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HEV Control Strategy for Real-Time Optimization of Fuel Economy and Emissions

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ABSTRACT

Hybrid electric vehicles (HEV's) offer additional flexibility to enhance the fuel economy and emissions of vehicles. The Real-Time Control Strategy (RTCS) presented here optimizes efficiency and emissions of a parallel configuration HEV. In order to determine the ideal operating point of the vehicle's engine and motor, the control strategy considers all possible engine-motor torque pairs. For a given operating point, the strategy predicts the possible energy consumption and the emissions emitted by the vehicle. The strategy calculates the "replacement energy" that would restore the battery's state of charge (SOC) to its initial level. This replacement energy accounts for inefficiencies in the energy storage system conversion process. User- and standards-based weightings of time-averaged fuel economy and emissions performance determine an overall impact function. The strategy continuously selects the operating point that is the minimum of this cost function. Previous control strategies employed a set of static parameters optimized for a particular drive cycle, and they showed little sensitivity to subtle emissions tradeoffs. This new control strategy adjusts its behavior based on the current driving conditions. Simulation results of the RTCS and of a static control strategy on a PNGV-type baseline parallel HEV (42 kW engine and a 32 kW motor) using ADVISOR are presented. Comparison of the simulations demonstrates the flexibility and advantages of the RTCS. Compared to an optimized static control strategy, the RTCS reduced NOx emissions by 23% and PM emissions by 13% at a sacrifice of only 1.4% in fuel economy.

INTRODUCTION

Prior HEV control strategies have used a static approach to control the vehicle operation and they have typically focused on improving fuel economy rather than emissions [1-3]. The approach presented here considers dynamic vehicle operating conditions that affect both fuel economy and emissions.

In 1994, the Center for Transportation Technologies and Systems at the National Renewable Energy Laboratory, a Department of Energy (DOE) Laboratory, developed a vehicle simulation tool called ADVISOR. DOE continues to refine and support this tool. Development of control strategies to address the specialized needs of hybrid vehicles evolved from this work. Simulations based on steady state fuel and emissions maps showed that there was a tradeoff between energy efficiency and low emissions. Figure 1 shows a schematic of desired operating locations on a compression-ignition, direct-injection (CIDI) engine map. For a spark ignition (SI) engine, the desired operating locations may be different, as shown in Figure 2.

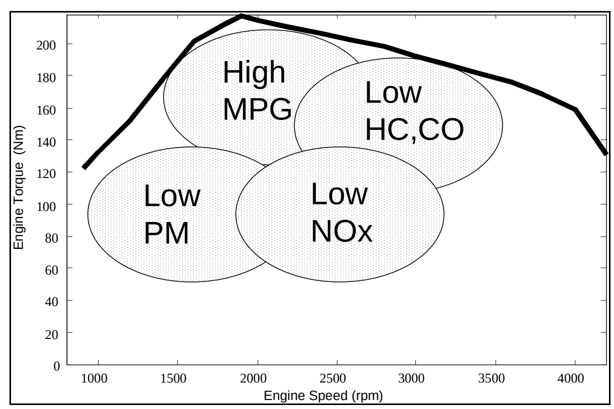

Figure 1: Fuel economy and emissions tradeoffs for a CIDI engine

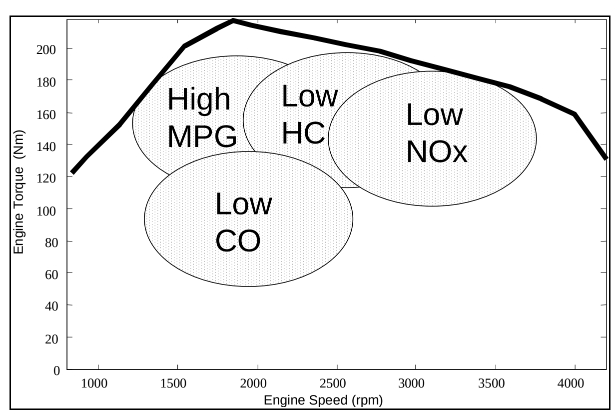

Figure 2: Fuel economy and emissions tradeoffs for an SI engine

On an IC engine's torque-speed map, the locus of maximum efficiency does not necessarily correspond to the loci of optimum emissions. In some cases, there are even two sections in the map of optimum performance. For a compression-ignition engine, the four regulated emissions are Hydrocarbons (HC), Carbon Monoxide (CO), Nitrous Oxides (NOx), and Particulate Matter (PM). In particular, there is a definite tradeoff between NOx emissions and energy use. The challenge for the control strategy is to simultaneously balance the goals of lower energy usage and lower emissions. Using the ADVISOR vehicle simulation tool [1,4-5], the RTCS was developed to better optimize a vehicle's performance in both areas.

PROBLEM DEFINITION

A driver typically controls vehicle speed by depressing the accelerator pedal to request positive torque or depressing the brake pedal to request negative torque. In a conventional vehicle, positive torque is supplied only by the combustion engine, and negative torque is supplied only by the brakes (with the exception of closed throttle engine braking energy, ignored here). Control is therefore straightforward: the engine supplies all positive torque, and the brakes supply all negative torque.

In a parallel hybrid vehicle, there is an additional source of torque available; the motor can draw electric energy from the battery to apply positive torque that accelerates the vehicle, and it can supply electric energy to the battery by applying negative torque that decelerates the vehicle. These two functions represent torque assist and regeneration, respectively.

The parallel hybrid vehicle controller must determine how to distribute the driver's single torque request into separate torque requests for the engine, motor, and brakes. For negative torque requests, the sum of the motor and brake torques must equal the driver's request.

$$T_{request,neg} = T_{motor} + T_{brake} \qquad \text{Eqn. 1}$$

For positive torque requests, the sum of the engine and motor torques must equal the driver's request.

$$T_{request,pos} = T_{engine} + T_{motor} \qquad \text{Eqn. 2}$$

Typically, negative torque requests can be handled with a relatively simple strategy: The motor recovers the maximum possible regeneration energy within constraints imposed by the motor, the battery, the brakes and vehicle stability considerations. The brakes only supply whatever is left over. In this way, the maximum amount of "free" braking energy is captured.

For a positive torque request, the choice is not as straightforward. For each driver's torque request, there is a range of combined motor torques and corresponding engine torques that will add up to the request. The goal of the strategy is to choose an operating point (distribution of torque requests) that minimizes the engine's fuel consumption and emissions. The net energy consumed by the motor (i.e. the energy drawn from the battery) must be negligible over the course of driving. If the vehicle increases or depletes the battery energy indefinitely, the battery will be damaged or its usable life will be shortened. Also, proposed Federal fuel economy tests for hybrid vehicles, such as SAE J1711 [6], will require that no net battery energy is consumed over the course of a test; any net consumption of battery energy would artificially inflate the vehicle's reported fuel economy.

Simple approaches to this problem of maximizing efficiency are not optimal. Applying as much electric motor torque as possible will temporarily minimize combustion engine fuel consumption, but that would eventually deplete the battery. Other approaches would predetermine the desired engine torque based on torque request, without regard to the vehicle's operating history. For instance, the engine can exclusively and completely fulfill all torque requests below its maximum for the current speed. Another such strategy would require that the engine torque request be at its most efficient or cleanest possible operating point. These strategies would not necessarily result in a balance of net charge in the battery; the battery would probably be charged or discharged over time, and the controller would eventually have to switch to an alternate strategy to restore the battery charge. That restoring strategy could compromise overall system efficiency. In addition, this purely efficiency-based approach does not consider emissions generated by the engine.

The RTCS distributes torque between the motor and the engine in order to both maintain SOC and optimize fuel economy and emissions.

