Hybrid and electrified vehicles have demonstrated significant fuel economy improvement, especially for city driving, and are gaining market acceptance. Hybrid and plug-in hybrid vehicles have captured about 3.3% of the U.S. market, with an annual sales growth this year of 65%, and they also account for more than 20% of the Japanese market. In Japan, the high market penetration is due to government incentives and high fuel prices (~ $8/gallon). The success of hybrid vehicles in Japan demonstrates the potential for hybrid vehicles in other urban markets with high fuel prices, such as large cities in Europe and Asia.

A hybrid powertrain contains at least two power sources, typically an internal combustion engine (ICE) as the primary power source, and a secondary power source, such as an electric motor. Hybrids save fuel by exploiting the additional flexibilities available in the design and operation of the hybrid powertrain, including load leveling, regenerative braking, engine shut-down, component right-sizing, and if available, manipulating the electronic continuously variable transmission. The added flexibility in the powertrain operation and design means model-based analysis, simulation and control play an even more prominent role in vehicle design and operation. In other words, having the best components (battery, motor, etc.) is not enough to ensure the success of an electrified vehicle. Top-notch performance is only achieved by the proper selection of powertrain configuration, proper sizing of all components, and optimal control, in addition to first-rate powertrain components.

In this article, we will review past successes and future challenges of model-based approaches for the analysis, design and control of hybrid vehicles. The takeaway message is that this is a field that has significant potential for future research and development.

**HISTORICAL PERSPECTIVE**

The origin of the hybrid electric vehicle (HEV) dates back to 1899, when Dr. Ferdinand Porsche, then a young engineer at Jacob Lohner & Co, built the first hybrid vehicle. The Lohner-Porsche gasoline-electric Mixte, used a gasoline engine rotating at a constant speed to drive a dynamo, which charged a bank of accumulators. These, in turn, fed current to electric motors contained within the hubs of the front wheels. In the United States, the first reference to a hybrid-electrical vehicle may be found in a 1905 patent filing by H. Pieper, a German-born Belgian. By the time the patent was issued in 1908, reciprocating ICEs had improved significantly and hybrid vehicles, much like battery-electric vehicles (BEVs), had disappeared from the market.

Nearly a century later, in 1993, eight agencies of the U.S. government formed a partnership with the three major automotive manufacturers to advance vehicle technology, with the goal of producing highly fuel-efficient vehicles. The Partnership for a New Generation of Vehicles (PNGV) involved DaimlerChrysler, Ford, and General Motors. It’s most widely publicized, but not only, goal was to develop production vehicles capable of achieving 80 miles per gallon (approximately 3 liters per 100 km) by 2003. The program ended in 2001, with the automakers having demonstrated (but not launched production of) the GM Precept, the Ford Prodigy and the Chrysler ESX. All of these vehicles were characterized by the use of lightweight materials, hybrid powertrains, and other technological innovations. PNGV provided the opportunity for substantial research to be carried out in collaborations among the automotive companies, their suppliers, national labs, and universities.

**HYBRID VEHICLES**

Hybrid vehicles are generally classified according to their powertrain architecture as shown in Figure 1. A series hybrid uses a large electric motor to propel the vehicle while using the ICE and a second electric machine to generate electricity to directly provide propulsion, or to charge a battery. The Diesel-Electric propulsion system used in locomotives would be an example of such architecture, and a similar concept can also be implemented in a hydraulic hybrid using hydraulic pumps and motors, and accumulators. A parallel hybrid can blend mechanical power from the ICE and the electric motor(s) through appropriate mechanical coupling and transmission elements to deliver mechanical power to the road or to recharge the battery. The Honda Civic Hybrid is an example, and such an architecture can also be realized in hydraulic hybrids using hydrostatic transmissions. A third configuration, the one that is most commonly found among production hybrid passenger vehicles today, is the power-split hybrid, in which the properties of both a series and parallel hybrids are achieved, frequently by using one or more planetary gear sets to couple two electric machines, to the ICE on one side, and to the driveline on the other. The
Toyota Prius is a commercially successful example of this architecture.

