Fundamental Design Analysis of a Dual-Fuel (Hydrogen and Gasoline) Extended Range Electric Vehicle Power Generation System

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ABSTRACT

Hydrogen is an ideal vehicle fuel for use not only in fuel cells, but also in a spark-ignition enabled Internal Combustion Engine (ICE). The combustion of hydrogen (H_2) fuel offers vastly superior tail-pipe emissions when compared with gasoline and can offer improved performance. H_2 is ideally suited for use in an extended range electric vehicle (E-REV) architecture where engine efficiency can be optimized for a single engine speed. H_2 ICE's are significantly more cost effective then an equivalent sized H_2 fuel-cell making them a better near term solution. Detailed technical analysis will be used to help illustrate the fundamental operation and performance characteristics of the dual-fuel E-REV Architecture. The variances and commonalities will be briefly discussed. Fundamental analysis will also be used to aid in the selection and integration of vehicle components such as the H_2 and gasoline fuel systems, batteries, generator, and transmission.

Keywords: E-REV, hydrogen, series hybrid, ZEV, dual-fuel

1 INTRODUCTION

The E-REV was first introduced to the North American auto market with the announcement of the 2010 Chevrolet Volt production model. Since then a number of E-REV and series hybrids have been announced for production by a variety of automakers. The vehicle architecture utilizes both electric motors and an ICE, but in a different manner than a parallel hybrid, as made popular by the Toyota Prius. Unlike a parallel hybrid, an E-REV provides power to the wheels only through the electric motor, whereas the ICE is used to run a small electrical generator which is in turn used to recharge the vehicle's battery pack. The vehicle typically has plug-in capabilities which allow the battery pack to be pre-charged at home every night during off-peak hours. The E-REV architecture possesses a number of unique advantages when compared to parallel hybrids and ICE based vehicles. Such advantages include zero tail-pipe emissions for short duration trips, reduced overall emissions and improved fuel economy. A basic architecture for the E-REV is shown in Figure 1.

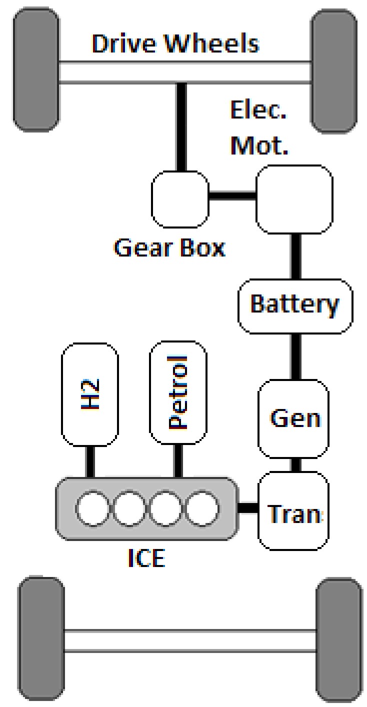

Figure 1 – Schematic of a Fundamental E-REV Concept Architecture

The E-REV is best identified as a near to intermediate term vehicle technology. While crude oil supplies continue to diminish a new fuel must be sought for future propulsion systems. While many experts predict that hydrogen will be the vehicle fuel of the future there is an equally compelling case for electricity and pure electric vehicles. Regardless the E-REV offers a unique platform for automotive development incorporating both electricity and the potential for hydrogen fuel research.

Hydrogen is highly abundant and possesses many beneficial properties that help lend itself to combustion. For example it burns nearly five times faster than gasoline in air, requires 14 times less energy to ignite and an octane number in excess of 130 when in a lean mixture with air. There is however a number of challenges with regard to the use of hydrogen in vehicles which occur at specific stages of the fuel lifecycle, they include: generation, distribution, and storage. [1, 2]

This paper attempts to quantify the E-REV as a complete system providing necessary technical analysis and a systematic approach to the design of an E-REV through the selection and integration of components into a new or existing vehicle. Empirical results from an actual E-REV build project will be used to support this work.

