Paper Number

A Preliminary Investigation into the Mitigation of Plug-in Hybrid Electric Vehicle Tailpipe Emissions Through Supervisory Control Methods Part 1: Analytical Development of Energy Management Strategies

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ABSTRACT

Plug-in hybrid electric vehicle (PHEV) technologies have the potential for considerable petroleum consumption reductions, possibly at the expense of increased tailpipe emissions due to multiple "cold" start events and improper use of the engine for PHEV specific operation. PHEVs operate predominantly as electric vehicles (EVs) with intermittent assist from the engine during high power demands. As a consequence, the engine can be subjected to multiple cold start events. These cold start events may have a significant impact on the tailpipe emissions due to degraded catalyst performance and starting the engine under less than ideal conditions. On current hybrid electric vehicles (HEVs), the first cold start of the engine dictates whether or not the vehicle will pass federal emissions tests. PHEV operation compounds this problem due to infrequent, multiple engine cold starts.

The research is broken down into two (2) distinct phases, involving both analytical and experimental areas. Phase I of the research, addressed in this document, focuses on the design of a vehicle supervisory control system for a pre-transmission parallel PHEV powertrain architecture. A suitable control system architecture is created and implemented into a standard vehicle modeling tool (in this case, the Powertrain Systems Analysis Toolkit). Energy management strategies are evaluated and implemented in a virtual environment for preliminary assessment of petroleum displacement benefits and rudimentary drivability issues.

Engine cold start events are aggressively addressed in the development of this control system, which leads to enhanced pre-warming and energy-based engine warming algorithms that provide substantial reductions in tailpipe emissions over the baseline supervisory control strategy. The flexibility of the PHEV powertrain offers the potential for decreased emissions during any engine starting event through powertrain "torque shaping" algorithms. The analytical work presented here is experimentally validated during Phase 2, the subject of a follow on paper.

INTRODUCTION

The research begins by developing a suitable vehicle model complete with an appropriate powertrain configuration and baseline control strategy. Each individual component model must be populated with performance data in order to adequately characterize the dynamics and efficiencies of the powertrain. The following sections develop the vehicle level model and baseline attempt at a reasonable control strategy for conventional, HEV, and PHEV operation. The focus of the baseline supervisory control strategy is for implementation into actual hardware for verification of the emissions reduction techniques.

VEHICLE MODELING

The vehicle chosen for this study is based on a typical compact sedan. This vehicle has been tested extensively in the Advanced Powertrain Research Facility (APRF) at Argonne National Laboratory (ANL) and has been validated using the Powertrain Systems Analysis Toolkit (PSAT). Therefore, validated test data for the vehicle is readily available for use and provides an excellent basis to begin modeling. The composition of the vehicle model can be broken down into two (2) basic constituents: mechanical components that comprise the physical vehicle, and the supervisory control strategies that manage the interactions of all relevant powertrain components within the vehicle. A complete summary of the hardware components and relevant data is presented in the next section, followed by a detailed description of the development of the control strategy. It is important to note that this vehicle is designed to be all-electric capable over the Urban Dynamometer Driving Schedule (UDDS).

Components

In order to successfully create a viable vehicle level model, powertrain components must be identified and respective data gathered. PSAT organizes the creation of an advanced powertrain vehicle model into a logical sequence of events, beginning with the selection of a powertrain configuration. As noted earlier, a pre-transmission parallel hybrid electric powertrain with single energy storage system provides the foundation from which to build the virtual PHEV. This is consistent with the powertrain configuration of the Mobile Advanced Technology Testbed (MATT) at ANL, which is a unique hardware-in-the-loop test system capable of emulating virtually any advanced powertrain configuration on a chassis dynamometer. Subsystem models are then chosen to populate each of the components of the powertrain. Corresponding initialization files provide the necessary interface for component characterization via data maps and variables.

The most important component models for this study are the engine, traction motor, and energy storage system. The energy storage system model is based on a proprietary model developed by researchers at ANL. The engine model is based upon an existing PSAT engine model that is scaled to match the characteristics of the gasoline engine currently in use on MATT. Table 1 outlines the pertinent components used to create the vehicle model in PSAT. A brief summary of the distinguishing characteristics of each powertrain component is provided in the table. Once each of the powertrain components has been identified and populated with the relevant data maps and variables, the control strategy must be developed and implemented.

Table 1 PSAT component modeling assumptions

COMPONENT PARAMETER	VALUE
Maximum engine power output:	104 kW
Peak engine efficiency	37%
Energy storage capacity	10.6 kW*hr
Nominal voltage	260 VDC
Continuous motor power	53 kW
Maximum motor power	75 kW
Peak motor efficiency	92%
Final drive ratio	3.5
Tire rolling radius	0.33 m
Tire rolling resistance	0.007
Vehicle mass	1685 kg
Frontal area	2.2 m2
Drag coefficient	0.33

Control Strategy: Development of the Vehicle System Control Module

The Vehicle System Control Module (VSCM) is a supervisory control system that dictates how each of the powertrain components behaves, as well as how each subsystem interacts with other onboard systems in order to meet basic operator demands. PSAT has a basic selection of powertrain supervisory control strategies to select from. These control strategies provide basic functionality and are excellent for use in directional or trade-off studies. While these control models are useful, a custom control model was created that offered full flexibility and adaptability for later stages of the research where emissions constraints would be considered. In addition, development of a custom control strategy was warranted in order to provide essential calibrateable parameters that would make the transition from simulation to real time hardware quick and easy.