An HEV is considered charge sustaining if the electric energy storage system is recharged only by power supplied by the ICE or by regenerative braking. If, on the other hand, the vehicle is designed to deplete stored energy in the battery during the course of a trip, ending the trip with a lower state of charge than at the start and requiring re-charging from the electrical grid, the vehicle is called charge depleting, or a plug-in hybrid (PHEV). The Chevrolet Volt is the first commercially produced example of such an architecture, although this concept was proposed and demonstrated in the early 1990s.

The charge-depleting vs. charge-sustaining distinction is not of practical use in hydraulic or mechanical hybrids, as very little energy can be stored in an accumulator or a flywheel, although during the PNGV years there was significant effort made to develop commercial flywheel batteries that would be capable of storing significant energy.

**GROUND VEHICLE MODELING AND ENERGY ANALYSIS**

To understand the potential benefits of any hybrid vehicle architecture we first need to understand vehicle energy and power requirements, which are imposed by its duty cycle. Duty cycles vary dramatically depending on the intended use of the vehicle, and range from the driving habits of the average consumer to requirements imposed by commercial or military vehicles.

**Forces acting on a vehicle**

The power required to motor a vehicle is known as the road load, and can be broken into several components: rolling resistance, vehicle internal frictional losses, aerodynamic drag, grade (if any), and inertial loads (accelerating the vehicle). A small portion of the power is used for accessory loads (e.g., alternator, air-conditioning compressor, power steering pump). In trucks or utility vehicles, a significant portion of the power may be used to drive equipment (e.g., hydraulic pumps) in addition to the accessory loads. Here we present a basic analysis of the forces acting on a vehicle, considering the vehicle as a lumped mass, and only accounting for longitudinal motion. With reference to Fig. 2, consider a vehicle of mass $M$, moving at a speed $V$ on a grade of angle $\alpha$. The total road load is defined as the force impeding vehicle motion:

$$ F_{\text{total}}(t) = F_a(t) + F_g(t) + F_f(t) + F_{\text{acc}}(t) \quad 1 $$

While the total power associated with this load is:

$$ P_{\text{total}}(t) = F_{\text{total}}(t) \cdot V(t) \quad 2 $$

The aerodynamic drag is modeled by:

$$ F_a = \frac{1}{2} \rho_a A_f C_d V^2 \quad 3 $$

where $C_d$ is the drag coefficient, $A_f$ is the projected vehicle frontal area, $\rho_a$ is air density, $V$ is the vehicle velocity, $D$ is the effective diameter of any vehicle relative velocity, where $D_{\text{air}}$ is the resultant vector of the head wind force.

A wide range of factors affect the total rolling resistance of the vehicle, including tire wear, inflation pressure, and vehicle mass. The rolling resistance force is often approximated by:

$$ F_r = Mg \cos \alpha C_r(V) \quad 4 $$

The rolling resistance coefficient, $C_r$, depends on the type of tire, the tire pressure, temperature, the vehicle mass and the road surface. Typically $C_r = 0.013 - 0.02$ for smooth pavement.

The force due to the road grade can be modeled as $F_g = Mg \sin \alpha$ where $a$ is the angle of the road with the horizontal (see Fig. 2). Thus, the total aerodynamic drag, rolling resistance and grade force resisting the motion of the vehicle is:

$$ F_{\text{total}} = \frac{1}{2} \rho_a A_f C_d V^2 + Mg \cos \alpha + Mg \sin \alpha \quad 5 $$

