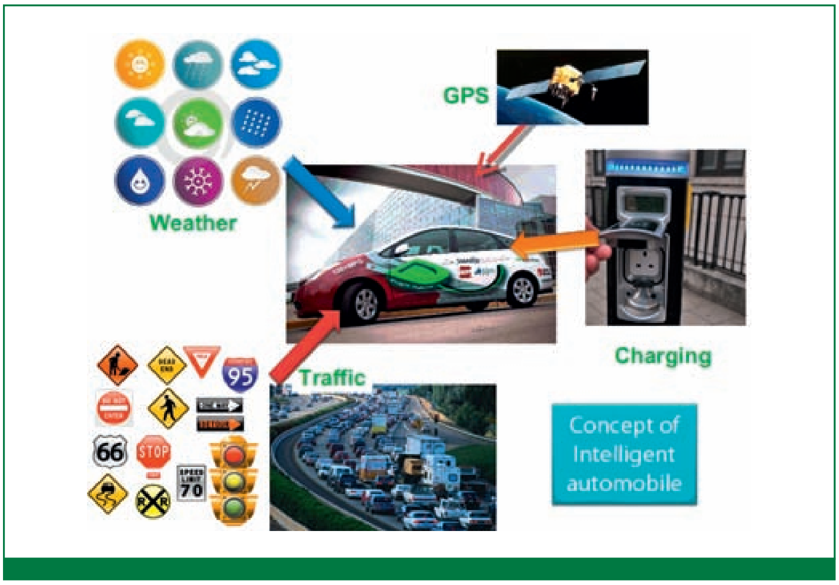
Intelligent Energy Management

of Plug-In Electric Vehicles with enviroment and traffic awareness



1. Introduction

Public awareness of climate change and of the importance of energy savings is increasing and governments are encouraging the use of renewable energy. A clear correlation can be observed between vehicle density (cars per 1000 inhabitants) and a country's GDP (gross domestic product); this suggests that as densely populated countries such as China, India, and Brazil achieve higher economic status, it can be expected that the demand for personal transportation will increase accordingly. Today, this demand can be directly translated into increased demand for petroleum, a fact that is hardly compatible with current data on oil production.

Plug-In Electric Vehicles (PEVs, whether hybrid or battery-only) are receiving a great deal of interest in the United States due to their energy efficiency, convenient and low-cost recharging capabilities and reduced use of petroleum. Recent improvements in lithium batteries technology are making PHEVs (plug-in hybrids) in particular a viable solution to reduce cost, petroleum consumption and emissions from the transportation sector. PHEVs aim at bridging the gap between pure electric vehicles and conventional vehicles using a hybrid electric powertrain [1]. Similar to a hybrid electric vehicle (HEV), a PHEV is powered by two energy sources, gasoline and electricity. In a HEV, the battery is charged using the engine and regenerative breaking and the battery state of charge is maintained around a constant value throughout the driving cycle. The improvement in fuel economy of HEV is achieved by the optimization of power split between battery and engine. A PHEV has greater battery capacity than a HEV and the ability to charge the battery from external sources such as the power grid, solar power, etc. The external charging ability allows the PHEV battery to be depleted during the vehicle operation and be charged when the vehicle is plugged-in, thus using electrical energy as a transportation fuel and displacing gasoline.

01 shows that a typical U.S. driver may benefit from a 50 percent reduction in total yearly operation costs [2]. In **01**, D1, D2 and D3 represent typical driving days for a U.S. driver, wherein D1 represents a typical commute to work; D2 represents a commuting day plus evening errands; D3 mimics a weekend trip, and the entire year is comprised of a suitably balanced mix of these representatives driving patterns.

In addition to fuel consumption and cost of operation, another important factor for a PHEV is the combined CO_2emissions from vehicles and electric power plants. The total CO_2emissions depend on the generation mix used to charge the PEV and therefore any results will depend on the regional power generation mix.

02 shows that CO_2 emissions related to the automotive sector could be decreased by PHEV and HEV use, in particular using a low-carbon source of energy (such as nuclear or renewable) to recharge PHEVs batteries, CO_2 emissions could be drastically reduced.