Prior to beginning the design it is important to understand the operational modes that exist within the vehicle. The project is further complicated by the addition of dual-fuel capabilities. The operation of the E-REV can be sub-divided into five modes as follows:

- **Charge Depletion Mode**, the battery is being used to provide power to the wheels and accessories.
- **Regenerative Braking**, the battery is being recharged by the regenerative capabilities of the electric motors which are providing resistance to travel in effect assisting in slowing the vehicle.
- **Hydrogen Charging**, the first of two fuel charging modes in which hydrogen fuel is combusted in the ICE and used to turn a generator.
- **Gasoline Charging**, the second of two fuel charging modes.
- **Re-fuelling**, Fuel 1 and/or Fuel 2 is depleted and is being re-filled from a variety of sources.

2 DESIGN CYCLE

The design cycle being proposed is tailored specifically for the technical design of a basic dual-fuel E-REV. It encompasses the components discussed in the following section (Sec. 3) and provides a means for effectively detailing the architecture for a new vehicle or a retro-fit project.

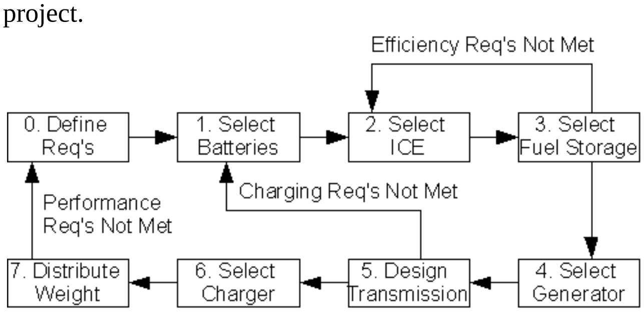

Figure 2 - Design Cycle Chart

As seen in Figure 2 above the design cycle begins with the definition of the vehicles requirements, which includes measures of performance, efficiency and economy. As the design process proceeds various feedback paths are available when requirements cannot be met using the current configuration. In this case it is necessary to re-design and reselect components to better match the requirements or to re-define unrealistic requirements which may have been made without consideration to cost or technical feasibility.

3 TECHNICAL DESIGN

3.1 Battery Selection

To begin the design process the first step is to define the basic capabilities of the vehicle that are dependent upon the batteries such as, all-electric range and top speed. Supplementary considerations include physical dimensions of the vehicle which constrain the battery volume and battery mass. From these initial constraints the batteries can then be selected. In order to quantify these key parameters and estimate their values several key equations will be utilized as an estimate of vehicle performance. The vehicles top speed can be estimated using Equation (1) [3].

$$V_{max} = \frac{-mgR\sqrt{(mgR)^2 - 2.586\cdot(DA)\cdot(-w * eff.)}}{1.293DA} \quad (1)$$

Where *m* denotes the vehicles mass, *g* the acceleration due to gravity, *R* the vehicles rolling resistance, *D* the drag force, *A* the vehicles frontal area, *w* the peak power output and *eff* the electrical drive train efficiency. Secondly, the vehicles range can be approximated using Equation (2) [4].

$$Range = \frac{250 * Capacity}{m^{0.6}} \quad (2)$$

A better approximation for the true capacity of the battery pack can be calculated by solving for the corrected Ah rating according to Equation (3) [4] and substituting that value into Equation (4) [4] along with the nameplate voltage of the battery pack.

$$Correct\ Ah\ Rating = \left\{\frac{\frac{Base\ Ah\ Rating}{DOD\ Factor}}{Peukert\ Factor}\right\} \quad (3)$$

$$Capacity = Corrected\ Ah\ Rating * V \quad (4)$$

The actual Ah rating of the battery pack can be determined by considering the Depth Of Discharge (DOD) and the Peukert effect, both of which depend highly on the chemistry of the batteries. The DOD Factor is used to determine the effective capacity of the battery pack by applying constraints on the amount of energy that is withdrawn from the batteries during each cycle. This depth of discharge consideration is especially important when dealing with batteries that exhibit a memory effect. The Peukert effect states that the faster you use the energy in a battery the less total energy is available. Table 1 illustrates DOD and Peukert Factors for Lead-Acid and Lithium Ion battery chemistries.