To overcome the road load, $F_{\text{total}}(t)$, the powertrain (conventional or hybrid) must supply a motive force at the wheel, $F_{MW}(t)$, which can be related to the wheel torque $T_{MW}(t)$, using the effective wheel radius, $R_{\text{eff}}$, by:

$$ F_{MW} = R_{\text{eff}} T_{MW}(t) \quad 6 $$

The balance of these forces determines the net acceleration (or deceleration) of the vehicle, according to Newton’s second law of motion:

$$ M_{\text{eff}} \frac{dV}{dt} = F_{MW}(t) - F_{\text{total}}(t) \quad 7 $$

where $M_{\text{eff}}$ is the effective mass of the vehicle referenced to the wheels, which is the sum of the vehicle mass plus the equivalent mass resulting from the moments of inertia of all rotating components, including engine and driveline. The latter is dependent on the transmission speed ratio if the vehicle is equipped with a multi-speed transmission.

Using the total load we arrive at the total required power:

$$ P_{\text{total}} = \frac{1}{2} \rho_a A_f C_d V^2 + Mg \cos \alpha + Mg \sin \alpha + V \cdot P_{\text{acc}} \quad 8 $$

in which $P_{\text{acc}}$ is the power required for the accessories.

**DRIVING CYCLES**

To evaluate fuel economy, emissions and performance of a vehicle, it is customary to use standard driving cycles, e.g. the Environmental Protection Agency (EPA) driving cycles, which are typically implemented on a
chassis dynamometer in the case of light-duty vehicles. These cycles are represented as traces of vehicle speed versus time. For example, the federal test procedure (FTP) schedule, commonly used to assess a light-duty vehicle’s fuel economy and emissions, covers a distance of 11.04 mi (17.77 km), for a duration of 1,874 s at an average speed of 21.2 mi/h (34.1 km/h). Prior to executing the FTP, the vehicle is kept in cold soak (i.e., a stabilized ambient thermal state) overnight. At the beginning of the test, the engine is fired and operated during the warm-up phase. At the end of the first portion of the cycle (i.e., the Federal Urban Driving Schedule, FUDS, shown in Fig. 3), the vehicle is stopped for a rest period of 10 minutes (hot soak). Then the beginning of the second FUDS cycle is executed. This overall procedure is designed to provide a representative sample of vehicles during their warm-up phase and operating at nominal operating temperatures.

Using the road load model, the force at the wheel is given by:

\[ F_{MW} = \frac{1}{2} \rho \ M \ g \ C_d \ a \ V^2 + M \ g \ \cos \alpha \ C_r + M \ g \ \sin \alpha + (M + M_{eq}) \ \frac{dV}{dt} \]

Assuming no grade (\( \alpha = 0 \)) and no wind, the power at the wheel is given by:

\[ P_{MW} = \frac{1}{2} \rho \ M \ g \ C_d \ a \ V^2 + M \ g \ V \ \cos \alpha + M_{eq} \ \frac{dV}{dt} \]

The energy to be provided at the vehicle wheels over the cycle is then given by:

\[ E_{MW} = \int P_{MW} \ dt = \frac{1}{2} \rho \ M \ g \ C_d \ a \ \int V^2 \ dt + M \ g \ \int V \ dt + M_{eq} \ \int \frac{dV}{dt} \ dt \]

In 11, the integral terms are vehicle independent, but are cycle dependent, while their coefficients are vehicle dependent.

One method for improving fuel economy is to recover and store as much of the vehicle’s energy as possible during decelerations. The process of storing the energy is commonly known as regenerative braking. Typically, the recovery of brake energy is only a fraction of the available energy. Analyzing a vehicle driving cycle to understand the potential availability of kinetic energy recovery is very important in selecting the appropriate hybrid vehicle architecture, and in choosing the best means for kinetic energy recovery. As an example, consider the FUDS cycle, shown in Figure 3, a relatively gentle driving cycle, chosen to represent urban driving, it would theoretically be possible to recover 3.6 MJ of energy if all of the kinetic energy during deceleration can be recovered. However, for safety reasons, regenerative braking systems cannot completely replace friction brakes.