The VSCM model was developed in a modular fashion in order to readily accept additional code insertion where necessary. The control system architecture is comprised of various control processes. The primary control processes of the VSCM are responsible for the status of the vehicle, the energy management and blending strategies, the regenerative braking functions, and energy storage control and status. Each of these control processes communicates with each other in order to facilitate the operation and interaction of the traction motor, energy storage system, and the engine. All calculations within the VSCM are power-based. This ensures consistency throughout each process of the VSCM, and minimizes error due to missed gear ratios that are necessary for torque-based calculations.

PHEV CONTROL STRATEGY APPROACHES

The supervisory control system of the PHEV powertrain must allow for both charge depleting (CD) and charge sustaining (CS) operation as appropriate over the entire usable state-of-charge (SOC) range of the energy storage system. While there are literally endless possibilities for energy management strategies to be implemented into the VSCM, four (4) distinct supervisory control algorithms will be evaluated as part of this research. One important note is that for the baseline development of the VSCM, emissions considerations are ignored such that a basis for comparison of the subsequent emissions control algorithms can be later evaluated (fuel economy impacts through simulation and emissions impacts through test).

Charge Depleting Operation

The two (2) main approaches for PHEV CD operation are referred to in this research as the ***maximum depletion*** and the ***blended*** mode. The maximum depletion approach is the simplest control method and strives to discharge the battery pack as quickly as possible by operating in all-electric mode until the lower SOC bound is reached.

The blended strategy makes greater use of the engine during the CD region of operation. The blended strategy applied in this research makes use of what will be referred to as charge preservation (CP) operation when the engine is running during CD. The distinction between CP and CS is that the VSCM does not allow any charging of the battery pack by the engine (using extra fuel) and does not use the motor for any propulsion (no discharge of the battery pack is allowed). The engine operates just as in a conventional powertrain and provides all propulsion for the vehicle. In this way, the energy in the battery pack is preserved until the engine shuts off and electric operation resumes where it “left off.” Another important concept applied in this strategy is that if the engine is commanded to operate, then it should be used to provide useful work. This is another reason why no discharging of the battery pack is allowed during CP operation (reduction of the required power from the engine). The CP mode is accomplished by temporarily setting the target SOC to the current SOC at the point when the engine was commanded to engage. The required power to maintain the SOC of the energy storage system is then set equal to zero such that no charging or discharging occurs.

Charge Sustaining Operation

For this particular pre-transmission parallel HEV powertrain architecture, there are two (2) approaches to CS operation that cover a majority of the functional envelopes of the subsystem components, with emphasis on the engine.

The first approach, referred to herein as the ***load following*** strategy, operates the engine much like a conventional vehicle where the commanded engine torque closely follows the demanded torque. Excess engine power can be used to charge the battery pack during periods of low power demand, such as cruising. The SOC is held tightly around a target SOC during CS operation. In this approach during HEV operation, the traction motor is operated in a more constant regime, whereas the engine manages all the transients.

The second approach, referred to herein as the ***engine optimal*** strategy, operates the engine much differently compared to the load following case. Here, the engine is commanded to operate at its most efficient load point based on the current engine speed. The motor acts as a generator and charges virtually all the time while the engine is running. SOC maintenance is handled by operating the vehicle in electric mode for a larger percentage of the time, particularly during urban styles of driving. In this approach during HEV operation, the engine is operated in a more constant regime, whereas the traction motor manages all the transient behavior necessary to adequately traverse the drive cycle.

Both the load following and engine optimal CS strategies were incorporated into the controller and expanded for PHEV operation. Figure 1 through Figure 4 represent a graphical summary of the simulation results of the fundamental operation of each case of the maximum depletion and blended strategies.

Figure 1 and Figure 2 illustrate the engine operation for the maximum depletion/load following case and the maximum depletion/engine optimal case, respectively. The maximum depletion cases feature all electric operation during the CD portion of the strategy, followed by either a load following or engine optimal charge sustaining phase. The load following case maintains the SOC tightly around the target SOC of 30%, as shown in Figure 1. As a consequence, the engine turns on much more frequently. The SOC for the engine optimal case, illustrated in Figure 2, is allowed to vary much more greatly around the target SOC.

This is due to the engine operating on its most efficient point, and consequently charges the battery to a much greater degree. As a result, the engine does not have to turn on as frequently, and makes use of the excess stored electrical energy to propel the vehicle. Less engine starts are desirable in order to potentially reduce THC and CO emissions.