BASELINE STATIC CONTROL STRATEGY

The baseline control strategy (BCS) currently used by ADVISOR for a parallel HEV is described here. Like the RTCS, the BCS attempts to minimize fuel use and balance SOC. Unlike the RTCS, the BCS does not consider recent vehicle operation, it does not account for battery energy, and it does not optimize emissions. Simulations comparing this strategy with the RTCS are presented in the Results section.

This baseline strategy uses the engine as a primary source of torque, and it uses the motor for supplemental power. When the battery SOC is low, the BCS switches to a charge mode in order to replenish the battery. The BCS attempts to minimize engine energy usage without regard to emissions or the effect of the motor or batteries during operation. Its operation is defined by six independent input parameters (see Table 1).

Table 1: Baseline Control Strategy Variables

Variable	Description
cs_hi_soc	highest desired battery SOC
cs_lo_soc	lowest desired battery SOC
cs_electric_ launch_spd	vehicle speed below which vehicle operates as a ZEV
cs_off_trq_frac	minimum torque threshold = fraction* T_{max} (SOC>low limit)
cs_min_trq_frac	minimum torque threshold = fraction* T_{max}; (SOC<low limit)
cs_charge_trq	an accessory like torque loading on the engine to recharge the battery pack

This electric assist control strategy in a parallel vehicle is a commonly found approach to hybrid control. For example, the basic control strategy of the Toyota Prius is an electric assist where the motor adds additional power when needed; the battery is mainly a peak power device [2]. The Prius uses the motor exclusively on takeoff and at low speeds. As another example, the Honda Insight uses the IC engine as the prime mover, with the motor assisting the engine on startup and acceleration [3].

ADVISOR's BCS uses the electric motor in a variety of ways:

1. The motor supplies all driving torque below a certain minimum vehicle speed. See Electric Launch Speed in Figure 3 (cs_electric_launch_spd).
2. The motor assists with torque if the required torque exceeds the maximum engine torque.
3. The motor charges the batteries by regenerative braking.
4. The engine shuts off when the torque request falls below a limit. See Off Torque Envelope in Figure 3 (cs_off_trq_frac).

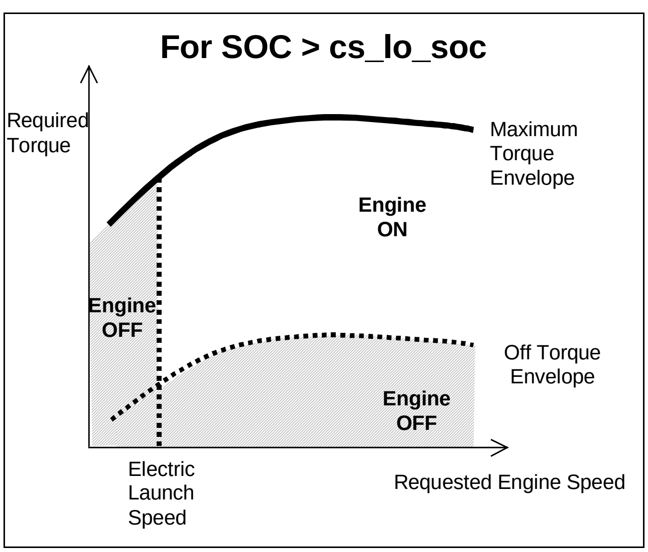

Figure 3: Baseline ADVISOR control strategy for high SOC

5. When the battery SOC is low, the engine provides excess charge torque (cs_charge_trq), which passes through the motor to charge the battery (see Case 1 in Figure 4). The engine does not output a torque below a minimum torque level (Case 2).

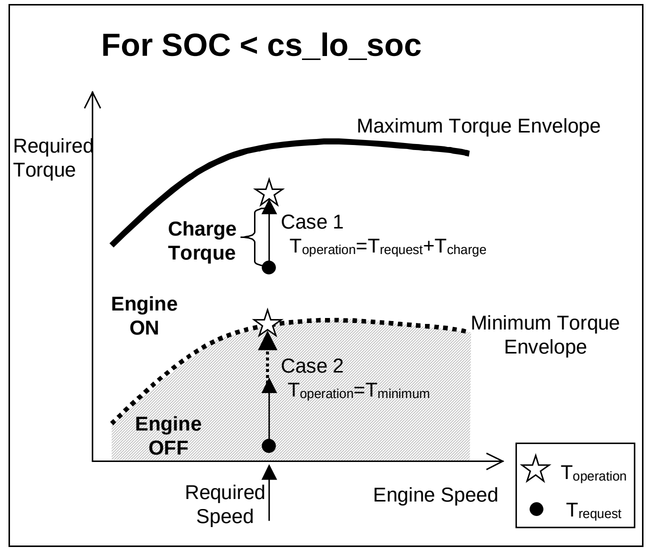

Figure 4: Baseline ADVISOR control strategy behavior for low SOC

The ability of this type of electric assist control strategy to optimize vehicle performance is limited. The engine often operates at non-optimal efficiencies and there is no direct way to effect improvements in emissions. The charging of the battery is performed at times that do not consider the loss paths for the particular operating point. The effort to address these limitations led to the development of a more advanced control strategy: the RTCS.

REAL-TIME CONTROL STRATEGY (RTCS)

The goal of the RTCS was to optimize both energy usage and emissions. Optimization criteria are defined by user-defined standards/targets. For example, the target could be 80 mpg (3 L/100 km) for fuel economy. Table 2 below lists the targets used in the RTCS, which are based on current Tier 2/LEV and PNGV limits and goals. The RTCS continuously evaluates vehicle performance in relation to these criteria.

Table 2: Fuel and Emissions Targets

Metric	*Value*	*Unit*
Energy	80[1]	mpgge (gas equivalent)
HC	0.125[2]	grams/mile
CO	1.7[2]	grams/mile
NOx	0.07[2]	grams/mile
PM	0.08[3]	grams/mile

1: PNGV goal
2: Tier 2 level proposed (see www.epa.gov/oms/tr2home)
3: LEV (see www.epa.gov/OMSWWW/lev-nlev)

GENERAL APPROACH

As defined above in the Problem Definition section, an ideal control strategy would account for the cost of using the motor to exchange battery energy as well as the cost of using the engine to consume fuel energy. When motor torque is applied, some charge is either added to (regeneration) or removed from (accelerating torque) the battery. In order to maintain a balanced SOC, any charge removed from the battery must eventually be replenished. Whenever the amount of charge moving into or out of the battery can be affected by the choice of operating point, the control strategy considers the value of that charge according to the equivalent amount of fuel it represents.

To choose an operating point, the RTCS calculates a cost function representing the aggregate effect on overall fuel consumption (described in the preceding paragraph) and emissions that would occur due to engine operation at all candidate operating points. The RTCS then selects the operating point with the minimum value of the cost function. The user is able to establish the relative importance of these constituent factors by adjusting their respective weightings. This approach implicitly incorporates the effects of many factors, including battery SOC, engine and catalyst temperatures, and recently absorbed regenerative energy.

The steps for implementing the RTCS are described below.

Step 1: Define the range of candidate operating points, represented by the range of acceptable motor torques for the current torque request.
Step 2: For each candidate operating point, calculate the constituent factors for optimization:
  a. Calculate the fuel energy that would be consumed by the engine.
  b. Calculate the effective fuel energy that would be consumed by electromechanical energy conversion.
  c. Calculate total energy that would be consumed by the vehicle
  d. Calculate the emissions that would be produced by the engine.
Step 3: Normalize the constituent factors for each candidate operating point.
Step 4: Apply user weighting to results from step 3.
Step 5: Apply target performance weighting to results from step 4.
Step 6: Compute overall impact function, a composite of results from steps 3-5, for all candidate operating points.

The final operation point was the operating point with the minimum operating point calculated in Step 6. These steps are outlined in Figure 5 and subsequently discussed in more detail.

