Proceedings of the
44th IEEE Conference on Decision and Control, and
the European Control Conference 2005
Seville, Spain, December 12-15, 2005

Advanced Propulsion Systems Education and Applications at The Ohio State University

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Abstract – **The College of Engineering at The Ohio State University offers a unique combination of graduate-level coursework and vehicle application opportunities for students specifically interested in advanced vehicle technologies and control. Graduate courses include a sequence in hybrid-electric vehicle energy analyses and control methods, a series on dynamic powertrain modeling and control, and a course on fuel cells for automotive applications. Ohio State graduate students can apply and build upon course knowledge from hands-on experience with advanced vehicle technology systems through a variety of methods; one specific instance of this is the development of a control strategy for an actual hybrid-electric system as part of Ohio State's involvement in the Challenge X competition, a multi-university program sponsored by General Motors Corporation and the United States Department of Energy.**

I. COURSE OPPORTUNITIES AT THE OHIO STATE UNIVERSITY

The Ohio State University College of Engineering presents several courses for high-achieving undergraduate or graduate students interested in automotive technologies. Taught by professors affiliated with the Ohio State Center for Automotive Research, the courses cover dynamic modeling and control of both conventional powertrain systems and advanced propulsion systems:

- **Energy Analysis of Hybrid-Electric Vehicles**. 3 credit hours (quarter scale). Focuses on the quantitative evaluation of energy consumption in road vehicles and potential benefits of a hybridized drivetrain. Uses the development of mathematical models to understand energy storage, energy conversion, and power flow in hybrid systems. Applies computer tools (MATLAB/Simulink) to simulate hybrid vehicle designs.
- **Modeling, Simulation, and Control of Hybrid Vehicles**. 4 credit hours (quarter scale). Introduces design optimization concepts and their potential applications to hybrid-electric vehicles. Focuses on the control of hybrid-electric vehicles through various optimization concepts and approaches. Uses numerical methods to solve energy optimization problems in hybrid electric vehicles.
- **Fuel Cell Systems for Automotive Applications**. 4 credit hours (quarter scale). Provides a description of the fundamental principles of fuel cell stacks, fuel cell systems, and fuel cell fuels. Covers modeling and control of complete fuel cell systems for automotive applications as well as the analysis of energy consumption on a "well-to-wheel" basis. Provides an overview of the integration, manufacturing, and infrastructure challenges of fuel cells and fuel cell systems.
- **Powertrain Dynamics**. 4 credit hours (quarter scale). Focuses on the dynamics between mechanical, fluid, and thermodynamic systems; sensors and actuators, and drivability and emissions. Uses computer tools to simulate dynamic powertrain models for understanding and analysis.
- **Powertrain Control**. 4 credit hours (quarter scale). Focuses on the design and implementation of control systems in conventional automobiles. Uses computer tools to simulate models of control systems using various techniques (such as state variable design, linear quadratic regulator design, etc.).

The previously described courses are further available to industry partners through a Certificate Program offered by the Ohio State Center for Automotive Research. Since the initiation of the program in 1995, Ohio State faculty (in collaboration with other international institutions, including ETH-Z and the University of Stuttgart) have successfully educated hundreds of practicing engineers through distance education means. The Certificates are intended to act as a stand-alone achievement; however, the Certificate credit hours could also be transferred to other accepting institutions. The program currently consists of two available certificates:

- **Certificate in Advanced Propulsion Systems**. Requires completion of the following courses: Energy Analysis of Hybrid-Electric Vehicle; Modeling, Simulation, and Control of Hybrid Vehicles; and Fuel Cell Systems for Automotive Applications.
- **Certificate in Powertrain Modeling and Control**. Requires completion of the following courses: Powertrain Dynamics; and Powertrain Control. Also requires completion of three self-paced minicourses on Internal Combustion Engine Fundamentals, Advances in Internal Combustion Engines, and Powertrain Systems in Europe.