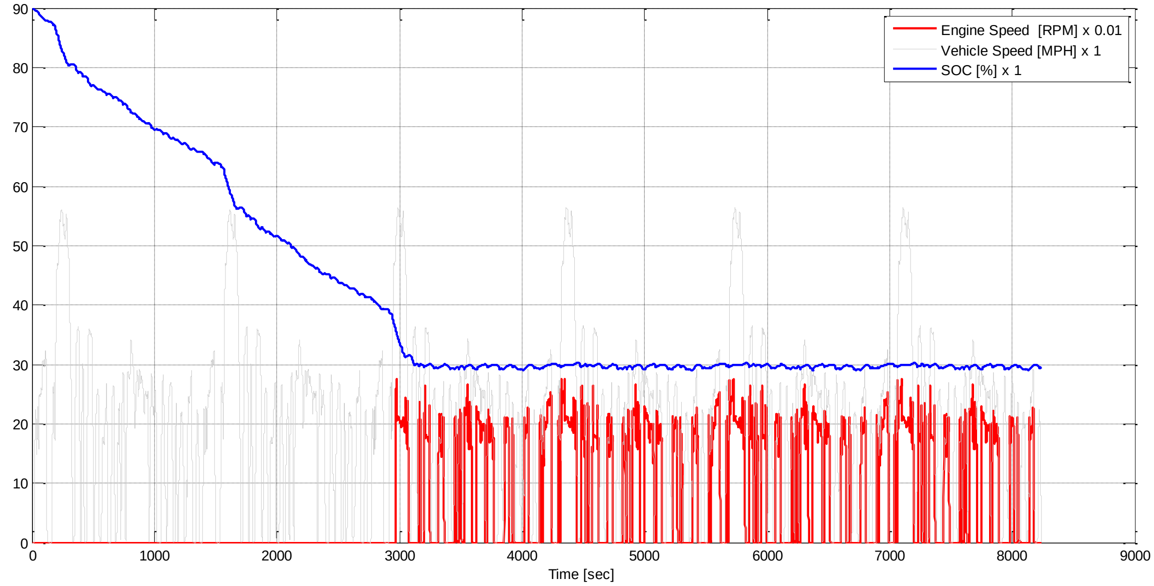

Figure 1. Baseline maximum depletion load following operating summary

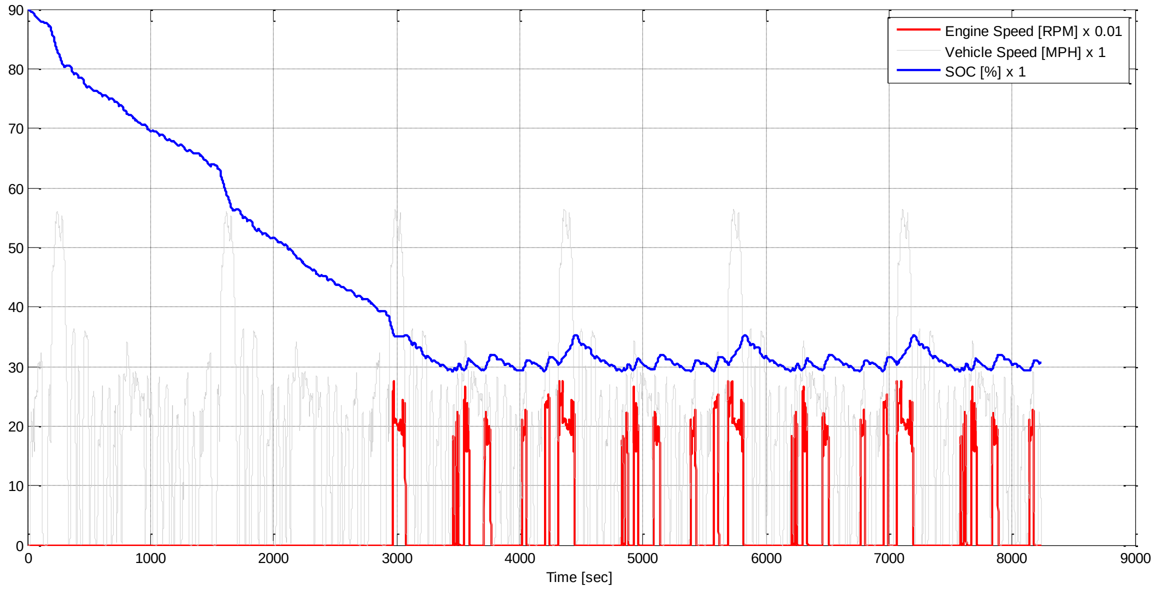

Figure 2. Baseline maximum depletion engine optimal operating summary

Figure 3 and Figure 4 represent the blended control strategy cases. The CD phase for both the load following and engine optimal strategies are identical. The philosophy for the blended CD operation is to operate in a CP mode. When the engine is requested to provide power during higher demands, the engine is operated much like a conventional, load following strategy. No charging or discharging of the energy storage system is allowed during CP mode. The concept is to load the engine when it is requested to operate such that it operates more efficiently, hence no discharging of the battery. Conversely, the purpose of CD is to rely mostly on electric power, so extra fuel should not be consumed to charge the battery pack. This approach is shown in the figures as a flat SOC line during engine operation for the CD portion of the simulation, such that the SOC of the battery pack is "preserved."

