

Energy, Economical and Environmental Analysis of Plug-In Hybrids Electric Vehicles Based on Common Driving Cycles

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ABSTRACT

The objective draw by this project is to develop tools for Plug-in Hybrid Electric Vehicle (PHEV) design, energy analysis and energy management, with the aim of analyzing the effect of design, driving cycles, charging frequency and energy management on performance, fuel economy, range and battery life.

A Chevrolet Equinox fueled by bio diesel B20 has been hybridized at the Center for Automotive Research (CAR), at The Ohio State University. The vehicle model has been developed in Matlab/Simulink environment, and validated based on laboratory and test.

The PHEV battery pack has been modeled starting from Li-Ion batteries experimental data and then implemented into the simulator.

In order to simulate "real world" scenarios, custom driving cycles/typical days were identified starting from average driving statistics and well-known cycles. The driving cycles are based on commonly accepted standardized cycles (FUDS, FHDS, etc) and then combined to reflect common driving habits, average commute time, thus resulting in an annual distance traveled of about 15.000 miles.

Several scenarios have been drawn considering different vehicle operation modes, i.e. EV (electric vehicle) and blended, different battery sizes, 6.97 and 8.87 kWh of stored energy and different charging availability, i.e. controlled (once a day, overnight) and uncontrolled (charging is possible whenever the vehicle is parked).

For a complete assessment of the benefits achievable by PHEVs, results are compared to two other vehicle architectures (equivalent in terms of available power): the hybrid version of the proposed model and the conventional ICE vehicle (stock vehicle converted into B20). Results show significant benefits of PHEVs in

terms of petroleum reduction, overall fuel cost and CO₂ emissions; it is also clear that none of the proposed configurations (i.e. different battery sizes) and vehicle operation modes (i.e. EV or blended) represents an absolute optimum, but the analysis strongly depends on the chosen objective function to minimize, vehicle components sizing and adapted strategies, fuel and electricity cost, charging availability and power grid generation mix.

INTRODUCTION

Plug-In Hybrid Electric Vehicles (PHEVs) are receiving a great deal of interest in the United States. Recent improvements in lithium batteries technology are making PHEVs a viable solution to reduce cost, petroleum consumption and emissions in the transportation sector. PHEVs aim at bridging the gap between pure electric vehicles (EVs) and conventional vehicles using a hybrid electric powertrain. The distinguishing feature of a PHEV is the ability of the vehicle to receive energy from the electrical grid to increase the state of charge of the battery. Just as there is dichotomy of HEVs from the belted starter-alternator system (like the General Motors BAS+ system), to more aggressive hybrids (like the Toyota Prius), there is a similar range of potential PHEVs. By way of example, the Chevy Volt scheduled for release in 2010 boasts an all electric range of 40 miles whereas vehicle conversions, such as the Hymotion system available for the Toyota Prius, only permit a continuous electric supplement to the hybrid system allowing more use of the electric motors. These different architectures as well as the habits of the individual owners will affect the performance of the vehicles, the impact on the grid, and the overall benefit to society.

PHEVs pose a unique problem for analysis, mainly because the vehicle performance has a stronger link to

customer usage patterns compared to a conventional vehicle or HEV. For these two types of vehicles, the fuel is the only net source of energy and this source of energy must always be present for the vehicle to operate.

A PHEV has much more flexibility since it has two sources of net energy, the fuel as well as the energy taken off of the grid.

The Center for Automotive is very active in the field of transportation electrification, specifically in activities related to electric vehicles, conventional hybrids and plug-in hybrid electric vehicles. Several research programs are currently underway, involving modeling, validation, road testing and vehicle engineering.

One of the projects consists in the conversion into PHEV of a hybrid Chevrolet Equinox fueled by bio diesel B20. As explained in the following section, this vehicle has been hybridized starting from a stock vehicle in the context of the Challenge-X competition.

The scope of the paper is to conduct an investigation and comparative analysis of the energy efficiency, emissions and refueling cost for different vehicle configurations/architectures/controls and scenarios, with respect to comparable ICE and HEV architectures.

