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Description of a Basic Vehicle Control Strategy for a Plug-In Hybrid Vehicle

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REPORT SUMMARY

This report describes development of a basic powertrain control strategy for a plug-in hybrid electric vehicle (PHEV).

Background
There are two significant differences between a PHEV and a conventional power-assist hybrid—the PHEV has a grid-recharged battery system and a vehicle control strategy specifically tailored to manage this onboard electric energy to provide for optimum vehicle performance and efficiency.

Objectives
- To explain the development of a basic vehicle control strategy for a plug-in hybrid electric vehicle.
- To outline the different operating modes of the vehicle and describe how the control strategy enables implementation of each one.

Approach
EPRI used custom vehicle modeling tools developed within the Matlab/Simulink programming environment to develop a basic vehicle control strategy for a PHEV Sprinter Van, a plug-in hybrid vehicle jointly developed by EPRI and DaimlerChrysler.

Results
A basic control strategy was developed for the PHEV Sprinter Van. This strategy incorporates the different vehicle operating modes—electric-only, charge-sustaining, charge-depleting, and engine-only.

EPRI Perspective
This research builds upon several years of EPRI work and technical leadership pertaining to plug-in hybrid vehicles. Understanding the development and particular requirements of the PHEV operating strategy is important to optimizing performance of any given vehicle. In addition, this work informs the debate regarding the appropriate level of electric mode capability required in a PHEV.

Keywords
Plug-in hybrid electric vehicle
Control strategy
Energy management
PHEV sprinter van
Electric mode
Charge depletion
Charge sustaining

CONTENTS

LIST OF FIGURES

LIST OF TABLES

1
INTRODUCTION

Overview

This report describes the development of a basic powertrain control strategy for a plug-in hybrid electric vehicle (PHEV). There are two significant differences between a PHEV and a conventional power assist hybrid—the PHEV has a grid-recharged battery system and a vehicle control strategy specifically tailored to manage this onboard electric energy to provide for optimum vehicle performance and efficiency.

PHEV Electric Mode Operating Capability

Recent stakeholder technical discussions have tended to focus whether or not PHEVs should be designed to operate with substantial capability to operate in an electric-only mode, using only battery energy delivered to the electric traction system for motive power. A number of technical experts and automotive industry representatives have recently declared support for a PHEV concept without a defined electric-only operating region. This type of PHEV would operate in a pure charge depleting mode with the combustion engine operating much of the time the vehicle is driving, probably never shutting off for more than a few minutes at a time.

The purpose of this report is not to attempt to answer the question of what level of electric mode operating capability is appropriate for different PHEVs. This debate is very complex and is influenced by a number of disparate factors, from advanced battery performance to regulatory requirements. The objective of this report is to describe the step-by-step development of a basic energy control strategy for a PHEV. It is necessary to clearly understand how each stage of PHEV energy management and operating strategy is implemented in order to understand the implications of either electric-only or charge-depleting operation in these types of vehicles. Future work in this project set will include simulation- and data-backed analyses focused on addressing questions of electric capability in PHEVs.

PHEV Sprinter Van

The vehicle control strategy described in the report was originally developed for the PHEV Sprinter Van, a parallel hybrid jointly developed by EPRI and DaimlerChrysler for testing and fleet feasibility demonstration by EPRI utility members and participants. The Phase 1 hybrid architecture for the PHEV Sprinter is a parallel hybrid with a single 70 kW electric drive motor. As the Sprinter van is a rear-wheel drive vehicle, the powertrain is arranged longitudinally in the vehicle—the combustion engine and electric motor are connected by an automatic clutch with the output shaft of the electric motor directly coupled to the torque converter of a standard

Mercedes five-speed automatic transmission. The automatic clutch permits complete decoupling of combustion engine from the rest of the powertrain, enabling a high level of electric mode operation of the vehicle, limited only by traction system performance.

Matlab/Simulink Development of Control Strategy

The basic vehicle control strategy outlined in this report was developed using vehicle simulation tools developed by EPRI to run on the Matlab/Simulink environment. Matlab and Simulink are the dominant modeling tools used in the automotive industry for the development of many different types of vehicle control systems.

Control Strategy Optimization

The vehicle control strategy described in this report incorporates many of the main features necessary for the operation of a PHEV. These features are implemented in a straightforward, basic manner to demonstrate the concepts of PHEV operating strategy and are not meant to represent a highly optimized control strategy. One example, is that a simple three-stage accel pedal interpretation is used to translate driver demand into powertrain torque scheduling between the electric motor and combustion engine. While the three-stage pedal interpretation is actually highly effective in real-world operation, it would be replaced by a more optimized engine/motor torque scheduling algorithm that would improve powertrain energy efficiency over a wide range of vehicle operating scenarios.

Problem Description

The vehicle control strategy is divided into four control algorithms:

- Energy management mode control
- Engine and electric motor torque control
- Engine On/Off control
- State-of-charge control

Each control algorithm is introduced with a general description of the control strategy. The control strategy is then described in detail by showing the Simulink blocks that are used to implement each control strategy in the vehicle simulation. The performance of the control strategy is then evaluated by the presentation of results of the Simulink-based vehicle simulations.

The requirements of the basic control strategy are that it must:

- Be realizable in Stateflow/Simulink to allow the code to be ported from vehicle to simulation and back,
- Allow for full function of the vehicle for calibration and testing of all of the vehicle control and energy management modes,

Not require detailed data regarding the performance and behavior of the vehicle components because some component data will not be available before initial testing,

Be simple and understandable to allow for the transfer of information and expertise regarding PHEV control.

There are other control strategies that EPRI and DaimlerChrysler have suggested and developed that may be substituted for these as vehicle development continues. The strategies and algorithms that are proposed here are designed to meet the above requirements while being as simple to implement and calibrate as is possible. In simulation, these proposed strategies are still sufficiently developed to lead to a significant reduction in fuel consumption compared to the conventional Sprinter and equal fuel consumption compared to the charge sustaining hybrid Sprinter. The charge sustaining fuel consumption results on the NEDC for these vehicles are presented in Figure 1-1.[1]

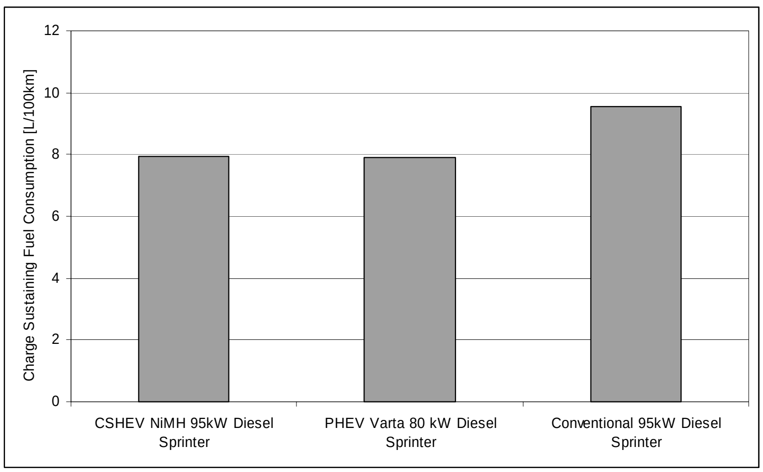

Figure 1-1
Charge Sustaining Vehicle Fuel Consumption on NEDC

The list of input and output signals for the Hybrid Controller as implemented in simulation on is presented in Table 1-1.

[1] The vehicle models for this comparison have previously been presented in the file *PHEV Sprinter Simulation Test Matrix - Phase 1 Prelim.xls*. This figure does not include the effect of ZEV range on PHEV fuel economy and therefore represents a worst case scenario.

Table 1-1
Hybrid Controller Input/Output Signal List as Implemented in Simulation

Hybrid Controller Input Signals

Name	Description	Source	Type	Units
drv_trq_dmd_hist	Driver Torque Demand from Accelerator Pedal Signal	Calculated within PCM from Accel Pedal	real	Nm
veh_spd_hist	Vehicle Speed	Calcuated within PCM from Speed Sens.	real	m/s
mc_spd_hist	Electric Motor Rotational Speed	Sachs Motor Controller	real	rad/sec
eng_trq_hist	Engine Output Torque Measurement	DC Engine Controller	real	Nm
ess_temp_hist	Maximum Battery Module Surface Temperature	Varta Battery Management System	real	degC
ess_curr_hist	Battery Current Measurement	Varta Battery Management System	real	A
ess_volt_hist	Battery Voltage Measurement	Varta Battery Management System	real	V
tx_gear_hist	Transmission Gear	Transmission Controller	real	-
mc_trq_hist	Electric Motor Ouptut Torque	Sachs Motor Controller	real	Nm
eng_on_hist	Engine On/Off Measurement	DC Engine Controller	bool	-
mc_temp_coeff_hist	Electric Motor Temperature Measurement	Sachs Motor Controller	real	0-1
cpl_cmd_hist	Normalized Engine Clutch Position	Engine Clutch Controller	real	0-1
eng_spd_hist	Engine Speed Measurement	DC Engine Controller	real	rad/sec
eng_temp_coeff_hist	Normalized Engine Temperature Measurement	DC Engine Controller	real	0-1
drv_key_on_dmd_hist	Driver Key On Signal	Body Control Module	bool	-

Hybrid Controller Output Signals

Name	Description	Source	Type	Units
ptc_eng_trq_dmd_hist	Engine Torque Demand	Hybrid Controller	real	Nm
ptc_mc_trq_dmd_hist	Electric Motor Torque Demand	Hybrid Controller	real	Nm
ptc_eng_on_dmd_hist	Engine On/Off Demand	Hybrid Controller	bool	-
ptc_brake_trq_dmd_hist	Mechanical Brake Torque Demand	Hybrid Controller	real	Nm

2
ENERGY MANAGEMENT MODE CONTROL

Introduction

Plug-in Hybrid Electric Vehicles can operate in a number of energy management modes. Examples of possible energy management modes that are uniquely relevant to PHEVs include:

Charge-sustaining (CS) Mode – A mode where the battery state-of-charge is controlled to remain within an operating window

Charge-depleting (CD) Mode – A mode where the battery state-of-charge is controlled to decrease during vehicle operation

Zero-emissions Vehicle (ZEV) Mode – A mode where operation of the fuel converting engine is prohibited. In this mode, the vehicle drives as an electric vehicle.

Fuel Converting Engine Only (ICE only) Mode– A mode where operation of the electric traction system is very limited. In this mode, the electric traction system does not provide tractive power to the vehicle.

All of these modes are selectable in the PHEV Sprinter. Energy Management Mode Control defines a strategy for switching among the energy management modes. Overriding of the vehicle controller using a manual switch is also possible.

Strategy Description

The proposed strategy defines a method of switching between energy management modes on the basis of Electric Traction System Performance Limits. The Electric Traction System Performance Limits are a composite of the performance limits of the subsystems of the electric traction system. These limiting subsystems can include the vehicle traction battery, electric motor, inverter, etc., and the performance limits may be a function of component temperature, temporal degradation, malfunction, ambient temperature, rotational direction, etc.

For the PHEV Sprinter, the energy management mode selected by the vehicle system controller is a function of the Electric Traction System Performance Limits (also referred to as Battery Power Discharge Limit, BDPL). For a BDPL greater than 60kw, ZEV mode is selected. For a BDPL between 30kW and 60kW, CDHEV mode is selected. For a BDPL between 10kW and 30 kW, CSHEV mode is selected. When BDPL is less than 10kW, ICE only mode is selected.

In each region of BDPL, the lower bound of the region represents the rough minimum amount of power that is necessary to maintain drivability and performance of the vehicle in each mode. For instance, roughly 60kW of electrical tractive power is necessary to meet performance and drivability goals in ZEV mode. If the power available from the electrical traction system becomes less than 60kW because of the temperature of the battery system, then the vehicle enters CDHEV mode. If the battery system then cools because of the lower electrical power required in CDHEV mode, ZEV mode will be selected as the BPL increases again.

As shown in Figure 2-1, there are many possible inputs to the BPL calculation. In reality, some of the inputs will be raw data such as battery temperature and some of the inputs will be component-level power limits that are calculated in other controller. The power limits for each subsystem of the electric traction system will be a function of the condition that subsystem. The battery power limit will be a function of the battery state-of-charge and module temperature. The EM power limit will be a function of the EM temperature and controller temperature. Generic example power limit functions are presented in Figure 2-2 and Figure 2-3. All of the power limits for each of the electric traction subsystems are combined in the BPL calculation and a charging and discharging electric traction system power limit is output. This output is used to select the energy management mode.