In addition to kinetic energy recovery, hybrid powertrain architectures also permit engine downsizing, as well as the ability to implement idle reduction strategies using engine start-stop technologies. Further, the electric drivetrain makes it possible to operate, in a torque-speed engine map, in regions with lower brake-specific fuel consumption.

**ENERGY STORAGE SYSTEMS**

Energy storage is the lynchpin of a hybrid vehicle. In HEVs such storage comes from electrochemistry, but it is also possible to store energy using fluid power and mechanical systems. In the present section we examine the most common energy storage system technologies. Figure 4 is a Ragone plot depicting the relationship between specific power and specific energy of various energy storage devices, including for comparison also energy conversion devices such as the internal combustion engine and the fuel cell. Clearly some energy storage devices are better suited for providing power, while others are more effective at providing longer-term energy. Even within one specific technol-
Electrochemical Energy Storage
Batteries, modeling and state of charge and state of health estimation

Thomas Edison tried to produce practical battery-electric vehicles about a century ago. Low battery energy density and reliability prevented success. Batteries continue to be the performance and cost bottleneck for all electrified vehicles today. Because batteries are expensive and subject to failure if not treated properly, vehicle manufacturers are faced with a tradeoff between a larger battery pack with higher cost allowing for less stressful demand, and a right-sized battery pack that causes batteries to be operated near their practical limits, with accelerated aging and reliability concerns. As an example, the NiMH battery pack in the Toyota Prius is only used in a region of SOC that corresponds to at most 25% of the battery capacity. Oversizing the battery pack has resulted in very reliable operation, with vehicles (and battery packs) currently on the road approaching ten years of service. To ensure safe, reliable and efficient operations of the traction batteries, an effective battery management system (BMS) must be developed. A BMS serves many functions that primarily rely on sensors, including temperature monitoring, over-charging and over-discharging prevention, and cell-to-cell imbalance detection and mitigation. Two of the most notable examples are the estimation of battery SOC and State-of-Health (SOH) \(^{11-12}\). For these two BMS functions, accurate battery models that can be implemented in real-time are necessary.

Both electrochemical models \(^{13-15}\) and equivalent circuit models \(^{16-18}\) have been applied to battery SOC and SOH estimation (see Fig. 5). The electrochemical models describe distributed electrochemistry behaviors in the electrodes and electrolyte and typically deploy partial differential equations with a large number of unknown parameters. The complexity often leads to significant computer memory and computation requirement and the models are usually over-parameterized and robust.

Equivalent circuit battery models use standard electric circuit elements as the building blocks to describe the battery voltage-current relationship. Despite the simple model structure, when proper complexity is included, battery behavior can be reconstructed with high accuracy. As an example, given the battery current profile, the voltage can be predicted with a standard deviation error as low as 6 mV\(_{\text{avg}}\), which is as accurate as the best validated results from electrochemical models, and more than adequate for practical BMS functions. Surprisingly, a simple RC circuit plus a resistance is adequate and robust as a model for SOC estimation \(^{16}\).

SOH has a different meaning for different applications. In battery packs used in HEVs, ohmic loss or impedance is important because it affects the maximum power that can be delivered by the battery. For PHEVs or BEVs the key performance bottleneck is battery capacity. Battery impedance is easy to calculate using the voltage-current information. The battery capacity can be measured when the battery is fully discharged and then charged in a laboratory. The field of SOH estimation is a relatively immature field and further development is still needed.

Electrochemical, or double-layer, or super capacitors

Electrochemical capacitors are a special class of capacitors with extraordinarily large energy densities compared to traditional capacitors, as well as significantly greater power densities in comparison to batteries. While supercapacitors are not appropriate replacements for batteries in most hybrid applications, they are well suited to certain duty cycles that require high-power capabilities and long life. An example of such an application is the refuse-hauling truck developed by Oshkosh Truck Corporation \(^{19}\), in which a supercapacitor energy storage system was used to exploit the frequent start-stop duty cycle of a residential refuse hauling truck.