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II. THE CHALLENGE X COMPETITION

Challenge X is a three-year series among seventeen North American universities with the goal of re-engineering a 2005 Chevrolet Equinox for improved fuel economy and reduced emissions while maintaining performance, utility, safety, and consumer acceptability. Headline sponsored by the United States Department of Energy and General Motors Corporation (GM), the program also attracts sponsorship from many other industry and government leaders. Teams achieve the goals of the competition by utilizing advanced hybrid powertrains, novel control strategies, alternative fuels, lightweight materials, and innovative emission control techniques. Challenge X emphasizes the development of these technologies by following a progression that is representative of GM's Global Vehicle Development Process. Consequently, the first year of the competition stresses the validation of the chosen hybrid systems in an out-of-vehicle environment. The goal is to then have properly engineered systems ready for implementation into the actual Equinox vehicle in years two and three. Overall, the Challenge X program is a team effort by government, industry, and academia to address and endorse solutions to energy and environmental issues related to the automobiles of today.

To complement their advanced vehicle propulsion education with actual hands-on experience and to gain topics suitable for research, several graduate students at the Ohio State Center for Automotive Research are active and effective participants of Ohio State's Challenge X team. In particular, graduate students that have taken any of the previously described courses contribute knowledge of modeling, simulation, and control that directly relates to the competition itself. One of the current tasks of the Challenge X team is the development of a supervisory control strategy, and the state of this topic is the remainder of this report.

III. VEHICLE ARCHITECTURE AND CONTROL SYSTEM

During the summer and fall of 2004, the Ohio State team engaged in an involved process to select a vehicle architecture for design, construction, and optimization for the Challenge X competition. The procedure included a literature research, vehicle modeling and simulation, a packaging and weight analysis, and an extensive decision matrix to deduce the final hybrid configuration. The chosen vehicle architecture for the Ohio State team is depicted in Fig. 1 and can be summarized as including a:

- Small Diesel internal combustion engine (ICE) and automatic transaxle driving the front axle.
- Integrated starter/alternator (ISA) directly and rigidly coupled to the Diesel engine.
- Larger second electric machine (EM) to drive the rear axle.
- High-voltage Nickel-metal hydride battery pack serving both electric machines.
- Separate inverter for each electric machine.
- Switchbox to route the high-voltage electrical power flow.
- DC/DC converter to power the 12V system.

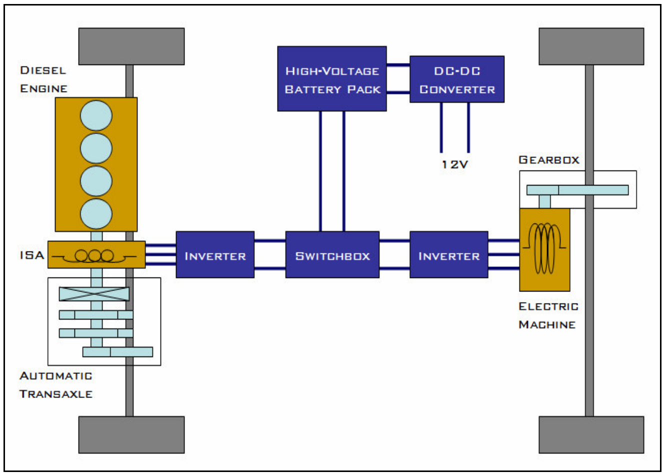

Fig. 1: Vehicle Architecture

IV. CONTROL STRATEGY

This specific paper exclusively focuses on the supervisory control strategy. It should be noted that the control described in this paper is high-level; in other words, it is appropriate for supervisory control strategy validation with respect to overall system energy management on a quasi-static model-based simulator. The final control strategy as actually implemented in the vehicle (or even used with a dynamic model-based simulator) must consider a more precise level of control on a lower, component level.

The following list of objectives guided the design of the primary control strategy:

- **Vehicle Mode Management**: The specific chosen hybrid architecture permits numerous vehicle modes. The appropriate mode and transmission gear must be selected and transitions between modes must be managed.
- **Power Request Satisfaction**: The driver's instantaneous power request (based upon pedal positions and available power at the current vehicle state and mode) must be met.
- **Fuel Consumption Minimization**: The primary control strategy must aim to minimize fuel usage on a global basis.
- **High-Voltage Battery State-of-Charge Management**: The proposed vehicle architecture is charge sustaining. As such, the primary control strategy must maintain the high-voltage battery state-of-charge between two specified boundaries.