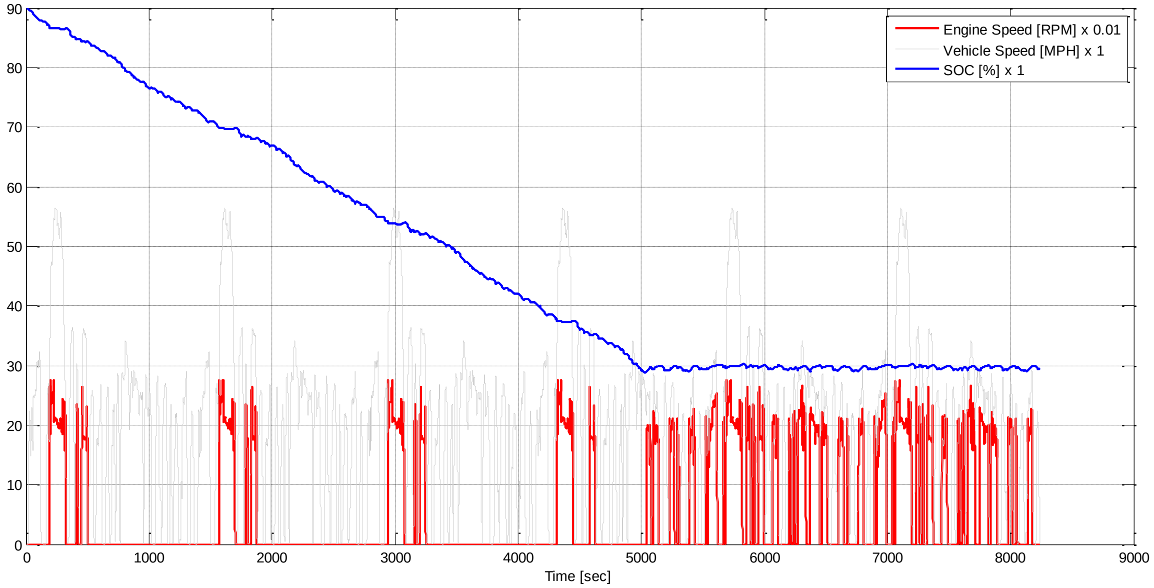

Figure 3. Baseline blended load following operating summary

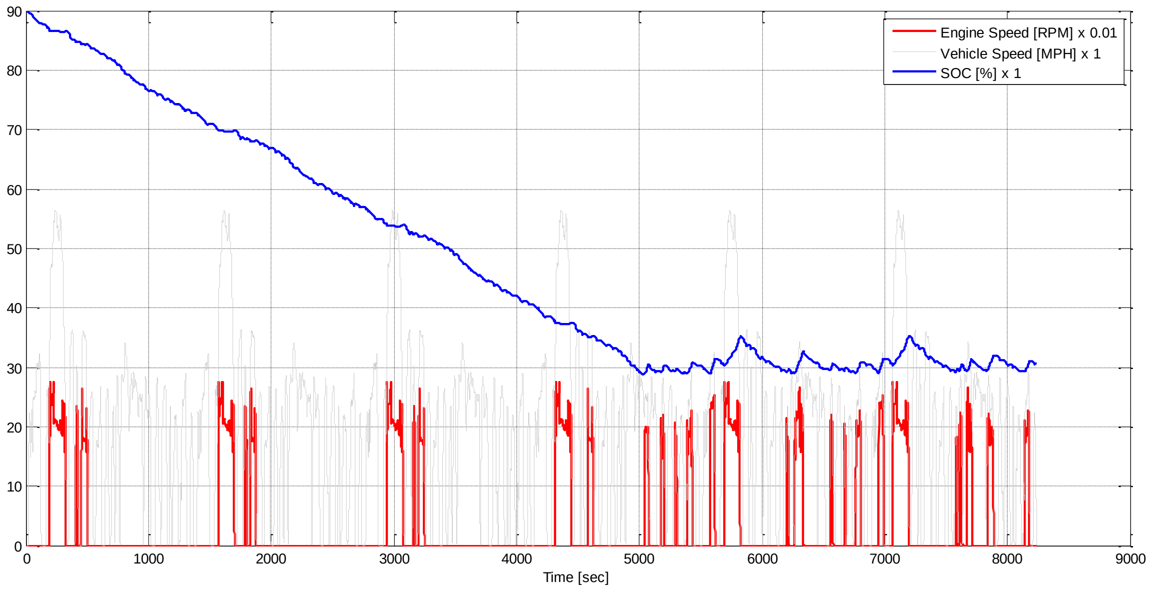

Figure 4. Baseline blended engine optimal operating summary

represents a comparison of the energy consumption for each individual strategy that was simulated. The energy consumption presented here is aggregate for the entire test regimen (6 consecutive UDDS driving cycles). For both the load following and engine optimal approaches, the fuel consumption of the vehicle is reduced in going from the maximum depletion case to the blended case. The engine optimal strategy provides marginally lower fuel consumption over the load following algorithm. The electrical energy consumption is slightly lower for both of the engine optimal cases, due mainly to the excessive charging of the energy storage system during engine operation. An important consideration when considering energy consumption (particularly fuel consumption) is that due to PSAT limitations, the simulations only predict hot start energy consumption.