Hydraulic energy storage systems

All hybrid vehicles available on the passenger car market today are HEVs. However, for heavy-duty applications hybrid hydraulic vehicles (HHVs) are excellent alternatives because they are more cost effective and have much higher power density and reliability. In addition, hydraulic actuators typically do not require a dedicated cooling system, which is advantageous for cost, reliability and packaging reasons. A major challenge for hydraulic actuators is the fact that hydraulic accumulators have much lower energy density, which means they are excellent “power boost” devices but do not have adequate energy for extended pure hydraulic driving range. The short burst of power means they are only suitable for urban operations and not highway driving. The size of the hydraulic accumulators and reservoirs also limit the applicability of hydraulic hybrid technologies to passenger cars.

Hydraulic hybrids are already available on the heavy vehicle market. Eaton Corp. has a parallel hybrid architecture (i.e., the Eaton Hydraulic Launch Assistant), which reduces fuel consumption by about 20-30%, and a serial hydraulic hybrid system which achieves a 50% fuel saving in urban cycles. Parker Hannifin
launched a serial hydraulic system in 2010 with similar fuel saving. Several other companies, including Bosch Rexroth, Caterpillar, and Komatsu are also developing hydraulic trucks or construction machines such as excavators, mostly based on parallel or power split configurations. We expect hydraulic hybrids to gain significant market share in the near future.

**Mechanical (kinetic) energy storage systems**

In addition to electrochemical and fluid power energy storage, energy can also be stored mechanically using a rotating disc (i.e., flywheel). Investigation into the concept of storing energy in a rotating disc for passenger cars was prompted by rising gasoline prices in the 1970’s. Andrew Frank at the University of Wisconsin investigated the idea of using a large flywheel to store energy and allow engine-off operations, which showed fuel economy improvements of up to 33%.

The introduction of kinetic energy recovery in race cars, starting with the 2009 Formula 1 racing season, prompted the development of regenerative braking systems with high power density, resulting in a high speed flywheel system with a full toroidal CVT with flywheel speeds exceeding 60,000 rev/min and 60 kW of power with a total system weight of only 25 kg. Flybrid Systems, under the license from toroidal CVT designer Torotrak, has been working with car manufacturers to bring the technology to production vehicles and have reported that up to 21% of the energy needed to propel a vehicle can be recovered from braking.

**MODELING AND CONTROL OF ELECTRIFIED VEHICLES**

**Modeling: hierarchy of models**

Control strategies for hybrid electric vehicles are aimed at meeting several simultaneous objectives. The primary one is fuel consumption, but minimizing engine emissions and maintaining or enhancing drivability are also important. Regardless of the powertrain topology, the essence of the HEV control problem is the instantaneous management of the power flows from energy converters to achieve the control objectives. One important characteristic of this general problem is that the control objectives are mostly integral in nature (fuel consumption and emission per mile of travel), or semi-local in time, such as drivability, while the control actions are local in time. Furthermore, the control objectives are often subject to integral constraints, such as maintaining the battery SOC within a prescribed range. Much can be learned from global optimization exercises over a priori known driving cycles. However, these solutions do not directly lend themselves to practical implementations.

In addition to minimizing vehicle energy use, vehicle designers must also meet a number of other practical constraints that present tradeoffs. Exhaust gas emissions, which are tightly regulated, can be significantly affected in a hybrid propulsion system. For example, engine starting and stopping cycles may have an impact on the thermal and chemical environment of the catalysts used in the exhaust aftertreatment system. Drivability is also strongly influenced by the architecture and control of a hybrid powertrain, as is vehicle noise-vibration-harshness (NVH). Miller presents an excellent overview of all of the challenges presented by hybrid propulsion systems, from an industrial perspective.