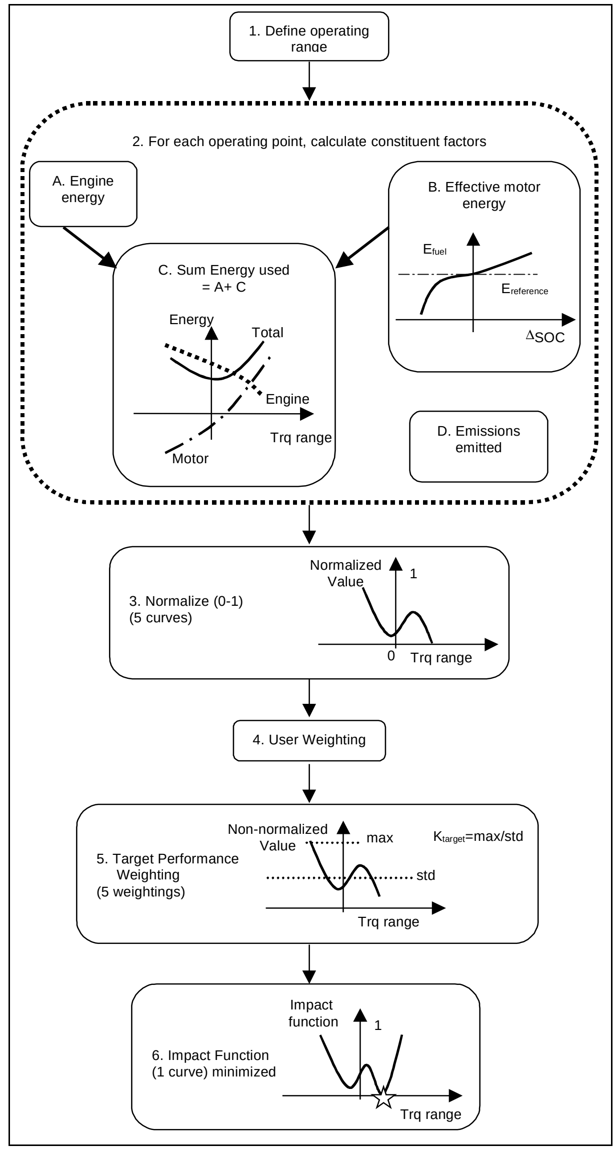

Figure 5: Real-Time Control Strategy Algorithm

STEP 1: DEFINE RANGE OF CANDIDATE OPERATING POINTS

The goal of the control strategy is to select an optimal operating point (distribution of engine and motor torques) that will satisfy the driver's current torque request at the current vehicle speed. The first step in the solution process is to determine the range of candidate operating points that will satisfy the driver's request. The process defines this range in terms of the motor torque request. Motor torque request completely describes a candidate operating point, since the sum of the torque requests must equal the driver's request torque (or the maximum available torque, if that is less than the request). This relation between engine, motor, and requested torque is described by Equation 3.

$$T_{engine} = T_{request} - ratio * T_{motor} \qquad \text{Eqn. 3}$$

Where

ratio: motor-to-engine gear ratio

The greatest possible positive motor torque defines one extreme of the candidate operating point range. This value is the minimum of three values:

1. The driver's torque request.
2. The maximum rated positive torque of the motor at the current speed.
3. The maximum available positive torque from the motor, according to limits imposed by the capability of the battery.

The greatest possible negative motor torque defines the other extreme of the candidate operating point range. This value is the maximum of:

1. The difference between the driver's torque request and the maximum positive torque available from the engine.
2. The maximum rated negative torque of the motor at the current speed.
3. The maximum available negative torque from the motor, according to limits imposed by the capability of the battery.

STEP 2: FOR EACH CANDIDATE OPERATING POINT, CALCULATE THE CONSTITUENT FACTORS FOR OPTIMIZATION

Again, the goal of the control strategy is to minimize energy consumption and emissions. To find this minimum, the strategy calculates the total energy consumption (actual fuel consumed by the engine and effective fuel consumed by the motor and batteries) and emissions across the entire allowable motor-engine torque combinations. The RTCS performs Steps 2a-2d for each candidate operating point.

<u>2a. Fuel energy consumed engine</u>

The actual fuel energy consumed for a given engine torque is affected by two things:

1. Hot, steady state engine fuel maps, and
2. Temperature correction factors.

For a given torque request and motor torque, Equation 3 sets the engine torque. At this torque and given speed, the engine map provides the fuel consumed by the engine when it is hot (see example map in Figure 6).

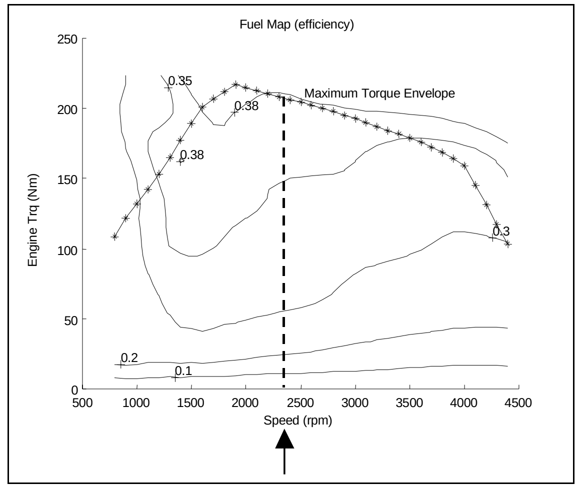

Figure 6: Engine Energy Efficiency Map

A cold engine uses more fuel than a hot engine. A cold engine correspondingly produces more emissions than a hot engine. To account for this phenomenon, the RTCS uses temperature correction factors based on ADVISOR's existing engine model. This model adjusts engine outputs by the following equation:

$$\text{Cold\_Use} = \text{Hot\_Use} * \left(\text{Coeff} + \left(\frac{95 - \text{Tengine}}{75} \right)^{\text{Exp}} \right) \quad \text{Eqn. 4}$$

$$\text{e.g. Fuel, cold} = \text{Fuel, hot} * \left(1 + \left(\frac{95 - \text{Tengine}}{75} \right)^{3.1} \right)$$

Where

Cold_Use:	cold consumption of output
Hot_Use:	hot, steady state variable output
Tengine:	temperature of engine coolant (°C)
Coeff:	a constant, varies with output
Exp:	a constant, varies with output

Equation 4 applies for all candidate 'outputs:' fuel consumption, HC, CO, NOx, or PM emissions. Sample values for fuel consumption for *Coeff* and *Exp* are 1 and 3.1, respectively. For example, if the engine coolant is cold (T_{engine}=20°C), the cold engine fuel use is 2X the hot value ($1+1^{3.1}=2$). In other words, a cold engine consumes twice as much fuel as a hot engine.

To further show how temperature can affect the cold-use values of fuel and emissions, Figure 7 plots the time history of vehicle speed, coolant temperature, HC catalyst efficiency, HC engine out emissions, and HC tailpipe emissions varying through an FTP cycle. In general, as the car drives through the cycle, the engine heats up, which causes the catalyst temperature to increase. As the catalyst temperature increases, the catalyst removal efficiencies increase.

