Preliminary Design, Simulation and Modeling of a Series Hybrid Commuter Vehicle with a Minimal IC Engine

Liqin Ni, Dean Patterson, Jerry L. Hudgins
Department of Electrical Engineering
University of Nebraska-Lincoln
209N WSEC PO Box 880511, Lincoln, NE 68588-0511
Phone: 402-472-5826
Email: lni2@bigred.unl.edu, patterson@ieee.org, jhudgins2@unl.edu

***Abstract* — This paper presents a method for designing battery capacity and output power for series plug-in hybrid electric vehicles. The simulation is based on the model of the dynamic equation of vehicle motion along the longitudinal direction. Besides the rolling resistance, aerodynamic drag and vehicle acceleration, the choice of chemical battery and the potential energy change with altitude, are also important factors for the simulation results.**

I. INTRODUCTION

Hybrid electric vehicles (HEV) are now entering the marketplace and the results indicate that they provide low-emission and high-efficiency. The typical hybrids found on the market today, those being sold by Toyota, Honda and Ford for example, follow a design philosophy that puts most of the burden of powering the vehicle on the combustion engine. However, almost every hybrid vehicle's gas mileage is less than 60 MPG [1]. In order to design a hybrid electric vehicle system with higher gas mileage and lower-emission, especially for urban driving, we decided to adopt a plug-in hybrid electric vehicle with a series power-train configuration or series plug-in hybrid electric vehicle (PHEV). The schematic of series plug-in HEV is shown in Fig. 1. The vehicle is propelled by electric motor only. The electric motor is powered by a battery pack or generator or both of them. This system uses a minimally small IC (internal combustion) engine for ranges greater than that possible with battery alone. The battery storage system can be recharged not only from the generator but also from the electric utility grid so that the vehicle is no longer dependent on a single fuel source.

Plug-in hybrid electric vehicles are a nice solution to improve fuel economy [2] — they can be recharged by plugging them into an ordinary electrical outlet and can travel a considerable distance on electric power alone. The typical daily driving distance is between 10 - 30 miles [2-3]. Thus, a plug-in hybrid car with at least a 30-mile range on battery power alone would allow most people to use no gasoline at all. Recharging would be accomplished by plugging their car batteries into an electric outlet at night. This practice would not only save consumers money at the pump, it would at the same time reduce the vehicle emissions to zero, being replaced by emissions from the electricity generation plant, if fossil fuels are used. Even those whose daily driving distance is farther than 30 miles and have to use some gasoline in their cars, have a very small fuel cost.

The advantage of a series hybrid is that the control system is relatively simple due to the lack of a mechanical link between the combustion engine and the wheels. The combustion engine runs at a constant speed and torque at its peak efficiency point, even as the car changes speed. During stop-and-go city driving, series hybrids are relatively the most efficient.

Energy storage plays a key role in the plug-in HEV and is closely related with their performance, fuel economy, cost, safety, weight and volume. Energy storages, so far, mainly include chemical batteries, flywheels, ultracapacitors or supercapacitors, and fuel for fuel cells. In this paper, only chemical batteries are discussed. In energy storage design, the power and energy capacities should be evaluated accurately, to satisfy the load requirement. Too large a capacity and high peak power will increase the cost, volume and complexity of the control system, while too small a capacity and low peak power will decrease the performance of the vehicle and decrease the range operating on battery power alone. The energy storage system cost is a major obstacle that must be overcome for a PHEV to be viable. Thus, the choice of battery parameters is also an important step in our project.