Each of these control problems, fuel economy and CO₂ emissions minimization, meeting regulated emissions constraints, achieving acceptable performance and drivability, requires the use of models appropriate for the task, and much work has been done to develop such models.

**Energy modeling and instantaneous optimization as a surrogate for global optimization**

The optimal energy management problem in a hybrid electric vehicle consists of finding the control $u(t)$ that leads to the minimization of the performance index $J$, where $m_f$ is the mass flow rate of fuel used:

$$J = \int_t^{t_f} \dot{m}_f(t, u(t)) dt$$

subject to constraints that are related to: i) physical limitations in the actuators and in the stored energy; and ii) to the requirement to maintain the battery SOC within prescribed limits. Since the minimization needs to be performed over an unknown driving cycle, a realizable solution to this problem is very difficult, if not impossible, to achieve. Three approaches
to solve this problem have been proposed over the years, namely, rule-based controls, local optimization solutions as surrogates of the global solution, and formal optimal control solutions, including Pontryagin’s minimum principle and dynamic programming.

A local optimization method that has demonstrated considerable success is the Equivalent fuel Consumption Minimization Strategy (ECMS), originally proposed by Paganelli\textsuperscript{23}. The method is based on accounting for the use of stored electrical energy, in units of chemical fuel use (g/s), such that one can define an “equivalent fuel consumption” taking into account the cost of electricity:

\[
E_{\text{net}} = E_{\text{net}}(t) = E(t) - E_{\text{chem}}(t) - E_{\text{cal}}(t) - E_{\text{mech}}(t)
\]

In eq, \(E_{\text{net}}\) is the energy capacity of the battery, \(Q_{\text{lhv}}\) is the lower heating value of the chemical fuel, and \(s(t)\) is the equivalent factor that assigns a cost to the use of electricity. Then, the global minimization problem is converted into a local minimization problem:

\[
\begin{align*}
\text{Global:} & \quad \min_{\{\tau_p(t), \tau_s(t), \tau_i(t)\}} \int_0^{\tau_f} m_{\text{eff}}(t) dt, \\
\text{s.t.} & \quad \text{SOC}(t) \leq \text{SOC}_{\text{max}}, \quad \text{SOC}(t) \geq \text{SOC}_{\text{min}}
\end{align*}
\]

where the virtual fuel consumption of the electric propulsion system is approximated by the use of an equivalent cost of the electricity, representing future fuel use required to replenish the stored electrical energy used in the present. The equivalence factor is cycle dependent, and can be adapted as a function of driving, geographical and traffic conditions\textsuperscript{24,25}. This approach has been shown to closely approximate the global optimal solution.

Formal optimal control methods have also been applied to this horizon optimization problem, using deterministic dynamic programming\textsuperscript{26-27}, stochastic dynamic programming\textsuperscript{28}, model predictive control, or Pontryagin’s minimum principle\textsuperscript{29-30}. Serrao et al. in\textsuperscript{31} present a comparison of deterministic dynamic programming, ECMS and a Pontryagin solution, and show that ECMS can in fact be interpreted as a Pontryagin minimum principle solution, in which the equivalent fuel consumption is the co-state in the Hamiltonian function that is minimized to achieve the minimum\textsuperscript{32}.

**DRIVABILITY AND NVH**

**Drivability** is a comprehensive term that encompasses vehicle responsiveness, operating smoothness and driving comfort\textsuperscript{33}. In general, the discomfort caused by vibrations and accelerations depends on the vibration frequency and direction, the point of contact with the body and the duration of vibration exposure. Vibrations between 0.5 and 80 Hz are significant in exciting human body response. The most effective excitation frequency for horizontal vibrations lies between 1 and 2 Hz and that for vertical vibrations is from 4 to 8 Hz. Vibrations ranging from 2.5 to 30 Hz generate strong resonance with amplified magnitude of up to 200–350\%, which may cause permanent damage on human organs and body parts. Drivability can be quantitatively evaluated by vehicle interior noise level, jerk amplitude and acceleration characteristics. Moreover, engine start/stop frequency is important in HEVs. Several quantitative measures used to assess drivability and noise, vibration and harshness (NVH) problems are discussed in\textsuperscript{34}.