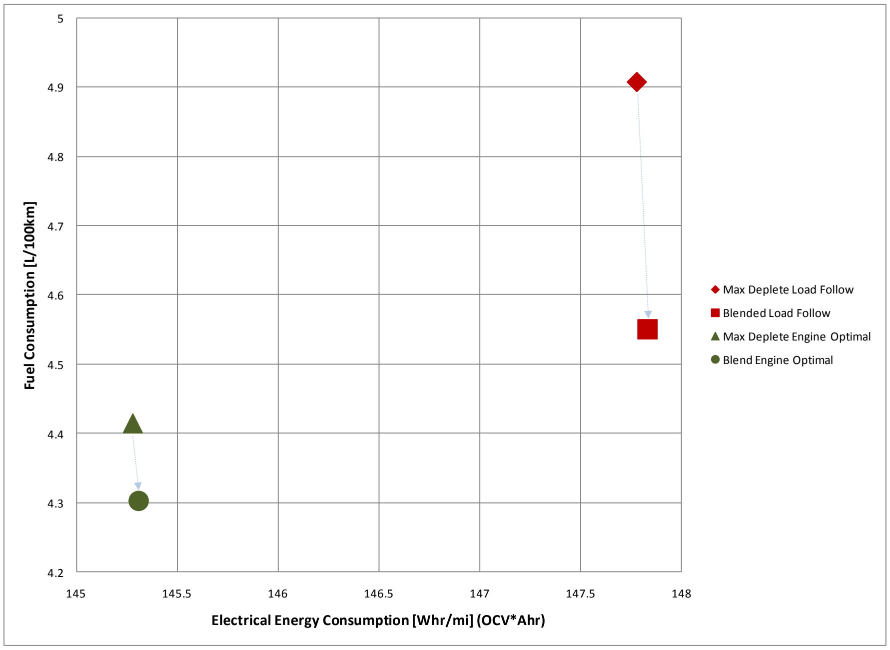

Figure 5. Simulation energy consumption results for baseline PHEV control strategies

CONTROL STRATEGY MODIFICATIONS FOR EMISSIONS

Engine Pre-Warming Strategy

The maximum depletion cases are addressed first. Here, all-electric operation from key switch on is maintained. However, a smoother transition strategy must be implemented that heats the engine at low loading prior to being relied upon as the primary power source. A key-on engine start strategy is not a desired option, but does provide a sound basis for an engine heating transition strategy in moving from CD mode into full CS operation.

At moderately low SOC values, in this case below 40%, a SOC transition strategy is implemented. A pre-warm up routine has been developed where the vehicle continues to function in a CD mode, relying on all electric power for propulsion. During this transition, the CP mode is activated. Upon reaching an engine start condition, the engine will start and be operated at a constant low torque command, in this case 15 N*m. As a first attempt, the pre-warm up routine is time based, and limited to operate for a total of 120 seconds. The pre-warm up routine resembles a conventional key-on engine start and idle period which is slightly accelerated by applying a light load to the engine to heat critical exhaust aftertreatment components. However, the traction motor is actuated to handle the transient power demands of the operator. PSAT simulation results for this strategy modified with emissions constrol constraints are shown graphically in Figure 6 compared to baseline results for the same portion of the multiple UDDS drive cycle.

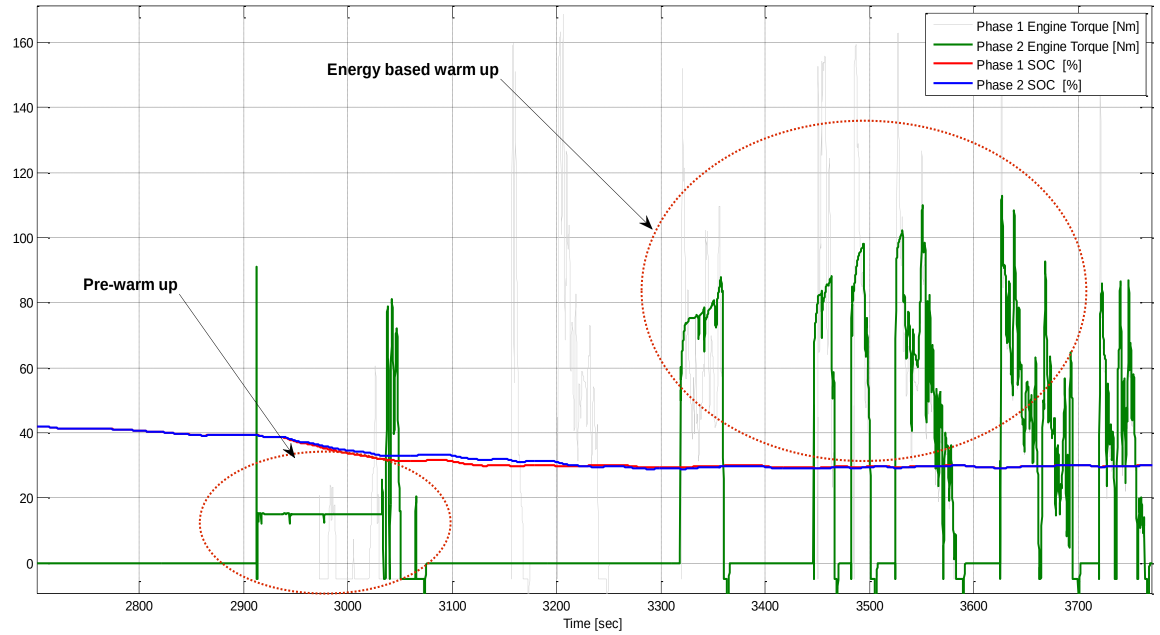

Figure 6. Maximum depletion pre-warm up and engine energy based warm up routines

The light loading of the engine actually reduces the commanded power of the traction motor, which in turn slightly “preserves” the SOC of the battery pack. This creates a delay in the next required engine start, which is the beginning of full CS operation of the PHEV powertrain.

