: Optimization, Energy Conversion, Kinetic Energy, Potential Energy, Efficiency, Software Development, Simulation

I. NOMENCLATURE

KE :Kinetic energy in kilojoules
PE :Potential energy in kilojoules
FE, F_n :Frictional energy in kilojoules
P :Power in kilowatts
ω :Angular velocity in radians per second
t :Time in seconds
η :Efficiency expressed as a percentage (%)
E :Energy of battery pack in Mega-Joules
τ :Torque in Newton-metres
R_{tire} :Tire resistance coefficient
n, n_s :Motor speed, motor synchronous speed in revolutions per second
m :Mass of vehicle in kilograms
r_{wheel} :Radius of vehicle wheel in metres
g :Gravitational constant in m/s^2
ρ :Density of air in kg/m^3
S_{ab}, S_{acc} :Distance traveled between two points and during acceleration in m
h :Elevation above sea level in metres
θ :Angle of inclination in degrees
c_d :Air drag coefficient
A_f :Front area of vehicle in m^2
V :Velocity of vehicle in m/s
SOC :State of charge of batteries as a %
a :Vehicle acceleration in m/s^2

II. INTRODUCTION

With the new drive from Hybrid Electric Vehicle (HEVs) to Plug-In Hybrid Electric Vehicle (PHEVs) there exists a need to ensure that the stored energy in the batteries pack is managed and utilized efficiently. At present with the conventional batteries used, HEVs and PHEVs can run as a purely electric vehicle for a range of up to 32km. Allowing the vehicle to manage the internal combustion engine (ICE) and electric motor (EM) energy delivery to the drive system will help in sustaining the charge on the batteries while improving on the resultant mileage of the vehicle and air quality through reducing fossil fuel consumption. Considerable research has been done and continues to be undertaken in finding a suitable energy source for the electric motor. This source should have the capability to store and discharge electrical energy needed for the vehicle peak energy requirement stages. One such energy source is super capacitors as presented in [Cheung *et al*] whereby the energy management strategy employed can result in a 30% reduction in the power supply system. This can have significant benefit in reducing the overall mass of the vehicle and the energy loss due to heat dissipation during the energy conversion process.

The batteries presently utilized in PHEVs and HEVs are Nickel Metal Halide (NiMH) and Lithium Ion (Li Ion). The efficiency, mass, storage capacity and cost of the battery pack are all four critical factors that contribute to the overall goal of achieving a purely electric vehicle with the range of a conventional ICE run vehicle. As presented in [Duvall], the behavior of a 50MJ NiMH battery pack used in a Daimyler Chrysler Sprinter Van showed considerable information on the rate of charge and discharge of the batteries during a 5 hr journey. The harnessing of the stored energy necessary for operating the electric motor during the acceleration and steady state is critical for improving the overall mileage of the PHEV. Simulation programs such as ADVISOR as presented in [Markel and Wipke] for an energy management system has shown promising results in the control of the ICE and EM based on the state of charge of the battery pack.

The concept behind a model to optimize on motor runtime is based on the dynamic behaviour of a motor vehicle during its acceleration, steady state and deceleration stages. This behaviour is directly related to the topology of the terrain and the number of acceleration and deceleration points. Understanding the dynamic behaviour of a PHEV as presented in [Amrhein and Krein] is critical in ensuring that the energy conversion process from the fuel, batteries, ICE, motor and transmission system is properly coordinated for realistic results to be obtained.

In this paper, the motor runtime optimization model proposed and software developed using Microsoft Visual Basic shall be based on a random journey generator subroutine which shall create a typical journey of any motor vehicle in a combination of highway and city runs with the main components of distance traveled, elevation above sea level and the number of possible acceleration and deceleration points. The software shall output the EM and ICE power requirement, angular velocity and length of time based upon a developed motor runtime optimization algorithm. This proactive/predictive energy based model and software for a Parallel PHEV drive train has the capability to optimize on motor runtime by forecasting on energy demand. The software program can be integrated with a vehicle's Global Positioning System (GPS) and elevation maps for practical implementation and testing. For further research and development in the area of drive systems and motor applications for PHEVs, the output of the software shall be used to test the effectiveness of the developed motor drive controllers.