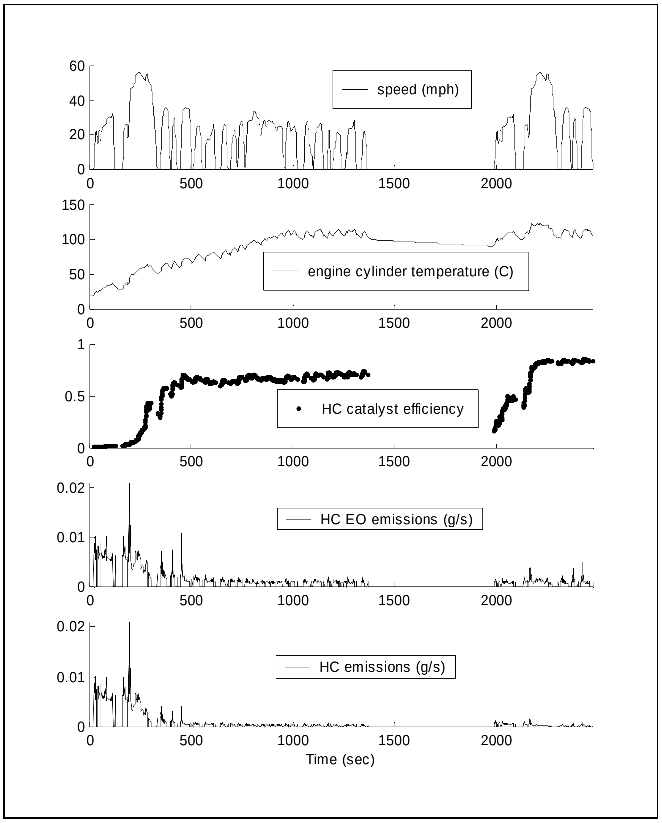

Figure 7: FTP Warm-up and HC Emissions

The fourth graph (HC Engine Out emissions) shows greater emissions at cold temperatures in comparison to hot engine emissions. When the engine temperature is below 70°C (before 500 seconds), the emissions are much greater (5X) than they are at hot temperatures (after 1000 seconds).

The fifth graph (HC emissions) shows the tailpipe emissions, which are reduced from engine-out emissions as a function of the catalyst removal efficiency. As the engine warms up (graph 2), so does the catalyst, which causes the removal efficiencies to increase (graph 3). Figure 7 shows that most of the emissions occur when the engine is cold.

Taking into account these temperature correction factors at each possible operating point, a curve of actual energy used by the engine vs. motor torque makes up the final output of Step 2a (see Figure 8).

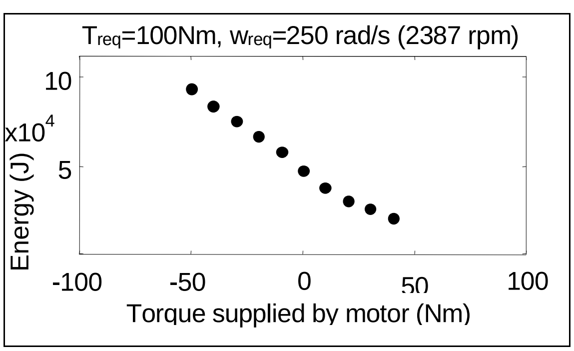

Figure 8: Engine Energy Use for a given speed

2b. Calculate the effective fuel energy that would be consumed by electromechanical energy conversion

It is not straightforward to account for inefficiencies due to exchanging energy with the batteries. Previous control approaches and test procedures have used a constant, predetermined number for battery energy in terms of fuel energy (e.g. SAE J1711 uses 38 kWh/gallon gasoline [6]). However, this is not a complete accounting. Any energy taken from the battery must eventually be replaced either by the engine or by regenerative braking.

The RTCS calculates the value, in terms of equivalent fuel energy, of any depleted battery charge that must eventually be restored (ΔSOC). This equivalent energy is a hypothetical energy required to replace the lost charge, which involves engine, motor, and battery efficiencies, and temperature related performance factors. The details of this calculation are somewhat involved, and they are presented here in 5 steps.

1. Find fuel energy vs. motor torque
2. Find ΔSOC vs. motor torque, accounting for free regenerative energy
3. Combine the above two curves into fuel energy vs. ΔSOC
4. Find equivalent energy by evaluating the curve from (3) at “replacement ΔSOC”
5. Adjust equivalent energy by a SOC regulation factor

1. Find fuel energy vs. motor torque

First, the RTCS finds the actual fuel energy that would be expended over the valid operating torque range. This relation is non-linear because the efficiency map of the engine is not linear.

At the maximum motor torque point (see A in Figure 9), the motor would supply all of the required torque and no energy would be required from the engine. As the motor torque decreases (see B in Figure 9), the engine load increases, therefore the fuel use would increase.

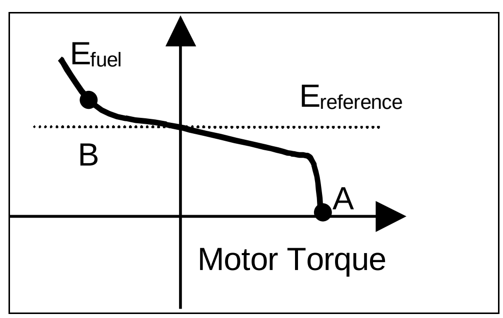

Figure 9: Fuel Energy vs. Motor Torque

The reference energy in Figure 9, $E_{reference}$, lies where T_{motor} is zero, or where the engine supplies all of the requested torque. This value is used below as a reference because if the vehicle were always *instantaneously* charge-neutral, it would never use the motor. $E_{reference}$ is the amount of energy that would be expended if the vehicle had no electric motor.

2. Find ΔSOC vs. motor torque, accounting for free regenerative energy

Next, the RTCS finds the change in SOC over the valid operating range. In general, the relation between ΔSOC and motor torque is not linear for two reasons: 1) the motor efficiency map is non-linear, and 2) charge and discharge resistances of batteries typically differ.

At the maximum possible motor torque (see A in Figure 10), electrical energy would be taken from the batteries and converted to mechanical rotational energy by the motor. The batteries would experience a drop in their SOC when discharged to supply this power to the motor, and therefore the ΔSOC (defined as SOC_{final}-$SOC_{initial}$) would be negative. At the opposite end of possible motor torque (see B in Figure 10), the batteries would typically be charging. If charging, the change in SOC would be positive. This behavior is shown as the bottom dotted line in Figure 10.

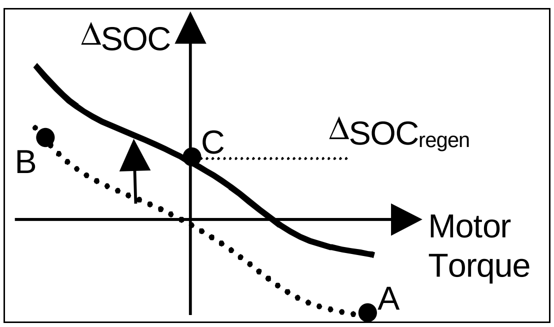

Figure 10: Delta SOC vs. Motor Torque

During operation, a hybrid vehicle recaptures a certain amount of energy through regenerative braking. The expected increase in SOC from regenerative braking is deemed "free energy" because no fuel energy must be consumed to obtain it. The RTCS accounts for this free energy in its choice of operating point by including ΔSOC_{regen} in this step. However, since the RTCS cannot predict future operating conditions or the exact amount of ΔSOC_{regen} the vehicle will see, the RTCS predicts ΔSOC_{regen} from past vehicle behavior.

The RTCS tracks the ΔSOC during the drive cycle and averages it over a time frame, which is user specified. This average ΔSOC_{regen} is taken as the expected free regenerative energy.

The value of ΔSOC_{regen} varies with the drive cycle. For example, an average expected increase in SOC over an FTP cycle is near 0.0024% SOC per second, or a 6% SOC increase over the entire cycle.

The time-averaged tracking of ΔSOC_{regen} allows the control strategy to adapt to different drive cycles. For example, over a city cycle with wide variations in speed, the regenerative braking would be significant and would be accounted for appropriately as free energy. Conversely, during a highway cycle, the average rate of increase in SOC is very low (0.001% SOC per second or 0.8% SOC increase over the entire HWFET cycle). The control strategy would ideally expect an amount of free energy that corresponds to the way in which the vehicle is driving.