A. *Vehicle Mode Management*

The Ohio State team has defined several discrete vehicle modes. The appropriate operating mode and transmission gear will be determined through event-based control dependent on vehicle inputs and states and is based upon the inherent benefits of that specific mode.

The vehicle begins in the *Vehicle Idle* mode at a key-on ignition state as initiated by the driver. In this mode, the three powertrain actuators rest inactively and all vehicle accessories (air conditioning compressor, etc.) operate electrically from the 12V grid as facilitated by the DC/DC converter. It should be noted that all further accessories typically coupled to and powered by the engine (e.g., power steering pump) are also driven electrically throughout all other vehicle modes as well. The *Vehicle Idle* mode remains logical so long as the high-voltage battery can amply power the electrical accessories: if the battery state-of-charge depletes too low, the vehicle transitions directly into the *Engine Start* mode. Otherwise, the vehicle rests in the *Vehicle Idle* mode until a positive accelerator pedal position input as initiated from the driver. At this point, the vehicle launches from rest via the rear electric machine and operates in an *Electric Only* mode. The rear electric machine both accelerates and decelerates (through regenerative braking) the vehicle in this mode. Three conditions exist at which point the vehicle leaves the *Electric Only* mode: (i) if the vehicle velocity exceeds that of a pre-determined threshold; (ii) if the accelerator pedal is fully depressed and thus indicates the driver's desire for additional power (from the engine), or (iii) if the high-voltage battery state-of-charge depletes to a level not conducive to supporting operation of the rear electric machine. The *Engine Start* mode is very brief: the vehicle resides in this mode so long as for the integrated starter/alternator to accelerate the Diesel engine to a proper operational speed. The vehicle itself continues to be propelled by the rear electric machine in a manner similar to that in the *Electric Only* mode. The commencement of fuel injection into the Diesel engine signifies the complete transition into the most-complex *Normal* mode. In the *Normal* mode, all three powertrain actuators operate in a manner according to further control theory explained later in this paper. The selection of automatic transaxle gear is summarized as follows: up and down shifts commence as the engine velocity reaches certain speed thresholds. These thresholds are functions of accelerator pedal position so that the Diesel engine operates at a greater velocity with greater output power potential as the accelerator pedal position is further depressed. The *Normal* mode is primarily defined for zero or positive power requests; when the power request turns negative (a non-zero depression of the brake pedal), the vehicle transitions into the *Deceleration* mode. The vehicle decelerates by a combination of aggressive regenerative braking and the conventional hydraulic brake system. To reduce the frequency of engine start/stops (especially from light or short brake pedal depressions), the Diesel engine remains in an idling condition during the *Deceleration* mode. Transaxle downshifts occur as the engine speed drops below certain and pre-determined threshold values. The vehicle reverts to the *Normal* mode as the power request turns positive, or the vehicle transitions into the *Electric Only* mode once the vehicle velocity drops below a certain threshold (given the high-voltage battery pack at a sufficient state-of-charge). It should be noted that an intermediate *Engine Stop* mode will likely exist between the *Deceleration* and *Electric Only* modes to provide a quick and smooth stop of the diesel engine. The progression returns to the *Vehicle Idle* mode as the vehicle decelerates to a complete rest.

B. *Power Request Satisfaction*

Instantaneous fuel economy and power delivery of a vehicle typically exhibit an inverse relationship to each other: the increase of one commonly results in the decrease of the other and vice versa. The goal of the great majority of hybrid vehicles is to increase fuel economy; however, the control strategy must also command the powertrain actuators as to continuously meet the driver's local power request. This requirement not only satisfies the driver (and thus creates a dependence of fuel economy on the driving behavior) but also aids in the overall safety of the vehicle.