III. MODEL ARCHITECTURE

The model architecture which has been developed for a PHEV with a parallel drive train that consists of four main components namely the ICE, EM, battery pack and transmission system. The basic laws of mechanics and energy conservation have been applied to meet the energy requirement of the system for sustenance of useful motion. For simulation purposes, the random journey generator, vehicle specifications and operating parameters shall be used to obtain the energy requirements of a typical journey. With the motor runtime optimization algorithm, the output power, angular velocity and period of operation of the motor shall be generated for easy integration with a drive controller. This is demonstrated in Figure 1. The developed motor runtime optimization model has been tested with Toyota HEV vehicle specifications for the Highlander, Camry, Prius and Touring.

A. Inputs

The motor optimization model implemented in this paper can be integrated with a GPS to give the necessary data of distances and elevation above sea level. For the simulation program, this data shall be generated with the use of a random generator function from Visual Basic. The generator will produce any journey of distance 150 km to 450 km. The angle of inclination with the horizontal shall not be greater than 45^{o}. In addition, for any typical journey, a random number of acceleration and deceleration points shall also be generated. This shall range from 4 to 18 each.

The conditions that govern the process for the optimization model developed must first be initialized. For this model these conditions referred to as the parameters shall include the vehicle velocity (km/hr), state of charge (SOC - %) of the batteries and the fuel level (%). Energy needed for the movement of any body is directly related to the physical dimension and mass of the body. The vehicle specifications for the Toyota range of HEVs as shown in Table I shall be integrated with the random journey data to calculate the kinetic energy requirement for each stage of the journey. In addition, the vehicle specification will provide the necessary data on fuel tank capacity and motor and ICE maximum rated power.

Once the user chooses the appropriate vehicle for the journey, the corresponding specifications together with the operating parameters and random journey data shall be used to optimize on the motor run time for every second of travel of the vehicle.

B. Energy and Efficiency

(1) Potential Energy

A vehicle will possess a finite amount of stored energy at any point in a journey. This energy is the potential energy (*PE*) and is given as:

$$PE_{initial} = PE_{fuel} + PE_{batteries} \tag{1}$$

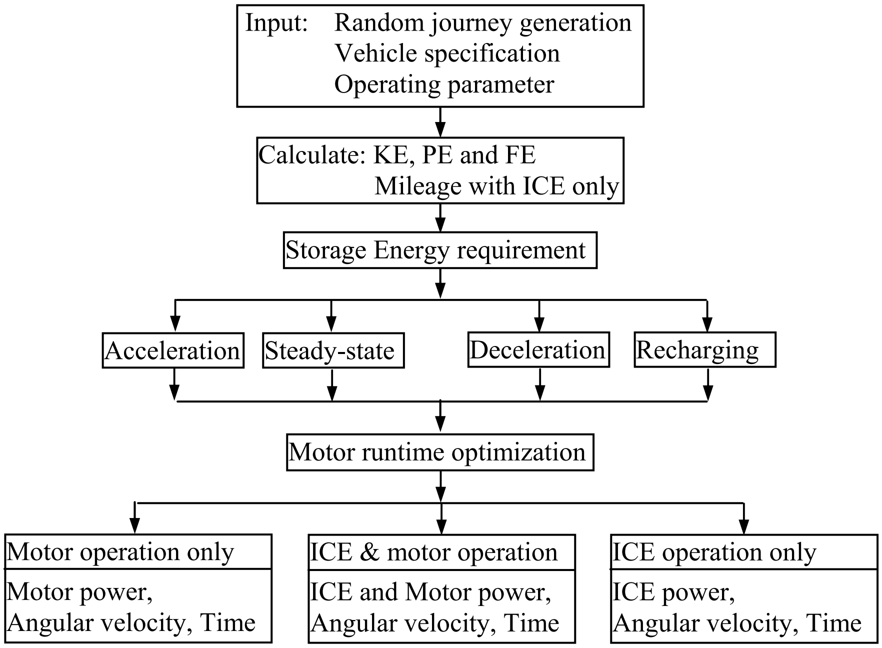


Fig. 1: Motor Runtime Optimization Architecture.

Table I: Vehicle Specification – Toyota HEV.