The RTCS accounts for the available free braking energy by shifting the curve in Figure 10 up by ΔSOC_{regen}. The curve is the raw ΔSOC for a given motor torque plus the ΔSOC_{regen}. Thus, if the motor is not used at all (T_{motor}=0), the SOC is expected to increase by ΔSOC_{regen} (see C in Figure 10).

3. Combine the above two curves into fuel energy vs. ΔSOC

The RTCS combines Figure 9 and Figure 10 (eliminating the variable of motor torque) to create a curve of fuel energy vs. ΔSOC. At the maximum motor torque, the fuel energy was low and the ΔSOC was negative (see A in Figure 11).

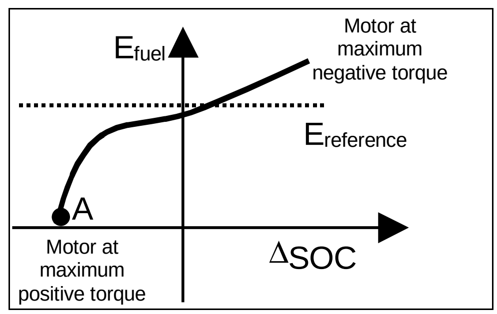

Figure 11: Fuel Energy vs. ΔSOC

4. Find equivalent energy by evaluating the curve from (3) at "replacement ΔSOC"

Revisiting the goal of this step, the RTCS chose to measure the electromechanical system's equivalent fuel energy by a hypothetical energy quantity that would replace lost charge. Overall in hybrid vehicle operations, battery energy used or gained is ignored in final fuel economy numbers if the final SOC is close to the initial SOC, i.e. if charge-neutral behavior is seen. Of course, through the cycle the SOC varies, but at the end of the cycle the SOC must lie near the initial SOC. The RTCS uses this same concept of eventually replacing charge, but implements the concept on a second-by-second basis. If the batteries were to remain at the same SOC at the end of the time step, there would be no effective energy consumed.

If the batteries are used during a time step (T_{motor}>0), the SOC decreases (see ΔSOC_{actual} in Figure 12). To have charge-neutral behavior, the SOC would eventually need to increase by the same amount. The RTCS finds this "replacement" SOC by simply flipping the sign of ΔSOC_{actual}.

$$\Delta SOC_{replace} = -1 * \Delta SOC_{actual} \qquad \text{Eqn. 5}$$

Evaluating the curve from Figure 11 at $\Delta SOC_{replace}$ gives a value for "total electromechanical-fuel energy" (see $E_{total,em}$ in Figure 12).

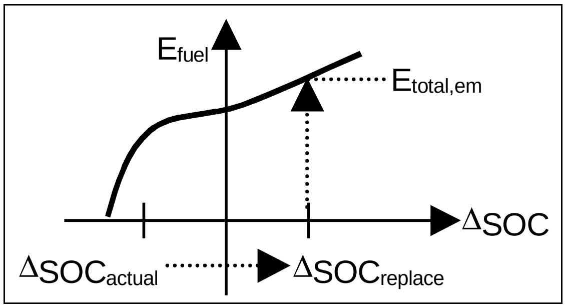

Figure 12: Finding Etotal,em

Part of the energy expended in $E_{total,em}$ meets the vehicle's torque requirements, rather than charging the battery. In order to account for this, the reference fuel energy is subtracted from the replacement energy.

$$E_{replace}=E_{total,em}-E_{reference} \qquad \text{Eqn. 6}$$

Note that in using this reference point, the RTCS allowed the effective replacement energy to be negative when the batteries were charging ($E_{total,em}<E_{reference}$).

The incremental fuel energy ($E_{replace}$) is set equal to the effective energy used by the motor/batteries. This replacement energy approach assumes that similar operating conditions (torque request and vehicle speed) will exist in the future.

5. Adjust equivalent energy by a SOC regulation factor

Ideally, using the replacement energy as a measure of the energy used by the batteries would regulate itself. In other words, the control strategy would charge the batteries if it were energy-cost advantageous, and discharge if the operating conditions were beneficial; the SOC would remain within a certain range.

There are several reasons one may wish to regulate the SOC more closely, which requires introduction of a regulation factor. These reasons include: 1) the optimal range of SOC travel may be larger than the desired ΔSOC for charge-neutral behavior, 2) the optimal SOC level may not be desirable (e.g. it would prefer to operate at too low SOC levels), or 3) emissions goals of the control strategy may push the operating points such that natural SOC regulation does not occur.

For these reasons, the RTCS uses a regulation factor that multiplies the replacement energy to control the SOC.

$$E_{replace,reg}= Regulation\_factor*E_{replace} \qquad \text{Eqn. 7}$$

The regulation factor is based on battery properties (through the high and low user defined SOC limits), and was developed using engineering judgement and simulation trial and error. When the SOC lies within a desirable range, the factor is near 1, meaning that the energy costs are neither scaled up or down (Figure 13).

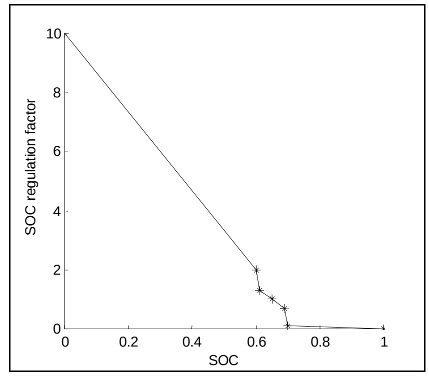

Figure 13: SOC regulation factor

At high SOC's, this factor is low and makes using the motor/batteries less "expensive" (in terms of energy cost). At low SOC's, the scale factor increases and it becomes more "expensive" to use the batteries (maximum value of 10 in Figure 13). With the regulation factor, it also became more worthwhile to charge the batteries at low SOC's since the replacement energy was negative.

<u>2c. Calculate total energy that would be consumed by the vehicle</u>

The RTCS combines the energy consumed by the engine and the effective energy usage from the motor/batteries into one total energy use for each possible motor/engine torque combination. Figure 14 shows an example energy sum for a vehicle torque request of 100 N·m at 250 rad/sec. The requested torque limited the maximum motor torque to 44.4 N·m (when multiplied by the motor-to-engine gear ratio of 2.25, the motor supplied the full 100 N·m to the vehicle).

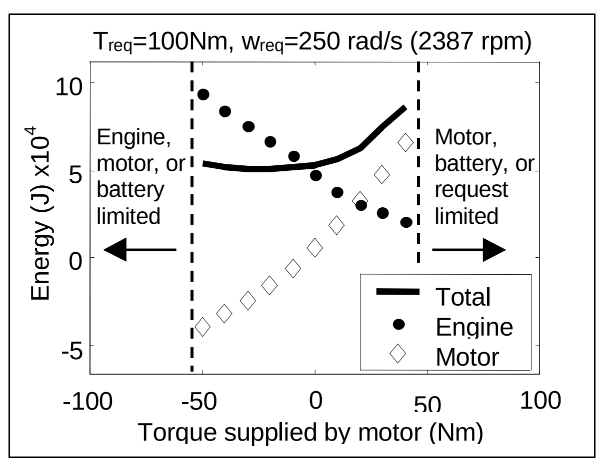

Figure 14: Total Energy Usage

2d. Emissions produced by engine

The calculation of emissions produced over the range of torque is very similar to the engine energy consumption calculation. The tailpipe emissions for a given engine torque are affected by three things:

1. Hot, steady state emissions maps,
2. Engine temperature corrections (emissions adjustments from Equation 4), and
3. Catalyst conversion efficiency (varying with temperature).