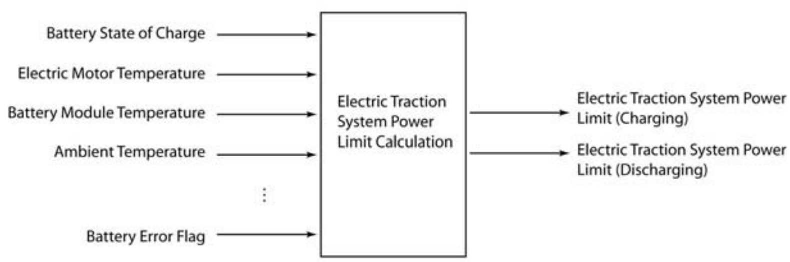

Figure 2-1
Example of I/O to Electric Traction System Power Limit Calculation for Energy Management Mode Control

Strategy Implementation

In simulation, the Electric Traction System Power Limits are all calculated within the vehicle system controller (Hybrid Strategy Controller). In the actual PHEV Sprinter vehicle some of the power limits will be calculated by other controllers and will be passed to the vehicle system controller as a suggested limit. These suggested limits should be incorporated into the Electric Traction System Power Limit calculation.

In simulation, the Electric Traction System Power Limits are derived from:

The limits of the battery system as a function of SOC, module temperature and a battery error flag, triggered by under-charge,

The limits of the electric motor as a function of motor temperature, battery voltage, motor current limit and a motor error flag, triggered by over-temperature

The ambient temperature of the environment.

As shown in Figure 2-2and Figure 2-3, each subsystem has limits on its power output. Figure 2-2and Figure 2-3 show generic examples of the output power limit functions for the battery and electric motor subsystems.

As more data becomes available on additional limits, they can easily be incorporated.

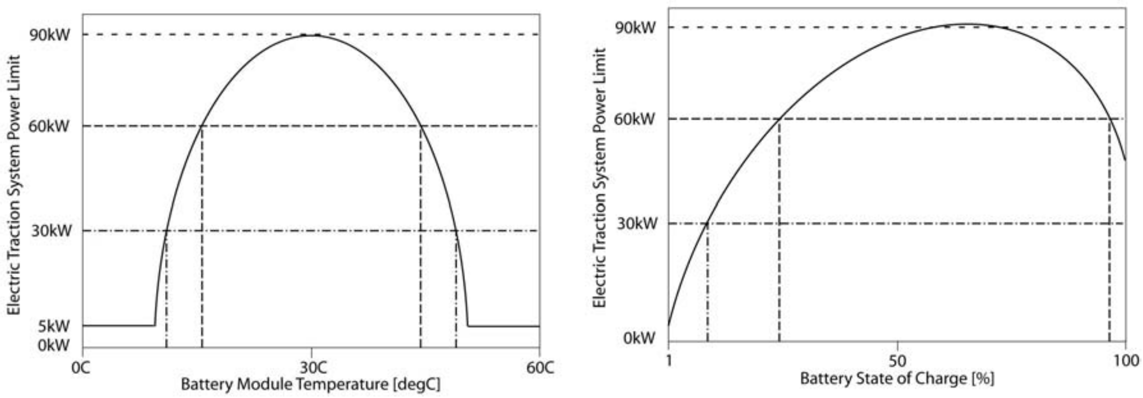

Figure 2-2
Examples of Electric Traction System Power Limits for Battery Subsystem

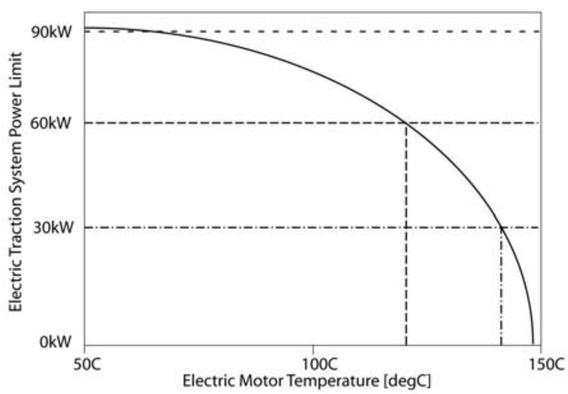

Figure 2-3
Examples of Electric Traction System Power Limits for Electric Motor Subsystem

Table 2-1 shows the data that is used to calculate the power limits of the battery system as a function of SOC and module temperature. In the Sprinter vehicle this data will be provided by the Varta battery management system. The battery power limits are transmitted to the block, shown in Figure 2-4, that calculates the maximum propulsive and regenerative torque of the electric motor. In the blocks labeled Prop/Regen Torque Allowed as a fxn of mc_curr_lim, the battery power limit is translated into a motor torque limit by using a map of electric motor performance. This calculation assures that the powertrain controller will not command a battery power that is greater than the battery power limit.

Table 2-1
Battery Charge/Discharge Power Limits

Battery Pack Maximum Output Power as a Function of SOC and Module Temperature, Units of kW/280 cells											
	0.0	***0.1***	***0.2***	***0.3***	***0.4***	***0.5***	***0.6***	***0.7***	***0.8***	***0.9***	***1.0***
45°	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
30°	0.0	0.0	60.4	65.4	68.9	73.3	77.1	81.1	84.4	85.4	84.9
20°	0.0	0.0	53.5	57.2	60.2	63.9	67.2	70.5	73.4	74.6	72.9
10°	0.0	0.0	44.9	48.2	51.0	53.6	56.6	59.4	61.4	61.8	60.7
0°	0.0	0.0	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5
-10°	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Derived by USABC Calcs from Varta Data * 0.7											

Battery Pack Maximum Output Power as a Function of SOC and Module Temperature, Units of kW/280 cells											
	0.0	***0.1***	***0.2***	***0.3***	***0.4***	***0.5***	***0.6***	***0.7***	***0.8***	***0.9***	***1.0***
45°	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
30°	-14.0	-14.0	-60.4	-65.4	-68.9	-73.3	-77.1	-81.1	-84.4	-85.4	-84.9
20°	-14.0	-14.0	-53.5	-57.2	-60.2	-63.9	-67.2	-70.5	-73.4	-74.6	-72.9
10°	-14.0	-14.0	-44.9	-48.2	-51.0	-53.6	-56.6	-59.4	-61.4	-61.8	-60.7
0°	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5
-10°	-0.7	-0.7	-0.7	-0.7	-0.7	-0.7	-0.7	-0.7	-0.7	-0.7	-0.7
Derived by USABC Calcs from Varta Data * 0.7											

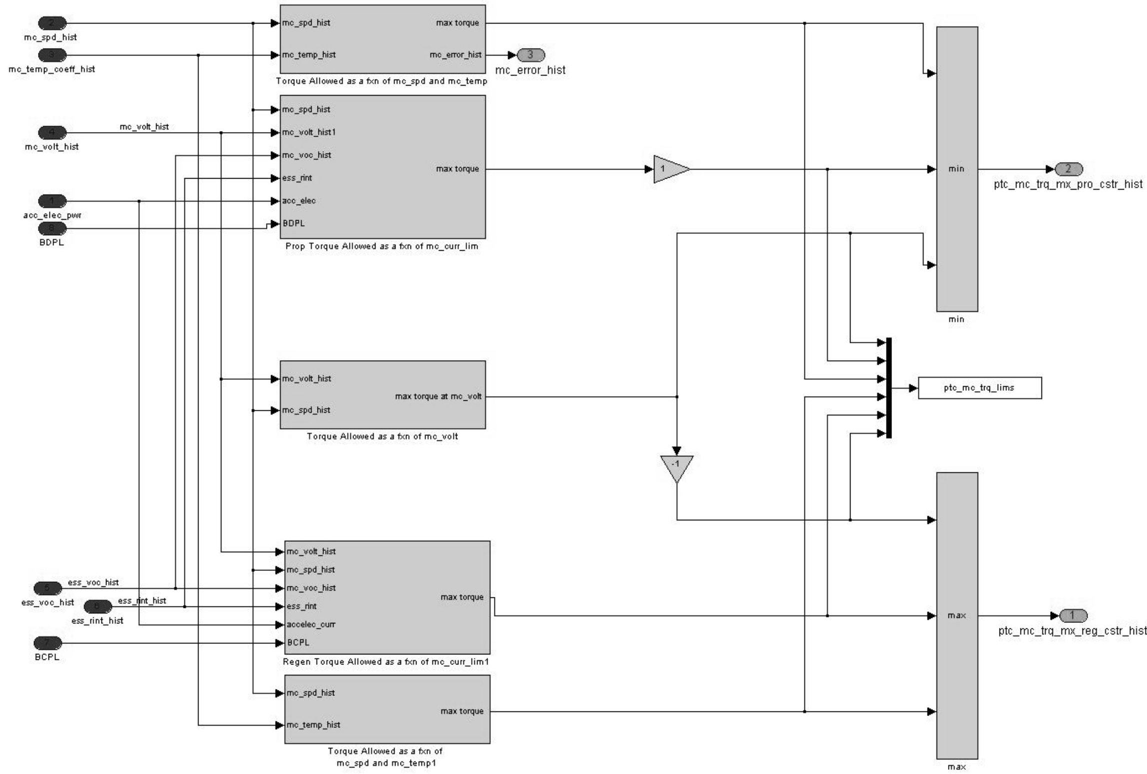

Figure 2-4
Electric Motor Propulsive and Regenerative Torque Limits (lib_p_par_1mc_conso_start_alter / p_par_1mc_conso_start_alter /VSC/Hybrid Energy Control Fun/CONSTRAINTS AND VEHICLE TORQUE DEMANDS/Constraints and Sensor Simulations/EM and Controller Torque Constraints)

Figure 2-5 shows the algorithm that controls Energy Management mode as a function of Motor Controller Torque Limit (ptc_mc_trq_mx_pro_cstr_hist). Error signals from the electric motor or battery cause the vehicle to enter ICEOnly Mode.

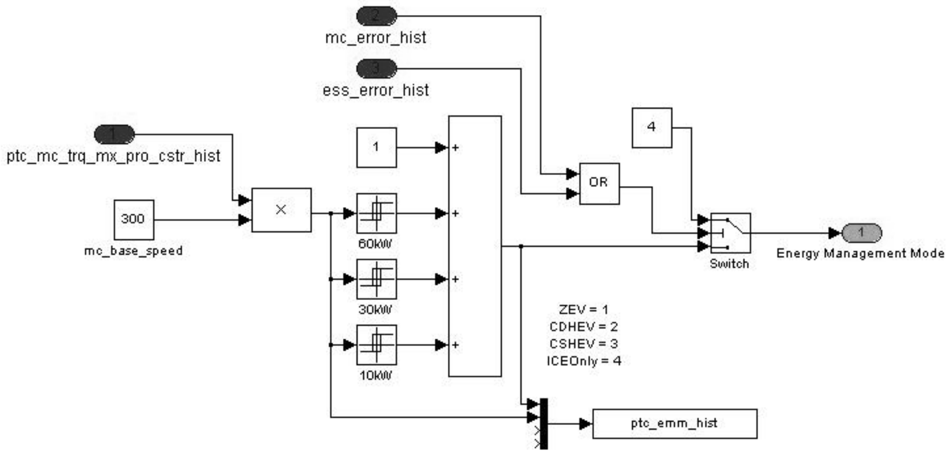

Figure 2-5
Energy Management Mode Controller (lib_p_par_1mc_conso_start_alter / p_par_1mc_conso_start_alter /VSC/Hybrid Energy Control Fun/CONSTRAINTS AND VEHICLE TORQUE DEMANDS/Constraints and Sensor Simulations/Energy Management Mode)

Strategy Evaluation

A primary benefit of the proposed scheme of energy management mode control is simplification of vehicle calibration. Vehicle system controller calibration for performance, driveability and fuel economy is a function of the electric traction system performance limits. The electric traction system performance limits can vary during vehicle operation as a function of any of component temperature, temporal degradation, malfunction, ambient temperature, rotational direction, etc. In prior art, the vehicle system controller must be calibrated to take into account the continuous fluctuations of the electric traction system performance limits. In this invention, the vehicle must only be calibrated for operation in each of the energy management modes.

Another benefit of the proposed scheme of energy management mode control is that energy management mode control is not performed dynamically as a function of quickly changing variables such as vehicle speed, accelerator position, etc. Where the energy management mode control is performed dynamically, the changes in vehicle behavior can be detected by the driver and can result in poor driveability. Because the driver does not provide any direct inputs into the energy management controller, the energy management mode is isolated from the driver's control.

Another benefit of the proposed scheme of energy management mode control is that it is a more robust system than the prior art. In the prior art, the transitions between zero-emissions, charge depleting and charge sustaining energy management modes are in some cases not explicitly defined or are only a function of state-of-charge[2,3,4]. By defining the mode selection to be a function of more variables, the performance of the vehicle is more consistent and the components of the vehicle are better protected.