**Gear shifting** is the most commonly studied class of drivability problem. Recent work on the control of automatic, (automated) manual, continuously variable and electrically variable transmissions is surveyed in\textsuperscript{35}. For vehicles equipped with (automated) manual transmissions, passive driveline damping is not sufficient to quickly dissipate the transient effects of abrupt torque changes in the absence of torque converters. Even in automatic and CVTs, pedal tip-in/tip-out may lead to noticeable disturbances when the torque converter by-pass clutch is locked. Similar issues also occur in BEVs and HEVs if the electric machines are rigidly coupled to the driveline. The oscillations that correspond to the fundamental driveline resonance frequency are often referred to as **shuffle** vibrations\textsuperscript{36}. Another undesired response characteristic, generally referred to as **shunt**, arises upon initial pedal application due the high rate of change of driveline torque. Typical pedal tip-in/tip-out related drivability issues are demonstrated in Figure 6. Figure 6a depicts the shunt and shuffle observed in a test vehicle when operated in pure electric mode with no torque compensation. A typical response delay experienced during engine-only operation is shown in Figure 6b. This figure also illustrates the brake release bump phenomenon that commonly occurs in automatic transmission equipped vehicles.

**Pedal feel** problems are more likely to occur in HEVs since the driver’s demand for power (or acceleration) can be met using different actuators through different paths\textsuperscript{37}. Additional drivability considerations may arise in hybrid vehicles due to the presence of multiple (often redundant) actuators and as a result of the operating principles of supervisory control strategies\textsuperscript{38}. Due to the complex nature of hybrid drivetrains, HEVs are usually operated in fully or partially mode-based control\textsuperscript{39}, that is, mode selection and switching is an integral part of the supervisory control strategy. Such a mode-based control is architecture dependent (e.g., a PHEV could operate in electric-only mode or in hybrid mode, with obvious differences in the control strategies implemented and in the actuators used). One common element that is present in virtually all hybrid vehicles is the engine start-stop function. Since the start-stop function is frequently used in hybrid vehicles, its seamless implementation is crucial for consumer acceptability\textsuperscript{39}. Mode transitions that affect drivability in HEVs are not limited to the engine start and stop events. For example, a mode change from hybrid operation to regenerative braking may excite driveline vibrations when the gear backlash reverses direction.

**EMISSIONS OPTIMIZATION**

The main selling point of **hybrid** vehicles is their superior fuel economy. While improved fuel economy typically has a trickle-down effect on emissions, this is not always the case. A well-known example is the lab test results of retrofitted Toyota Prius vehicles with larger (~5 kWh) battery packs\textsuperscript{40}, designed to enable plug-in operation. While the added battery energy improves overall fuel economy, the longer time interval between engine starts and stops caused the catalytic converter to not heat up properly. Therefore, tailpipe emissions at least
an order of magnitude worse than a production Prius were measured. In this particular case, the engine-out emission did not change much, but the catalytic converter light-off was seriously affected. Since the conversion efficiency of a cold catalyst is very low, fast catalyst warm-up and sustainment are the keys to minimizing tailpipe emissions.

To include tailpipe emission, in addition to fuel economy, in the performance index, catalyst temperature needs to be added as a dynamic state in the hybrid powertrain model. The catalyst can be treated as a thermal mass with engine exhaust gas as a heating source, and heat exchange with ambient air as the main heat loss. Then there are at least three ways to solve this combined fuel economy–emission problem. The fuel economy and emission can both be included in the cost function with tunable weights; the fuel economy optimization problem can be solved with emission as a constraint; or emission can take priority during cold start and then switch to fuel economy dominant after catalytic converter light-off.