Main Energy-Based Warming Strategy

Once the engine completes the pre-warm up routine, a main energy-based torque limiting routine is employed to further warm the engine and exhaust aftertreatment system in a gradual manner. This approach effectively reduces high torque spike demands of the engine. In essence, the main engine warm up concept is a scaling factor that modifies the maximum available engine power consisting of two (2) primary components.

The first component of the energy based torque limiting scaling factor is derived from analysis of a conventional vehicle cold start (MATT operated as a conventional vehicle using the same component matrix). The cumulative engine output energy, E_{tot}, is calculated and normalized based on the 3 MJ value (derived from MATT conventional vehicle cold start data) for successful conventional vehicle engine warm up, and is given by the expression

$$N_{energy} = \frac{\int_0^{E_{tot}} P_{eng\_des}(t)\, dt}{E_{tot}}$$

where,

N_{energy} is the engine energy based scaling factor,

E_{tot} is the total energy required for successful engine warm up, and

P_{eng_des} is the commanded engine power from the VSCM.

Modern ECUs have internal algorithms that can infer actual engine output, however, desired engine output was used in this research to demonstrate the concept. The energy-based torque limiting strategy is shown graphically on the right side of Figure 6. From the figure, it is clear how the maximum output of the engine is slowly ramped as as the total energy used by the engine increases.

The second component of the energy based torque limiting scaling factor is based on vehicle speed. The engine torque is limited more at lower vehicle speeds where wheel torque requests are typically greater to accelerate the vehicle. This approach is based on a calibrated one-dimensional look-up table and accounts for up to a maximum value of 0.5 for the scaling factor of the torque limiting routine.

Finally, the total scaling factor, N_{total}, for the torque limiting engine warm up routine is given by the expression below. N_{total} never can reach unity until N_{energy} saturates and N_{veh_speed} is greater the maximum speed threshold (40 MPH in this case).

$$N_{total} = N_{veh\_speed} + \frac{1}{2} N_{energy}, N_{total}\ between\ \{0, 1\}.$$

Once the engine has completed both the pre-warm up and main engine energy based warm up algorithms, normal HEV operation of the powertrain resumes, with the addition of a one other feature developed for the modified emissions control strategy. One of the issues identified during the analysis of the baseline simulated data was excessive engine torque spikes, particularly during engine starting events. This type of engine operation has been shown in the literature to contribute significantly to the production of CO and THC. Fortunately, this HEV powertrain offers a high degree of flexibility for shaping both the commanded engine and traction motor torque values to deliver the proper wheel torque demanded by the operator.

During hot starts of the engine, a ramp based blending of the engine torque output with the traction motor torque has been implemented to remove these short periods of high engine torque demands. The behavior of the algorithm functions much like a signal rate limiter, but offers more flexibility to actually shape the engine torque for best performance and lowest emissions. As a starting point for assessment of the algorithm, a linear ramp has been implemented. Figure 7 illustrates simulation results for the engine torque ramp algorithm compared against previous baseline results. For the purpose of this example, the torque is ramped up over a period of seven (7) seconds. This relatively long ramp time actually removes the majority of high load peaks during initial vehicle acceleration with respect to the UDDS test cycles. The actual torque-shaping algorithm could be improved upon hardware verification in future work.

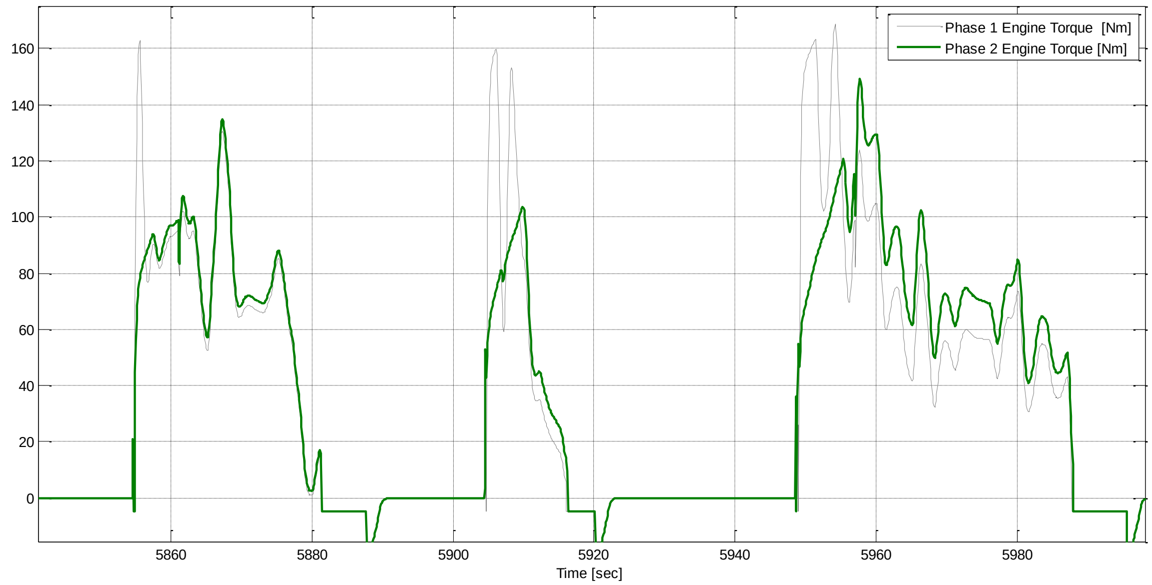

Figure 7. Engine ON torque ramp routine

Figure 8 represents a more detailed view of the hybrid operation of one (1) of the events depicted in Figure 7. Traction motor torque is included to show how the perceived loss of powertrain torque due to torque limiting of the engine is replaced by traction motor torque during these transients. The progression of hybrid functionality is outlined in this figure from left to right as:

- Electric launch – the traction motor provides all of the necessary power to propel the vehicle.
- Engine start with electric assist – as the engine torque is ramped up, the traction motor provides auxiliary torque to provide the required total wheel torque.
- Normal hybrid operation with cruise charging – the engine torque has been fully ramped up and becomes the primary source of propulsion. Excess available engine torque is used to charge the battery pack in order to replenish electrical energy consumed during electric launch and assist.
- Regenerative braking – the engine is shut off to conserve fuel during decelerations to vehicle idle. The traction motor is used to recover mechanical energy from the vehicle to further replenish electrical energy that will be used to repeat the process upon the next driver request.

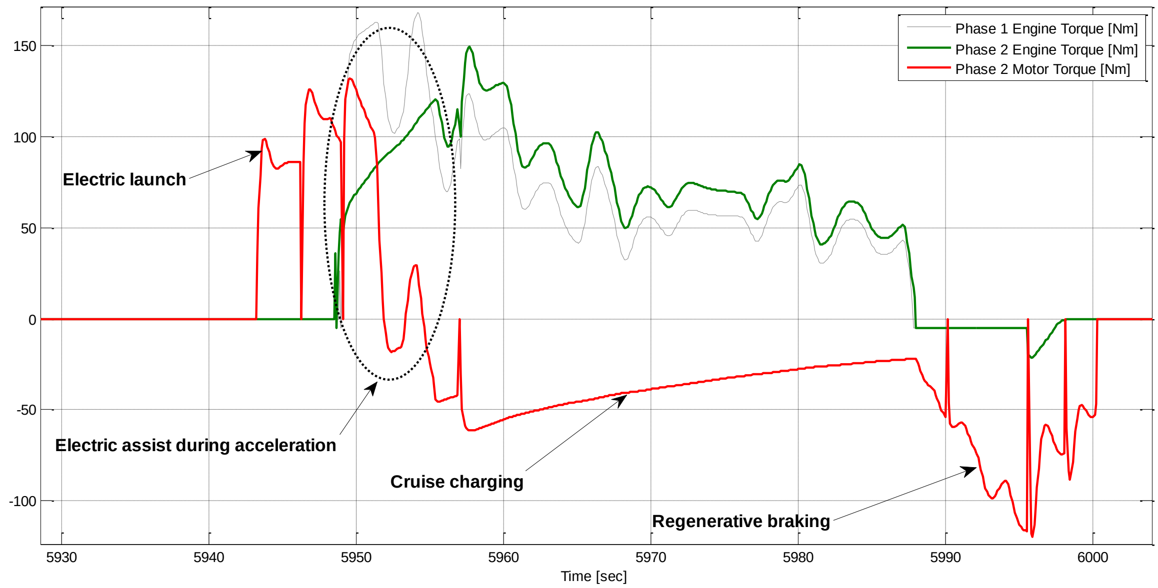

Figure 8. HEV component operation during engine start and torque limiting routine

Blended Strategy Modifications for Emissions

The blended strategy builds upon the concepts developed to reduce the emissions of the HEV powertrain. All current production level HEVs function similarly to their conventional vehicle counterparts with respects to key-on events – their engines are commanded to turn on immediately. The reason for such blatant consumption of fuel is two-fold. The first reason is the focus of this research – to reduce emissions. The second reason is qualitative, which is that consumers are accustomed to the engine starting when they turn the key on, and expect the same no matter whether the vehicle can operate all electrically or not. However, this may change as plug-in vehicles become more and more common in the marketplace.

Therefore, the VSCM has been modified to command an engine start upon a perceived key-on signal. However, this command is not tied directly to the key-on signal. A cold start flag has been added to the strategy such that when “cold” engine conditions are detected, the engine is commanded to turn on. This can be either from a first time engine on, or from a prolonged period of low power electric driving. In the case of a true cold start, the engine is switched on and goes into the pre-warm up routine and is followed by the main energy based warm up routine discussed previously. The difference in the blended case is that the engine is not allowed to shut off until both warm up constraints have been completely satisfied.

In the later case, the exhaust aftertreatment system may not necessarily be at ambient temperatures, but still may be at or near conditions that would adversely affect the emissions conversion efficiency. Here, a modified energy based warm up strategy is engaged, and is triggered by the primary catalyst brick temperature. Most modern ECUs have catalyst models that can predict catalyst temperature and performance. As a surrogate for a complex thermal catalyst model (which is outside the scope of this research), the actual measured catalyst temperature will be used. The total engine energy requirement, E_{tot}, is reduced far below the 3 MJ limit previously established. The torque limiting period is substantially reduced during restart conditions such as this in order to minimize discharging the battery unnecessarily while the engine is operating during CD operation. Figure 9 illustrates the main and secondary engine energy based cold start algorithm used for the blended strategy that will be implemented into hardware.