Figure 2-6 and Figure 2-7 show the behavior of the Energy Management Mode controller over a representative cycle. Here the vehicle begins the cycle with a cold engine and cold battery (5 degC) and an SOC of 40%. Because the engine is cold, the engine warms up for the first 100 seconds (as shown in Figure 2-6). Because the batteries are cold, the battery discharge power limit is low and the vehicle is forced into charge sustaining energy management mode (EMM 3, as shown in Figure 2-6, panel 1). As the batteries warm up the battery discharge power limit increases (Figure 2-7, panel 2) and the EMM switches to the charge depleting hybrid mode (EMM 2, as shown in Figure 2-6, panel 1). Finally, as the battery SOC decreases, the battery discharge power limits also decrease and the vehicle goes back into charge sustaining operation (EMM 3, as shown in Figure 2-6, panel 1)

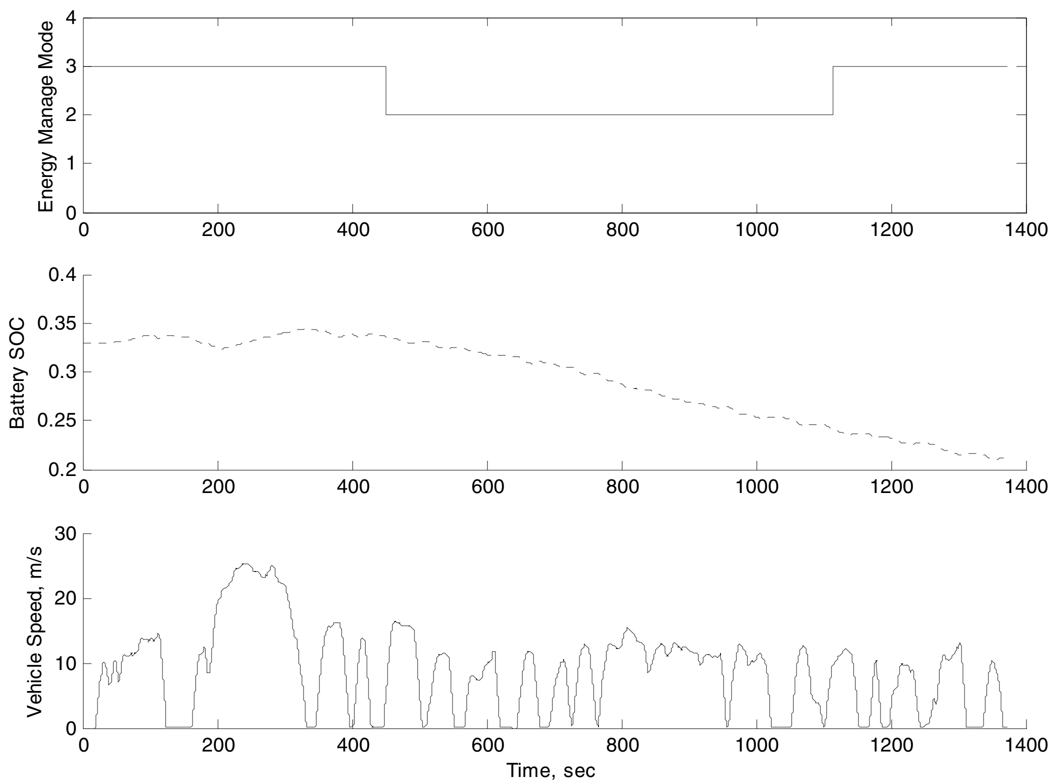

Figure 2-6
PHEV Sprinter Simulation Results on FUDS, with Battery Module Warm-up

[2] Alexander, M., et al. A Mid-Size Sedan Design for High Fuel Economy and Low Emissions: The UC Davis FutureCar. 1999.

[3] US Patent 6,116,363, A. A. Frank

[4] Markel, T. Wipke, K. Modeling Grid Connected Hybrid Vehicle using ADVISOR. NREL.

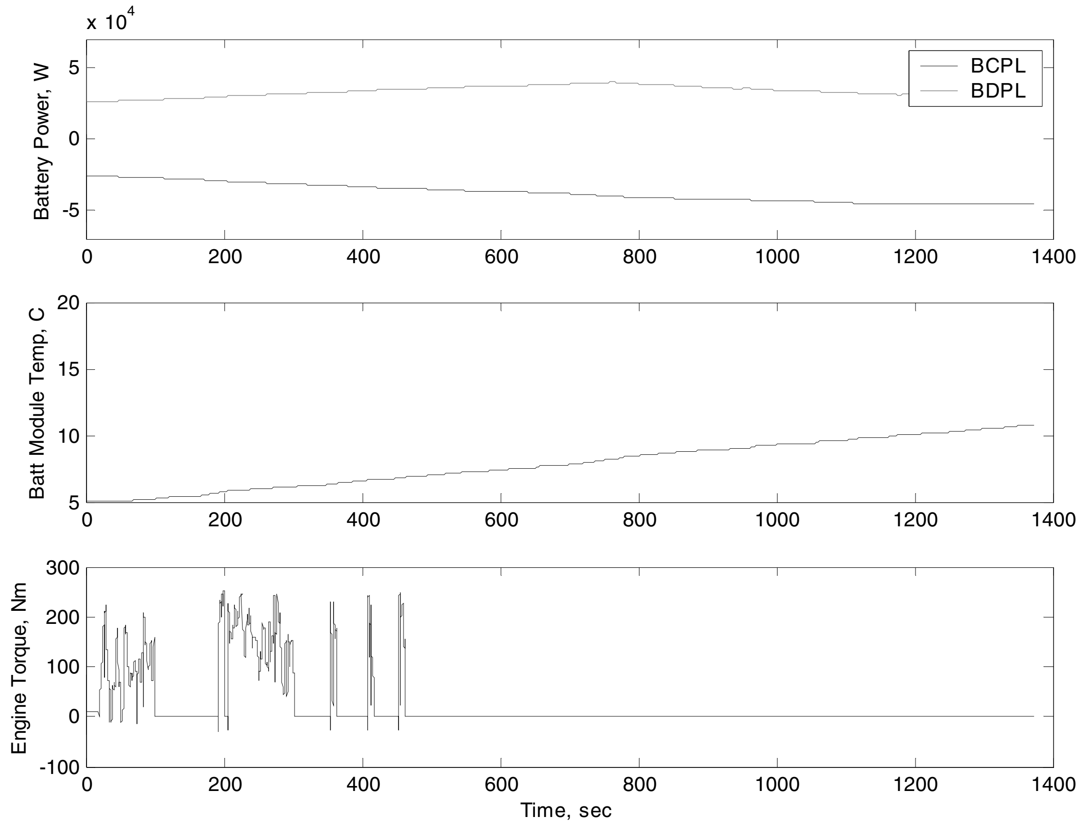

Figure 2-7
PHEV Sprinter Simulation Results on FUDS, with Battery Module Warm-up

3
ENGINE AND ELECTRIC MOTOR TORQUE CONTROL

Introduction

The purpose of the engine and electric motor torque control in HEVs is to improve the efficiency of the vehicle system while meeting the torque request of the driver.

Strategy Description

The torque proportioning control algorithm proposed for this workpackage is the 3-stage pedal interpretation strategy. In EV mode, this strategy commands electric motor torque based on the position of the accelerator pedal. In HEV modes, this strategy divides the accelerator pedal position into three stages corresponding to three different modes of powertrain torque production. A graphical presentation of the 3-stage pedal interpretation strategy is presented in Figure 3-1.

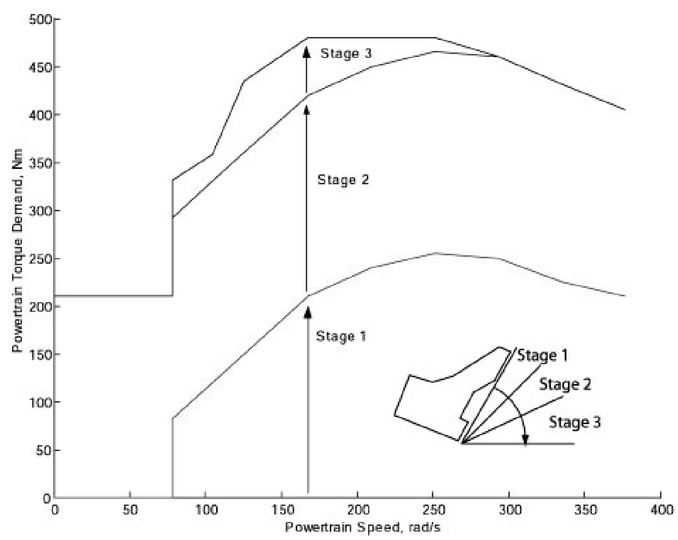

Figure 3-1
Three Stage Pedal Interpretation

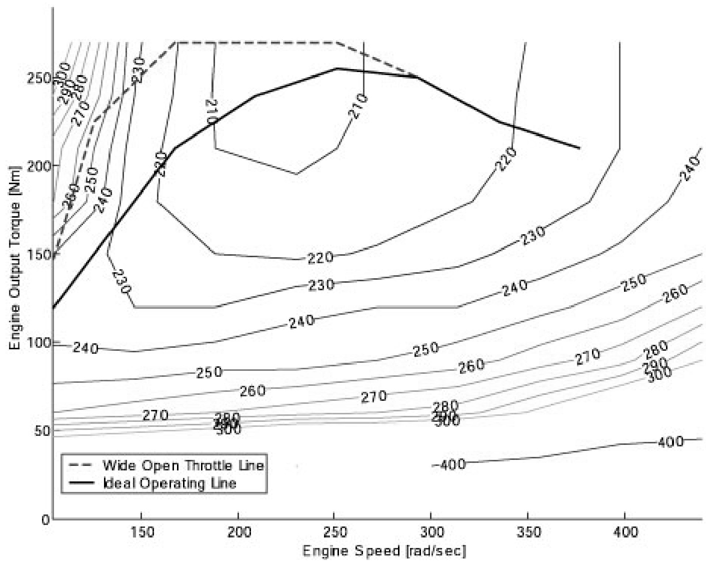

Figure 3-2
Ideal Operating Line for OM611 Diesel Engine over a map of BSFC (g/kWhr)

In stage 1, the pedal position linearly dictates engine torque between closed throttle and the Ideal Operating Line (IOL). The IOL is the locus of points of minimum BSFC as a function of power output, and can be approximated as a function of engine speed. The IOL for the OM611 diesel engine is illustrated in Figure 3-2. In stage 1, the torque commanded can be any value between closed-throttle motoring torque of the engine and the IOL.

In stage 2, the pedal position linearly dictates the electric motor torque as a function of the maximum torque of the electric motor. The maximum electric motor torque can be calculated as a function of speed. In stage 2, the commanded powertrain output torque can be commanded to any value between the IOL and the sum of the IOL and the EM maximum torque. In stage 2, the engine always produces IOL torque and the EM torque is commanded by the position of the accelerator pedal.

In stage 3, the accelerator pedal commands engine torque between the IOL and the wide-open-throttle line of the engine. In stage 3, the EM produces maximum torque and the engine torque is commanded by the accelerator pedal position. Engine torque between the IOL and the wide-open-throttle line is commanded

Strategy Implementation

As shown in Figure 3-3, the Vehicle System Controller (Hybrid Controller) is split into three main blocks:

Constraints and Vehicle Torque Commands – This block defines the constraints on the electrical traction system including motor torque limits, motor power limits, and battery power limits. This block also performs some simulation of calculations that will be performed by other control nodes in the actual vehicle including state-of-charge estimation, and accessory power draw estimation. This block also determines the energy management modes and performs a simulation of the accelerator pedal position as a function of driver torque demand. This block also determines the vehicle torque demand from the driver torque demand.

Speed and Torque Control States – This block determines which control state the vehicle is in and calculates control signals for the electric motor, engine and braking systems.

Engine Pull-up and Pull-downs – This block determines the status of the engine and issues engine on and off commands.

