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Control System Development for an Advanced-Technology Medium-Duty Hybrid Electric Truck

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ABSTRACT

The power management control system development and vehicle test results for a medium-duty hybrid electric truck are reported in this paper. The design procedure adopted is a model-based approach, and was based on the dynamic programming technique. A vehicle model is first developed, the optimal control action that maximizes fuel economy is then solved by the dynamic programming method. A near-optimal control strategy is subsequently extracted and implemented in the MATLAB XPC-Target rapid-prototyping system, which provides a convenient environment to adjust the control algorithms and accommodate various I/O configurations. Dyno-testing results confirm that the proposed algorithm helps the prototype truck to achieves an impressive 45% fuel economy improvement over the benchmark vehicle.

INTRODUCTION

Hybrid powertrain is among the most visible transportation technology developed over the last decade. Starting from the ground-breaking PNGV effort in the early 1990's, the introduction of Prius and Insight hybrid vehicles in the late 1990's, to the planned 2004 lineup of close to 10 commercially available vehicles, hybrid vehicles have moved quickly from concept to reality. This quick acceptance is mainly due to the potential of hybrid technologies in reducing fuel consumption and emissions, especially for vehicles driving in urban areas with many starts and stops.

To design a viable hybrid vehicle to justify the added cost, and to explore the full potential of the more complex/capable powertrain, three challenging engineering problems need to be carefully addressed: vehicle configuration, component selection and sizing, and intelligent control and coordination.

In 2001, Federal Express, together with the Alliance for Environmental Innovation, a leading environmental advocacy group, challenged Truck Manufacturers to develop a full production-scale environmentally preferable vehicle, with functionalities similar to the current FedEx "White" delivery truck (1999 W700-series). This next-generation truck needs to achieve a few very demanding specifications on emission and fuel economy.

In this paper, the design of a power management control system for the prototype truck produced by the Eaton Innovation Center, with the collaboration of the Automotive Research Center (ARC) in the University of Michigan, is described. The truck that employs this control system features a "Direct Hybrid" powertrain system, which integrates an advanced diesel engine, an electric motor, a Lithium-Ion battery, and an Eaton automated manual transmission. The electric motor, clutch, transmission, inverter, and the battery are incorporated to form a Hybrid Drive Unit. The motor is directly linked between the output of the clutch and the input to the transmission. This architecture provides regenerative braking during deceleration and allows more efficient motor assist and recharge operations by the engine.

The control of hybrid powertrains is more complicated than the control of ICE-only powertrain. First, one needs to determine the optimal operating mode among five possible modes (motor only, engine only, power assist, recharge, and regenerative). Furthermore, when the power assist mode or the recharge mode is selected, the engine power, motor power and transmission gear ratio all need to be selected to achieve optimal fuel economy, emissions reduction, charge balance, and drivability. With the increased powertrain complexity and the need to achieve multiple objectives, we adopted a two-level control architecture. A supervisory powertrain controller (SPC) sits at the top to manage the operation of the hybrid powertrain system. The supervisory powertrain controller is designed to include the following functions: power management strategy, transmissions shifting control, smooth operation logic, I/O communication, and system monitor and diagnosis. At every sampling time, the supervisory powertrain controller sends commands (set points or desired states) to each sub-system control module and receive sensor signals and diagnostic status from each sub-system. The low-level control systems manipulate the local-level inputs to follow the SPC commands as long as other local constraints were not violated.

To ensure that the SPC achieves a guaranteed level of performance and robustness, a model-based design process was adopted. First, models and look-up tables for all sub-systems are developed or documented. A vehicle model, based on the MATLAB/Simulink/ Stateflow platform was then developed for vehicle performance analysis and control algorithm development. The SPC control was developed based on the dynamic programming technique, which aims to maximize fuel economy without sacrificing drivability. A near-optimal control strategy is then extracted and implemented in the MATLAB XPC-Target rapid-prototyping system, which provides a fast and easy way to adjust the control algorithms and accommodate various I/O configurations. More importantly, the entire development process of the control system provides a seamless environment of control algorithm design, implementation, and testing for flexible hybrid powertrains.

PROTOTYPE HYBRID TRUCK INTEGRATION

FedEx Express and the Alliance for Environmental Innovation jointly lead a Future Vehicle Program (FVP) to develop the next generation delivery truck. The goal of the program is to improve the fuel economy by 50% and to reduce NOx and PM emissions by 90% over the current FedEx W700 delivery truck. In order to achieve this aggressive performance requirement, Eaton has designed and integrated a prototype hybrid electric truck while the vehicle dimensions and operation remain virtually unchanged.