To meet the power request, the control strategy must know the power request; thus, it is necessary to continuously calculate the power request which varies between vehicle modes and depends upon several states and inputs. The particular through-the-road vehicle architecture as chosen requires analysis of the power request as perceived at the road. More pointedly, the presence of the torque converter effectively uncouples the engine speed from the other states of the vehicle. Consequently, the torque converter efficiency η_{tc} is highly variant (unlike the assumed constant efficiencies of the transaxle η_{tr} and gearbox η_{gb}), and thus the effect of the engine at the road varies greatly as well. The importance of recognizing this concept is apparent when considering the fuel economy strategy of the subsequent section. In other words, commanding powertrain actuators to minimize equivalent fuel consumption while meeting a power request defined on the shaft output power capabilities does not make sense (or minimize fuel consumption) when considering the fuel economy (overall system result) as a metric. Therefore, the general form of the road power request $P_{rd,rq}$ at a particular moment in time involves the accelerator pedal position α and the brake pedal position β (both between zero and one) such that:

$$P_{rd,rq} = \alpha \cdot P_{rd,mx} + \beta \cdot P_{rd,mn} \tag{1}$$

The maximum power potential at the road $P_{rd,mx}$ is defined to be solely the contribution from the three powertrain actuators, while the minimum power $P_{rd,mn}$ further considers the conventional hydraulic brake system. Specifically, the control strategy of every relevant mode assumes a parallel braking system in which a brake pedal depression simultaneously causes both hydraulic braking and regenerative braking. It should be noted that the maximum and minimum road power potentials vary between vehicle modes and as a result of vehicle state (because of the state of the engine, battery limitations, vehicle stability considerations, etc.). However, the control strategy assumes that the driver uses the vehicle response as the basis for subsequent pedal commands (instead of absolute pedal displacements) and thus makes the proper pedal position adjustments in an attempt to achieve the desired vehicle response.

By definition, the power request in the *Vehicle Idle* mode is zero since the vehicle exists in a resting condition while the accelerator pedal position remains undisturbed. At the instant that the driver depresses the accelerator pedal (and thus enters the *Electric Only* mode) a power request ensues; however, this power request is initially somewhat ambiguous since the vehicle velocity, and thus road power availability, is zero. Therefore, for modes in which the power request consideration at the road proves redundant because of lone operation from a single powertrain actuator, the torque request at the components output shaft is sufficient for consideration (instead of the power request at the road). Moreover, for all modes, the defined power request is satisfied by the Diesel engine, integrated starter/alternator, and rear electric machine torque requests $(T_{ice,rq}, T_{isa,rq}, T_{em,rq})$, since these powertrain actuators commonly accept some sort of torque request (as opposed to a power request) as the appropriate input. For the *Electric Only* mode, the torque request is singularly met by rear electric machine torque and this implies:

$$\begin{aligned} T_{ice,rq} &= 0 \\ T_{isa,rq} &= 0 \\ T_{em,rq} &= \alpha \cdot T_{em,bt,mx} + \zeta_{em} \cdot \beta \cdot T_{em,bt,mn} \end{aligned} \tag{2}$$

The power limitations of the high-voltage battery pack influence the maximum and minimum torque curves of $T_{em,bt,mx}$ and $T_{em,bt,mn}$, respectively. A ζ_{em} gain factor multiplies the brake pedal position to resultantly increase the proportionality of regenerative braking from the rear electric machine. This product saturates such that $\zeta_{em} \cdot \beta \in [0, 1]$. The gain is also adjusted to decrease regenerative braking at large high-voltage battery state-of-charge and further regulates regenerative braking during situations of suspect vehicle stability (due to overly excessive rear-axle braking).

The *Engine Start* mode requires the rear electric machine to continue operation in a fashion as described by (2). Torque output from the Diesel engine itself remains zero as its velocity ω_{ice} accelerates to a proper operational velocity $\hat{\omega}_{ice}$ via the integrated starter/alternator. Until further experimentation and realization, the torque request to perform the engine start operation is modeled in a proportional-integral fashion with P_{isa} and I_{isa} as the controller coefficients:

$$T_{isa,rq} = P_{isa}\left(\hat{\omega}_{ice} - \omega_{ice}\right) + I_{isa}\int_{t_0}^{t}\left(\hat{\omega}_{ice} - \omega_{ice}\right)dt \tag{3}$$