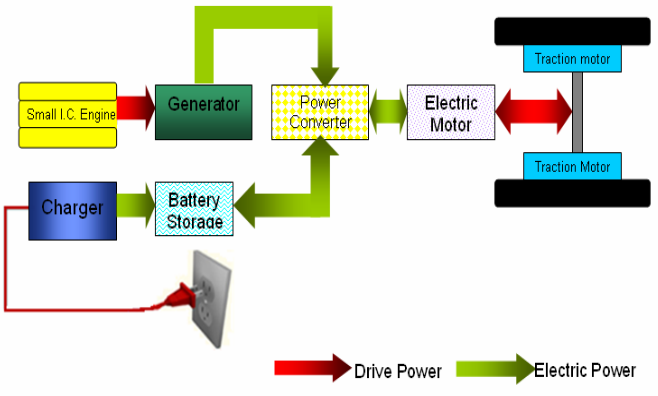

Fig. 1 Series plug-in hybrid vehicle system.

This paper, according to the dynamic equation of vehicle motion along the longitudinal direction, simulates the battery state of charge (SOC) and the battery output power in an electric power drive mode and with a given driving condition. It also provides the battery consumption at different driving distances and calculates the battery capacity to meet the ranges on battery power alone. The simulation considers rolling resistance, aerodynamic drag, grading resistance, or potential energy change with altitude, regeneration braking, system energy loss, and the battery efficiency. Comparing this model to other methods [4][5], the driving condition used in this simulation not only includes the speed at different times, it also considers the change of altitude of the roads. In this paper, we do a test journey around the city of Lincoln, Nebraska. The test is used to get the data of the roads altitude, and the vehicle speed including starts and stops for typical urban driving which can then be used in the simulation. Relevant technical parameters of the vehicle are taken from specifications of the 2004 Toyota Prius. The paper examines two different kinds of batteries — Lithium Polymer (LiPo) battery and Nickel Metal Hydride (NiMH) — as the energy storage system. Finally, the paper analyses the results of different kinds of batteries and the results of a changeable altitude of roads and a constant altitude of road.

II. SIMULATION MODEL

Most roads have a non-zero gradient. While the vehicle is moving, there is resistance that tries to stop its movement. The resistance usually includes tire rolling resistance F_{roll}, aerodynamic drag F_{aero}, and uphill resistance F_g (which becomes an impetus during downhill), as shown in Fig. 2. The tractive effort, F_{tot}, is produced by the battery energy in this paper and is transferred through the transmission and final drive to the wheels. The tractive effort is required to overcome the resistance effort and to accelerate the vehicle. In the longitudinal direction, the dynamic equation of vehicle motion can be described by the following relation:

$$F_{tot} = F_{roll} + F_{aero} + F_g + F_{acc} \tag{1}$$

According to [6], equation (1) can be expressed as:

$$F_{tot} = Pf_r \cos a + \frac{1}{2}\rho A_f C_D (V + V_w)^2 + m_v g \sin a + m_v \frac{dV}{dt} \tag{2}$$

P is the normal load, acting on the center of the rolling wheel. In this paper, $P = m_v$g.

f_r is the rolling resistance coefficient.

α is the road angle (refer to Fig. 2).

ρ is air density, 1.202 kg/m^3.

A_f is vehicle frontal area.

C_D is the aerodynamic drag coefficient.

V is the vehicle speed.

V_w is the wind speed in the vehicle's moving direction.

m_v is the mass of vehicle.

g is acceleration of gravity.

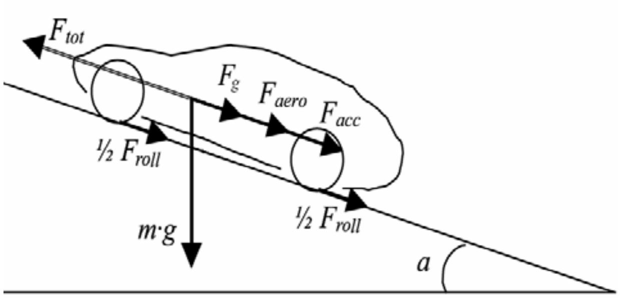

Fig. 2 Forces acting on the vehicle.

$\frac{dV}{dt}$ is the acceleration of the vehicle.