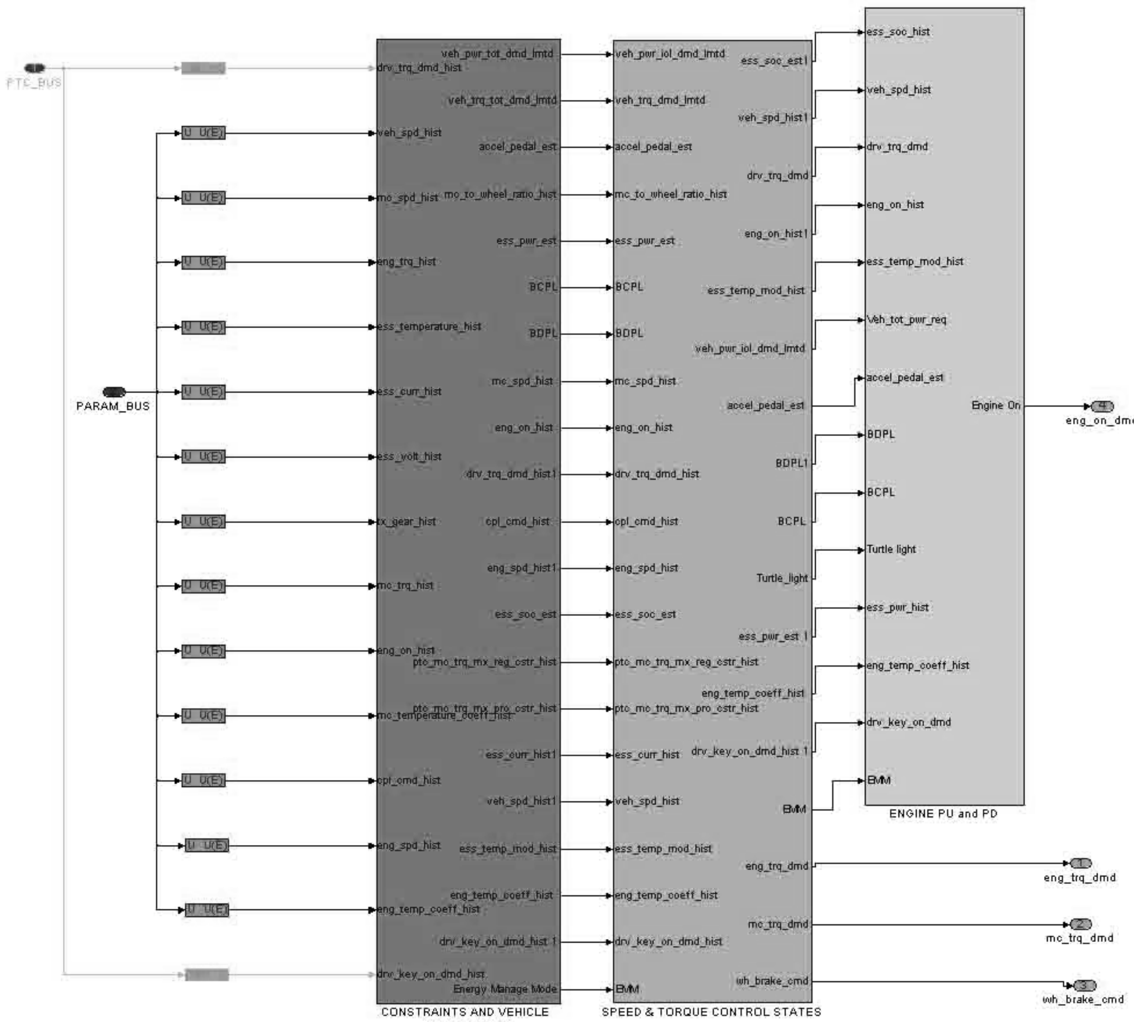

Figure 3-3
Overview of Hybrid Conroller (lib_p_par_1mc_conso_start_alter/ p_par_1mc_conso_start_alter /VSC/Hybrid Energy Control Fun)

The Hybrid Controller (VSC) is designed to play a limited role within the vehicle controller. Low-level control of engine/motor coordination, engine clutch closing, etc. are handled by other algorithms within the vehicle controller.

Figure 3-4 shows the block within the Constraints and Vehicle Torque Commands subsystem that calculates vehicle torque demand. In this block, the additional torque demands on the vehicle are added to the driver torque demand. The driver torque demand should be calculated from the accelerator pedal position. The additional torque demands are:

Battery Charge/Discharge Demand (Used for SOC control)

Mechanical Accessory Power

Losses within the Electric Motor

Electrical Accessory Power

The vehicle torque demand is limited by the maximum powertrain torque in propulsion and the maximum powertrain torque in regeneration and an artificial maximum powertrain torque (*ptc_tx_trq_max = 385Nm*).

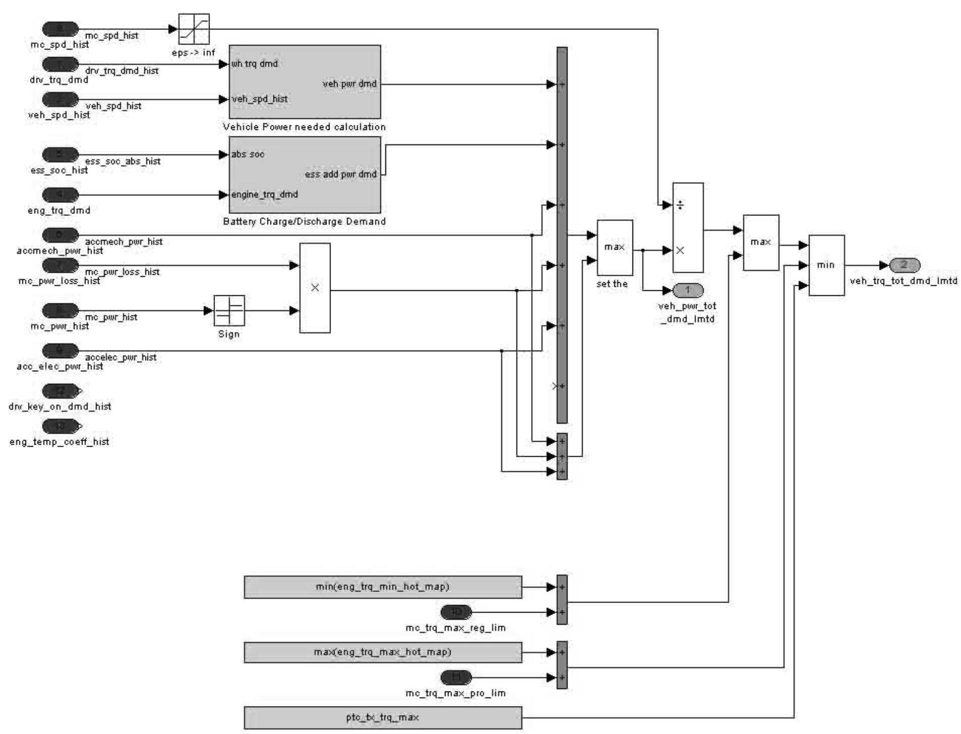

Figure 3-4
Vehicle Torque Demand (lib_p_par_1mc_conso_start_alter/ p_par_1mc_conso_start_alter /VSC/Hybrid Energy Control Fun/ CONSTRAINTS AND VEHICLE TORQUE DMDS/Torque required from Vehicle)

Figure 3-5 shows the structure of the controller that determines the global powertrain control state. The states are called by the function call signals that come from the Stateflow Controller (Idle/Turtle Light/ICE Start/ICE Stop Controller). The possible control states are:

Engine On Idle Function – This function determines motor and engine torque command when the engine is on and the vehicle is idling.

Motor Only Idle Function – This function determines the motor and engine torque commands when the engine is off and the vehicle is idling.

Normal Driving Function – This function determines the motor and engine torque commands when the vehicle is driving and not idling. The engine and motor may be either on or off.

Engine Starting Function – This function determines the motor and engine torque commands when the engine is starting. Engine startup error checking can be performed in this function.

Engine Stopping Function - This function determines the motor and engine torque commands when the engine is stopping. Engine shutdown error checking can be performed in this function.

The brake controller is a controller that runs parallel to the Stateflow Controller and determines the amount of braking torque to be supplied by the mechanical brakes.

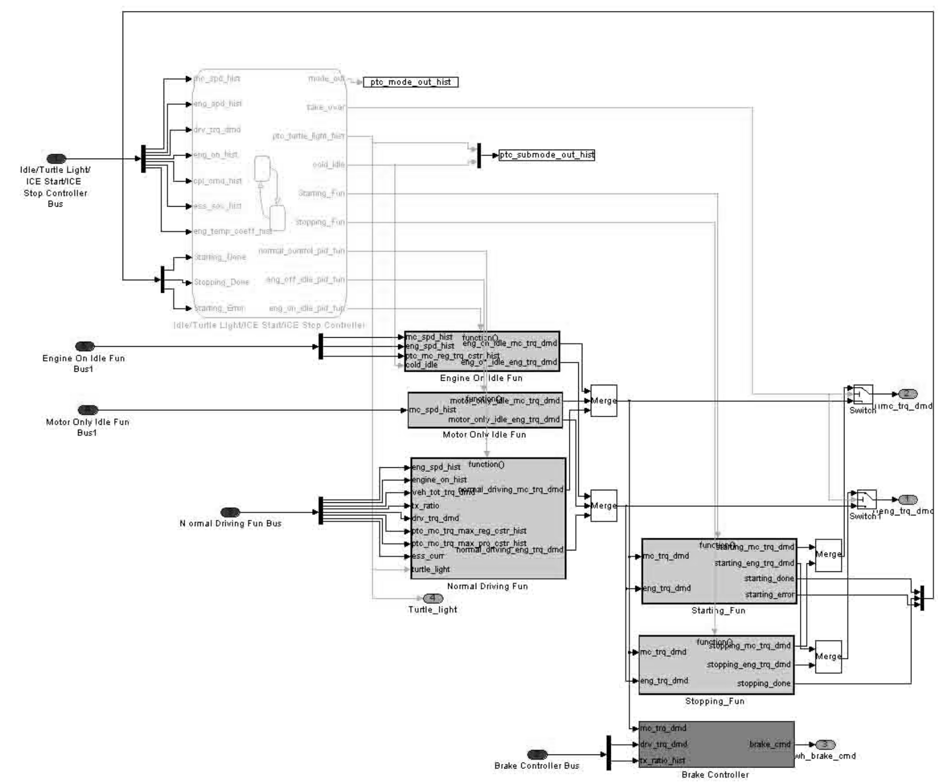

Figure 3-5
Global Speed and Torque Control State Control (lib_p_par_1mc_conso_start_alter/ p_par_1mc_conso_start_alter /VSC/Hybrid Energy Control Fun/ SPEED & TORQUE CONTROL STATES/Subsystem)

Figure 3-6 shows the Normal Driving Function called by the Stateflow Controller. The 3-stage pedal interpretation strategy is implemented in the block titled Match ICE Torque to Power Dmd. The torque signal output from that block is limited by

> The maximum torque of the engine as a function of speed (Engine Maximum Torque Calculation),

A block that assures that when the engine is off, the torque command to the engine is zero (Zero Trq Dmd at ICE Off).

The engine torque command is an input into the block that determines EM torque demand. As implemented the engine torque command is determined as a function of total vehicle torque demand and the EM torque command is a function of engine torque command and driver torque command. This has the effect that when the vehicle torque demand is different than the driver torque demand the EM will either regenerate or motor to make up the difference.

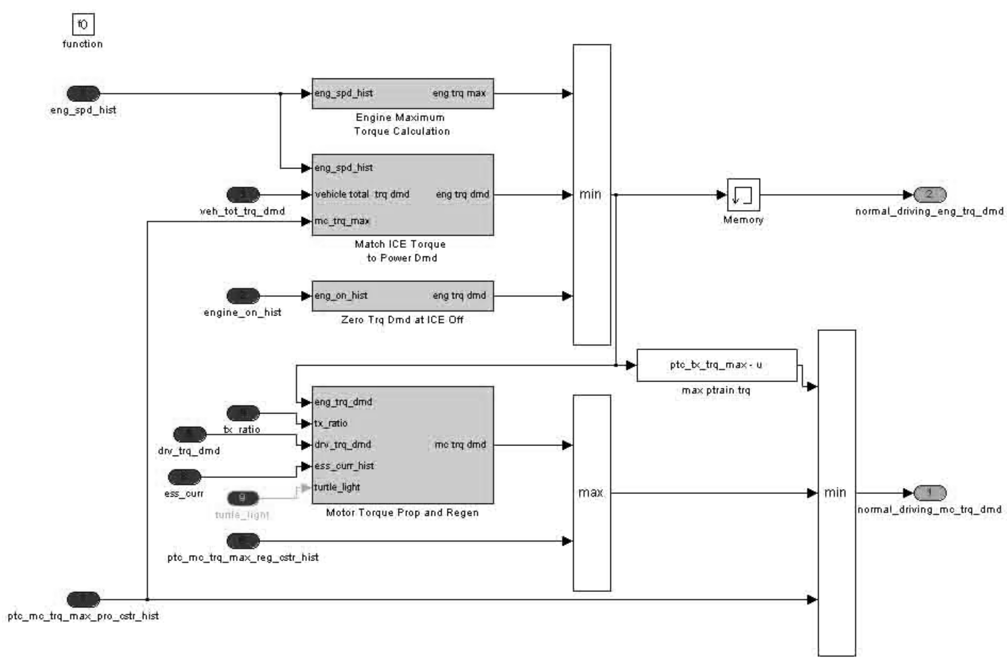

Figure 3-6
Normal Driving Function Called by the Speed and Torque Control Stateflow Machine (lib_p_par_1mc_conso_start_alter/ p_par_1mc_conso_start_alter /VSC/Hybrid Energy Control Fun/ SPEED & TORQUE CONTROL STATES/Subsystem/Normal Driving Fun)

Figure 3-7 shows the 3-stage pedal interpretation strategy as implemented in the PHEV Sprinter simulation. When the vehicle total torque demand is less than the IOL plus the maximum motor torque, then the engine torque demand is the minimum of the vehicle torque demand and the IOL. When the vehicle total torque demand is greater than the sum of IOL and maximum motor torque, then the engine torque command is the difference between the maximum motor torque and the total torque demand. Maximum motor torque is calculated in the subsystem shown in Figure 2-1.