DESCRIPTION OF THE PHEV SIMULATOR

The analysis is conducted in simulation, using energy-based models of hybrid powertrains. Such models, developed at The Ohio State University Center for Automotive Research (OSU-CAR) and described in the following sections, are characterized by a modular structure, which allows one to make changes to the vehicle configuration and energy management strategy.

HEV PLATFORM - The simulators used in the study build upon the energy-based model Cx-Sim [1], [2] and [3] designed and validated for the Challenge-X student competition project, and implemented in MATLAB - Simulink environment.

Challenge-X was a competition held during 2005-2008 among seventeen North American universities, with the goal of re-engineering a production vehicle for improved fuel economy and reduced emissions while maintaining performance, utility, safety, and consumer acceptability. Teams achieve the competition goals by integrating advanced hybrid powertrains, novel control strategies, alternative fuels, lightweight materials, and innovative emission control techniques [4].

The OSU Challenge-X vehicle is based on the series/parallel configuration shown in Figure 1, while Table 1 describes main vehicle components.

The chosen vehicle architecture includes a downsized Diesel engine and a six-speed automatic transmission driving the front axle. The engine is coupled to a belted starter/alternator (BSA) [5], while a larger second electric machine (EM) is used to drive the rear axle. The energy storage system includes a high-voltage NiMH battery

pack. Furthermore, the choice of biodiesel, and in particular B20, is due to better performances in terms of energy consumption and greenhouse gas emissions on a well-to-wheel basis [6].

Table 1 Description of the main vehicle components

COMPONENT	TYPE	SPECIFICATIONS
CHASSIS	Mid-size SUV	2005 Chevrolet Equinox
ENGINE	1.9L Diesel	4 Cylinder, 16v, Euro 4, 103 kW @ 4000 rpm, 305 Nm @ 2000 rpm, 17.5:1 Comp. Ratio, Bore 82.0 mm, Stroke 90.4 mm.
BELTED STARTER/ALTERNATOR [5]	Permanent Magnet	Kollmorgen Servomotor and Accompanying Electronics, 10.6 kW Nominal Power, 124 Nm Peak Torque, 4150 r/min Max Speed.
POWER TRANSMISSION	Belt & Sprocket	48 Tooth Sprocket, Bolted In Place of Harmonic Dampener; 48 Tooth Sprocket Locked to Motor Shaft. Sprocket Diameter 12mm, Transmission Ratio 1:1.
ENERGY STORAGE	NiMH Batteries	38 Panasonic Prismatic Modules, 7.2V, 6.5 Ah.

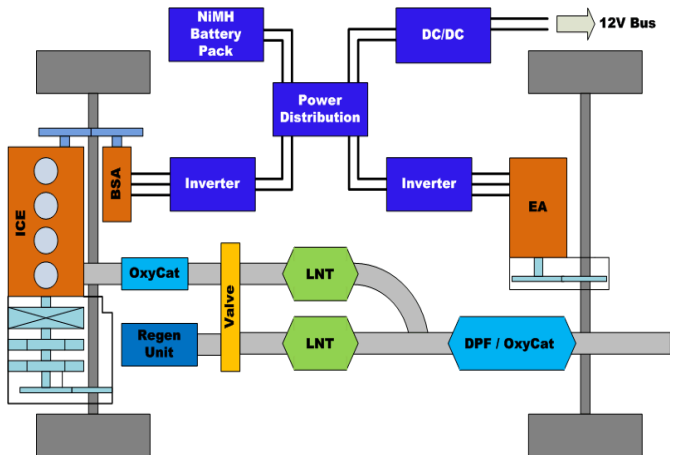


Figure 1: The Challenge-X architecture [1]

The series-parallel split-hybrid configuration allows for a variety of modes such as pure electric drive, electric launch, engine load shifting, motor torque assist, and regenerative braking.

Based on the configuration described above, the Cx-Sim simulator was developed. The model was built following an energy-based approach and validated on sets of components data and driving tests [1], [2].