According to Mechanical power definition and equation (2), the total tractive energy J_{tot} and demand power P_{demand} can be expressed as:

$$\begin{aligned} J_{tot} = F_{tot}s = (Pf_r \cos a + \frac{1}{2}\rho A_f C_D (V + V_w)^2 \\ + m_v g \sin a + m_v \frac{dV}{dt})s \end{aligned} \tag{3}$$

$$\begin{aligned} P_{demand} = F_{tot}V = (Pf_r \cos a + \frac{1}{2}\rho A_f C_D (V + V_w)^2 \\ + m_v g \sin a + m_v \frac{dV}{dt})V \end{aligned} \tag{4}$$

Where s is the driving distance of the vehicle and V is the vehicle speed.

It is assumed that the energy loss from the battery due to vehicular energy management is J_{loss} and the battery discharge/charge efficiency is η_d/η_c. The battery energy $J_{battery}$during discharge and charge can be expressed, respectively, as:

$$J_{battery} = (J_{tot} + J_{loss}) / \eta_d \tag{5}$$

$$J_{battery} = (J_{tot} + J_{loss})\eta_g \eta_c \tag{6}$$

And the battery output power $P_{battery}$ can be expressed as:

$$P_{battery} = \frac{dJ_{battery}}{dt} = \frac{\Delta J_{battery}}{\Delta t} \tag{7}$$

Where η_g is the regeneration efficiency and t is the vehicle drive time.

III. INITIALIZATION OF SIMULATION

According to the simulation model, we need the vehicle parameters, such as C_D, m_v and A_f, energy losses, vehicle speed and the road gradients as simulation inputs. Relevant vehicle technical parameters for this simulation are listed in TABLE I [7][8], which taken from the specifications for the 2004 Toyota Prius. However, the energy storage parameters are different with the Toyota Prius, as shown in TABLE II. This paper examines two different kinds of chemical batteries as energy storage system to calculate the battery capacities.

Energy loss J_{loss} includes the electric circuit loss and hybrid drive system loss [9]. The electric circuit loss is assumed to be 5%. The hybrid drive system loss includes gear losses, motor-rotor losses, and other gear losses. According to [9], the hybrid drive system losses in 2004 Toyota Prius vehicle are related to the motor shaft speed, as shown in Fig. 3.

During simulation, road features and vehicle speeds are the two main determining factors. *Road features* are the geographic properties of the road, such as up-hill grades and down-hill grades. *Vehicle speeds* contains stops (velocity of zero), acceleration, constant speed, and braking or deceleration. Both road features and vehicle speeds were initially treated as random variables, but are determined by the regions where the vehicles are running, and traffic situations.

Therefore, in order to achieve a more realistic result in the simulation, these entire road features and vehicles speeds need to be considered during the calculations. This research involved logging a driving test on a specific route around the city of Lincoln, Nebraska. The route is shown in Fig. 4. The total distance of the test route is 18.2 miles, and total time is 2980 s. The altitude of roads is measured by topographic map according to its longitude and latitude, and the results are shown in Fig. 5. The vehicle speed is measured by a Global Position System device, (Delorme Tripmate GPS Navigation), and results are shown in Fig. 6. The maximum speed of vehicle is 44.2 mph (miles per hour) and average speed is 22.0 mph.

TABLE I
TOYOTA 2004 PRIUS SPECIFICATION

Mass m_v (lb)	Wheel dia. (inch)	f_r	C_D	A_f (m^2)
2890	15	0.008	0.26	2.16

TABLE II
ENERGY STORAGE SPECIFICATIONS FOR THIS SIMULATION

Battery	Wh/kg	Useable SOC	η_d	η_c
Lithium Polymer	143	~70%	0.95	0.95
NiMH	46	~40%	0.84	0.84