VEHICLE SYSTEM CONFIGURATION

The Eaton prototype hybrid vehicle is constructed based on a FedEx W700 step van that uses the Freightliner Custom Chassis Model MT45 with a standard Utilimaster body. The baseline Cummins 5.9L diesel engine was replaced by a DaimlerChrysler OM904 4.3L diesel engine. The baseline Allison automatic tranmission and torque converter were replaced by an Eaton Hybrid Drive Unit containing the automatic clutch, electric traction motor, and an AutoShift transmission. The resulting hybrid electric powertrain, shown in Figure 1 is a parallel hybrid configuration that has the capability to provide five different operational modes: motor-only, engine-only, power-assist, recharging, and regenerative braking. The engine is connected to the automatic clutch which is electronically controlled to smoothly engage and disengage the engine during the vehicle launch and stop scenarios. The electric motor is directly mounted on the output shaft of the engine. In other words, the engine and electric motor use the same driving shaft to transfer the power and no torque coupler device is required in this configuration. The blended torque of the engine and motor drives the AutoShift transmission which is a shift-by-wire automated manual transmission (AMT) system. This allows the AutoShift to operate like an automatic transmission while possessing high efficiency as the manual transmission. It should be noted that the chassis and body of the baseline truck were modified only minimally to enable the hybridization. There were no changes to major chassis systems such as brakes, wheels and tires. The basic specifications of the vehicle are given in Table 1.

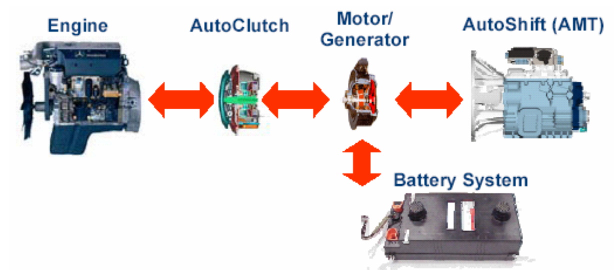

Figure 1: Eaton hybrid electric powertrain

Table 1: Basic vehicle specifications

Engine	I4, 4.3L, 170HP
Transmission	6 speed, Automated Manual
Electric Motor	Peak Power: 44 kW Peak Torque: 420 Nm
Battery	Li-Ion type Nominal Voltage: 340 V Energy Storage: 2.5 kWh
Wheels	19.5 inch, steel
GVWR	16000 lbs
Cargo Area	700 cubic feet
Rear Axle Ratio	3.31

DIRECT HYBRID SYSTEM

Eaton Direct Hybrid System consists of the following three major components: Hybrid Drive Unit, Power Electronics Carrier, and Supervisory Powertrain Controller.

<u>Hybrid Drive Unit</u>

The Hybrid Drive Unit is composed of the electric traction motor, automatic clutch and automated transmission. The assembly of the Hybrid Drive Unit is shown in Figure 2. This straightforward and compact drivetrain design increases the overall system efficiency and allows easy integration and packaging.

Power Electronics Carrier

The Power Electronics Carrier is an assembly that contains the motor controller/inverter, battery modules, battery controller, and coolant circulation components. The assembly is designed to combine power electronics devices and energy storage devices to reduce the cost and space requirement.

Figure 2: Hybrid Drive Unit assembly

Supervisory Powertrain Controller

The Supervisory Powertrain Controller is an electronic control unit that controls the operation of the hybrid system through multiple inputs and outputs, monitors the system status, and manages communication with other on-board systems. It plays a crucial role in coordinating overall vehicle systems and maximizing the potential for improving the fuel economy and reducing the exhaust emissions. The details about the control architecture will be described in the following section.

CONTROL SYSTEM ARCHITECTURE

The hybrid vehicle is an integrated system that consists of many sub-systems including engine, transmission, motor, battery, clutch, brakes, etc. Each sub-system is also a complex system that has its own functionality and desired performance. In this case, almost every sub-system is equipped with sensors, actuators, and a control system to regulate its behavior. Moreover, all sub-systems need to be coordinated in an optimal manner to achieve different objectives, e.g. fuel economy, emissions reduction, charge balance, and drivability. With this increasing complexity of powertrain system and the need of achieving multiple objectives, an integrated vehicle-level controller is required to accomplish the task [1].