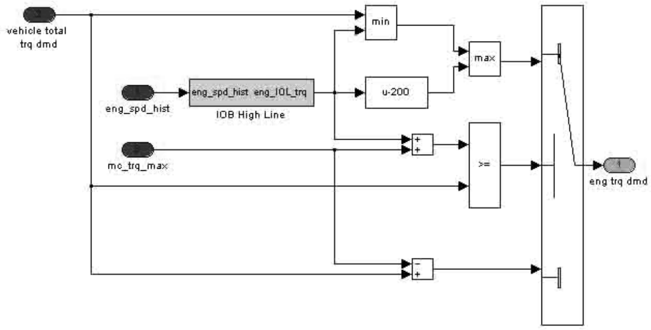

Figure 3-7
Implementation of 3-Stage Torque Control Algorithm (lib_p_par_1mc_conso_start_alter/ p_par_1mc_conso_start_alter /VSC/Hybrid Energy Control Fun/ SPEED & TORQUE CONTROL STATES/Subsystem/Normal Driving Fun/Match ICE Torque to Power Dmd)

Strategy Evaluation

The 3-stage pedal interpretation strategy has the primary benefit of requiring very little information about the performance and efficiency of the powertrain components in order to function.

Simple additions to the 3-stage pedal interpretation strategy can improve the efficiency of the vehicle even further. By limiting the minimum torque that can be produced by the engine, the efficiency of the vehicle can be increased slightly. Figure 3-8 through Figure 3-10 show the operating points of the engine on the 505 cycle. As the width of the allowed operating band decreases, the engine efficiency increases and the vehicle fuel economy increases. These gains come at the cost of drivability and emissions performance.

Another possible addition to the 3-stage pedal interpretation strategy can improve the drivability and emissions of the vehicle. By applying a rate limiter can be to the engine torque request signal, the engine gets isolated from the dynamics of the driver commands and the road. The efficiency of the vehicle does not increase significantly with this modification.

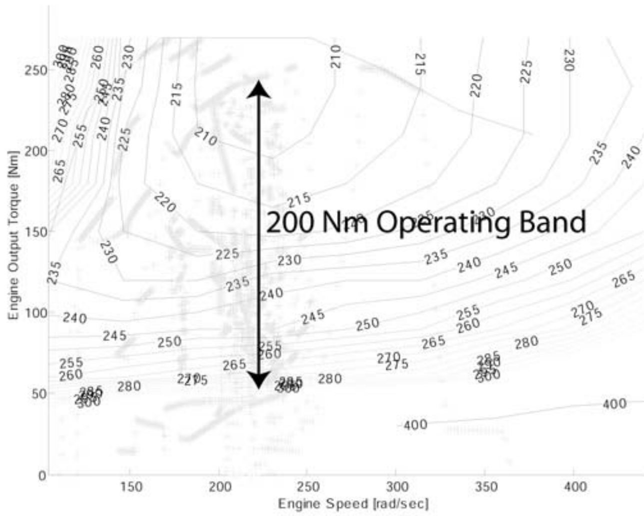

Figure 3-8
Engine Operating Band Width of 200Nm

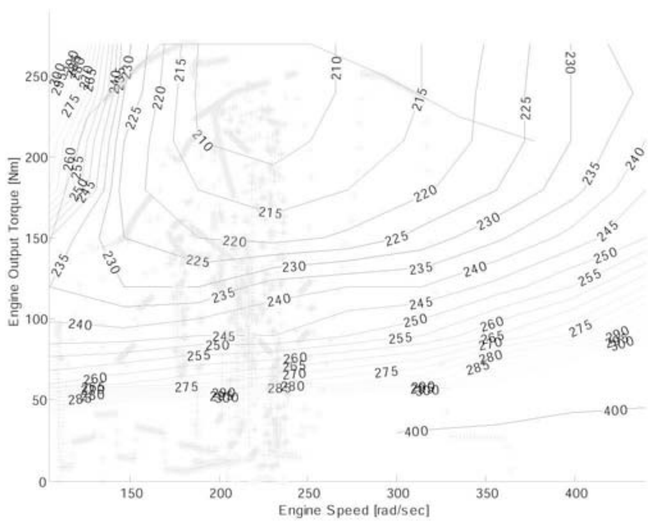

Figure 3-9
Pure 3-Stage Pedal Interpretation

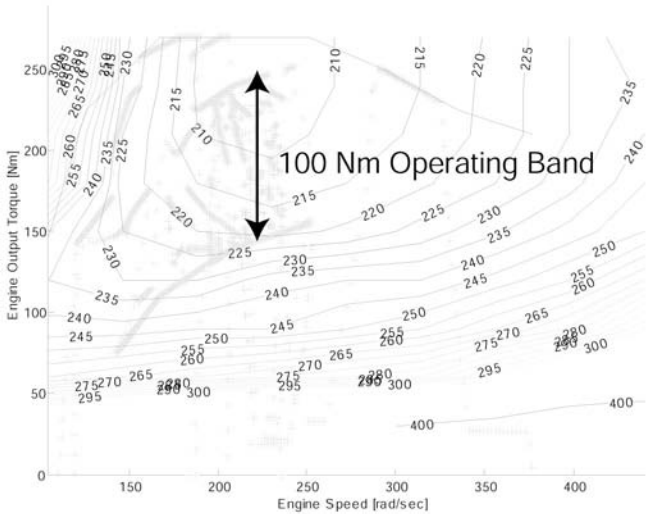

Figure 3-10
Engine Operating Band Width of 100Nm

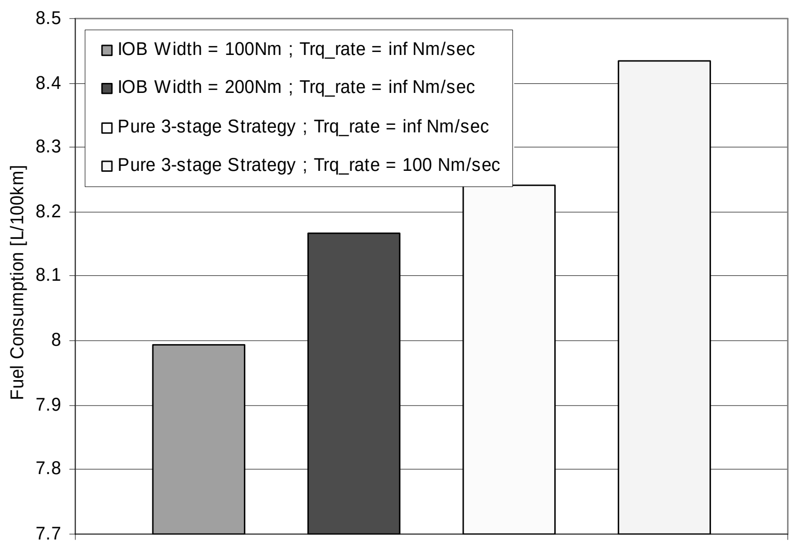

Figure 3-11
Fuel Economy Simulation Results for Variations on the 3-Stage Pedal Interpretation Strategy

4
ENGINE ON/OFF CONTROL

Introduction

In a PHEV, the reasons to turn on the internal combustion engine in charge sustaining modes are:

1. To recharge the battery at high efficiency,
2. To protect the battery from thermal problems,
3. To protect the battery from overpower,
4. To maintain a minimum state of charge,
5. To extend the range of the vehicle,
6. To meet driver torque demands greater than the EM torque,
7. Stability of engine operation for emissions control

The reasons to turn on the internal combustion engine in charge depleting modes are:

1. To protect the battery from thermal problems
2. To protect the battery from overpower
3. To meet driver torque demands greater than the EM torque
4. Stability of engine operation for emissions control

These reasons are used as justification for the engine on/off control algorithm.

Strategy Description

Engine on/off control is determined by the presence of three signals: Inhibit Pull Down (IPD), Inhibit Pull Up (IPU), Engine On and Engine Pull Up (PU). Engine Pull Up is the signal that commands the engine start up procedure. Engine On signals that the engine is on. Inhibit Pull Down is a signal that keeps the engine on even when the Engine Pull Up flag is off. Inhibit Pull Up is a signal that keeps the engine off even when the Engine Pull Up flag is on. Inhibit Pull Up is only used to enforce the EV mode.

The engine on/off control system can be represented as:

Engine_On(k+1) =
((*Inhibit_Pull_Down* .AND. *Engine_On*(k)) .OR. *Pull_up*) .AND. NOT(*Inhibit_Pull_Up*).

There are a number of general algorithms that are used to determine the Pull Up and Inhibit Pull Down commands. One algorithm that may require further exposition is the Pull Up/Inhibit Pull Down (PU/IPD) Loop, shown in Figure 4-1. The purpose of the PU/IPD Loop is to make the operation of the engine more stable while actively controlling the condition of the engine as a function of a variable, in this example, state-of-charge). The thresholds that are shown in Figure 4-1 are labeled **_min*, **_on*, and **_off* in ascending order. In each of the four divisions created by those thresholds, the command issued to the Engine on/off controller is different depending on the history of the state-of-charge signal. Starting from the upper right of the PU/IPD Loop diagram, if the state-of-charge is decreasing from greater than *ess_soc_off* and passes through *ess_soc_off*, no engine on/off command is issued. As the signal passes through *ess_soc_on*, an Inhibit Pull Down command is issued. If the battery SOC continues to decrease, even with an IPD signal, and the signal goes below *ess_soc_min*, an engine pull up is issued. If, instead, the battery SOC increases and passes through *ess_soc_min*, then the IPD signal will be removed. The effect of the transitions between the thresholds is different if the battery state-of-charge is coming from *ess_soc_min*. The net effect of the PU/IPD Loop is to maintain the battery SOC between *ess_soc_off* and *ess_soc_on* for most operating conditions. If the SOC drops below *ess_soc_min*, then the engine is turned on to charge the battery so that the controller can maintain operation on the upper right portion of the loop.

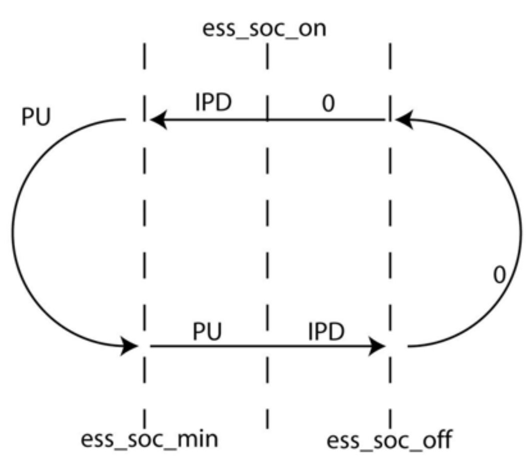

Figure 4-1
Inhibit Pull Down Loop for State of Charge

Strategy Implementation

As shown in Figure 4-2 and Figure 4-11, there are ten possible engine pull up commands, a single inhibit pull up command and five inhibit pull down commands. The state-of-charge PU and the two state-of-charge IPD commands make up a single PU/IPD loop for state-of-charge control. The Electric Traction System Power Limit PU and the two Electric Traction System Power Limit IPD commands make up a single PU/IPD loop for Electric Traction System Power Limit control. As detailed in Table 4-1, there are a total of eleven subsystems or conditions for engine on/off control. The purposes of each Engine On/Off Control System are presented in

Table 4-2.