Vehicle Model	General Specifications	ICE Specs	Electric Motor Specs	Air Drag Coefficient C_d	Net Power (kW)
Highlander	Mass – 2727kg Fuel Tank-65.1L Wheel Rad-0.2159m Mileage- 25/26	156kW 5600rpm	123kW 4500rpm	0.34	201
Camry	Mass – 1673kg Fuel Tank-65.1L Wheel Rad-.2032m Mileage- 40/38	118kW 6000rpm	105kW 4500rpm	0.27	140
Prius	Mass – 1333kg Fuel Tank-45.04L Wheel Rad-0.1905m Mileage- 60/51/55	57kW 5000rpm	50kW 1200-1540rpm	0.26	82
Touring	Mass – 1333kg Fuel Tank-45.04L Wheel Rad-0.2032m Mileage- 60/51/55	57kW 5000rpm	50kW 1200-1540rpm	0.26	82

The potential energy is converted into kinetic energy (KE) by the electric motor and ICE. The vehicle potential energy $(PE_{vehicle})$ at any point in time is a function of the initial potential energy ($PE_{initial}$), kinetic energy generated by the engine (KE_{ICE}) and motor (KE_{motor}), engine loss (ICE_{loss}), motor loss ($Motor_{loss}$) and frictional loss as shown in (2).

$$PE_{vehicle} = PE_{initial} - \left[\left(KE_{ICE} + ICE_{loss}\right) + \left(KE_{motor} + Motor_{loss}\right) + Frictional\ Loss\right] \tag{2}$$

The change in potential energy of a vehicle due to a change in position can be represented by (3) where θ is the angle of inclination, g the gravitational constant, m the mass of the vehicle and S_{ab} is the distance traveled between a and b.

$$\Delta PE_{ab} = mgh_b - mgh_a = mg \sin \theta . S_{ab} \tag{3}$$

(2) Frictional and Kinetic Energy

The kinetic energy required to travel between any two points a and b can be represented by the potential energy of the body at the two points and the resistance to motion. The resistance to motion is due to the air drag and the frictional force between the tire and the road. The frictional energy (FE) is represented by (4) below.

$$FE = \frac{1}{2} c_d \rho A_f v_{veh}^2 S_{ab} + R_{tire} mg S_{ab} \tag{4}$$

where ρ represents the ambient air density, A_f is the frontal vehicle area and R_{tire} is the rolling resistance. The kinetic energy as expressed in (5) is a function consisting of the potential and frictional energies.

$$KE_{ab} = KE_a - \left[\left(\Delta PE_{ab}\right) + FE_{ab}\right] \tag{5}$$

For an entire journey, the equation representing the kinetic energy is given in (6) below where n represents the number of subset journeys within the entire journey.

$$KE_n = \frac{1}{2} m v_n^2 = \sum_{n=0}^{n=j} \left[KE_{initial_n} - \left\{\left(mgh_{b_n} - mgh_{a_n}\right) + FE_n\right\}\right] \tag{6}$$

(3) Efficiencies and Batteries

The efficiencies of the EM, ICE and batteries for this model and software development shall be assumed as constant for varying load conditions. The second version of the software will use the details of the efficiencies curves for the ICE, EM and batteries. In this situation, the output of the software shall be used to control the EM based on energy requirements. The efficiencies of the components are as follows: ICE = 25%, EM=85%, Batteries=50%.

For the purpose of this model and software, the Toyota battery packs shall be replaced with a larger battery pack comprising of Nickel Metal Halide (NiMH) batteries with a storage capacity of 28.26MJ. Due to the rate of charging during normal ICE and braking runs, electrical energy is normally injected to the battery at a far faster rate than it can be converted to chemical energy in the battery. This results in heat dissipation from the battery and an average charging efficiency of 50%. The energy available from the batteries at any point in time can be represented by the "State of Charge – SOC".

$$SOC(\%) = \frac{E_{energyavailable}}{E_{batterycapacity}} x100 \tag{7}$$

The SOC together with the power requirement shall be used to determine the running mode of ICE and motor. The minimum SOC shall be 10%.

C. Electric Motor (EM)

For this paper and in HEV application the electric motor should operate in the region where the torque is constant for variation in speed. This normally occurs within the pull-out torque envelope and for speeds less than the base or synchronous speed, n_s.

$$\left.\begin{aligned} &P = \omega\tau \\ &P \infty \omega \quad for \qquad \tau_{\min} \le \tau \le \tau_{\max},\ n \le n_s \end{aligned}\right\} \tag{8}$$

We shall set the maximum velocity of the vehicle: $V_{\max} = 200\,km/hr = 55.56\,m/s$

$$\omega_{\max,wheel} = V_{\max}\, r_{wheel} \tag{9}$$

The wheel angular velocity must be translated through the gear system and transmission to the EM. This shall be called the transmission ratio (*TR*).