The control strategy implemented manages the torque demands to the engine, BSA and rear electric motor, based on the Equivalent Consumption Minimization Strategy (ECMS) [7], [8], [9], [10] and [11]. The approach splits the power flows in order to instantaneously minimize a cost function defined as the effective fuel consumption considering the effect of the battery:

$$J(t) = \int_0^{T_f} \dot{m}_{eq}(t) dt = \int_0^{T_f} (\dot{m}_{ice}(t) + \dot{m}_{batt,eq}(t)) dt \quad (1)$$

where $\dot{m}_{ice}$ is the fuel consumption of the ICE and $\dot{m}_{batt,eq}$ is the equivalent fuel consumption. While the former is estimated directly from the engine fuel consumption maps, the latter is calculated indirectly from the energy flows to and from the battery pack. Any energy consumption in the battery is replenished by running the engine. This allows for establishing a direct correspondence between the electrical current flows and the equivalent fuel consumption, calculated by means of the equivalency factor used in the ECMS strategy.

As already mentioned, the simulator was validated on the basis of the Challenge X HEV configuration, using information from the components datasheets and experimental data from road tests. This allows for establishing the performances of the HEV as a benchmark for the other configurations that will be presented in this study, namely Conventional Vehicle (CV) and PHEVs.

CONVERSION TO PHEV – The vehicle will soon be converted into PHEV, with an additional lithium battery pack. To guarantee a proper design and optimal control strategies, the analysis is being performed in simulation; next steps will include battery pack engineering and testing, system integration, etc.

In order to simulate the performance of PHEVs, the HEV simulator was modified by substituting the battery pack and the control strategy.

For a conventional HEV, the electrical storage system is sized to operate the vehicle in Charge Sustaining (CS) mode, namely maintaining nominally constant battery State of Charge (SOC). Conversely, the energy storage system in PHEVs must be larger than in HEVs in order to enable for extended electric range and to take advantage from the capability of recharge directly from the power grid.

Furthermore, because the high energy and power density requested, Li-Ion technology appears as most adequate for PHEVs. For this reason, the NiMH battery stack used in the simulator was replaced with a series of GAIA Li-Ion cells of 33 Ah each, whose specifications are shown in Table 2.

Table 2 GAIA Battery specifications [12]

	WEIGHT	1450 g
	NOMINAL VOLTAGE	3.2 V
	NOMINAL CAPACITY	33 Ah
	ENERGY DENSITY	183 Wh/l
	POWER DENSITY	5140 W/l

The model characterizing the battery dynamic response is a second order RC circuit, where the parameters have been identified on laboratory tests conducted at OSU-CAR [13]. In order to maintain a simple model structure, the thermal and aging effects were not considered.

The application of ECMS for the energy management of PHEVs introduces new challenges, mainly because the energy stored in the batteries is no longer directly related to the equivalent fuel consumption. In order to properly estimate the cost of the on-board energy flows, the interaction between the vehicle and power grid must be accounted for.

In case of PHEVs, the ECMS follows the same principles as in conventional HEVs but it includes different constraints and, according to the new recharge capability, the objective function of the minimization problem needs to be redefined.

First of all, the cost function must consider both the fuel consumption of the ICE and the electricity depleted from the battery. Different approaches may be adopted to account for the energy that is initially stored in the batteries when the vehicle is connected to the grid, as discussed in the following sections. Furthermore, the ECMS could be refined by including additional terms in the cost function, e.g., emissions or the total operation cost.

The supervisory control algorithm considered for PHEV simulation is based on ECMS, with a new cost function that accounts not only for the ICE fuel consumption but also considers other factors associated with the electric energy, namely costs and emissions given by the production of electricity.

$$J(t) = \int_0^{T_f} (\dot{m}_f(t) + J_{elec}) dt \quad (2)$$

where, $\dot{m}_{ice}$ is the mass flow of fossil fuel into the internal combustion engine, T_f is the duration of the considered driving pattern, and J_{elec} is the cost function associated with the electricity consumption.

In addition, the following constraints must be satisfied at each time t :

$$SOC_{min} \leq SOC(t) \leq SOC_{max}$$