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Modeling operating modes, energy consumptions, and infrastructure requirements of fuel cell plug in hybrid electric vehicles using longitudinal geographical transportation data

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ABSTRACT

The fuel cell plug in hybrid electric vehicle (FCPHEV) is a near-term realizable concept to commercialize hydrogen fuel cell vehicles (FCV). Relative to conventional FCVs, FCPHEVs seek to achieve fuel economy benefits through the displacement of hydrogen energy with grid-sourced electrical energy, and they may have less dependence on a sparse hydrogen fueling infrastructure. Through the simulation of almost 690,000 FCPHEV trips using geographic information system (GIS) data surveyed from a fleet of private vehicles in the Puget Sound area of Washington State, USA, this study derives the electrical and hydrogen energy consumption of various design and control variants of FCPHEVs. Results demonstrate that FCPHEVs can realize hydrogen fuel consumption reductions relative to conventional FCV technologies, and that the fuel consumption reductions increase with increased charge depleting range. In addition, this study quantifies the degree to which FCPHEVs are less dependent on hydrogen fueling infrastructure, as FCPHEVs can refuel with hydrogen at a lower rate than FCVs. Reductions in hydrogen refueling infrastructure dependence vary with control strategies and vehicle charge depleting range, but reductions in fleet-level refueling events of 93% can be realized for FCPHEVs with 40 miles (60 km) of charge depleting range. These fueling events occur on or near the network of highways at approximately 4% of the rate (refuelings per year) of that for conventional FCVs. These results demonstrate that FCPHEVs are a type of FCV that can enable an effective and concentrated hydrogen refueling network.

Introduction

The personal transportation vehicle fleet is primarily fueled by petroleum-based liquid fuels which are largely non-renewable, harmful to air quality, and a significant source of greenhouse gas emissions [1]. Fuel cell plug-in hybrid electric vehicles (FCPHEV) have been advanced as a zero-emissions concept to decrease the dependence of light-duty vehicles on petroleum and to reduce the tailpipe pollution and net GHGs emitted from vehicles [2–10]. Conceptually, a FCPHEV is a type of plug-in hybrid electric vehicle (PHEV). A hybrid electric vehicle (HEV) uses a combination of fuel and electrical energy sources to power the car while driving, but does not have a charger or other means to recharge the electrochemical battery from the electric grid. A PHEV is a type of HEV that is able to draw energy from the electrical grid through an

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onboard charger to recharge the electrochemical battery pack [11]. The ability to recharge the battery pack from the electric grid allows the PHEV to drive a limited distance using energy derived from grid electricity. This driving mode is labelled as a charge-depleting (CD) mode. In this driving mode, the battery's state of charge (SOC) decreases over the driving distance as electrical energy is used by the vehicle to power the wheels. Once the battery of the PHEV reaches a predetermined SOC, it will switch over to a charge sustaining (CS) driving mode for the remaining duration of the trip. During CS mode, fuel energy maintains the SOC of the battery until the battery pack is recharged using electric energy from the grid. A FCPHEV is a PHEV that uses a fuel cell to provide the motive power for range extension and for CS mode.

FCPHEVs are a particularly relevant technology case because of the present state of fuel cell powerplant technology and hydrogen infrastructure. Fuel cell and hydrogen storage system costs have been decreasing with time towards long-term goals [12,13]. The reduction in costs has been driven by increasing production volumes, advances in fuel cell stack and balance of plant technologies, and decreases in the price and required quantities of raw materials such as platinum and graphite. The decreasing production cost of fuel cell systems has allowed FCVs and PHEVs to become more competitive with conventional vehicles (CV) at present than they have at any other time in history. The FCPHEV represents a near term opportunity for fuel cell powerplants to reach mass-market commercialization without the fuel cell component being strictly cost competitive with internal combustion engines. Various researchers have demonstrated that FCPHEV can be lower cost, and lower emission than comparable conventional vehicles, and that FCPHEV will have significant value towards compliance with federal and state emissions and fuel economy regulations in the US [2–5,7,8].