$$TR = \frac{\omega_{motor\max}}{\omega_{wheel\max}} \tag{10}$$

From (8) we can relate the angular velocity of the motor to the output power. For $n \le n_s$

$$\frac{P_{motor\max}}{\omega_{motor\max}} = K \tag{11}$$

K is the power/angular velocity ratio. The output power of the motor for any speed less than the synchronous speed with constant torque is given as:

$$P_{motor} = \omega_{motor} \frac{P_{motor\max}}{\omega_{motor\max}} = \omega_{motor} K \tag{12}$$

D. Battery Energy and Fuel Consumption

The user shall initialize the SOC and fuel level at t=0. During the journey and once in every second, the program shall update the SOC level and fuel level based on the output of the optimization routine for the motor runtime. Equations (13) and (14) shown below shall be used to obtain this information.

$$SOC_n = SOC_{n-1} - \left[\frac{P_{motor}\,(t_n - t_{n-1})}{E_{batterycapacity}\,\eta_{motor}}\right] \times 100 \tag{13}$$

$$Fuel_n = Fuel_{n-1} - \left[\frac{P_{ICE}(t_n - t_{n-1})}{E_{Fuelcapacity}\,\eta_{ICE}}\right] \times 100 \tag{14}$$

IV. CHANGE OF VEHICLE POSITION

A vehicle's movement will have the following stages acceleration, steady state and deceleration. For a PHEV, energy is transferred from potential to kinetic energy and also back to potential energy during the regeneration and recharging stages of the batteries. An understanding of the dynamics of these stages is essential in building the model required.

A. Linear and Non-Linear Accelerations

Linear acceleration is the process whereby a vehicle starts from rest, *u=0* and after some finite time *t*, it attains its final velocity, *v*. The rate of change of velocity for the period *t* is a constant and is referred to as the linear acceleration, *a*.

For the purpose of this model and software, linear acceleration shall be considered. The HEV will achieve a speed of 100 km/hr or 27.78 m/s in 8.1s. As such the acceleration shall be:

$$a = \frac{v-u}{t} = \frac{27.78-0}{8.1} = 3.429\, m/s^2 \tag{15}$$

From the equation of motion for linear acceleration, we can obtain the distance traveled during acceleration. (16) gives the tool to calculate the distance, S_{acc} the vehicle will travel during its acceleration stage.

$$S_{acc} = Vt_{acc} + \frac{1}{2} at_{acc}^2 \tag{16}$$

The kinetic energy (KE_{acc}) during this period given in (17) is a function of the *KE* for a flat surface, the potential energy (*PE*) and the frictional energy (*FE*) required to overcome the frictional force.

$$KE_{acc} = KE_{accflatsurface} + PE_{acc} + FE_{acc} \tag{17}$$

The kinetic energy is equivalent to the work done which is the product of the force and the distance moved in the direction of the force and is represented in (18).

$$KE_{accflatsurface} = maS_{acc} \tag{18}$$

Potential energy is the energy a body possesses by virtue of its position and is a function of the body's mass, *m*, the gravitational constant *g* and the change in vertical distance ($S\sin\theta$) and is expressed in (19).

$$PE_{acc} = mgS_{acc} \sin\theta \tag{19}$$

As the vehicle moves from rest, the frictional force, as explained in B, will contribute to the energy requirement for sustained movement and acceleration. This is given in (20) below.

$$FE_{acc} = \frac{1}{2} c_d \rho A_f v_{veh}^2 S_{acc} + R_{tire} mgS_{acc} \tag{20}$$

Knowing the *KE* required and the period of time, the power requirement can be calculated from (21a).

$$P_{acc} = {KE_{acc}}\big/{t_{acc}} \tag{21a}$$

For non-linear acceleration, the equations of motion can be in the form

$$u = -\mu(s).g \tag{21b}$$

$$s = \frac{g}{u} h(s) \tag{21c}$$

$$h(s) = \mu(s)\left(s - 1 - \frac{mR^2}{J} \right) + \gamma_b \tag{21d}$$

The differential of the velocity (*u)* with respect to time will give the nonlinear acceleration. Non-linear acceleration shall not be utilized for this version of the software due to the number of other factors considered with regards to the vehicle energy requirement based on the journey characteristic. Such acceleration can be considered for an upgraded version of the software.