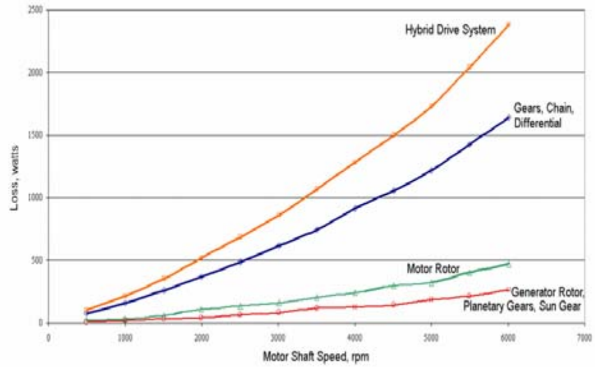

Fig. 3. Hybrid electric drive system losses at different motor shaft speeds.

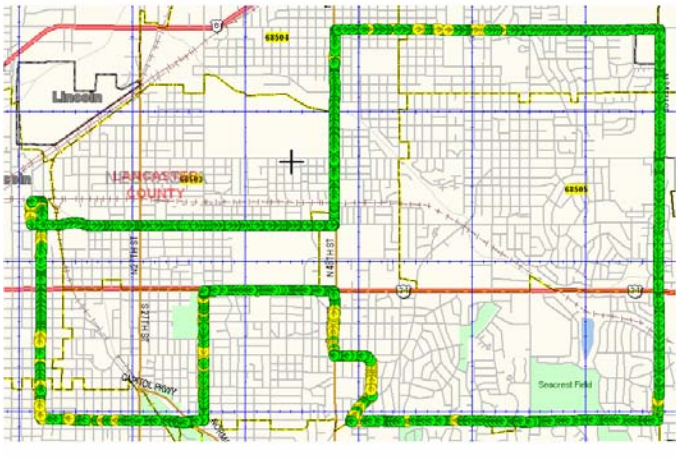

Fig. 4. The driving test route around Lincoln urban.

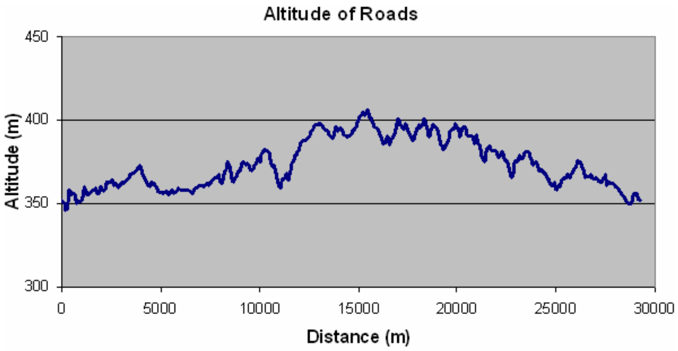

Fig. 5. Altitude variation of road.

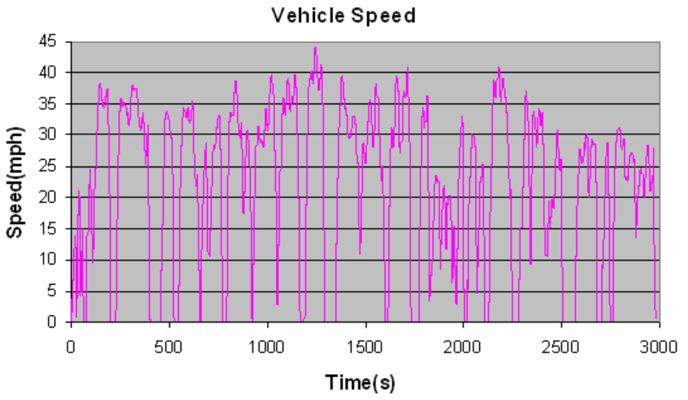

Fig. 6. Driving speed schedule of vehicle.