One intriguing but unanalyzed conceptual characteristic of the FCPHEV is that FCPHEVs are hydrogen powered vehicles with less reliance on the current sparse hydrogen infrastructure [4,5,9]. Because FCPHEVs can fuel from both electricity and hydrogen, full function of the FCPHEV may require a lower geographic density of the costly hydrogen infrastructure than would a FCV. This study seeks to quantify the costs and benefits of FCPHEVs in terms of their reliance on hydrogen infrastructure. Using a geographic information system (GIS) transportation dataset of 377 drivers and hundreds of thousands of trips, we can model and compare the electrical and hydrogen energy consumption of these drivers were they to drive FCVs and FCPHEVs using various mode control strategies. By understanding when and where the hydrogen storage tank of the FCPHEV must be refueled, the proposed vehicle-level geographic and fuel economy analysis can quantify whether or not the FCPHEV concept can reduce hydrogen vehicles' dependence on hydrogen infrastructure.

Methods

Data sources

Because the mode under which PHEVs operate is a function of battery SOC, the energy consumption of PHEVs is particularly sensitive to driving conditions. To calculate the real-world distribution of trip distances, driving types, charging frequency, and charging location, this study uses the dataset from the Puget Sound Regional Council (PSRC) Traffic Choices Study, gathered between 2004 and 2006 [14]. The PSRC data set provides a mix of urban and highway vehicle travel for the participants within the Puget Sound region of Washington State, USA. The purpose of the PSRC survey was to monitor the use of toll roads by daily commuters in and out of the cities within the Puget Sound region, but it is readily adaptable to other transportation research efforts. The number of households, vehicles, and trips surveyed for the PSRC database is presented in Table 1. The PSRC data set encompasses trips of varying distance (1–250mi, 1–403 km) and destinations (work, home, store, etc.). An on-vehicle global positioning system (GPS) receiver recorded the vehicle location at intervals of 0.1–0.2 mi (0.1–0.3 km) throughout the vehicles' trips. The vehicles of the PSRC database were studied for different time periods. This means that some vehicles have less than a year of trip data, while some vehicles have more than a year of trip data. For the purposes of this study, the results for each vehicle were normalized to a year of driving when calculating yearly energy consumption and yearly distance travelled.

Vehicle fuel economy modeling and control strategies

The vehicle energy consumption of the FCPHEV (as implemented in this study and others) is characterized by two consumptions: the CD electric energy consumption (where hydrogen fuel consumption is zero), and the CS hydrogen fuel consumption (where net electricity consumption is zero). The CD electric energy consumption of the FCPHEV varies from 213 ACWh/mi (132 ACWh/km) for a FCPHEV with 10 mi (16 km) of all-electric range to 220 ACWh/mi (136ACWh/km) for a FCPHEV with 40 mi (65 km) of CD range. The CS hydrogen fuel consumption of the FCPHEV varies according to its CD range and the type of driving, as presented in Table 2. These fuel economies represent the performance of a modern, medium-sized vehicle. The urban CS FE is derived from FCPHEV simulations on the urban dynamometer drive schedule (UDDS), and the highway CS FE is derived from FCPHEV simulations on the highway fuel economy driving schedule (HWFET). The capacity of the hydrogen storage of the FCPHEV is 4.95 kg of hydrogen gas [8].

For both the CS and CD fuel and energy consumptions, the FE of the vehicle decreases with increasing battery capacity and CD range. These inputs to this investigation are the results of a physics-based vehicle simulation exercise, where the increase in consumption is traceable to an increase in vehicle mass with increasing battery capacity.

Two control strategies for managing how and when to use CD and CS mode were developed and then compared. The first

Table 1 – Details of the scope of vehicles and trips studied in the PSRC travel survey.

PSRC database	
Households	254
Vehicles	377
Total Trips	>689,000