TWO-LEVEL HIERARCHICAL CONTROL ARCHITECTURE

Two-level hierarchical control architecture is used in controlling the prototype hybrid powertrain as shown in Figure 3. The supervisory powertrain controller (SPC) represents a high-level vehicle control system that can coordinate the overall powertrain to satisfy certain performance target such as fuel economy and emissions reduction. Based on the driver's demand (e.g. accelerator and brake pedal signals) and current state of the sub-systems (e.g. engine speed, motor speed, SOC, etc.), the high-level powertrain controller must determine the desired output to be generated by the sub-systems (e.g. engine torque, motor torque, requested gear, etc.). These desired output signals are sent to the corresponding sub-systems and become the commands for the lower-level control system of each sub-system. These lower-level control systems include engine electronic control unit (ECU), motor ECU, transmission controller (TCU), and battery controller, which are normally provided by sub-system supplier/OEM. A CAN bus provides communications between the supervisory control system and each low-level control system. For most of the cases, the task of the low-level controller can be treated as a classical regulating/tracking control problem. The low-level control systems can also be designed for different goals, such as improved drivability, while ensuring the set-points commanded by the high-level controller are achieved reliably. The two-level control architecture indicates that the supervisory controller only controls the hybrid vehicle by using higher-level control signals such as power, torque, and speed while the low-level variables such as fuel injection, current, voltage are kept within the low-level controllers. This makes it possible to simplify and expedite the control design. It should be noted that much attention has been paid to the design of the sub-system controllers due to the dominance of conventional vehicles and continuing research on the electric vehicles. The related technologies are relatively mature. However, a systematic design approach for the high-level control system in hybrid vehicles is still lacking and

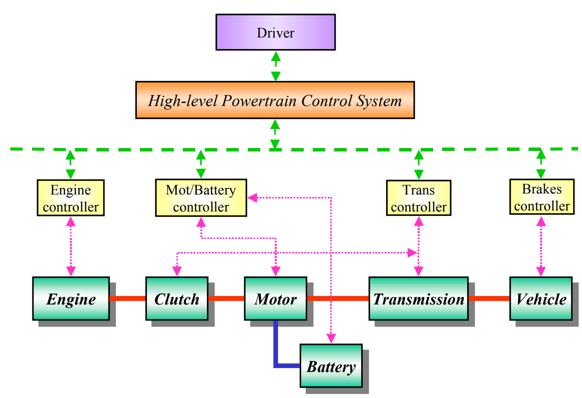

Figure 3: Hierarchical control architecture of a hybrid electric vehicle

needs to be developed.

SUPERVISORY POWERTRAIN CONTROLLER

In this study, we will concentrate on the development of supervisory control strategy for the hybrid vehicle. The command from the supervisory controller is assumed to be perfectly executed before the next time step (1 sec). In order to achieve the desired performance in fuel economy, emissions reduction, drivability, and safety, the supervisory powertrain control system needs to include the following key functions regarding the optimal operation of the energy conversion and storage devices: power management strategy, regenerative braking control, transmission shift logic and shifting control, vehicle launch control, and system fault detection. These functions are partitioned into modules and carefully designed to achieve desired performance. The major functions are described as follows.

Regenerative braking control

Regenerative braking is one of the key advantages of hybrid vehicles. The dissipative kinetic energy during braking can be recaptured by applying negative torque to the electric motor. Since the regenerative braking and traditional friction braking co-exist in the vehicle, the coordination between these two braking systems to achieve driver's braking demand is a main function of the regenerative braking control. Because of the fact the hydraulic friction brake in the prototype vehicle is not electrically controlled, a parallel braking system that can simultaneously apply hydraulic braking and regenerative braking is used. The driver brake input corresponds directly to the hydraulic braking torque since the hydraulic brake line is directly connected to the brake pedal. The amount of regenerative braking torque that can be added to the hydraulic braking torque is calculated by considering the electric motor torque characteristics, vehicle speed, and driver feel.

Transmission shift logic and shifting control

The gear position of the transmission has a significant influence on fuel economy and emissions because it influences the operating point of the engine. This simple fact is sometimes overlooked in the design of control strategies for hybrid vehicles. In the supervisory control system, the requested gear position is a control signal sent to the transmission control system. This requested gear command is determined by a gear shifting logic based on the vehicle status information such as input shaft speed of the transmission, current gear position, and driver pedal command. Most of the existing literatures use a heuristic approach [2] or static optimization [3] to design the shift logic for hybrid vehicles. However, in order to improve fuel economy, emissions, drivability, and shifting quality simultaneously, the shift logic requires an integrated design approach by considering the overall hybrid powertrain (engine, electric motor, and transmission) together.

Coordinating the hybrid powertrain to accomplish the gear-shift process of the automated manual transmission is another important task of the SPC. The control functions in the SPC include the clutch engage/disengage control, and torque/speed control of the engine and the motor. The gear shifting in the AMT is controlled by the transmission controller, TCU. After the SPC issues a shifting request to the transmission controller, there are four steps to perform the gear shift. First, the torque commands of the engine and motor from SPC are reduced to zero so that the dog clutch in the AMT can be disengaged. The gear is then shifted into the neutral position (step 2). The third step is to synchronize the input shaft speed with the desired output shaft speed of the new gear by using speed control of the engine/motor from the SPC. When the speed difference is small enough, TCU will shift the gear into the new gear position, which is the last step of the sequence. The control of the entire gear-shifting process is designed to ensure the shift duration and shift shock are minimized.