Table 4-1
Summary of Engine On/Off Control Subsystems

Engine On/Off Control System Name	Type	Relevant Parameters	
		Name	Value
State-of-charge	PU/IPD Loop	ptc_ch_min_soc ptc_ch_on_soc ptc_ch_off_soc	0.16 0.17 0.21
Vehicle Speed	Stateflow	Tau ptc_ess_soc_index ptc_p_fc_on_spd_line	10 [0 0.197 0.217 0.218 0.307 0.750 1.0] [-1.7 8.5 17.0 20.0 30.0 30.0 30.0] (m/s)
Battery Pack Temperature	Relay	ptc_p_engine_off_ess_temp_high ptc_p_engine_off_ess_temp_low	30 (degC) 29 (degC)
Total Power Request	Relay	Tau ptc_p_total_power_request_high ptc_p_total_power_request_low	10 55 (kW) 26 (kW)
Accelerator Pedal Position	Threshold	ptc_p_accel_percent_engine_on	75%
Battery Discharge Power Limit	PU/IPD Loop	ptc_etspl_off ptc_etspl_on ptc_etspl_min	35 (kW) 30 (kW) 15 (kW)
Battery Discharge greater than discharge limit	Threshold	Tau ptc_p_ess_pwr_max_frac	1 80%
Engine Minimum on time	IPD	ptc_p_eng_t_on_min	10 (sec)
Turtle Light	Relay	ptc_ess_soc_turtle_light_off ptc_ess_soc_turtle_light_on	18% 15%
Engine Coolant Temperature	Relay	ptc_coolant_eng_pull_up_high ptc_coolant_eng_pull_up_low	80% of Operating Temp. 78% of Operating Temp.
Driver Operated Starter Command (Key On)	Threshold	none	none

Table 4-2
Design Purposes of Engine On/Off Control Systems

Engine On/Off Control System Name	Type	Design Purposes	
		Charge Depletion	Charge Sustaining
State-of-charge	PU/IPD Loop	none	4,7
Vehicle Speed	Stateflow	3	5,6
Battery Pack Temperature	Relay	1,2	2,3
Total Power Request	Relay	3	1,5,6
Accelerator Pedal Position	Threshold	3	6
Battery Discharge Power Limit	PU/IPD Loop	2	3
Battery Discharge Greater Than Discharge Limit	Threshold	2	3
Engine Minimum on time	IPD	4	7
Turtle Light	Relay	none	3,4,7
Engine Coolant Temperature	Relay	4	7
Driver Operated Starter Command (Key On)	Threshold	4	7

In a PHEV, the reasons to turn on the internal combustion engine in charge sustaining modes are:

1. To recharge the battery at high efficiency,
2. To protect the battery from thermal problems,
3. To protect the battery from overpower,
4. To maintain a minimum state of charge,
5. To extend the range of the vehicle,
6. To meet or anticipate driver torque demands greater than the EM torque,
7. Stability of engine operation for emissions control.

The reasons to turn on the internal combustion engine in charge depleting modes are:

1. To protect the battery from thermal problems,
2. To protect the battery from overpower,
3. To meet or anticipate driver torque demands greater than the EM torque,
4. Stability of engine operation for emissions control.

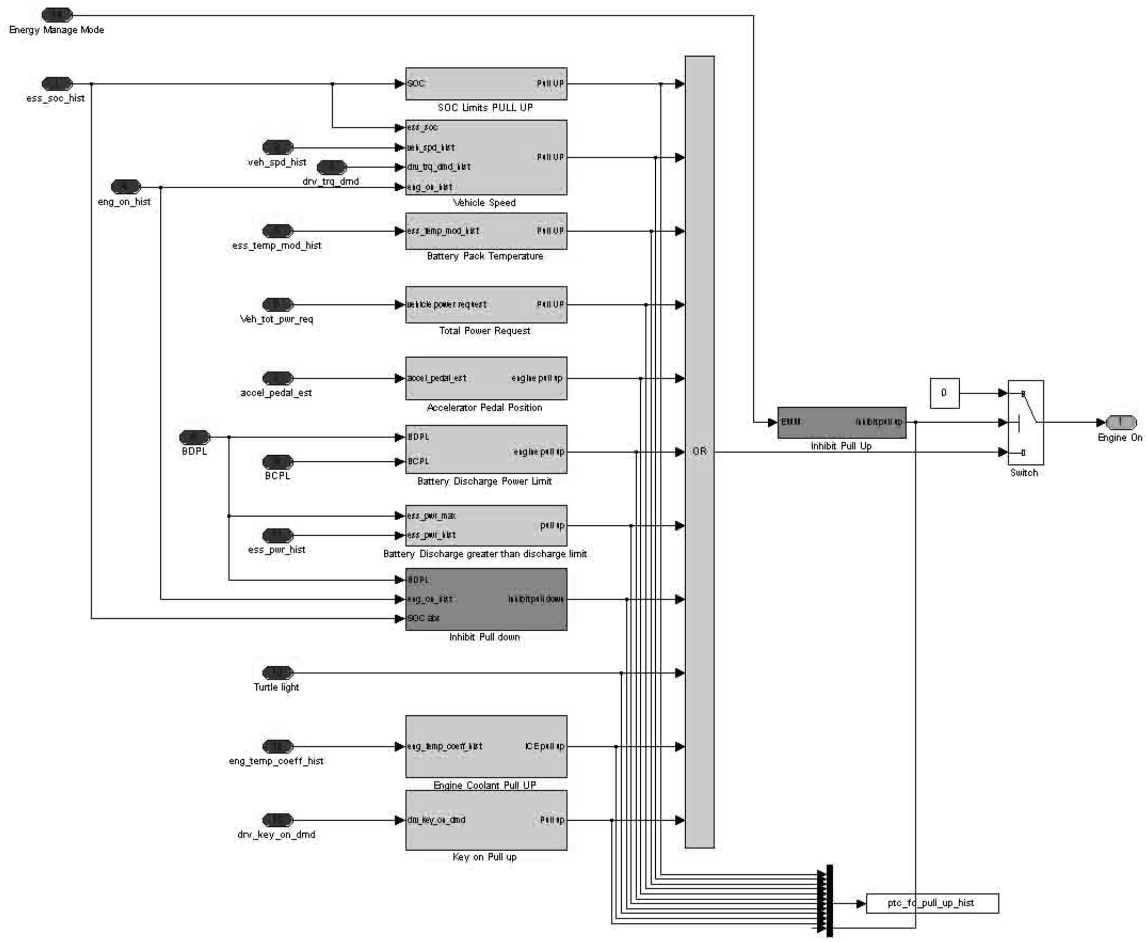

Figure 4-2
Overview of Engine On/Off Control Block (lib_p_par_1mc_conso_start_alter/ p_par_1mc_conso_start_alter /VSC/Hybrid Energy Control Fun/ ENGINE PU and PD)

Figure 4-3 shows the inside of the SOC Limits Pull Up Block. The relay forms part of the SOC IPD Loop. At present, the relay switch off point is 16% and the switch on point is 17%. Because the SOC thresholds are so low this PU does not have an effect at high SOC.

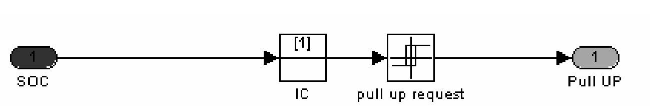

Figure 4-3
Algorithm for SOC Pull Up (lib_p_par_1mc_conso_start_alter/ p_par_1mc_conso_start_alter /VSC/Hybrid Energy Control Fun/ ENGINE PU and PD/SOC Limits PULL UP)

Figure 4-4 shows the inside of the Vehicle Speed Pull Up Block. Control of engine pull up is performed using the Stateflow machine shown in Figure 4-5. The inputs to the Stateflow machine are engine on history, vehicle speed and two signals that represent the vehicle speed thresholds for engine pull up and pull down. The Stateflow controller outputs a PU when the vehicle speed crosses the lower_lim threshold. The controller removes the PU when the vehicle speed crosses either the lower_lim threshold or the upper_lim threshold, going down. If the vehicle is driving at relatively high speed between the thresholds for more than 30 seconds, then the engine PU command is issued. This system promotes stable operation of the engine and turns off the engine during long, high-speed decelerations to optimize regeneration.

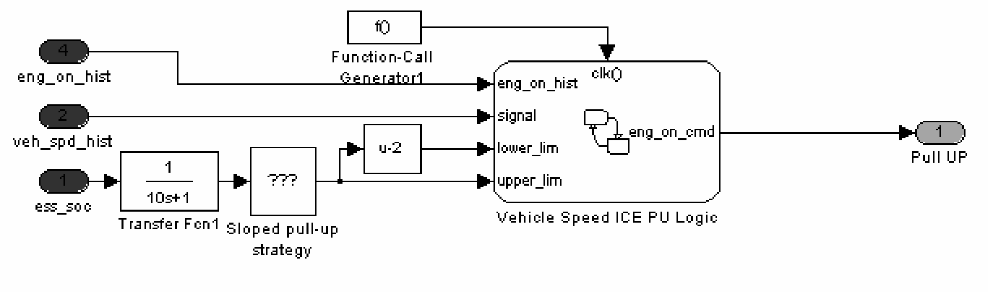

Figure 4-4
Vehicle Speed/SOC Pull Up (lib_p_par_1mc_conso_start_alter/ p_par_1mc_conso_start_alter /VSC/Hybrid Energy Control Fun/ ENGINE PU and PD/Vehicle Speed)

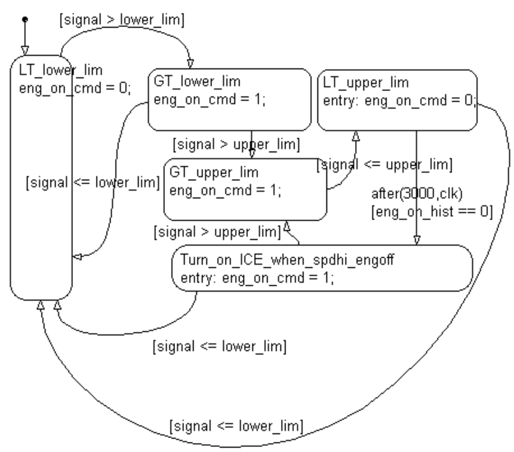

Figure 4-5
Stateflow Controller for Vehicle Speed/SOC Pull Up (lib_p_par_1mc_conso_start_alter/ p_par_1mc_conso_start_alter /VSC/Hybrid Energy Control Fun/ ENGINE PU and PD/Vehicle Speed/Vehicle Speed ICE PU Logic)

Figure 4-6 shows the Battery Temperature Pull Up. Turning on the engine when the battery temperature gets high reduces the power flow through the battery and reduces ohmic heating of the batteries.

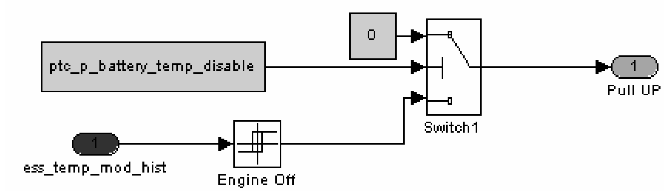

Figure 4-6
Battery Temperature Pull Up (lib_p_par_1mc_conso_start_alter/ p_par_1mc_conso_start_alter /VSC/Hybrid Energy Control Fun/ ENGINE PU and PD/Battery Pack Temperature)

Figure 4-7 shows the Total Power Request Pull Up. The vehicle total power request signal is calculated by the CONSTRATINTS AND VEHICLE TORQUE DEMANDS block. This signal represents the amount of power required from the battery pack when the vehicle is running in EV mode and the amount of power requested from the engine when the engine is on. The purpose of this engine pull up controller is to turn on the engine when the power draw from the batteries and electric motor is very high.

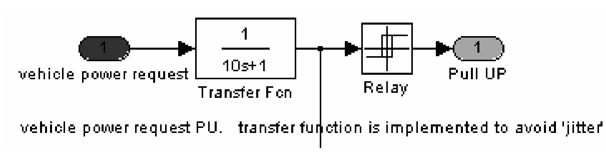

Figure 4-7
Total Power Request Pull Up (lib_p_par_1mc_conso_start_alter/ p_par_1mc_conso_start_alter /VSC/Hybrid Energy Control Fun/ ENGINE PU and PD/Total Power Request)

Figure 4-8 shows the Accelerator Pedal Position Pull Up. The accelerator pedal estimation is a signal that is generated in simulation based on the driver torque demand. The purpose of this signal is to anticipate high torque and high power driving conditions.

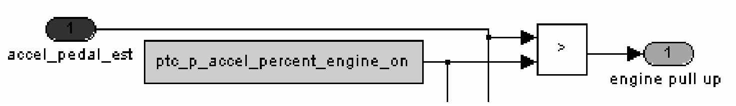

Figure 4-8
Accelerator Pedal Pull Up (lib_p_par_1mc_conso_start_alter/ p_par_1mc_conso_start_alter /VSC/Hybrid Energy Control Fun/ ENGINE PU and PD/Accelerator Pedal Position)

Figure 4-9 shows a part of the PU/IPD Loop for the Electric Traction System Power Limits (BDPL).