IV. RESULT OF SIMULATION

According to equations (3), (5), (6) and the test data shown on section III, the demands on battery energy at different distances and times can be determined, and the results are shown in Fig. 7. According to the results, we know how much battery energy is consumed at different driving distances. For example, designing an energy system with a 15 miles range on battery power alone, a LiPo battery energy system needs 2.54 kWh usable energy, while a NiMH battery energy system needs 3.07 kWh usable energy because of different efficiency between these two kinds of batteries.

Moreover, for a 15 miles range PHEV or HEV15, a LiPo battery energy system needs 3.63 (2.54/0.7) kWh capacity when its usable SOC window is 0.7, while NiMH battery energy system needs 7.68 (3.07/0.4) kWh capacity when its usable SOC window is only 0.4. Fig. 8 is the state of charge of LiPo battery between 0.2-0.9 and NiMH battery between 0.4-0.8. Expanding the usable SOC window drastically reduces the total battery capacity requirement, which can substantially reduce the energy storage system cost and volume.

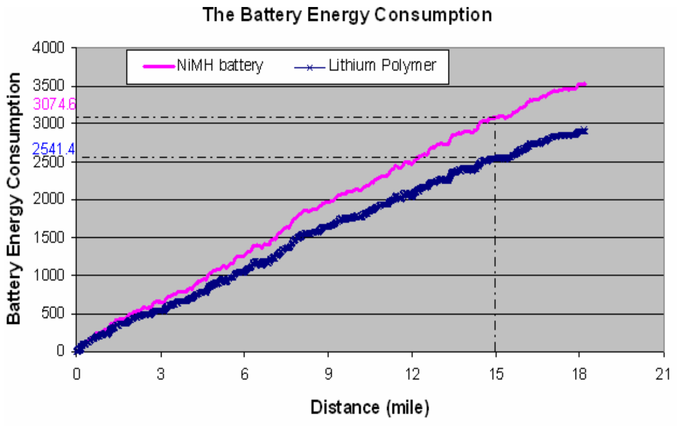

Fig. 7. Battery energy consumption during drive.

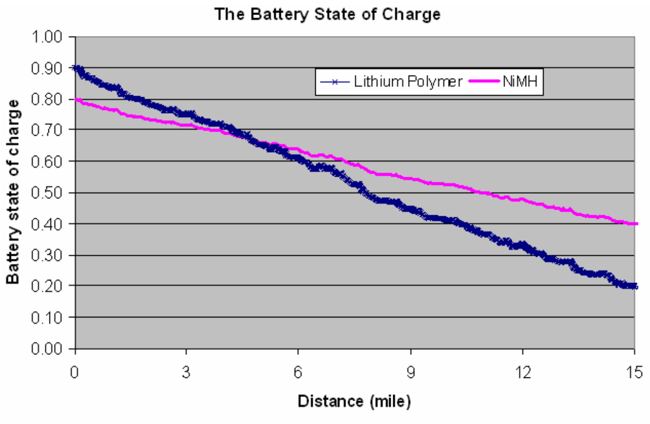

Fig. 8. Battery SOC during drive cycle.

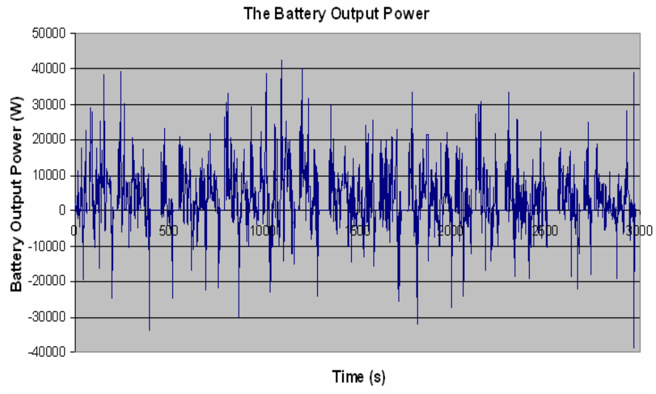

Fig. 9. Output power of the battery along a graded road.