B. Steady State

For the steady state condition, the vehicle would have built momentum during the acceleration stage and would then travel at constant velocity. During this period, the power requirement for each second is less than that for the acceleration stage and it is represented by (22) and (23) below.

$$KE_{steadystate} = \frac{1}{2} m v^2 \tag{22}$$

$$P_{steadystate} = \frac{KE_{steadystate}}{t_{steadystate}} \tag{23}$$

C. Deceleration

Deceleration is a necessary process to bring the vehicle to rest. The kinetic energy the vehicle possessed during the steady state stage is dissipated as the velocity decreases. This *KE* can be captured by the motor in a regenerative mode for the charging of the batteries. In the regenerative mode, the motor power is negative and is presented by (24) below.

$$P_{regenerative} = -\omega_{motor} \frac{P_{motor\max}}{\omega_{motor\max}} = -\omega_{motor} K \tag{24}$$

As stated in Section II-B, the battery efficiency will directly influence how much of the transformed deceleration energy is captured. This can be represented in (25) below.

$$E_{batterycaptured} = \left[\omega_{motor} \frac{P_{motor\max}}{\omega_{motor\max}} \right] \eta_{motor} \eta_{battery} \tag{25}$$

D. Recharging of Batteries and Plug-In

The recharging of the batteries occurs when the $SOC \leq 10\%$. In this situation, the ICE must deliver extra power to meet the needs of recharging and also the *KE* requirements for the vehicle motion. The EM is not used in the motoring mode during the recharging cycle. Recharging will occur during acceleration and steady conditions. Equation (25) above will govern this condition. The ICE will have to deliver:

$$P_{ICErecharging} = P_{journeystage} + P_{regenerative} \tag{26}$$

It was found that for a parallel drive train PHEV, this was not an effective method of recharging the batteries and it negatively affected the mileage of the vehicle. This result was justified by the efficiencies of the ICE, motor and battery, for every 100J of fossil fuel energy used; only 10.6J of energy was stored in the battery. It was decided that for the recharging mode of operation, the ICE alone will operate with energy captured from deceleration utilized for recharging the batteries. Ideally in this situation if the journey was completed, the vehicle should be plugged-in to the electrical grid for trickle charging which would have a higher efficiency rate for the battery than the direct fast charge through the ICE.

V. MOTOR RUNTIME OPTIMIZATION ALGORITHM

Having obtained the energy requirement for the journey with the power requirement for each stage, we can optimize on the motor runtime. Ideally, the motor should run 100% of the time with its power supplying the energy requirement for each second of the journey. However, in practice, this is not possible due to the energy requirement being greater than the motor full load capacity or the battery does not possess enough energy to run the motor at the particular load requirement. We can analyse these scenarios with three (3) different conditions, namely

i. *Motor Output Power can meet or exceed power requirement of journey state* i.e.

$$P_{motor} \geq P_{acc}\,, \qquad P_{motor} \geq P_{steadystate} \tag{27}$$

ii. *SOC will not drop to less than 10% if motor is used.* With this condition, the model will be able to determine the effect the energy draw will have on the battery before the process is implemented. The motor can still operate at a reduce power which will not cause the SOC to decrease to less than 10%. The ICE will provide any shortfall in the power requirement needed to satisfy the load demand. This is represented by (28) to (31).

$$\left[\frac{P_{battery} - P_{acc}}{E_{capacity}}\right] t_{journeystage} \geq 10 \tag{28}$$

$$P_{motor} = P_{battery} - \left[\frac{0.10 * E_{capacity}}{t_{journeystage}}\right] \tag{29}$$

$$P_{ICE} = P_{acc} - P_{motor} \tag{30}$$

$$P_{ICE} = P_{ss} - P_{motor} \tag{31}$$

iii. *SOC<10.* If this condition is true, the motor can no longer run. It is the point whereby “plug-in to the grid” is required. For the parallel drive train PHEV, the motor shall run in the regenerative mode whereby equations (24) and (25) shall apply for the recharging of the battery pack using the energy captured by deceleration of the vehicle during the journey. The ICE shall be the only component for this scenario that will convert potential energy to kinetic energy for the vehicle’s propulsion. The condition will be reset to false once enough deceleration energy has been captured by the battery to cause the SOC to increase to the preset upper limit.

The truth table given in Table II forms the basis of the motor runtime algorithm and it was successfully implemented for an entire journey run. For each second of the journey, the motor and ICE power requirement was simulated successfully. For example, for decision path (4) the condition is “100”, the motor possesses enough power to perform the task of propelling the vehicle, condition (i) is TRUE or “1” and the SOC is at that moment is greater than 10%, condition (iii) is FALSE or”0”. However, condition (ii) is FALSE or “0” which states that the battery’s SOC will decrease to less than 10% if the task is performed. The motor can still run at a lower power output without allowing the SOC to drop to less than 10%. The ICE will compensate for the deficit power required to complete the task. By doing this, we are aiding in optimizing the motor runtime and power output. The power delivery equations are so stated for this decision path in Table II.