Hot maps (see Figure 15) evaluated at a given speed give curves of grams per second (Figure 16) for each of the four pollutants (HC, CO, NOx, and PM). ADVISOR's existing catalyst model calculates temperature-dependent catalyst efficiencies.

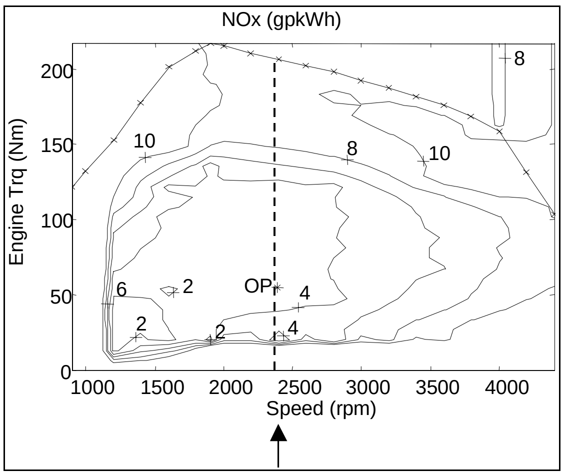

Figure 15: NOx gpkWh map (OP=Operating Point)

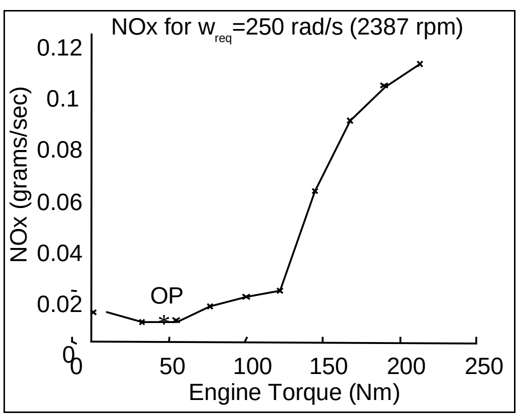

Figure 16: NOx g/s for given engine speed

STEP 3: NORMALIZE THE CONSTITUENT FACTORS FOR EACH CANDIDATE OPERATING POINT

The goals of minimizing energy and minimizing emissions can conflict with each other. The most efficient operating point will likely produce more pollution than less efficient operating points. Moreover, minimizing the amount of one pollutant can increase the amount of another.

Recognizing this, a second goal of the strategy is to allow prioritization of the relative importance of minimizing the fuel use and each of the pollutants. This prioritization (weighting) is described by Steps 4 and 5 below. However, one cannot directly compare energy used (in Joules) and emissions output (in grams). In order to combine and weight the five metrics, they are first converted to a similar non-dimensional scale.

To facilitate this, the RTCS normalizes each of the five metrics for each prospective operating to be a value between 0 and 1 (see Figure 17). Zero corresponds to the minimum value of that metric at the current operating point ($T_{request}$ and $w_{request}$). One corresponds to the maximum value.

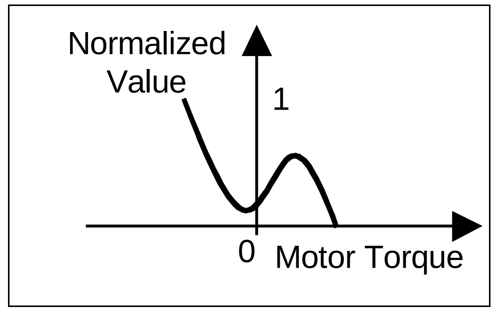

Figure 17: Normalized Variable

STEP 4: APPLY USER WEIGHTING TO RESULTS FROM STEP 3 (K_{USER})

The relative importance of each of the normalized metrics is determined by two weighting factors. The first is a user weighting for energy and the four emissions. This is basically a boolean switch for the user to toggle if he chooses to ignore certain emissions.

STEP 5: APPLY TARGET PERFORMANCE WEIGHTING TO RESULTS FROM STEP 4 (K_{TARGET})

Target Performance Weighting Factors allow the strategy to weight the impact of each of the metrics according to the particular performance targets for the vehicle. Setting these targets does not, however, automatically ensure that the vehicle reaches the targets. This weighting simply allows the relative significance of the metrics to be seen.

Default values for these targets in the simulations were the Tier 2/LEV and PNGV limits/targets defined previously in Table 2. The ability of the user to specify targets allows the user flexibility. For example, a user can choose to lessen the fuel economy target to 40 mpg, and decrease the PM target to 0.02 g/mi if he were more focused on obtaining low emissions than high fuel economy.

The control strategy uses a time-averaged speed (e.g. the average speed over the past five seconds) to find 'instantaneous' energy use and emissions targets (J/s and g/s). See Equation 8 for the calculation of the new targets.

$$\text{New Target } \frac{[g]}{[s]} = \frac{\text{Target [g]}}{\text{[mi]}} * \frac{\text{Avg Spd [mi]}}{\text{[hr]}} * \frac{\text{[hr]}}{\text{3600[s]}} \quad \text{Eqn. 8}$$

The target performance weighting is a single number equal to the ratio of the maximum value along the given motor torque-space to the instantaneous standard (see Figure 18 and Equation 9).

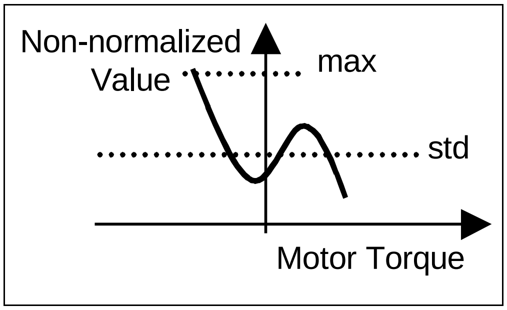

Figure 18: Finding Ktarget

$$K_{target} = \frac{\text{max of time averaged vehicle performance}}{\text{target performance}} \quad \text{Eqn. 9}$$

For example, if the maximum energy usage is 8×10^4 J and the time-averaged speed determines that the goal of 80 mpg corresponds to 1×10^4 J, then the K_{target} for energy usage at the given time step is 8. A value of K_{target} of 8 means that if the control strategy picks the worst possible point for energy usage and continues to operate in a similar condition, the vehicle will be expected to end up with a fuel economy 8 times worse than the target, or 10 mpg.

STEP 6: COMPUTE OVERALL IMPACT FUNCTION, A COMPOSITE OF RESULTS FROM STEPS 3-5, FOR ALL CANDIDATE OPERATING POINTS

The final step of the process calculates a single impact function that accounts for the effects of all of the energy and emissions values, which are appropriately weighted.

The normalized variables (Step 3) and the two weightings (Steps 4 and 5) combine to form this overall impact function defined by Equation 10.

$$\text{Impact} = \frac{\sum(K_{user} * K_{target} * \text{normalized variables})}{\sum(K_{user} * K_{target})} \quad \text{Eqn. 10}$$

The RTCS minimizes the impact function to find the point with the lowest weighted energy consumption and emissions.

Figure 19 shows the overall impact function and the constituent normalized energy and emissions curves for a vehicle torque request of 55 N·m at 210 rad/sec (2005 rpm).