Hence, the choice of battery and battery parameters, especially the usable SOC window, are crucial and dramatically affect the ranges operating on battery power alone.

According to equation (7), we can simulate the battery output power, shown in Fig. 9. The energy storage system is choosen as a LiPo battery, and the road altitude profile is shown in Fig. 5. According to simulation, the peak output power is nearly 41kW. The battery power works in a broad region and change very quickly and frequently. The combination of chemical batteries and ultracapacitors are now applied in energy storage system to reduce the battery peak power and improve cycle life [10][11]. The ultracapacitors provide peak power to meet the high power requirement during vehicle acceleration, or absorb the peak charging power during regenerative braking.

Fig. 10 is the battery output power with constant altitude and other condition are the same with Fig. 9. Compared Fig. 10 with Fig. 9, it is obvious that the changeable altitude could affect the battery output power. The changeable altitude can increase the battery power in the period of uphill, or decrease the battery power in the period of downhill. Fig. 11 is the battery SOC with changeable altitude and unchangeable altitude. It shows that the larger gradient in the roads affects the battery SOC more. Therefore, the gradient of the driving altitude profile cannot be ignored.

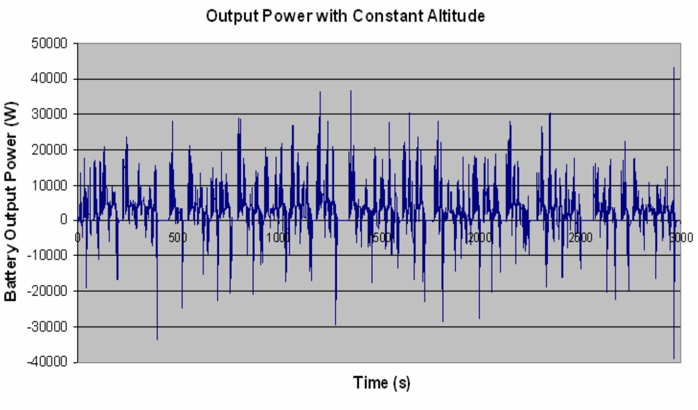

Fig. 10. Output power of battery along a zero-gradient road.

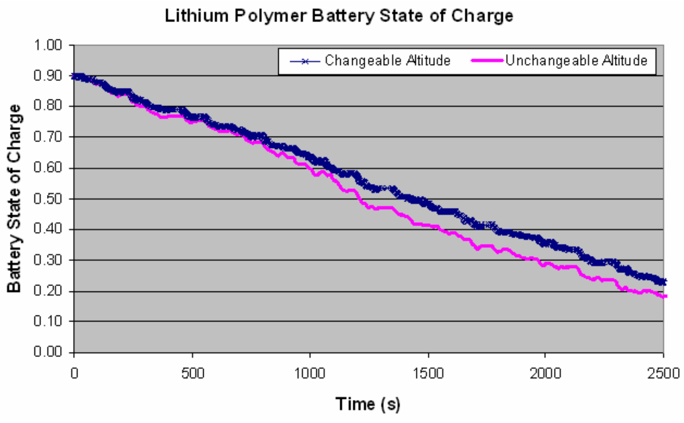

Fig. 11. Battery SOC with different road gradients.

V. CONCLUSIONS

This paper presents the energy storage capacities and power requirement for series plug-in HEV in the form of case studies considering a typical urban drive cycle. The model of simulation is based on a simple dynamic equation of vehicle motion and it is convenient to determine the battery parameters which can satisfy the vehicle requirement. The model and approach can be applied to other vehicles and energy storage systems.

The study results illustrate that the requirement of battery capacities for different kinds of batteries might be very different even if the vehicle has the same range on battery power alone. Moreover, the potential energy change with altitude is also an important factor and can't be ignored in the evaluation of battery capacity and output power.

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