VI. SOFTWARE DEVELOPMENT

The model was implemented using Visual Basic Express Edition. The main aspect of the software development process was the creation of dynamic arrays for the storage of the simulated data. Due to the random journey generation, the size of the array could not be fixed. In addition fixed memory allocation for each array element results in insufficient memory space. Figure 2 shows the Graphic User Interface Screen which is the input screen for setting all operating parameters needed to initialize the optimization algorithm.

The input fields for the GUI are vehicle make and model, starting point elevation above sea level, average vehicle velocity, fuel level (%) and state of charge (%). The software program will allocate the constants value for the respective fields based on Tables I - Vehicle Specification, Toyota HEVs. The fields referred to as follows: vehicle front area, tire rolling resistance, drag coefficient, ambient air density, wheel radius, net power, fuel tank capacity, engine, motor and battery efficiencies, battery capacity and vehicle mass. The Random Journey Generation Screen presented in Figure 3 shows in detail the kinetic energy requirement for the journey with the actual journey path, distances and change in elevation above sea level. Screen III, shown in Figure 4 displays the results stored in the arrays for the entire journey. It is the critical screen used in troubleshooting and also for implementation of the integration module in Version 2 of the software program with a motor drive system. This screen displays for every

Table II: Motor runtime optimization truth table.

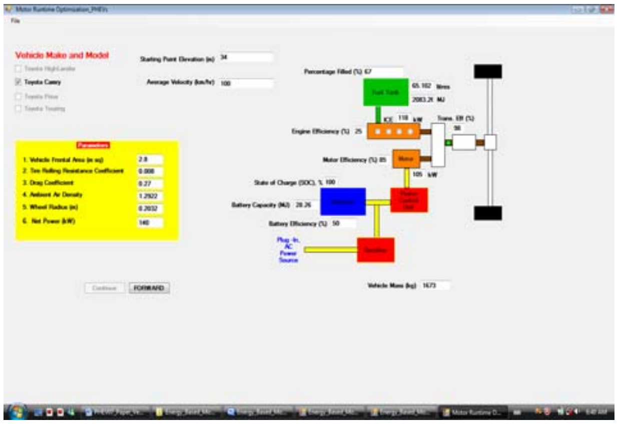
Decision Path	CONDITION			Optimization Decision	Power Delivery
	(i)	(ii)	(iii)		
0	0	0	0	ICE and Motor	$P_{motor} = P_{ICErated} - P_{acc}$ $P_{motor} = P_{ICErated} - P_{ss}$
1	0	0	1	ICE, regeneration during deceleration Plug-in Required	$P_{ICE} = P_{acc}$ $P_{ICE} = P_{ss}$ $P_{motor} = - P_{regenerative}$
2	0	1	0	ICE and Motor	$P_{motor} = P_{ICErated} - P_{acc}$ $P_{motor} = P_{ICErated} - P_{ss}$
3	0	1	1	ICE, regeneration during deceleration Plug-in Required	$P_{ICE} = P_{acc}$ $P_{ICE} = P_{ss}$ $P_{motor} = - P_{regenerative}$
4	1	0	0	ICE and Motor	$P_{motor} = P_{battery} - \left[\frac{0.10 * E_{capacity}}{t_{journeystage}}\right]$ $P_{ICE} = P_{acc} - P_{motor}$ $P_{ICE} = P_{ss} - P_{motor}$
5	1	0	1	ICE, regeneration during deceleration Plug-in Required	$P_{ICE} = P_{acc}$ $P_{ICE} = P_{ss}$ $P_{motor} = - P_{regenerative}$
6	1	1	0	Motor Only	$P_{motor} = P_{acc}$ $P_{motor} = P_{ss}$
7	1	1	1	ICE, regeneration during deceleration Plug-in Required	$P_{ICE} = P_{acc}$ $P_{ICE} = P_{ss}$ $P_{motor} = - P_{regenerative}$

second, the distance traveled, the EM and ICE power, the EM angular velocity, SOC (%), fuel level (%) and the decision path of the optimization algorithm.

The optimization results graphical screen shown in Figure 5, displays all the data stored in the dynamic array for the SOC (red line), fuel level (blue line) and motor power (yellow line) for the entire journey. From this screen it is possible to note the points where the motor is in the motoring and regeneration modes and at what point plug-in to the grid is needed. It also displays the acceleration, steady state and deceleration points of the vehicle. The acceleration points are noted from the positive peaks in the EM power, steady state in the constant EM power over a period of time and deceleration by the negative peaks in the EM power. The ripples shown in the SOC is indicative of the regeneration during deceleration and the consumption of electrical energy by the EM during acceleration.