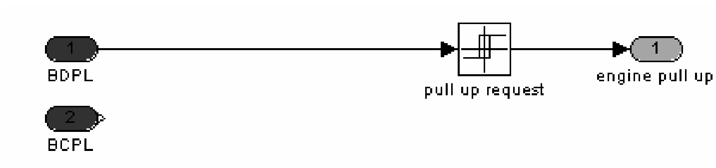

Figure 4-9
Electric Traction System Power Limits Pull Up (Battery Discharge Power Limit) (lib_p_par_1mc_conso_start_alter/ p_par_1mc_conso_start_alter /VSC/Hybrid Energy Control Fun/ ENGINE PU and PD/ Battery Discharge Power Limit)

Figure 4-10 shows the Engine PU that is a function of battery discharge power. The purpose of this controller is to limit the long-period discharge power of the battery system.

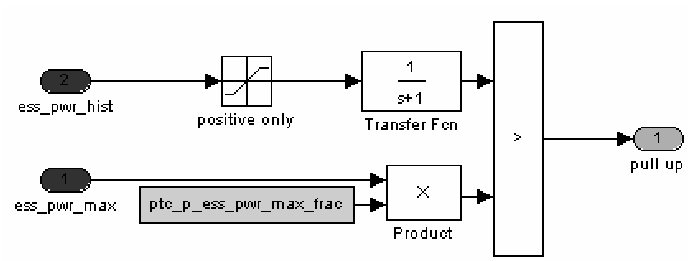

Figure 4-10
Battery System Power Pull Up (lib_p_par_1mc_conso_start_alter/ p_par_1mc_conso_start_alter /VSC/Hybrid Energy Control Fun/ ENGINE PU and PD/Battery Discharge greater than discharge limit)

Figure 4-11 shows the five Inhibit Pull Down blocks. All of the blocks except for Engine Minimum On Time are associated with PU/IPD Loops. The Engine Minimum On Time block keeps the engine on for at least 10 seconds for every time that it is started. Figure 4-12 shows the blocks that implement the downcycle portion of the PU/IPD loop for battery SOC. This is representative of the structure of all of the PU/IPD loops.

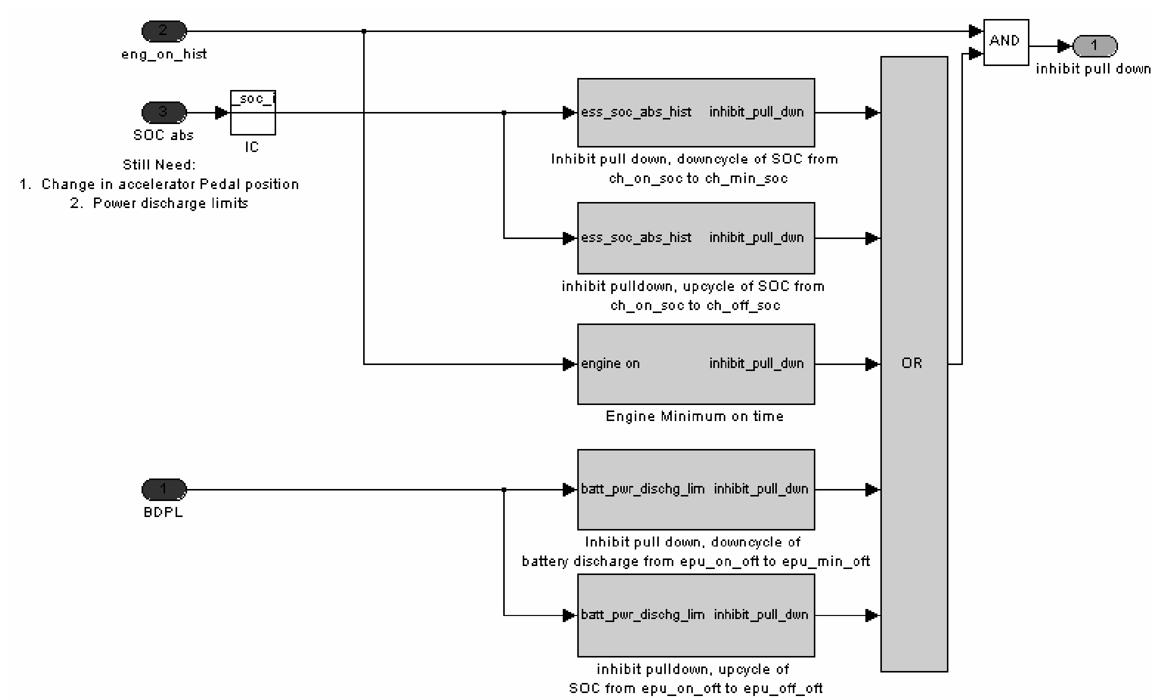

Figure 4-11
Inhibit Pull Downs (lib_p_par_1mc_conso_start_alter/ p_par_1mc_conso_start_alter /VSC/Hybrid Energy Control Fun/ ENGINE PU and PD/Inhibit Pull Down)

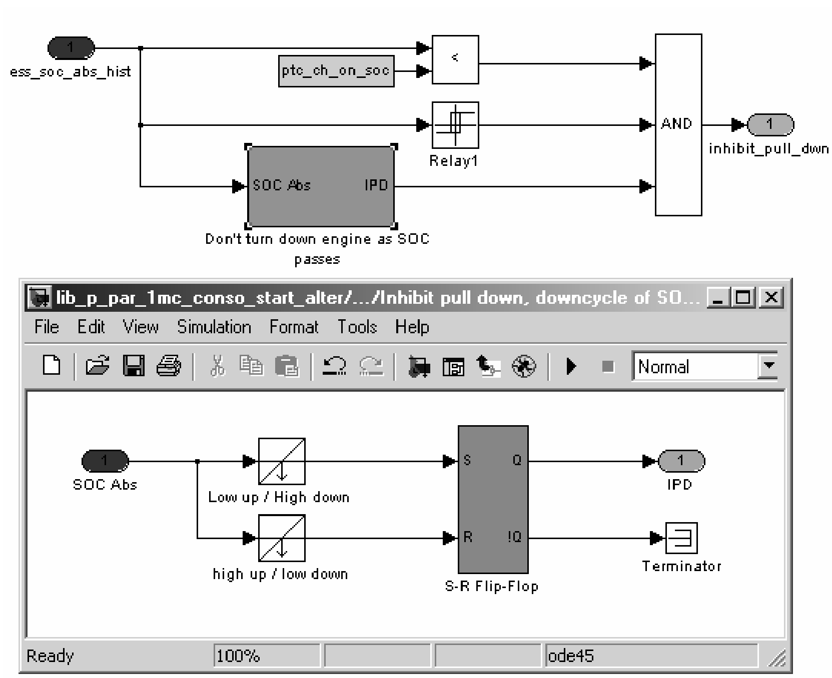

Figure 4-12
Implementation of Inhibit Pull Down Loops for State of Charge (lib_p_par_1mc_conso_start_alter/ p_par_1mc_conso_start_alter /VSC/Hybrid Energy Control Fun/ ENGINE PU and PD/Inhibit Pull Down Inhibit pull down, downcycle of SOC from ch_on_soc to ch_min_soc)

Strategy Evaluation

The feasibility of the Engine On/Off Controller proposed is very dependant on the details of implementation in the vehicle. As present, it is assumed that the engine on/off control in the simulation is accurate, relative to the vehicle. If there are large time delays in turning on or off the engine, or if there are large time delays in ramping up engine torque, then these effects will need to be incorporated into the simulation and into the control system.

As shown in Figure 4-13, the engine on/off control system is stable and effective.

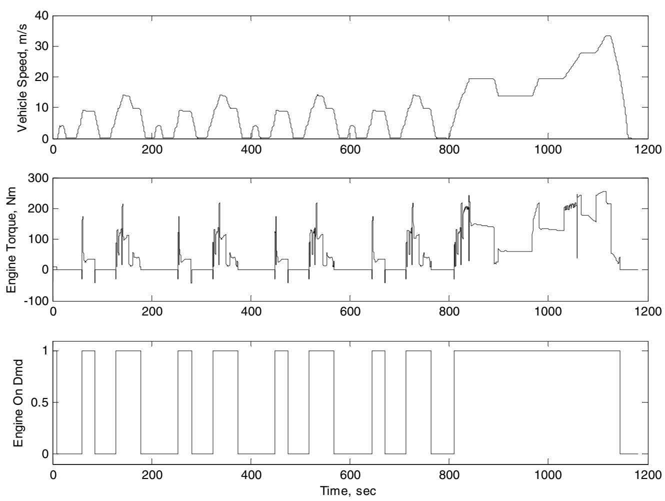

Figure 4-13
Engine On/Off Controller Behavior

As shown in Figure 4-14, the Engine On/Off Stateflow Controller works to turn the engine on at a relatively low speed and turn it off during periods of deceleration. Because charging takes place while the engine is on, the positive slope of the engine turn on speed function means that in most cases, the engine will turn on at a low-engine-speed, high torque condition and will turn off during a higher-engine-speed, lower torque condition. Turning the engine off for long decelerations improves the vehicle efficiency by allowing for effective regenerative braking and reducing engine-on time.

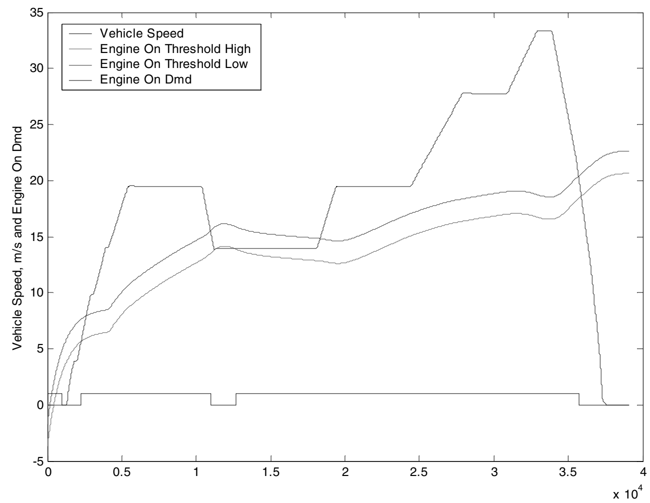

Figure 4-14
Engine On/Off Stateflow Controller Behavior

Figure 4-15, Figure 4-16 and Figure 4-17 illustrate the engine pull up signals that are used for the EUDC, 505 and US06 drive cycles.

In Figure 4-15, at time 0, the engine is turned on by the *11. Key On* signal. This signal turns on the engine when the driver turns the key to start in charge sustaining mode. For the next ten seconds, the engine is held on by the *Inhibit Pull Down* (IPD) signal that corresponds to the minimum engine on time of 10 seconds. When all of the engine pull up signals are equal to zero, the engine will turn off. This happens on the EUDC at time of 10 seconds. At roughly time 50 seconds, the engine is pulled up again by the *2. Veh Spd PU* signal that is related to vehicle speed. For the first 10 seconds of this pull up, the IPD signal is also present to make sure that the engine does not turn off in the first 10 seconds of its being on. Again, when the *Veh Spd PU* is removed at time 110 seconds, the engine is turned off. Finally, the engine is again started by the *Veh Spd PU* and held on by the IPD and the *Total Pwr PU*, which is a function of the vehicle total power demand.

In Figure 4-16, we can see the similar general behavior as was seen on the EUDC cycle, where the engine is pulled up by a number of different pull up signals and is held up by the minimum engine on time IPD and the *Veh Spd PU.* Because the 505 cycle is a lower speed, urban cycle, the engine comes on and off more often. The difficult to identify engine pull up signals that occur at a time of 40, 170, 190 seconds are *5. Accel Pedal PU*. This signal is required on the 505 because of the lower speed, higher acceleration demands of the 505 cycle.