The concern of a zero velocity does not exist in the *Normal* mode because a release of the brake pedal causes vehicle movement through a power transfer through the torque converter from the Diesel engine (even at an engine idling condition). Any combination of the three powertrain actuators can contribute power in the *Normal* mode; therefore, the power request must consider the power that can be delivered to the road. This power request (solely defined as positive for the *Normal* mode) can be expressed as:

$$P_{rd,rq} = \alpha\left(\omega_{ice} \cdot T_{ice,mx} \cdot \eta_{tc} \cdot \eta_{tr} + P_{rd,mx,e}\right) \tag{4}$$

The maximum power at the road as contributed from the electric machines $P_{rd,mx,e}$ can be expressed as:

$$P_{rd,mx,e} = \max\left[\omega_{ice} \cdot T_{isa} \cdot \eta_{tc} \cdot \eta_{tr} + \omega_{em} \cdot T_{em} \cdot \eta_{gb}\right] \tag{5}$$

where the angular velocity of the rear electric machine is ω_{em}. Equation (5) is subjected to the power limitation of the high-voltage battery $P_{bt,mx}$:

$$\omega_{ice} \cdot T_{isa} / \eta_{isa} + \omega_{em} \cdot T_{em} / \eta_{em} \le P_{bt,mx} \tag{6}$$

where η_{isa} and η_{em} are the electrical-to-mechanical efficiencies of the integrated starter/alternator and rear electric machine, respectively. The specific component torque requests to meet the power request at the road is significantly more complex than the other modes; as explained in the next section, the *Normal* mode works to minimize the equivalent fuel consumption in addition to satisfying the driver's power request at the road.

The *Deceleration* mode solely satisfies negative power requests through a combination of conventional hydraulic braking and regenerative braking. The rear electric machine singularly supplies a negative torque to the driveline such that:

$$\begin{aligned} T_{ice,rq} &= 0 \\ T_{isa,rq} &= 0 \\ T_{em,rq} &= \zeta_{em} \cdot \beta \cdot T_{em,bt,mn} \end{aligned} \tag{7}$$

As in the *Electric Only* mode, the ζ_{em} factor can work to increase regenerative braking for improved overall vehicle energy efficiency or can decrease regenerative braking to ensure vehicle stability and respect high-voltage battery state-of-charge limits.

C. Fuel Consumption Minimization

The primary reason (and benefit from a consumer standpoint) for hybrid technology in automotive applications is to minimize the vehicle fuel consumption. This goal exists in a global sense: it is desired to command the powertrain actuators so as to minimize fuel consumption m_f over the complete life of the vehicle:

$$\left\{ T_{ice}(t), T_{isa}(t), T_{em}(t) \right\} = \arg\min \int_0^{t_f} \dot{m}_f \, dt \qquad (8)$$
$$for \;\; t = 0 \ldots t_f$$

This responsibility of the control strategy to command the powertrain actuators so as to minimize approximate global fuel consumption is only relevant for the mode(s) that contain a sufficient number of degrees of freedom. In other words, fuel consumption minimization logic only occurs in the *Normal* mode in which the positive power request can be satisfied by numerous combinations of powertrain actuator power deliverances.

It is relevant to note that the driving cycle over the life of the vehicle, or even the near future, is not known beforehand. Therefore, the global goal of (8) must be addressed in real-time with a particular and local control solution. The chosen method for resolution of this issue involves considering the instantaneous (local) rate of equivalent fuel consumption $\dot{m}_{f,eq}$. This general approach is labeled the Equivalent Consumption Minimization Strategy [1] and strives to reduce the global challenge of (8) into the local problem of:

$$\left\{ T_{ice}, T_{isa}, T_{em} \right\} = \arg\min \dot{m}_{f,eq} \quad at \;\; each \;\; t \qquad (9)$$

while satisfying the power request satisfaction and respecting the torque limitations of the powertrain actuators. The basis of the Equivalent Consumption Minimization Strategy recognizes that, for a charge-sustaining hybrid-electric architecture, all vehicle energy originates solely from the fuel tank (i.e., the electrical battery simply acts as an energy buffer over a long period of time). Further application of this reasoning leads to mathematical definitions of the local equivalent fuel consumption. For instance, an extraction of power from the high-voltage battery pack (for use through the electric machines) may instantaneously save a quantity of Diesel fuel, but this immediate advantage requires an electrical replenishing at some point in the future (non-locally). Consequently, this power drawn from the high-voltage battery P_{bt} correlates to an instantaneous equivalent fuel *usage* $\dot{m}_{f,bt,eq}$. The formulation of an equation that expresses this equivalent fuel usage considers both the high-voltage battery pack efficiency η_{bt} and a theoretical average charging efficiency that represents energy path from the Diesel engine to the high-voltage battery pack:

$$\dot{m}_{f,bt,eq} = P_{bt} \big/ \left(Q_{lhv,d} \cdot \eta_{bt} \cdot \overline{\eta}_{ch} \right) \quad \text{if } P_{bt} > 0 \qquad (10)$$

Similarly but oppositely, driving electrical power into the high-voltage battery pack requires further effort (and thus fuel) from the Diesel engine, but this instant burden facilitates a contribution from the electrical powertrain at some moment in the future. Therefore, this electrical power input into the high-voltage battery pack associates with an instantaneous equivalent fuel *savings*. The equation formulation again considers the high-voltage battery pack efficiency and the efficiency of a discharging path, such that:

$$\dot{m}_{f,bt,eq} = P_{bt} \cdot \eta_{bt} \big/ \left(Q_{lhv,d} \cdot \overline{\eta}_{ch} \right) \quad \text{if } P_{bt} < 0 \qquad (11)$$

Appropriately then, the total equivalent fuel consumption simply adds the rate of actual Diesel fuel consumption to the electrical equivalent rate of fuel consumption into or out of the high-voltage battery pack:

$$\dot{m}_{f,eq} = \dot{m}_f + \dot{m}_{f,bt,eq} \qquad (12)$$

The only source of ambiguity with the Equivalent Consumption Minimization Strategy involves a definition of the $\overline{\eta}_{ch}$ and $\overline{\eta}_{dis}$ values. This paper refers to these parameters as the *average charging and discharging combined efficiency values*. In this sense, the average combined efficiency values represent the series of inefficiencies that a unit of energy would experience during an average route from the fuel tank to the high-voltage battery pack or vice versa. Therefore, utilization of the Equivalent Consumption Minimization Strategy requires either an assumption of component average efficiency values or a determination of the "best" values through modeling, simulation, and/or experimentation. The latter approach typically works more favorably in achieving minimal fuel consumption as the average efficiency values are treated as calibration parameters (which surfaces a great advantage of the Equivalent Consumption Minimization Strategy: it can be applied to a wide variety of hybrid configurations). Further details of the specific determination of the $\overline{\eta}_{ch}$ and $\overline{\eta}_{dis}$ calibration parameters are discussed in subsequent sections.

D. High-Voltage Battery State-of-Charge Management

Charge-sustaining architectures dominate the current hybrid vehicle market as a consequence of the transparency upon the typical consumer; the driver may notice the benefits (improved fuel economy, smooth vehicle launch, etc.) but really appreciates the normalcy as compared to conventional vehicles. In other words, the consumer does not need to electrically charge a charge-sustaining hybrid: as with conventional vehicles, trips to the gas station (hopefully less frequent) are all that are required.

The premise of a charge-sustaining hybrid vehicle involves maintaining the high-voltage battery pack state-of-charge between two pre-defined boundaries. For a specific battery chemistry, these limits are chosen so as to ensure a sufficient life of the battery pack, be consistent with the voltage range of the inverters of both electric machines, and avoid excessively large internal resistances. As mentioned previously, the logic for mode selection inherently (to an extent and for some of the modes) maintains high-voltage battery state-of-charge within the limits by switching modes as deemed appropriate. For instance, the vehicle transitions out of the *Vehicle Idle* and *Electric Only* modes if the state-of-charge depletes too low. Further, the ζ_{em} factor fades out regenerative braking at large state-of-charges so as to not exceed the upper boundary. However, the *Normal* mode, as explained thus far to satisfy the power request and minimize fuel consumption, does not inherently contain any high-voltage battery pack state-of-charge control. The state-of-charge control for the *Normal* mode is implemented in the two following ways:

- Strict limits for the high-voltage battery pack state-of-charge, and
- Adaptive tuning of the combined average efficiency values

The strict limits control simply acts as a hard boundary: it will not allow the electric machines to operate in such a way that cause the high-voltage battery state-of-charge to drift outside of the pre-determined boundaries. The method taken to implement the strict limit involves formulating a correction factor on the maximum power into ($P_{bt,mx}$) or out of ($P_{bt,mn}$) the high-voltage battery. Therefore, the power request satisfaction and fuel consumption minimization control techniques actually respect the *corrected* high-voltage battery power limitations $P_{bt,mx,cor}$ and $P_{bt,mx,cor}$:

$$\begin{aligned} P_{bt,mx,cor} &= \left(1-\zeta_{bt,dis}\right)P_{bt,mx} \\ P_{bt,mn,cor} &= \left(1-\zeta_{bt,ch}\right)P_{bt,mn} \end{aligned} \qquad (13)$$

These power correction factors ($\zeta_{bt,dis}$ and $\zeta_{bt,ch}$) are defined as a function of state-of-charge so that they impart a negligible influence when the state-of-charge does not approach either its upper or lower limit.

As described previously, there exists a certain level of ambiguity with the combined average efficiency values $\overline{\eta}_{ch}$ and $\overline{\eta}_{dis}$. Simulation reveals better combinations of these calibration values (typically between zero and one) than others in terms of achieving high fuel economy for a certain driving cycle. Most often, the preferred values influence a state-of-charge profile that fluctuates freely between the state-of-charge limits without hovering near or continuously reaching those boundaries. Therefore, it is reasonable to assume that maximum fuel economy is achieved if the battery state-of-charge profile has a continuous freedom to fluctuate in either direction; in other words, when the battery state-of-charge avoids reaching either strict limit. This logic is the reason behind implementation of adaptive tuning control with respect to the high-voltage battery state-of-charge.

As expected, variation of the combined average efficiency values influences the high-voltage battery to have a tendency to charge or discharge. For instance, an alteration of the values towards 0 increases the magnitude of the equivalent electrical fuel consumption and thus results in the tendency to increase charging of the high-voltage battery while depleting it less. Oppositely, an adjustment of $\overline{\eta}_{ch}$ and $\overline{\eta}_{dis}$ towards 1 decreases the magnitude of the equivalent fuel consumption and thus causes increased depletion and less charging of the high-voltage battery. Therefore, on-line tuning of the combined average efficiency values presents a method for battery state-of-charge (s_{bt}) control.

$$\begin{aligned} \overline{\eta}_{ch} &= \overline{\eta}_{ch}(s_{bt}) \\ \overline{\eta}_{dis} &= \overline{\eta}_{dis}(s_{bt}) \end{aligned} \qquad (14)$$

The overall goal with this approach involves keeping the average efficiency values close to those found during simulation. In this way, high-voltage battery state-of-charge can be maintained and fuel economy maximized without knowing any driving cycles *a priori*. A further application of the adaptive tuning method considers the recent driving history of the vehicle in an attempt to predict the near driving future. A reasonable prediction can lead to less tuning and more favorable values or, at the very least, can provide a base value from which to tune from.

V. CONCLUSION

Ohio State's participation in the Challenge X competition is a single example of undergraduate and graduate students applying classroom material to extensive and nontrivial engineering problems. The combination of these opportunities with a mature academic curriculum focused in advanced propulsion systems offers Ohio State students an experience that prepares them to make a positive impact in today's ever-changing and complex automotive industry.

REFERENCES

[1] Paganelli, G., et al. "General Supervisory Control Policy for the Energy Optimization of Charge-Sustaining Hybrid Electric Vehicles". Journal of SAE of Japan. Vol. 22. 2001.

[2] Sciarretta, A., M. Back, and L. Guzzella. "Optimal Control of Parallel Hybrid Electric Vehicles". IEEE Trans. of Control Systems Tech. Vol. 12. No 3. 2004. pp. 352-363.

[3] Lin, C.-C., et al. "Power Management Strategy for Parallel Hybrid Electric Truck". IEEE Trans. of Control Systems Tech. Vol. 11. No 6. 2003. pp. 839-849.