As a case study, the software program was run for the Toyota Camry HEV specifications with an average velocity of 100km/hr, starting elevation above sea level of 12m, fuel level of 100% and a SOC of 100%. A random journey of 249km with seven different stages was generated that had a maximum acceleration power requirement of 139.83kW and a maximum steady state power requirement of 101.38kW. This is highlighted in Table III.

The software program uses a minimum SOC of 10% for the ICE to work only and for condition (iii) to be set to TRUE or “1”. Once the energy captured due to deceleration causes the SOC to reach 25%, condition (iii) is reset to FALSE or “0” and both the ICE and Motor can be used to deliver the required power needed. A further improvement in the mileage capability was made possible by equating the amount of energy required to complete the journey to the SOC. This adaptive variation in the upper charge limit of the SOC will help in optimizing the energy captured from deceleration for useful work, maximizing motor run time and output and minimizing ICE run time and output, thereby improving the PHEV mileage without a further plug-in. This algorithm was successfully implemented with the success rate based on the available deceleration energy and the journey characteristic for the remaining journey.



Starting Point Elevation (m) 34

Average Velocity (km/hr) 100

☐ Toyota Highlander

☑ Toyota Camry

☐ Toyota Prius

☐ Toyota Touring

1. Vehicle Frontal Area (m sq) 2.8
2. Tire Rolling Resistance Coefficient 0.008
3. Drag Coefficient 0.27
4. Ambient Air Density 1.2922
5. Wheel Radius (m) 0.2032
6. Net Power (kW) 140

Percentage Filled (%) 67

65.102 litres

2083.26 MJ

ICE 110 kW

Trans. Eff (%) 98

Engine Efficiency (%) 25

Motor Efficiency (%) 85

105 kW

State of Charge (SOC), % 100

Battery Capacity (MJ) 28.26

Battery Efficiency (%) 50

Vehicle Mass (kg) 1673

Fig. 2: Graphic user interface (GUI).

Fig. 3: Random journey generation.

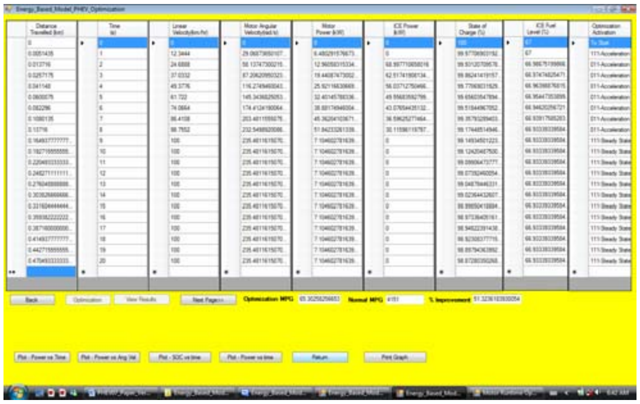


Fig. 4: Optimization results, tabular display for interfacing with external controller.

Table III: Random journey path with energy requirements.

Journey	Vehicle Mileage (km)	Elevation above Sea Level (m)	KE (MJ)	P_{acc} (kW)	P_{ss} (kW)
0	0	12	0.00	0.00	0.00
1	58	96	19.97	81.96	93.50
2	82	122	15.93	139.83	17.83
3	92	42	6.97	136.25	15.60
4	93	46	11.66	135.98	101.38
5	193	108	25.68	137.61	6.94
6	247	22	11.77	125.53	5.72
7	249	20	2	136.14	73.95