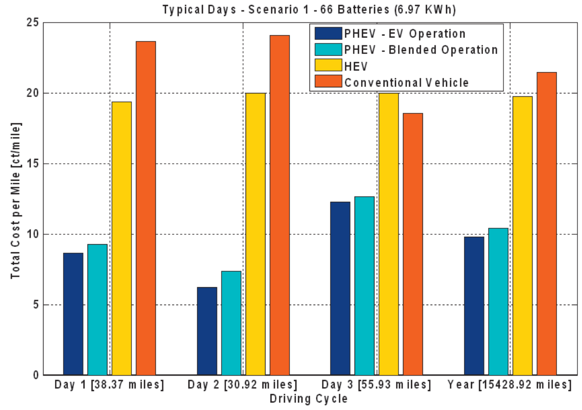
03 shows the impact of different generation mix on total CO_2 emissions, comparing annual per vehicle CO_2 emissions of a PHEV charged with different countries' energy mix, e.g. in Switzerland the electricity is produced using hydroelectric and nuclear plants without emitting GHG therefore a PHEV will not produce pollutants emissions to recharge its batteries [3].

2. Energy management of PHEVs

Energy management algorithms for PHEVs are crucial for vehicle performance. Energy management strategies in a PHEV are similar to those employed in HEVs, with the additional degree of freedom corresponding to the ability to deplete the battery pack to obtain electric tractive power in significant quantities, coupled to the possibility of recharging the pack [4].

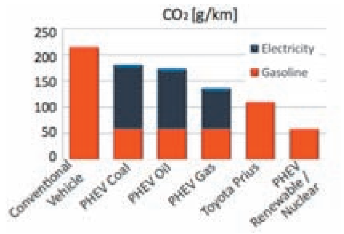
A heuristic comparison of different energy management strategies with respect to online implementation and information requirements is graphically shown in **04**. Dynamic Programming (DP) is a numerical optimization methodology that can compute the optimal solution, but that it is practically impossible to implement on a vehicle since it requires complete information of the future driving cycle. DP also requires a large amount of memory and computational power to perform the optimization. Other algorithms, such as rule-based algorithms, or other online optimization methods like Equivalent Consumption Minimization Strategy (ECMS) [5] and stochastic dynamic programming [6], can on the other hand be implemented on board of a vehicle. These algorithms do require some information to perform offline optimization or tuning of the parameters but it is typically less than that required by dynamic programming. As one might imagine, there is a trade-off between information requirements and algorithm performance.

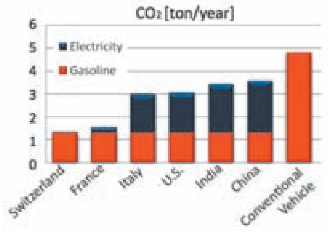
For instance, the EV mode control is a simple method with two stages – charge depleting



01

Comparison of PHEV with HEV and conventional vehicle based on operating cost for typical US driver.





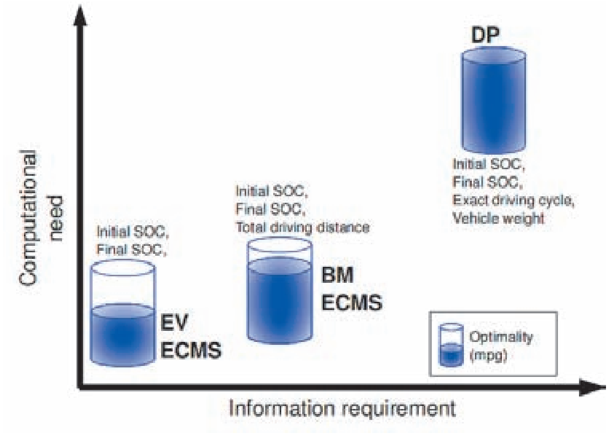
02/03

Vehicles CO_2 emissions comparison.

Effect of generation mix on CO_2 emissions.