Chemistry	**DOD Factor**	**Peukert Factor**
Lead-Acid	1.25	1.8
Li-Ion	1.25	1.05

Table 1 - Battery Approximation Factors [4]

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3.2 ICE Selection

The second major sub-system which must be defined is the vehicle's internal combustion engine. Unlike a conventional vehicle or parallel hybrid, the ICE of an E-REV is significantly smaller and often uses forced induction to increase the power to displacement ratio. A number of motor concepts exist for the combustion of hydrogen and gasoline. Figure 3 depicts four such typical ICE solutions. The amount of power that the hydrogen injection produces when compared to a standard gasoline carbureted engine is also shown. However, there is a trade off; with increased power gains comes a greater need for complex electronic controls and higher developmental costs [5].

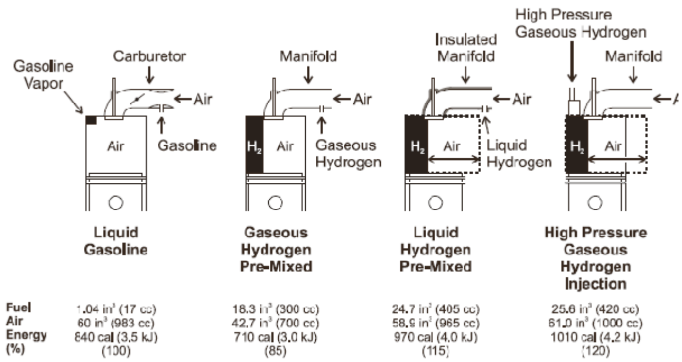

Figure 3 - ICE Comparison [5]

Once a suitable technology has been found the engine must be tuned for a single RPM band for each of the fuels. Dynamometer testing will help to yield the optimal efficiency points for each fuel. With dynamometer data the engines BMEP and thermal efficiency can be calculated according to Equations (5) and (6) [6]. To find the thermal efficiency it is important to consider the relationship of energy input to mechanical energy output. The power output p is then divided by the mass flow of fuel $\dot{m}_f$ multiplied by the Lower Heating Value (LHV) of the fuel.

$$\eta_{th} = \frac{P}{\dot{m}_f * LHV} \quad (5)$$

The Brake Mean Effective Pressure (BMEP) represents the average gas pressure within the cylinder minus the pressure required to overcome friction. It provides an excellent perspective on the operating conditions of the motor. It can be calculated directly from the dynamometer results by using the horsepower *hp* values at various RPM's *N* and the parameters of the engine. Such parameters include the displacement *D*, the stroke length *L*, and the number of cylinders *M*. The most efficient operating points can then be chosen for each fuel [6].

$$BMEP = 1{,}008{,}000 \frac{hp}{D^2 LMN} \quad (6)$$

3.3 Fuel Storage

The H_2 and gasoline storage volumes can be quantified by first determining the range requirements for the vehicle. By using the range as a constraint the amount of fuel energy required and subsequent volumes and in the case of hydrogen pressures can be calculated. The energy equations for hydrogen and gasoline are shown in Equations (7) and (8) [7]. The energy in hydrogen is dependent upon the pressure *P*, the volume *V*, the molar gas constant *R*, the temperature of the gas *T*, the molar mass of H_2 gas W_H and the Lower Heating Value (LHV). The energy of gasoline is approximated using the volume and the LHV.

$$E_H = \frac{PV}{RT} * W_H * LHV \quad (7)$$

$$E_{gasoline} = V_{gasoline} * LHV \quad (8)$$

By using the energy values calculated by using Equations (7) and (8) as well as the thermal efficiency of the motor, the amount of electrical energy delivered to the batteries can be calculated. Using Equation (2) the range extension capabilities of the vehicle can be approximated for each fuel as in Equation (9).

$$Extended\ Range = \frac{250 * E_{Fuel} * \eta_{th} * \eta_{drivetrain}}{m^{0.6}} \quad (9)$$

3.4 Generator

The generator acts to convert mechanical energy into electrical energy which can be used to recharge the E-REV's battery pack. The generator is typically a DC electric motor and in its most simple iteration a brushed DC motor which offers efficiencies upwards of 95%. For a brushed DC motor a simple comparison of torque and efficiency can be made to aid in the selection process. The efficiency can be calculated using Equation (10) [3]. Where, we have voltage output *V*, current *I*, and internal resistance *R*, are used in conjunction with the rotational speed *N*, and the motor constant *K*.

$$\eta = \frac{K * I * N}{(V - IR)/I} \quad (10)$$

The generator must be carefully matched with the batteries and ICE in order to generate a proper voltage and current output. A voltage converter may be needed if peak efficiency points do not match the battery voltage.