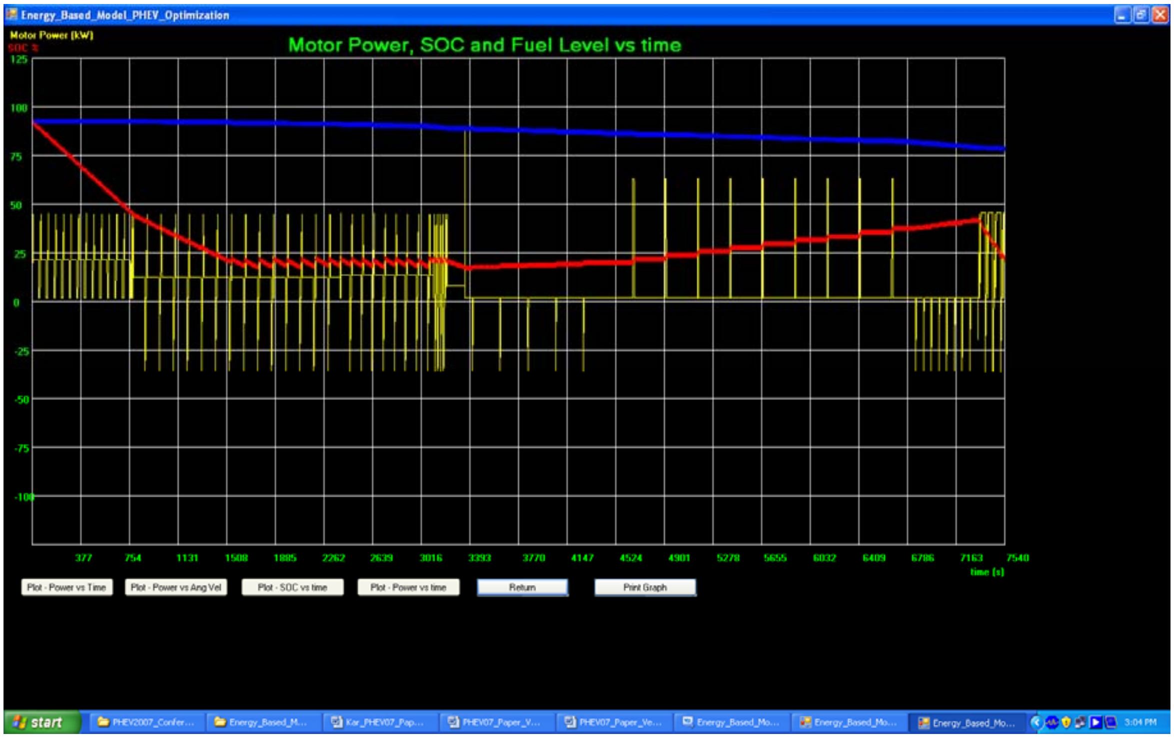


Fig. 5: Optimization results.

VII. SIMULATION RESULTS

The software program optimized on the motor runtime and power output during the first 99.37 km or 3732 s of the journey through the activation of decision paths 0, 2, 4 and 6 as illustrated in Table II. During this period the SOC for the battery decreased by 90% with a 3.5% consumption of fuel. This equates to a vehicle mileage of 102.5mpg. Ideally at this point, where the SOC = 10% and as indicated as “X” in Figure 6, the vehicle should be “plugged-in” to the electrical grid if the journey was completed. Condition (iii) described in Section (IV) becomes TRUE or “1” and the electric motor is disengaged from the drive train at this point. As the vehicle continues the journey, decision paths 1, 3, 5 and 7 becomes active with the motor in regenerative mode for capturing the energy available from deceleration. For this simulation the upper range of the SOC after a first discharge of the battery was set to 25%. It took another 3866 s or 1.07 hrs for the battery to be recharged to an SOC of 25% which equates to 4.239 MJ of energy and indicated as point Y in Figure 6. At the point the SOC = 25%, condition (iii) was reset to FALSE or “0” and decision paths 0,2,4,6 becomes active once gain. The 4.239 MJ of energy recovered together with further energy recovery from other deceleration points during the remaining journey was utilized to optimize on motor runtime and output power.

The mileage of the vehicle with an ICE run only is 45.89 mpg, with the electric motor and the software program, the overall mileage for the entire 249km, 9220s, 2.56hrs journey increased to 58.26mpg, a 26% improvement.

Fig. 6: Motor power, SOC and fuel level versus time for entire journey.

VIII. CONCLUSION

It can be concluded from these results that optimizing on the motor runtime and output power for a PHEV can improve the overall mileage of the vehicle. The software when integrated with a vehicle‘s GPS system will have the capability to generate its own journey path based on the GPS data and calculate the energy requirement needed for the particular route. The output of the developed model and software can then be integrated with the ICE and EM controllers. For the simulated results shown, the SOC was fixed for an upper and lower limit. The completed version of the software has demonstrated that varying the upper limit of the SOC for recharge based on the energy requirement needed to complete the journey after the plug-in point has elapsed has further improved the mileage of the vehicle. This has assisted in improving the vehicle mileage during this period, resulting in an overall improvement in the PHEV mileage capability, ultimately helping in improving the air quality.

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