SUMMARY

The desire to reduce carbon emissions due to transportation sources has led over the past decade to the development of new propulsion technologies, focused on vehicle electrification (including hybrid, plug-in hybrid and battery electric vehicles). These propulsion technologies, along with advances in telecommunication and computing power, have the potential of making passenger and commercial vehicles more energy efficient and environment friendly. In particular, energy management algorithms are an integral part of plug-in vehicles and are very important for achieving the performance benefits. The optimal performance of energy management algorithms depends strongly on the ability to forecast energy demand from the vehicle. Information available about environment - temperature, humidity, wind, road grade etc., and traffic – traffic density, traffic lights etc., is very important in operating a vehicle at optimal efficiency. This article outlines some current technologies that can help achieve this optimum efficiency goal. In addition to information available from telematic and geographical information systems, knowledge of projected vehicle charging demand on the power grid is necessary to build an intelligent energy management controller for future plug-in hybrid and electric vehicles. The impact of charging millions of vehicles from the power grid could be significant, in the form of increased loading of power plants, transmission and distribution lines, emissions, and economics. Therefore this effect should be considered in an intelligent way by controlling/scheduling the charging through a communication based distributed control.



04

Comparison of the control strategies. DP: Dynamic Programming, BM ECMS: Blended Mode control using ECMS, EV ECMS: EV mode using ECMS. (ECMS: equivalent consumption minimization strategy).

(all electric) and charge sustaining. The control algorithm selects only the electric motor as long as the battery state of charge (SOC) is greater than a threshold value. Once the SOC reduces below this value, the control algorithm switches to charge sustaining (PHEV behaving like a HEV). In blended mode control, the objective is to achieve lower limit of SOC only at the end of trip. The battery SOC is reduced slowly throughout the trip, and the SOC profile followed in this control can be optimally selected by principles from optimization theory, like dynamic programming. This method can provide better fuel economy, but at the cost of higher information requirement.

ECMS is based on the fact that in general a hybrid vehicle the energy consumption from the battery is replenished by running the engine. Therefore, battery discharging at any time is equivalent to some fuel consumption in the future. For PHEV applications, the ECMS needs to consider also the energy coming from the grid: this effective fuel consumption is used as the objective function for control optimization while the input to the ECMS algorithm is total power demand. The ECMS searches the best combination between the engine and motor power, which minimizes the effective fuel consumption.

3. Information requirement

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

The performance of the energy management algorithm is closely related to the power demand throughout the driving trip. The power demand depends on the road, weather conditions and velocity profile, which in turn is dependent on traffic and geography. The performance of energy management can be improved if it is optimized for the driving conditions and weather pattern. Therefore, information about the driving route, a weather forecast, and traffic conditions, are very important in guaranteeing optimal performance of the energy management strategy. 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 is useful for the energy management algorithm optimization and plays crucial role in the fuel economy and battery utilization, as it 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. ITS information can improve vehicle energy efficiency and mobility with route planning. Road static information, real-time traffic flow, battery charging station locations and real-time prices and other information is useful in determining an optimal route for energy efficiency and short travel time. **05** shows a concept of such an intelligent energy management algorithm and its integration with ITS data.

An intelligent energy management algorithm will have access to GPS location of the vehicle along with expected route information, traffic conditions, current temperature, and driving history of the vehicle. Based on this information the vehicle energy management algorithm will forecast the traffic condition, and power demand from the vehicle. The algorithm will then optimize its decisions to optimally select battery usage and reduce fuel consumption, emissions, etc. In this way an intelligent energy management strategy will adapt itself to the changing weather and traffic conditions to give best performance.

It is worth noting that the future information about the weather, velocity profile and PHEV charging is not exact and complete i.e. it is not possible to predict exact velocity profile for complete driving trip, but it is possible to predict the velocity profile in statistical sense i.e. prediction of average velocity, average acceleration, idle time, stop time etc. It is also possible to predict the availability of charging station, cost of electricity etc. to control the battery state of charge and charging. Such quantities can be calculated from trip information, GPS, communication with the infrastructure etc.; also many conditions can be predicted for weather, e.g. temperature, rain, snow etc. The task of predicting all such quantities and use them to perform energy management optimization is clearly overwhelming. One objective of this article is to suggest the most important factors that affect the performance of the energy management system. For example, the velocity profile depends on the road events and traffic conditions such as a traffic light, stop sign, pedestrian crossings, etc. Similarly, the initial SOC is a function of charging habits and infrastructure availability. We call the systematic analysis of these conditions Impact Factor Analysis, and describe it in the next section.