Power management strategy

The power management strategy in the SPC is crucial for balancing between efficiency and performance of hybrid vehicles. The term "power management" refers to the design of the higher-level control algorithm that determines the proper power (torque) level to be generated, and its split between the motor and the engine while satisfying the power (torque) demand from the driver and maintaining adequate energy in the energy storage device. It should be noted that the power management could be either torque-based or power-based strategy depending on the application. Since the engine ECU and motor ECU both accept the torque command, the torque-based strategy is used in this study.

Many existing power management strategy employs heuristic control techniques such as control rules/fuzzy logic for the control algorithm development. The intuition of this approach is based on the concept of "load-leveling", which attempts to operate the irreversible energy conversion device such as ICE or FC in an efficient region and uses the reversible energy storage device as a load-leveling device to compensate the rest of the power demand. However, due to the unknown nature of future power demand, a charge sustaining strategy is needed to maintain the SOC level in the load-leveling devices. The thermostat SOC strategy, in which the SOC is cycled between low and high limit, was often used in many studies due to its robustness [4]. Another popular strategy is to adopt a rule-based structure by defining a set of thresholds to implement the control logic [5]. The thresholds could then be identified through optimization process or tuned by a set of simulations over a given driving cycle. There has been much other research on implementation of load-leveling and charge-sustaining strategy by using fuzzy logic technique [6 and 7]. The fuzzy logic concept is essentially a rule-based system that relies on intuition and heuristic way to identify the controller. Another effective approach is to consider the dynamic nature of the system when performing the optimization [8]. Furthermore, the optimization can be performed with respect to a time horizon, rather than for an instant in time. In general, power split algorithms obtained from dynamic optimization approaches are more accurate under transient conditions, but are computationally more intensive.

The output of the power management strategy is the motor torque command and engine torque command, which are designed for the purpose of fuel economy and drivability. These torque commands are normally sent directly to the sub-system controllers, e.g. motor ECU and engine ECU. However, the torque commands will be overridden under certain conditions. One situation is when there exists a sub-system fault. For example, if the battery fault exists, the torque commands from the power management will be bypassed and SPC will request the engine to satisfy the driver demand as much as possible. Another example is that during a gear shift, the torque/speed control servo control function will override the command from the power management strategy.

SUPERVISORY CONTROL STRATEGY DESIGN

The main objective of the supervisory control strategy design is to develop a near-optimal and practical power management strategy that determines the proper torque split and gear selection for the prototype hybrid truck to minimize the fuel consumption at all times; meanwhile, it also satisfies the following constraints.

- Meet the power demand from the driver.
- Maintain state of charge of the energy storage device.
- Achieve certain drivability requirements.

Moreover, the design procedure is required to be systematic, accommodating multiple objectives, cost-effective, and re-useable. In this study, we use a model-based design approach based on the simulation and dynamic optimization to extract implementable, near-optimal control rules, which are then implemented in the vehicle by using a rapid prototyping tool. The control strategy could be tested and tuned in the simulation environment, hardware-in-the-loop (HIL), and field test in a fast and cost-effective way.

SIMULATION MODEL DEVELOPMENT

The first step of the model-based design process is to develop a simulation model for the hybrid truck. The vehicle model is constructed to directly resemble the layout of the physical system. In order to have a high degree of flexibility, the model is implemented in the MATLAB/Simulink/Stateflow software environment, as shown in Figure 4. Links between main modules represent the physical parameters that actually define the interaction between the components, such as shaft torque and angular velocity, or electrical current and voltage. A feed-forward simulation scheme is employed so as to enable studies of control strategies under realistic transient conditions, where everything starts with the driver action and the "pedal position" signal being sent to the supervisory powertrain controller. The HEV controller contains the power management logic and sends control signals to the components modules based on the feedback about current operating conditions. Finally, a "driver" module was built to allow the feed-forward simulation in order to follow a prescribed vehicle speed schedule. The PI controller fulfills that role and provides the driver demand signal and braking based on the specified speed setting and the current vehicle speed