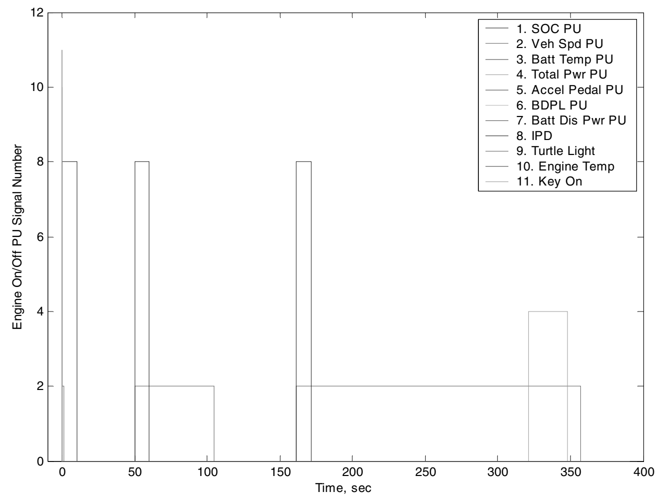

Figure 4-15
Engine On/Off Controller Pull Ups for EUDC CS HEV Mode

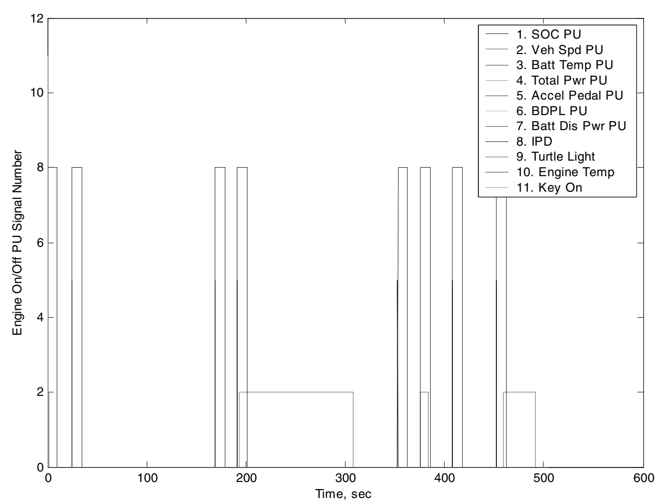

Figure 4-16
Engine On/Off Controller Pull Ups for 505 CS HEV Mode

In Figure 4-17, the vehicle is driving the US06 cycle, which is a very high speed, high acceleration cycle. In this case, the engine is pulled up by signals 11, 8, 5, 4, and 2 at different times over the course of the cycle. The *Veh Spd PU* and the IPD signals serve to keep the engine on at high-speed, high power situations and to provide stability of operation to the engine.

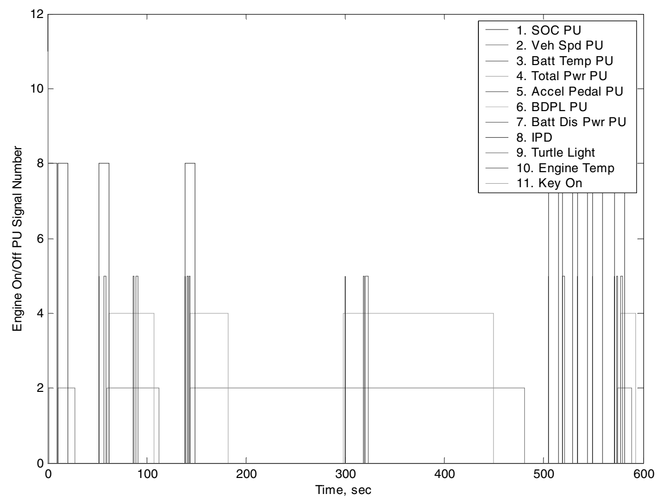

Figure 4-17
Engine On/Off Controller Pull Ups for US06 CS HEV Mode

5
STATE-OF-CHARGE CONTROL

Introduction

The purposes of the state-of-charge control algorithms are to maintain the battery state-of-charge during charge-sustaining operation. Although regenerative braking can be used to maintain SOC, an active SOC control is required to assure that the SOC remains within an optimum range.

Strategy Description

The state-of-charge control for the PHEV Sprinter is made up of three parts: Engine On/Off Control, the Battery Charge Power Demand block and the Turtle Light Controller.

Strategy Implementation

The Engine On/Off Control Subsystems that contribute to state-of-charge control are:

State-of-Charge PU/IPD Loop,

Vehicle Speed Stateflow Machine,

Battery Discharge Power Limit PU/IPD Loop.

The Battery Charge Power Demand block is labeled Battery Charge/Discharge Demand in Figure 3-4. This block adds a battery charge power command to the vehicle total power demand. For each control cycle, the difference between the vehicle total torque demand and the driver torque demand is the amount of torque that the electric motor will either supply or regenerate. As shown in Figure 5-1, transmission of the Battery Charge/Discharge Demand signal is dependent on the engine torque command. When the engine torque command is greater than 50 Nm, the Battery Charge/Discharge Demand signal is passed to the vehicle total power demand summation. The Battery Charge/Discharge Demand signal is a function of SOC as shown in Figure 5-2.

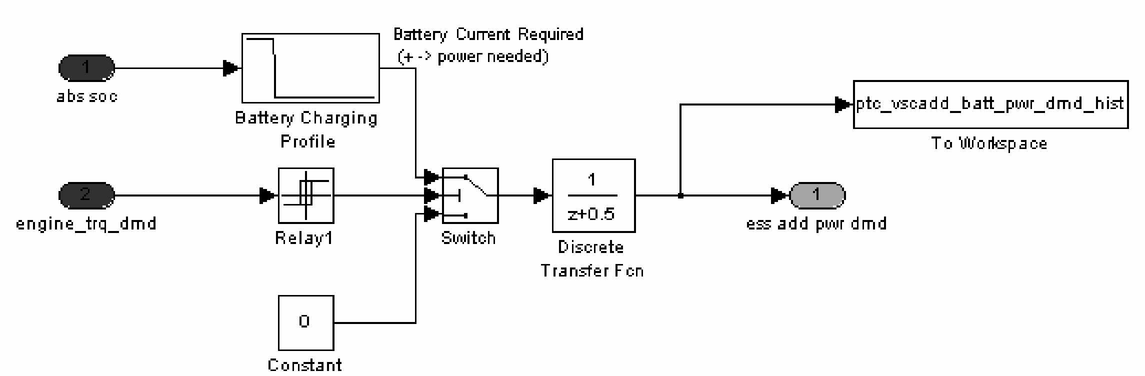

Figure 5-1
Battery Charge and Discharge Demand (lib_p_par_1mc_conso_start_alter/ p_par_1mc_conso_start_alter /VSC/Hybrid Energy Control Fun/ CONSTRAINTS AND VEHICLE TORQUE DMDS/Torque required from Vehicle /Battery Charge/Discharge Demand)

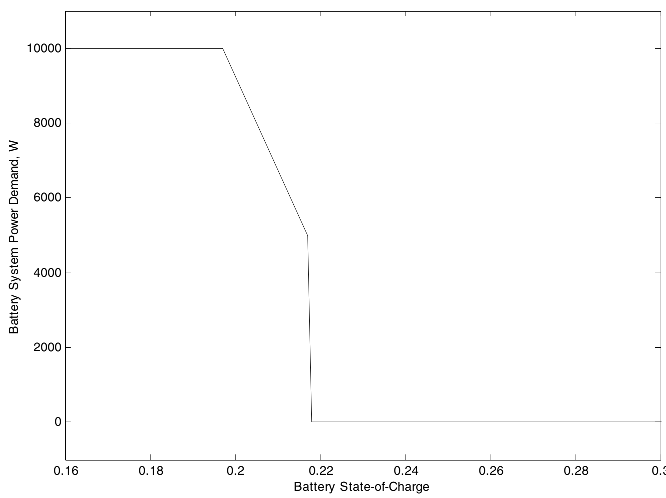

Figure 5-2
Battery Charge Demand Profile

The Turtle Light is a condition where the battery SOC has reached an absolute minimum. In general, this condition should only be met when the vehicle is required to use electrical power, at low SOC, over a long period. The Turtle Light condition can be reached by applying 100% accelerator pedal signal at low state of charge.

Activation of the Turtle Light changes the control within the Motor Torque Prop and Regen block shown in Figure 3-6. As shown in Figure 5-3, the operation of the electric motor switches to control around battery current.

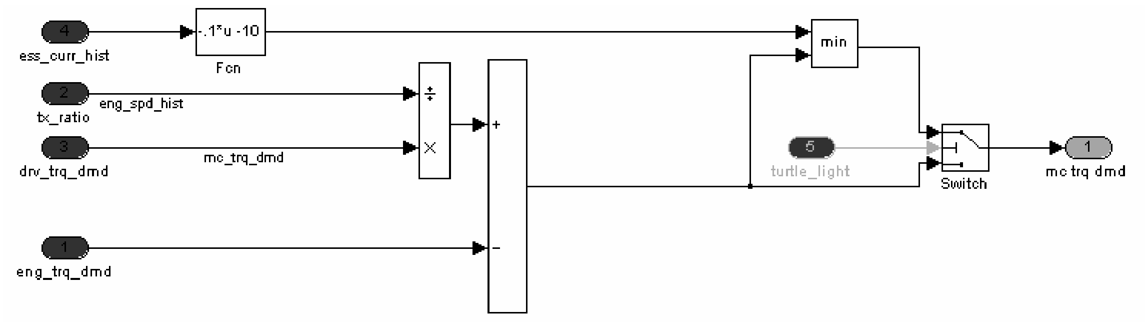

Figure 5-3
Electric Motor Torque Control in Normal State (lib_p_par_1mc_conso_start_alter/ p_par_1mc_conso_start_alter /VSC/Hybrid Energy Control Fun/ SPEED & TORQUE CONTROL STATES/Subsystem/Normal Driving Fun/Motor Torque Prop and Regen)

Strategy Evaluation

The SOC control strategy has the ability to control SOC in simulation, regardless of vehicle loading conditions or drive cycle.

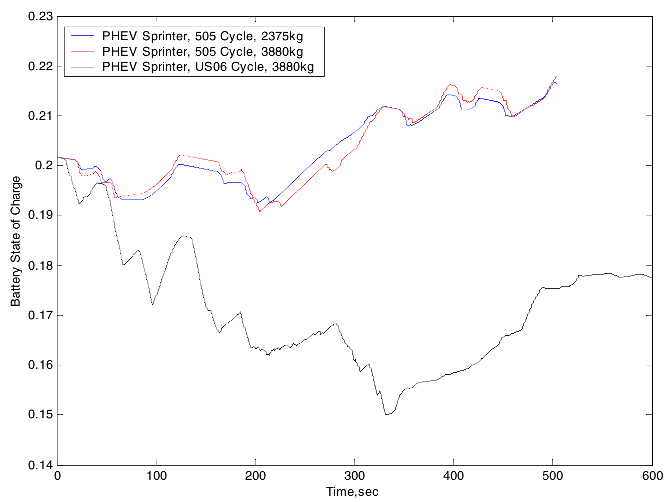

Figure 5-4
Simulated Battery State of Charge over 505 and US06 Cycles for PHEV Sprinter at Test Weight and Gross Vehicle Weight.

The Turtle Light strategy for terminal state-of-charge control is effective although it does limit the performance of the vehicle. As shown in Figure 5-5, when the Turtle Light threshold is hit, the EM torque control switches to battery current feedback. Even when the EM torque demand is high, the EM reduces torque output and the battery SOC is stabilized.

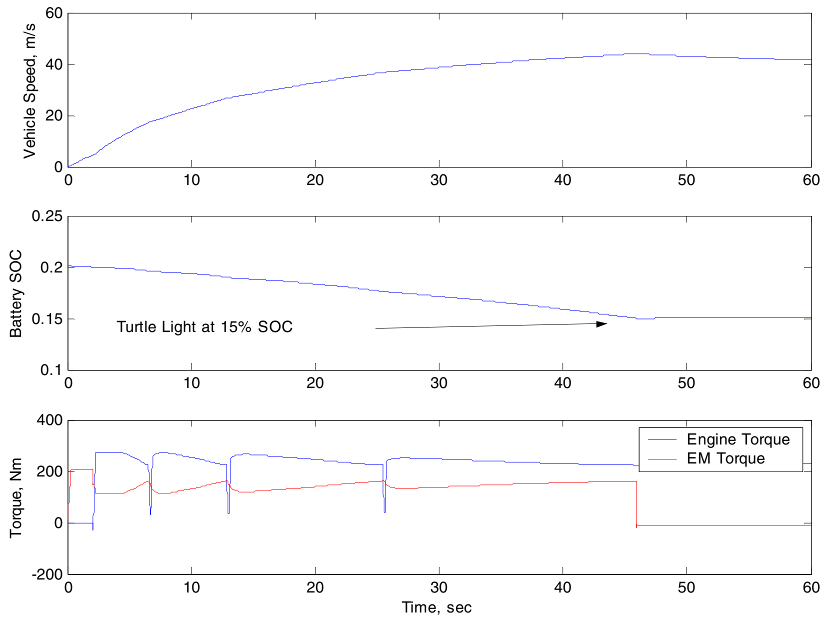

Figure 5-5
Standing 100% Acceleration Test at Low SOC. Turtle Light comes on at 46 sec.

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