**PREDICTIVE/ADAPTIVE ENERGY MANAGEMENT AND IMPLICATIONS OF ITS**

Driving cycles and velocity profiles have great impact on the performance of hybrid vehicles in terms of overall energy consumption, fuel economy and emissions. It has been suggested that road type and traffic condition, driving habits, and vehicle operation modes have various degrees of impact on vehicle fuel consumptions. In addition, incorporating knowledge derived from intelligent transportation systems (ITS) about online driving pattern recognition and traffic and geographical information in control strategies is another path towards the optimization of PHEV energy management.

Intelligent Transportation Systems (ITS) allow the vehicle to communicate with other vehicles and the infrastructure to collect information about surrounding and expected events in the future, e.g. traffic condition, turns, road grade, rain, snow, temperature, etc. Such information can assist in designing algorithms such as stochastic dynamic programming, model predictive control, etc. ITS information can be utilized for long-term trip forecast as well as short-term velocity and power profile prediction. Static and dynamic information including road grade and road surface conditions, speed limits, traffic light locations and timing, and real-time traffic flow speeds can be used to build a long term forecast of the overall trip to the destination. At the same time, information about the immediate surroundings, such as lane changing and turning decisions of the host and surrounding vehicles, and estimation of waiting time for turning on red, left turns and stop sign queuing, is helpful for refining short term prediction of future driving profile.

Advances in GPS, telecommunication, and portable computing devices will change many aspects of vehicle energy management. In the future, we will see fuel-efficient, environment- and traffic-aware vehicles that integrate ITS and telematic systems with electrified propulsion technology to achieve optimal energy management.

**FUTURE OUTLOOK**

As the penetration of plug-in vehicles (PEVs) increases, their impact on the power grid cannot be neglected; thus, consideration of increased electric power demand and of the timing of vehicle charging must be included in the control/optimization process. In the future it will become necessary to analyze information in real time to quantify the effects of infrastructure, environment, and traffic flow on vehicle fuel economy and emissions, and to permit the application of forecasting and optimization methods for the energy management of PEVs.

The electric grid and the transportation system are the two largest sectors that produce greenhouse gas emissions. When large numbers of vehicles are electrified and draw power from the electric grid, it is important to aim for reduced overall greenhouse gas emissions, rather than just shifting emissions from tailpipes to power plant stacks. Alternatives to coal or natural gas to provide energy for electrified vehicles are therefore attractive. Using electricity generated from wind power to charge vehicles is one such alternative: not only does electricity from wind have a lower carbon footprint, but plug-in vehicle charging is also an effective way to mitigate wind intermittency. Electricity generated from solar power has similar characteristics, except that it is generated during daytime and is better suited for at-work PEV charging rather than charging at home.

In 36 states and the District of Columbia there is now a renewable power portfolio mandate. Other countries have already set an example on how to integrate renewableables in the power grid, e.g., Denmark primarily uses hydropower to smooth variations in wind generation. Controlling the charging of plug-in vehicles to alleviate the impact to the grid has been studied, including the idea of using plug-in vehicles as ancillary services to the grid, possibly with significant renewable power sources connected to the grid. Modeling and simulating this integrated system requires information on detailed grid load profiles, power generation pricing and carbon emissions, wind statistics, vehicle usage statistics. In addition, charging control must balance multiple factors: grid stability, fully-charging all vehicles, minimizing data collection and communication, and overall system carbon emission minimization.

In conclusion, the design, modeling and control of hybrid vehicles is a subject rich in research opportunities for the dynamic systems and control community. We hope to have conveyed in this article the extent to which this subject lends itself to advances in dynamic modeling and model-based control.
ACKNOWLEDGEMENTS

We would like to acknowledge the invaluable contributions of our colleagues and students at University of Michigan and Ohio State University. We are grateful for financial support from the automotive industry as well as from the U.S. National Science Foundation, Department of Energy, and Army.

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