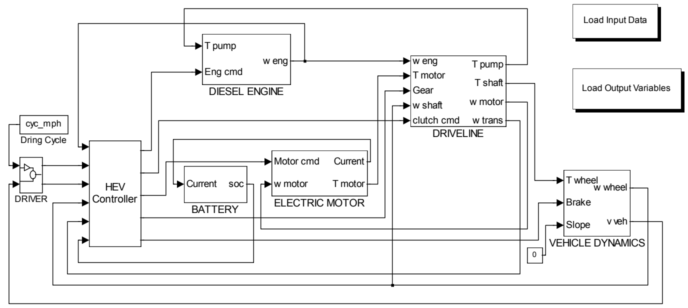

Figure 4:Hybrid electric truck simulation model

The driving cycle used in the simulation as well as the final chassis dynamometer test is shown Figure 5. This test cycle was provided by FedEx which can be described as a modified version of the 1975 Federal Test Procedure (FTP) test cycle. Only the first 1372 seconds of the FTP is used and an engine shutdown at every other vehicle stop is added to represent the average daily drive cycle of FedEx trucks.

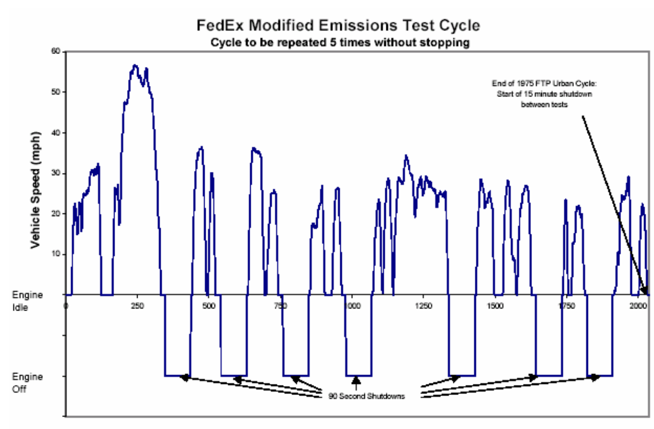

Figure 5: Customized FedEx delivery truck test cycle

DYNAMIC-PROGRAMMING BASED APPROACH

It is known that the main control challenge for HEV is to determine the proper operation mode, and the power/torque split ratio between the two power sources and the gear-shifting schedule. However, control strategies based on engineering intuition or trial-and-error commonly fail to achieve satisfactory improvement due to the complex nature of HEV dynamics and the trade-off among multiple objectives (fuel economy, emissions and drivability). In this section, a design procedure based on the Dynamic Programming technique for the design of a sub-optimal control strategy is described.

Dynamic Optimization Problem Formulation

The control of HEVs is formulated as an optimal control problem in the Dynamic Programming approach [9]. The goal is to find a sequence of control actions, including the engine torque, motor torque, and gear selection, of the hybrid powertrain to minimize a cost function, which is the sum of fuel consumption for a defined driving cycle:

$$\min J = \min_{\{T_{e,k}, T_{m,k}, g_k\}, k=0,1,..N-1} \sum_{k=0}^{N-1} W_{fuel,k}$$

where k is the index of the time step, N is the total number of steps of the driving cycle, $W_{fuel,k}$ is the engine fuel flow rate, and the time step is chosen to be long enough that all these "commands" can be executed by the servo-loop controllers and that no frequent changes from the main loop controller will happen. For this work, we chose to have the time step at one second.

System Equations

Once a driving cycle is given (e.g., Figure 5), the wheel torque $T_{wh,req}$ required to follow the speed profile can be determined for each time step by inversely solving the vehicle dynamics. The corresponding wheel speed $\omega_{wh,req}$ can be computed by feeding the required wheel torque to the vehicle model in order to include the wheel dynamics and slip effect. Combining this procedure with the defined state/input grid, a simplified hybrid powertrain model can be represented as a discrete-time dynamic system

$$SOC_{k+1} = SOC_k + f(SOC_k, g_k, T_{e,k}, T_{wh,req,k}, w_{wh,req,k})$$

$$g_k = \begin{cases} 6, & g_k + shift_k > 6 \\ 1, & g_k + shift_k < 1 \\ g_k + shift_k, & \text{otherwise} \end{cases}$$

It can be seen that there are only state variables: the battery state of charge, SOC_k, and the transmission gear number, g_k. The control inputs to this dynamic system are the engine torque, $T_{e,k}$ and gear shifting command, $shift_k$, which is constrained to take on the values of –1, 0, and 1, representing downshift, hold and up-shift, respectively. It should be noted that the motor torque becomes a dependent variable instead of a control variable due to the driveline torque constraint

$$T_{wh}(T_{e,k} + T_{m,k}, g_k, \omega_{wh,req,k}) + T_{brake,k} = T_{wh,req,k}$$

where T_{wh} is the wheel torque propagated from the sum of the engine torque and motor torque through the driveline, and $T_{brake,k}$ is the hydraulic braking torque. By imposing this equality constraint, we can ensure that the vehicle follows the desired driving cycle closely.