4. Impact factor analysis

The research described here is centered on real world driving data from a PHEV fleet operated by Center for Automotive Research at The Ohio State University. This database currently contains more than 100,000 miles of vehicle data throughout the year with many different variables such as longitude, latitude and altitude from GPS, vehicle velocity, coolant temperature, fuel consumption, battery SOC, current etc. from vehicle CAN bus, along with time and date. The GPS data is sufficiently accurate so that it can be used to exactly locate the vehicle on the road and also determine the lane. This data is used in this analysis to find the velocity traces during road events and then perform the statistical analysis.

05

Concept of intelligent energy management for a PHEV.

In this process, an Impact Factor Knowledge Base has been constructed, with important information on which factors have the largest impact on performance, and which factors are most important for subsequent development of energy management strategies in optimizing fuel economy. Using these tools, a generalized sensitivity analysis will be conducted to delineate and prioritize variables, configuration/sizing and control parameters, usage pattern, etc. according to performance benefits. The initial part of this task is to intelligently reconstruct a real world dynamic transportation map from both the static data (GPS, GIS, Mapping, etc.) and dynamic data (V2I, V2V information exchange/broadcast) for the purpose of PEV energy management optimization. The critical task is to identify what information can be used to improve fuel economy and to determine the requirements on this information.

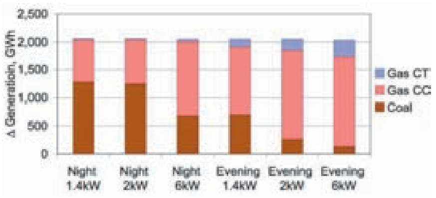
Different events are defined for weather, road, driving and charging conditions e.g., traffic lights, stop signs, turns, lane changing, driving in snow, rain, temperature effect, charging availability, charging power, etc. A more elaborate list is given in Table 1. Initially, the impact of the single events on the velocity profile is analyzed. The goal is to determine how such events affect velocity profile of the vehicle and how this information can be used to optimize the PHEV energy management strategy. Next, a specific route is consid-

Weather conditions	*Road and traffic*	*Charging*
Snow	*Intersections (Stop signs, Yield signs, Turns)*	*Availability (At home, Workplace)*
Rain	*Road grade*	*Policy (Controlled, Uncontrolled)*
Fog	*Traffic light (Numbers, Stop time, Distance between lights, Synchronized?)*	*Charging power (Level I, Level II)*
Wind	*Traffic density*	*Electricity cost*
Ice	*Pedestrian crossing*	
Temperature	*Ramps*	
	Speed limits	

T01

Impact Factors.

ered to find the important velocity statistics e.g., average velocity, maximum acceleration, stop time, etc. which have large impact on the fuel consumption. Similarly, the effects of ambient temperature, humidity, and air density on PHEV energy utilization and fuel economy are analyzed.



06

Effect of charging time on generation mix [7].

5. PHEV charging

Local distribution grid load pattern may change and some power lines, substations can become overload quickly. The charging load can increase the emissions from the power generators based on the generation mix of the power grid. The increase can be very high that that the net emission (tailpipe + power grid) could be larger than that of the conventional vehicles.

PHEV charging is performed when the vehicle is stopped. So the charging time and duration is dependent on the user. Vehicle charging is reflected as a load or demand on the grid, so it is necessary to study the effect of vehicle on the grid and the effect of different level of market penetration of PHEVs into the automotive sector. As the number of vehicles increase the charging demand may exceed the grid capacity or may cause severe constraints on its operation. The time and location of the vehicles determine whether the effect of the PHEV charging will be on local grid or regional power system. PHEV charging may require more generation capacity, more transmission and distribution capacity to meet the electrical power demand. One possible behavior, which could be rewarded by appropriate electricity pricing policies, would see PHEVs being charged primarily at night, with reduced effects on the grid. But in general, charging time during the daytime is a very important factor in determining the fuel consumption, emissions and cost of electricity for a PHEV, as illustrated in **06**. **06** shows the result of a study performed using the ORCED model for generation dispatch in the Virginia-Carolina control region [7]. The time of charging decides which generators will be used to satisfy the increased demand; for example, evening charging would increase natural gas combined-cycle generation while night time charging would increase coal-fired power generation, with clear implications with respect to cost and emissions.

Thus, time-of-charging can have a significant impact on the emissions and the generation associated with electricity used as a transportation fuel. From the figure, it is clear that in most cases the power plants used to satisfy incremental loads in the early evening are gas combined cycle and gas turbine power plants. The evening scenarios have the majority of the generation coming from these plants, while in the nighttime charging scenarios most of the added generation comes from coal. Although night charging will result in minor impact on the grid, it is worth noting that the energy mix for night charging has a higher coal-fired plant content.