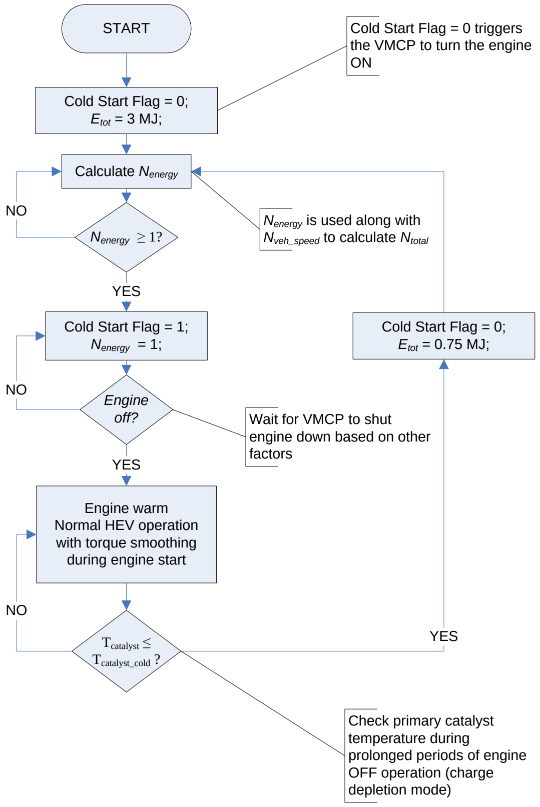

Figure 9. Engine energy based cold starting algorithm for the blended strategy

Another important change to the CD operation of the blended strategy is the use of a variable engine power threshold to start the engine. For the baseline, the total engine power threshold was calculated as a fixed percentage of the maximum available motor power for a given motor speed. The fixed percentage used during the baseline was 50%. In the interest of the engine running more frequently, a variable maximum motor power percentage was implemented using SOC as an input.

A linear ramp was used in the form of a look-up table, such that any shape could be more easily implemented later. The modified engine power threshold to command an engine start is given by the simple expression

$$P_{eng\_on\_CD} = N_{eng\_on\_CD} \times P_{motor\_max}$$

where $N_{eng\_on\_CD}$ is a function of the SOC of the battery pack and is shown graphically in Figure 10. This preliminary approach is based on a simple lookup table in order to verify functionality and merit.

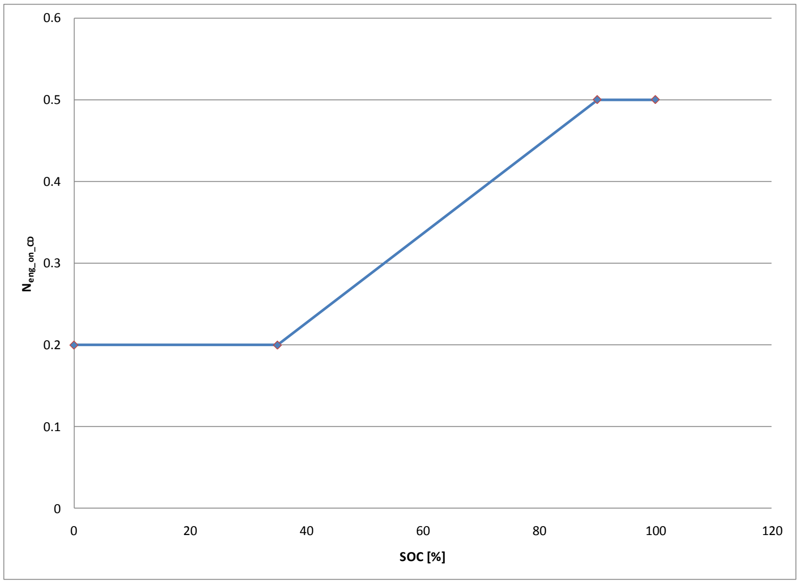

Figure 10. Graphical representation of the Phase II engine power on threshold factor, $N_{eng\_on\_CD}$

SUMMARY/CONCLUSIONS

PHEVs do have the potential for substantial reductions in fuel consumption for the transportation sector. However, care must be taken when designing and implementing PHEV supervisory control strategies such that the tailpipe emissions are not adversely effected. When and how the engine is operated in PHEVs is critical to the success and of these perceived “green” vehicles.

In this research, supervisory control strategies were developed for a representative PHEV test that included provisions for emissions reduction algorithms. Baseline energy management strategies were developed with respect to maximizing fuel economy alone. These strategies include “cold” engine starting under high load demands, which most likely would be ineffective with respect to emissions reduction.

Engine cold start events were aggressively addressed, which led to enhanced engine warming and pre-warming algorithms. Key–on engine starting was employed to mimic conventional vehicle operation. The engine pre-warming and warming techniques will be implemented and tested experimentally in order to determine if substantial reductions in emissions over the baseline PHEV control strategies can be acheived.

The flexibility of this all-electric capable PHEV powertrain allows the potential for decreased emissions during engine starting events through powertrain “torque shaping” algorithms. The focus of these enhancements was to replace high engine torque demands during starting with “clean” electric motor torque. The percieved outcome of this approach is to be effective for the reduction of NO_x emissions.

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