Inequality Constraints

During the optimization procedure, it is necessary to impose inequality constraints to ensure safe and smooth operation of the engine, motor, and battery. In general, these practical considerations can be written in mathematical form as

$$\begin{aligned} &\omega_{e\_\min} \le \omega_{e,k} \le \omega_{e\_\max} \\ &T_{e\_\min}(\omega_{e,k}) \le T_{e,k} \le T_{e\_\max}(\omega_{e,k}) \\ &T_{m\_\min}(\omega_{m,k}, SOC_k) \le T_{m,k} \le T_{m\_\max}(\omega_{m,k}, SOC_k) \\ &SOC_{\min} \le SOC_k \le SOC_{\max} \end{aligned} \quad (1)$$

where ω_e is the engine speed, and the battery SOC limits, $SOC_{\min}$ and $SOC_{\max}$ are 0.4 and 0.7, respectively, which are recommended by the battery manufacturer. Besides, performing gearshifts in the grade is critical to the automated manual transmission. In order to reduce the possibility of missing synchronization, the restriction of the gear shifting selection is also taken into account in the optimization as follows

$$\begin{cases} \omega_{wh,req,k} \cdot R_f \cdot R_g(g_{k+1}) > \omega_{in\_\min}, & \text{if } shift_k = 1 \\ \omega_{wh,req,k} \cdot R_f \cdot R_g(g_{k+1}) < \omega_{in\_\max}, & \text{if } shift_k = -1 \end{cases} \quad (2)$$

where $\omega_{in\_\min}$ and $\omega_{in\_\max}$ are minimum and maximum allowable input shaft speed, respectively. R_f is the gear ratio of the final drive, and R_g is the gear ratio of the transmission.

Augmented Cost Function

The basic power management problem stated above does not contain any constraint to limit the use of electric energy. Therefore, the optimization algorithm has a tendency to deplete the battery to attain minimal fuel consumption. Therefore, a terminal penalty on SOC is introduced to maintain the battery energy.

$$G_N(SOC_N) = \alpha\left(SOC_N - SOC_d\right)^2 \quad (3)$$

where SOC_d is the desired SOC at the end time of the cycle and α is the weighting factor. The purpose is to ensure the SOC move back to its desired value (which is usually set to be equal to the start value) at the end of the driving cycle.

In addition, the minimization of the fuel consumption without considering dynamic constraints of the gear would result in frequent gear shifting, which is unfavorable to the transmission and also undesirable to the driver. Hence, an extra term that penalizes the use of gear changes is defined

$$L_k = \beta \cdot \left| g_{k+1} - g_k \right| \quad (4)$$

By adding Eqs. (3) and (4) into the original cost function, the augmented cost function becomes

$$\min J = \min_{\{T_{e,k}, shift_k\}, k=0,1,..N-1} \left\{ \sum_{k=0}^{N-1} \left[W_{fuel,k} + L_k \right] + G_N \right\} \quad (5)$$

Dynamic Programming Results

Dynamic programming is a powerful tool to solve general dynamic optimization problems. The main advantage is that it can easily handle the constraints and nonlinearity of the problem while obtaining a globally optimal solution. The DP technique is based on Bellman's Principle of Optimality, which states that the optimal policy can be obtained if we first solve a one stage sub-problem involving only the last stage and then gradually extend to sub-problems involving the last two stages, last three stages, …etc. until the entire problem is solved. In this manner, the overall dynamic optimization problem can be decomposed into a sequence of simpler minimization problems as follows [9]

Step $N-1$:

$$J^*_{N-1}(SOC_{N-1}, g_{N-1}) = \min_{T_{e,N-1}, shift_{N-1}} \left[W_{fuel,N-1} + L_{N-1} + G_N(SOC_N) \right]$$

Step k, for $0 \le k < N-1$

$$J^*_k(SOC_k, g_k) = \min_{T_{e,k}, shift_k} \left[W_{fuel,k} + L_k + J^*_{k+1}(SOC_{k+1}, g_{k+1}) \right]$$

where $J^*_k(SOC_k, g_k)$ represents the optimal cost-to-go function or optimal value function at state SOC_k and g_k starting from time stage *k*. The above recursive equation is solved backwards to find the optimal control policy. The minimizations are performed subject to the inequality constraints shown in Eqs. (1) and (2).

The DP procedure described above produces an optimal, time-varying state-feedback control law, i.e., $u^*_k(SOC_k, g_k)$. This optimal control policy can then be used to drive the hybrid vehicle along an optimal trajectory such that the cost function (5) is minimized. Simulation results under the optimal DP policy are shown in Figure 6. The engine power and motor power trajectories represent the optimal operation between two power movers to achieve the best fuel economy. The initial condition of SOC and gear position in the simulation are 0.6 and first gear, respectively. Since the final desired SOC in Eq. (3) was selected to be 0.6, the simulation shows the SOC trajectory returns to 0.6 at the end of the cycle.