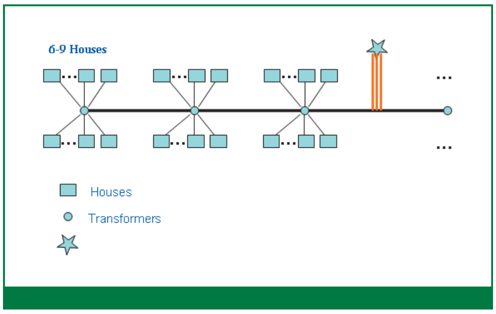
Therefore, apart from the optimization of energy management of PHEVs, it is also important to intelligently control the charging behavior. If all vehicle controllers independently decided to charge without any external signal, grid stability could be compromised. Therefore it is necessary to provide a centralized charge-enabling control to each vehicle. This control could be provided by the grid operator (e.g.: an Independent System Operator, or ISO). The concept of 'Smart Charging' relies on communication interface between the power grid and the vehicle to control the charging time and avoid diverse effect on the power grid. Each vehicle is equipped with a communication interface, either a wireless link, internet connection etc. This interface provides the commands to the vehicle and also it sends signals back to ISO. The signals may include power availability in the vehicle battery, power usage history, power absorbed from and supplied to the grid etc.

6. PHEV impact on transformer

The characteristics of electric power generation, transmission and distribution in the U.S. are such that experts have clearly identified local distribution as the most likely component of the chain to be adversely affected by unregulated PEV charging. This section presents one study performed to find the impact of PEV charging on the local distribution transformer. The findings of this study may assist in determining the most suitable local/regional charging strategies for PEVs. Currently, in the U.S. electric power to single-occupancy home residence is provided by a transformer that typically feeds several units (4-10 houses depending on the transformer size), as shown in **07**. Based on the existing design, the total power load is less than the maximum limit of the transformer, which means that the transformers can work safely, without overheating, and meet their intended design life of at least 20 years. However, with more and more PEVs to be used in the future, will residential transformers still be able to meet the new load demand without undue reduction in their life? Currently, there are three levels of charging rates for PEVs: level I to level III. For the purpose of illustration, we consider level-II charging, which delivers approximately 4 kW at 240 V.

Transformer life is a complicated function of electrical load and ambient temperature. Generally, heat is the biggest enemy of transformer life. One simple rule of transformer safe use of to set a limit to peak load duration, based on some empirical tables or maps, such that during a day the transformer load cannot exceed some value, which is determined by the preload level.

08 takes a 25-kVA transformer for example. In this case, we assume that four PHEVs are charged at night with Level II charging. A simple estimate shows that the average preload for the 25-kW transformers is about 75 percent Based typical industry guidelines, to meet its design life goals, peak load (about 37.5 kW) should not exceed 3 hours for the transformer. Obviously a PEV without any intelligent control cannot guarantee that the transformer will not be overloaded for an excessive period of time. It should be expected that in the future intelligent PEVs will have access to this information from the utility companies via a communication link, and will be able to make decisions about charging time and power considering the limitations of the local distribution system.



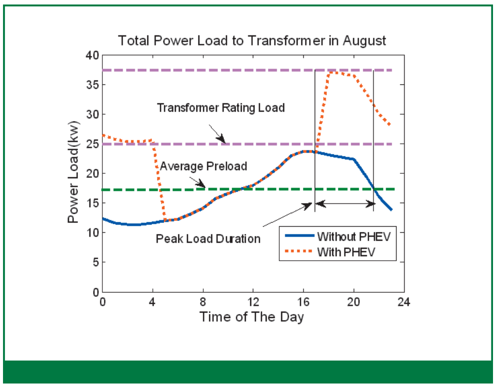
07

Topology of power grid and houses.

7. Closure

Advances in GPS, telecommunication, and portable computing devices will change many aspects of vehicle energy management. This article suggests that 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.

Further, the impact of PEVs on the power grid cannot be neglected when large numbers of these vehicles are introduced in the market; 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 plug-in electric and hybrid vehicles.



08

PHEV load on the transformer. Red dotted line shows increased demand from PHEV charging.

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