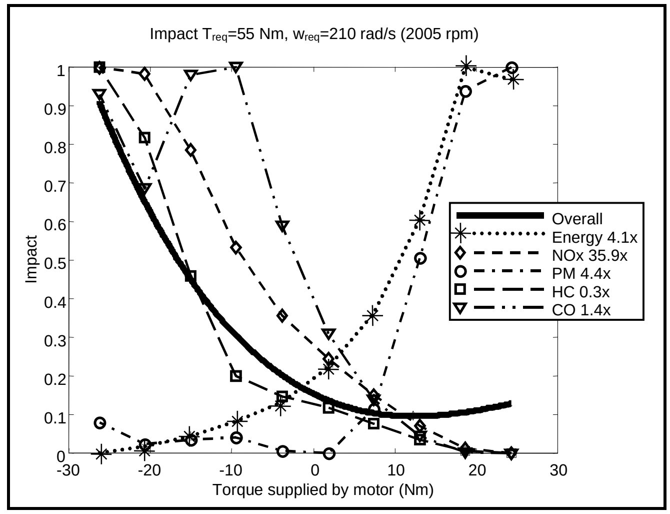

Figure 19: Overall Impact Function

The following points are illustrated in Figure 19:

- Energy weighting factor is 4.1X. This means the maximum energy usage possible (operating where the normalized variable is 1) would use 4.1 times more energy than required to reach the target.
- NOx weighting factor is 35.9. This is the most significant driver of the overall impact curve.
- PM weighting factor is 4.4
- HC weighting factor is 0.3 (performance is better than the target requires)
- CO weighting factor is 1.4
- The energy curve increases with increasing motor torque, i.e. it was energy-cost intensive to use the motor to supply part of the vehicle's requested torque.
- The normalized NOx curve decreases with increasing motor torque.
- PM behavior increases with increasing motor torque
- CO curve has alternating behavior—it first goes up then down with increasing motor torque.
- Minimum impact operates the motor at 12.5 N·m.

The normalized emissions curves show different behavioral trends. At every second of vehicle operation these tradeoffs exist. The impact curve in Figure 19 shows that the NOx curve dominates the behavior with its large weighting factor of 35.9 and the minimum impact occurs where the motor supplies a small amount of torque to the vehicle.

RESULTS

A sample hybrid vehicle was simulated using the two control strategies described above: an optimized version of the baseline static control strategy from ADVISOR, and the RTCS.

The vehicle used in the simulations was a PNGV-type vehicle. Its components and characteristics included:

- 42 kW CIDI engine (scaled from Volkswagen 67 kW 1.9 L Turbo Diesel engine, data from ORNL)
- 32 kW AC motor (scaled from Westinghouse 75 kW continuous AC induction motor, data from a published paper)
- Twelve 18 Ah lead acid batteries (Optima spiral-wound VRLA, data from NREL tests)
- Mass of 1028 kg (2266 lbs)
- Coefficient of drag (C_d) of 0.2
- Frontal area of 2 m^2.

These components are all available in the public version of ADVISOR. The base VW diesel engine included features such as direct fuel injection, turbo, and EGR. The vehicle met PNGV acceleration time targets of 0-60 mph within 12 sec, 40-60 mph within 5.3 sec and 0-85 mph within 23.4 sec.

ADVISOR simulated the vehicle's response (fuel economy and emissions) over five drive cycles:

- Federal Test Procedure (FTP)
- Highway Fuel Economy Test (HWFET)
- US06 (cycle with high accelerations)
- Japanese 10-15
- New European Driving Cycle (NEDC)

Initial conditions during the simulations were cold (20°C) for the FTP, and hot (35-500°C, depending on the component) for the rest of the cycles. The change in SOC between the beginning and end of the cycles was less than ±0.5% SOC, such that the simulations were considered charge-neutral.

OPTIMIZED BASELINE CONTROL STRATEGY RESULTS

An optimization over the city-highway (FTP-HWFET) cycles found ideal values for the six parameters in the baseline static control strategy (see Table 1) that maximized fuel economy and minimized the four emissions of interest: HC, CO, NOx, and PM. The optimization results were subject to meeting grade and acceleration constraints (e.g. sustaining ≥6% grade).

The optimization utilized the program VisualDOC from Vanderplaats R&D [7] to adjust the parameters within a viable user-selectable range. A simulation in ADVISOR of the vehicle over the city-highway cycles yielded fuel economy and emissions results. These were compared to targets and a performance metric was calculated.

The optimization went through two main steps: 1) Design of Experiments (DoE) and 2) optimization runs. The DoE step used Koshal design to pick points near the edge of the design space and ran simulations at those points. Koshal design was chosen because a small number of simulations were required (~25 analyses as opposed to ~250 analyses if a full combinatorial approach would have been employed). The optimization runs then used points from the DoE to construct response surface approximations for each of the constraints (e.g. 0-60 mph acceleration) and each of the outputs (e.g. fuel economy). These response surface approximations were then used in conjunction with SQP (Sequential Quadratic Programming) to find values of the six parameters that would give the maximum performance.

The final control strategy values for this optimization over the city-highway cycles were recorded and used in the following simulations. In general, this optimization process is lengthy (one optimization solution takes 45-90 minutes), limits the vehicle's maximum performance to the cycles chosen for the optimization runs, and is only applicable to the particular vehicle optimized.

ADVISOR simulations of the chosen vehicle over the five drive cycles with city-highway optimized baseline control strategy parameters resulted in vehicle performance as given in Table 3.

Table 3: Baseline ADVISOR results, optimized over city and highway

Cycle	*FE*	*HC*	*CO*	*NOx*	*PM*
	mpgge	*g/mi*			
FTP	49.6	0.107	0.334	1.104	0.063
HWFET	68.8	0.013	0.022	0.47	0.026
US06	45.4	0.024	0.02	1.528	0.073
1015	56.9	0.013	0.023	1.027	0.027
NEDC	58.5	0.019	0.034	0.76	0.033

Only the 3-bag weighted FTP emissions numbers can be compared directly to Tier 2 targets. The other cycles' emissions numbers should be compared to the RTCS results presented below. In general, the static control strategy's fuel economy numbers were lower than desired, and the NOx numbers were much higher than the Tier 2 target.

The following points are derived from Table 3 for the optimized static control strategy:

- Fuel economy is highest on the HWFET by as much as 50%
- Fuel economy on the other cycles varies by 29%
- FTP HC, CO, and PM emissions are lower than targets (see Table 2) by 14%, 80%, and 21%
- FTP NOx emissions exceed targets by 15.8X

The vehicle's control strategy parameters showed little sensitivity to optimization over different cycles. For example, the above optimization process was repeated for the FTP cycle, and then just for the US06 cycle. The resulting optimized parameters only showed a 0.8% difference in fuel economy between the two optimizations.

REAL-TIME CONTROL STRATEGY RESULTS

ADVISOR simulations of the same PNGV-type vehicle with the RTCS over the five drive cycles gave vehicle performance detailed in Table 4. For these simulations, all of the user-defined weightings were set to 1 (or 'on'), and the performance targets were set to the values given in Table 2.

Table 4: Real-Time Control Strategy Results

Cycle	*FE*	*HC*	*CO*	*NOx*	*PM*
	mpgge	*g/mi*			
FTP	49.8	0.106	0.328	0.829	0.054
HWFET	67.9	0.015	0.03	0.411	0.024
US06	48.4	0.026	0.021	1.129	0.067
1015	54	0.014	0.027	0.852	0.022
NEDC	56.3	0.02	0.038	0.613	0.029

The most significant advantage of the new RTCS is in reduced NOx emissions. The following points are derived from Table 4 for the RTCS:

- Fuel economy is again the highest on the HWFET by as much as 40%
- Fuel economy on the other cycles is more consistent than the static control strategy; it varies by 16%
- FTP HC, CO, and PM emissions are lower than targets (see Table 2) by 15%, 81%, and 33%
- FTP NOx emissions exceed targets by 11.8X. While this is still significantly above the NOx target, the reduction in NOx emissions from the static control strategy is apparent.

The control strategy has flexibility over a variety of drive cycles. In addition, the flexibility in the control strategy means that it easily adapts to different vehicles.

It should be noted that ADVISOR models emissions outputs based on steady state emissions maps, while true transient emissions may vary from these estimates. A relative comparison of the fuel economies and emissions is therefore a more accurate way of assessing the benefits of the RTCS.