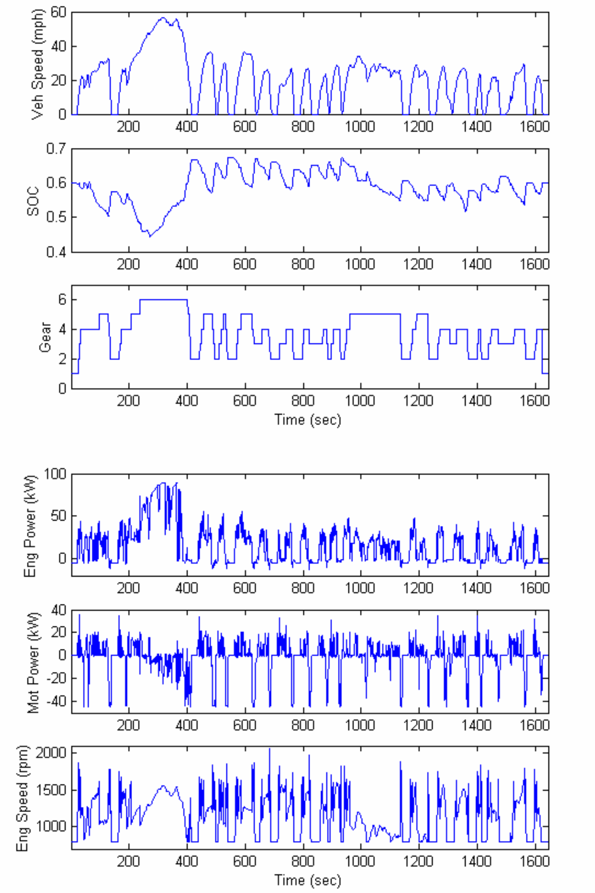

Figure 6: DP simulation results

RULE-BASED CONTROL STRATEGY IMPLEMENTATION

Although the Dynamic Programming approach provides an optimal solution, the resulting control policy is not implementable under real driving conditions because it requires the knowledge of future speed and load profile. The result is, on the other hand, a benchmark which other control strategies can be compared to and learn from. Therefore, the second part of the control design procedure involves knowledge extraction from DP results to obtain implementable rule-based control algorithms (Figure 7). Overall, the behaviors to learn include the transmission gearshift logic and the power-management strategy. The gearshift logic was found to be crucial for the fuel economy of hybrid electric vehicles. From DP results, the optimal gear operational points and upshift/downshift points are plotted on the standard transmission shift-map to identify an optimal shifting schedule as shown in Figure 8. The identified shifting schedule defines the optimal upshift and downshift thresholds to the gear selection control unit, which is implemented in Simulink/Stateflow (Figure 8).