3.5 Transmission

In order to drive the generator it may be necessary to design a transmission between the generator and the ICE. In this case, a simple chain drive is explored. The chain speed *S* is calculated as in Equation (11) [8] with known values *P* for the chain pitch, *N* for the number of teeth on the drive sprocket and *n* the rotational speed of the drive sprocket.

$$Chain\ Speed, S = \frac{P \cdot N \cdot n}{12} \left(\frac{ft}{min}\right) \quad (11)$$

The chain tension is calculated as in Equation (12) [8] by considering the horsepower rating of the ICE *HP* and the chain speed *S*. A suitable chain can then be selected using a roller chain selection table from a reputable manufacturer.

$$Chain\ Tension, T = \frac{33{,}000 \cdot HP_T}{S} \ (lbs.) \quad (12)$$

Finally, the efficiency of the chain drive can be calculated by using Equation (13) [9]: with initial power P_o, rotational speed of the drive sprocket ω_o, the number of teeth on the drive sprocket N_o, and the work done on the chain to overcome friction W.

$$\eta = \frac{P_o}{P_o + N_o \omega_o \Sigma W} \quad (13)$$

3.6 Battery Charging

Although the generator will provide the vast majority of the recharging to the batteries the charger is important to ensure that a cheap off-peak charge can fully restore the battery pack after usage. The battery charger must be matched to the battery chemistry and system voltage. A simple approximation for charge time, which neglects balancing time of a high cell count parallel pack, can be approximated using Equation (14). The pack capacity that was previously calculated using Equation (4) is simply divided by the power output of the battery charger.

$$Charging\ Time_{Charger} = \frac{Capacity}{P_{Charger}} \quad (14)$$

3.7 Weight Distribution

Finally, once the vehicle's primary components have been selected the parts can be distributed throughout the vehicle. Consideration must first be given to safely routing and mounting high pressure components such that possible leaks do not enter the vehicle compartment and are free to escape into the atmosphere. During the design process consideration must also be given to the weight distribution and subsequent center of mass created by the addition of the new components. Very simply, the center of mass can be determined using Equation (15) by summing the masses and positions of each component along the X, Y, and Z axis' from some known datum. The center of mass is important as it may affect ride quality and handling.

$$(X, Y, Z)_{COM} = \frac{\sum m_i x_i}{\sum m_i}, \frac{\sum m_i y_i}{\sum m_i}, \frac{\sum m_i z_i}{\sum m_i} \quad (15)$$

4 IMPLEMENTATION AND RESULTS

As a result of completing the technical analysis in Sec. 3 above, a sample E-REV specification has been compiled and presented in Table 2 for the conversion of a 250cc Dune Buggy, chosen for its simplicity and open chassis.

Component	Specification
Batteries	48V/200Ah, 9.6 kWh, C3 600A, 59 kg, Cycles > 2000
ICE	250cc, 4-stroke, Carb., 10.5 kW/17.6Nm
Fuel Storage	11L Gasoline/7000psi 94.3L (11L eq.) H_2
Electric Motors	Brushed DC, 12-48V, Continuous 100A, Peak 330A 2min, 13.6kg
Charger	120-240 VAC, Charge Time: 6 h @ 48VDC
Vehicle	Sand Rail Dune Buggy, 523 kg

Table 2 - Sample E-REV Specification

5 CONCLUSIONS

A method has been proposed and implemented for the design and development of an experimental dual-fuel E-REV architecture depicted in Figure 1. The architecture provides a number of important benefits when compared to conventional vehicles and parallel hybrids. Such benefits include zero emissions travel for short duration trips, improved overall emissions and fuel economy, and a reduced reliance on fossil fuels. Furthermore, the architecture offers a chance to explore the use of hydrogen and promote the generation, distribution, and storage technologies required to increase the validity of a hydrogen economy.

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