CONTROL STRATEGY COMPARISONS

Figure 20 compares the baseline ADVISOR control strategy, optimized over the FTP-HWFET cycles, and the RTCS both to the targets defined in Table 2 and to each other. A value of less than one meant that the goal or standard was met.

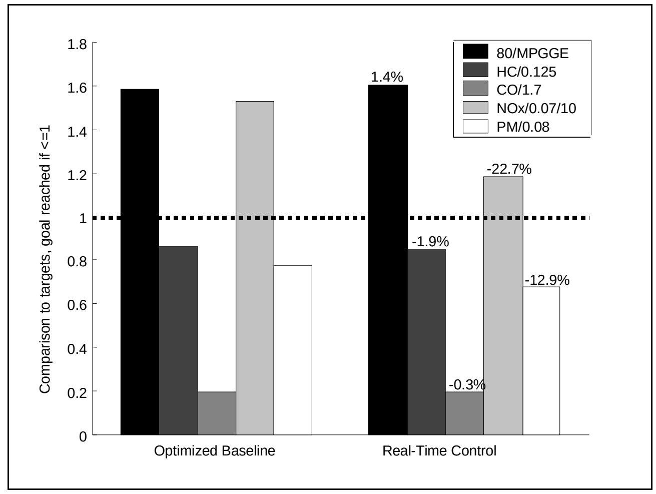

Figure 20: Comparison of Baseline to Real-Time Control Strategy

The numbers above the Real-Time Control bars in Figure 20 were percentage increases in the variable over the optimized baseline, such that a negative number meant better performance (lower emissions or energy use).

Figure 20 shows the following:

- Energy consumption of the vehicle with the RTCS to increased 1.4% in order to decrease emissions.
- The most significant emission reduction was a 22.7% decrease in NOx.
- PM showed a substantial 12.9% decrease.
- HC emissions dropped from the baseline level by 1.9%, staying below target levels.
- CO emissions dropped 0.3%, staying below target levels.

The NOx emission comparison was more important than the other emissions comparisons because it lay above the target line (corresponding to a value of 1 in Figure 20).

Figure 21 compares the RTCS to the baseline control strategy over the set of five drive cycles. From left to right in the figure, the average cycle speed increases. A value less than one meant that the RTCS performed better than the baseline.

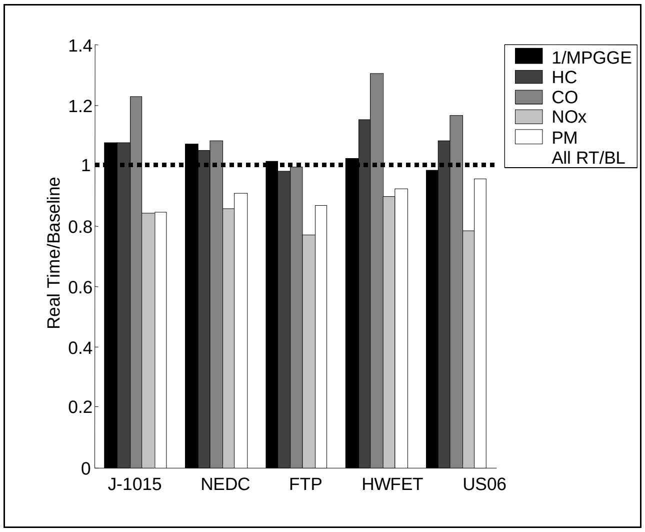

Figure 21: Real-Time/Baseline for 5 drive cycles

Figure 21 shows the following:

- For most of the cycles, NOx and PM were significantly lower (17% NOx and 10% PM on average) than the baseline performance, at the sacrifice of a slight increase (3.4% average) in energy consumption (or lower mpgge).
- The HC and CO emissions were higher than the baseline because the absolute value of the emissions was much lower than the target values (see magnitudes given in Table 2). The RTCS's impact function therefore did not weight them as heavily as NOx, whose value was greater than the target Tier 2 value.

An additional note about the RTCS that cannot be seen through FTP emissions numbers is an added emissions reduction benefit during real-world driving conditions. Real-World conditions are simulated in a test procedure defined in ADVISOR [4] that runs the vehicle through a set of drive cycles and start/stop conditions that covers 16 days. The real-world benefit of the RTCS was a decrease in NOx emissions of 21%, a decrease in PM emissions of 10%, and a fuel consumption increase of 5%, in comparison to the static control strategy.

CONCLUSION

Comparing the results of the baseline static, piecewise control strategy in ADVISOR to the unified, impact-function based real-time approach toward control of a hybrid vehicle showed the flexibility of the new control strategy. There were several new concepts related to the Real-Time Control Strategy:

- Recognizing that energy will be exchanged with the battery during the course of driving, the strategy quantifies the value of battery charge based on the equivalent amount of fuel that battery energy represents.
- Noting that the equivalent fuel value of the battery energy varies with vehicle operation, the strategy constantly updates the equivalent value of the battery energy.
- In order to balance the potentially conflicting goals of fuel economy and emissions reduction in the choice of operating point, the strategy allows the relative importance of fuel economy and emissions to be rated. An overall impact function predicts cycle performance (mpg, gpm) based on instantaneous fuel and emissions performance and the vehicle speed, and combines five goals into one goal.

The flexibility of the control strategy was in:

- User-selectable weighting factors. This could allow a vehicle to adjust its control strategy based on its driving location or local control limits (e.g. if moving from Nevada to California, the targets could be adjusted to LEV standards, and the fuel economy target could be lowered)
- Real-time adjustment to driving cycles based on expected free regenerative braking energy
- Incorporation of temperature effects on fuel use, engine-out emissions, and catalyst behavior

The RTCS resulted in:

- Significant NOx and PM emissions benefits over the optimized static control strategy for the FTP cycle (23% and 13% drop) at the price of a slight drop in fuel economy
- Better emissions performance over a range of drive cycles, coupled with comparable energy consumption
- Smaller variation in fuel economy over a range of cycles (BCS: 29% down to RTCS: 16%)

The RTCS focused on problem emissions, such as NOx, while the static control strategy parameters were not sensitive to the individual emissions.

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

ADVISOR:
ADvanced VehIcle SimulatOR

BCS:
Baseline Control Strategy, currently the parallel control strategy used in ADVISOR (electric-assist)

CARB:
California Air Resources Board

Charge-neutral:
Charge-neutral vehicle behavior refers to maintaining the charge of the batteries over a cycle. Typically, a change in SOC of <0.5% is determined charge-neutral.

CIDI:
Compression Ignition Direct Injection

CO:
Carbon Monoxide

ΔSOC:
Delta SOC, $\Delta SOC = SOC_{final} - SOC_{initial}$

DoE:
Design of Experiments, used in optimization algorithm

DOE:
Department Of Energy

EGR:
Exhaust Gas Recirculation, engine feature for emissions reductions

EO:
Engine Out, refers to emissions coming from the engine that have not yet passed through the catalytic converter

EPA:
Environmental Protection Agency

FTP:
Federal Test Procedure, "city" cycle for city-highway tests

GPM:
Grams per mile

HC:
HydroCarbons

HEV:
Hybrid Electric Vehicle

HWFET:
Highway Fuel Economy Test

IC:
Internal Combustion

LEV:
Low Emission Vehicle

MPG:
Miles Per Gallon

MPGGE:
Miles Per Gallon Gasoline Equivalent

NEDC:
New European Drive Cycle

NOx:
Nitrous Oxides

NREL:
National Renewable Energy Laboratory

ORNL:
Oak Ridge National Laboratory

PM:
Particulate Matter

PNGV:
Partnership for a New Generation of Vehicles

RTCS:
Real-Time Control Strategy

SI:
Spark Ignition

SOC:
State Of Charge

VRLA:
Valve-Regulated Lead Acid

VW:
Volkswagen

ZEV:
Zero Emissions Vehicle