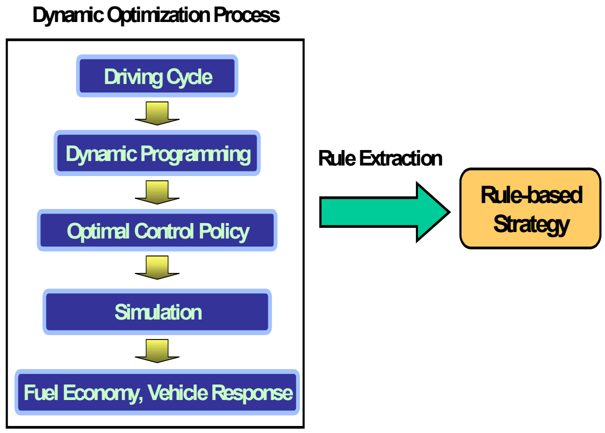

Figure 7: DP-based design process

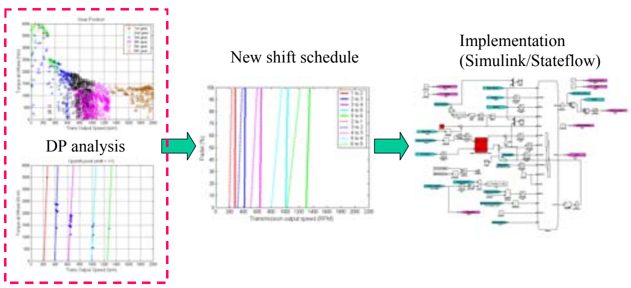

Figure 8: Optimal gearshift logic

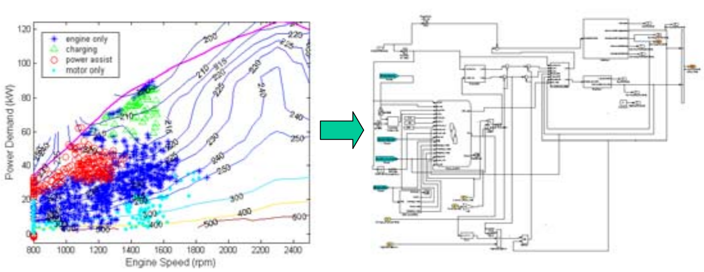

Figure 9: Optimal power split strategy

CONTROL SYSTEM TESTING AND CALIBRATION

Once the supervisory powertrain controller is developed, the control system can be tested and redesigned in phases as shown in Figure 10. The SPC developed in the last section can be first evaluated by using the simulation model. This simulation phase allows the algorithms and parameters in the SPC to be examined and tuned before the hardware prototype is available. In order to reduce the development time and cost, Eaton chose xPC Target, a PC-based rapid control prototyping tool, to implement the SPC in the prototype vehicle. The Simulink/Stateflow-based SPC model on the host computer can be built and downloaded to the xPC Target via an Ethernet connection. The xPC Target PC/104 stack consisted of a 400MHz CPU, an A/D board, an Ethernet card, a D/A board, two CAN boards, a timer/counter board, and a power supply board. An LCD display is used as the target display to the driver. Real-time data can be captured using a host computer from xPC Target and plotted using MATLAB for later analysis. This rapid prototyping system enables the engineers to test and operate the real components in the Hardware-in-the-loop phase and test the vehicle on the road in a real driving phase. From the real-time measurement, the engineers could quickly analyze the performance of the SPC, modify the controller model, and build and download the modified code to xPC Target in a fast and cost-effective manner.

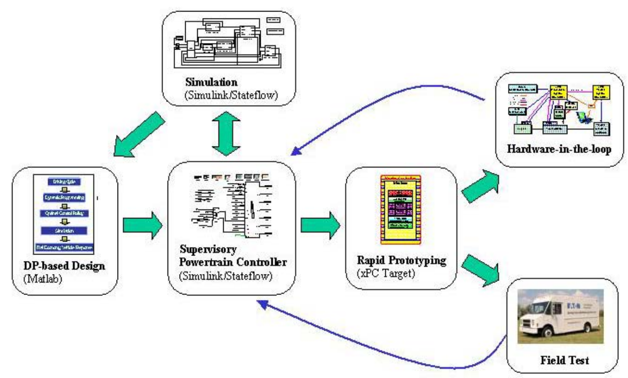

Figure 10: Model-based control design iteration

CHASSIS DYNAMOMETER TESTING RESULTS

The SPC algorithm is implemented on the prototype vehicle (for details, please see the companion paper "`Class 4 Hybrid Electric Truck for Pick Up and Delivery Applications`" presented separately in this conference). The dynamometer tests were conducted by the Southwest Research Institute, and the results from 5 repetition runs are averaged and reported in Table 2. In Table 2, the "Baseline control strategy" refers to a classic load-leveling type rule-based algorithm implemented on the same hybrid truck. The "DP-based control strategy" refers to the sub-optimal rule-based strategy trained on DP data. The highlight of the results is that while it is very important to install good hardware (battery, motor, etc.) and to choose a smaller and more efficient engine, it is also very important to carefully design the power management algorithm. A simple rule-based algorithm which takes advantage of only engine operation efficiency results in a 31% fuel economy improvement (over existing FedEx, ICE-engine only truck). However, proper software change (with no real add-on cost) brings in another 14% of improvement. The trickle-down effect also helps to improve NOx emission slightly.

Table 2: Dynamometer testing results over the modified FTP cycle

Comparison of Eaton hybrid truck to the baseline truck	Baseline control strategy	DP-based control strategy
Fuel Economy (MPG)	31 % increase	45 % increase
NOx (g/mile)	50% reduction	54% reduction

CONCLUSION

The design of the power management strategy for HEV by extracting rules from the Dynamic Programming results has the clear advantage of being model based and near-optimal. By solving, and analyzing the DP results, an improved rule-based control strategy was developed and implemented on a prototype medium-duty truck produced by the Eaton Corporation. Dynomometer test results show that the proposed design procedure resulted in a high-performance control algorithm. The fuel economy of the hybrid electric truck was examined by SWRI independently and was found to be 45% higher over the ICE-only benchmark truck.

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

Abbreviations

AMT: Automated Manual Transmission
ECU: Electronic Control Unit
ICE: Internal Combustion Engine
SPC: Supervisory Powertrain Controller
SOC: Battery State of Charge
DP: Dynamic Programming
TCU: Transmission Control Unit