Research in Transportation Economics 52 (2015) 65–71

Contents lists available at ScienceDirect

Research in Transportation Economics

journal homepage: www.elsevier.com/locate/retrec

The economics of the transition to fuel cell vehicles with natural gas, hybrid-electric vehicles as the bridge

Andrew Burke*, Lin Zhu

Institute of Transportation Studies, University of California, One Shields Ave., Davis, CA 95616, USA

ARTICLE INFO

Article history:
Available online 21 November 2015

JEL classification:
Q2
Q3
Q4

Keywords:
Natural gas
Hydrogen
Hybrids
Fuel cells
Costs
Markets
Transitions

ABSTRACT

Detailed comparisons are made between various types of light-duty vehicles fueled with natural gas and hydrogen. Natural gas vehicles are designed as charge sustaining hybrid vehicles (HEV) and hydrogen fueled vehicles (FCV) are powered by a fuel cell. All the vehicles have a range of 400 miles between refueling stops. This paper is concerned primarily with the near-term time period in which the fuel cell technology is maturing and the hydrogen infrastructure is being constructed both with respect to refueling stations and the source of the hydrogen being distributed. Detailed computer simulations are presented for vehicle classes from compact cars to mid-size SUVs. Energy (MJ) and volume (L) of fuel storage required to meet the 400 mile range target for each vehicle using natural gas and hydrogen are compared. Costs of the vehicles simulated are projected for 2015–2030. Cost results indicate that the costs of ownership of the natural gas HEVs and the hydrogen fuel cell vehicles become close in the 2025–2030 time period. CO_2 emissions from natural gas fueled hybrid and fuel cell vehicles are calculated and compared for hydrogen and electricity from natural gas. Ways in which the introduction of the natural gas fueled vehicles could be a bridge to the mass marketing of fuel cell vehicles are discussed.

1. Introduction

There is considerable interest (Cannon, 2012; Hefner, 2009; Nuboer, 2010; Wokaun and Wilhelm, 2011) in increasing the use of natural gas as a fuel in the transportation sector primarily because it has a lower carbon intensity ($gmCO_2/MJ$) than either gasoline or diesel fuel. Presently (2014) most of the activity in this area in the United States is concerned with the use of natural gas in heavy- and medium duty trucks and transit buses. However, there is much greater interest in using natural gas for light-duty passenger cars, SUVs, and pick-up trucks in Europe and Asia as a means of reducing tail-pipe emissions such as CO, HC, and particulates. This has resulted in the European car manufacturers providing a number of models that can operate on natural gas and gasoline depending on which fuel is available. Italy has provided financial incentives for car buyers to purchase natural gas fueled vehicles (LeFevre, 2014). As a result, Fiat markets a relatively large number of models that are natural gas fueled and Italy has over 75% of the natural gas cars in Europe. There are presently less than 600 natural gas refueling stations in the United States and over 4000 stations in Europe.

There is, however, considerable discussion of the use of hydrogen fuel cells in light-duty vehicles in North America, Europe, and Asia. In fact, several auto manufacturers are planning (Baker, 2015; Pfanner, 2015) to begin marketing fuel cell vehicles in 2015. One of the impediments to marketing fuel cell vehicles is the lack of an extensive infrastructure for the hydrogen fuel. In addition, there is uncertainty regarding the acceptance of the public of the use of a gaseous fuel in their vehicles. In the past, there has been considerable discussion (Parish, 2005; Pfanner, 2015) of the use of natural gas in light-duty vehicles as a bridge to the use of hydrogen in vehicles. One of the reasons this discussion has not been taken seriously in the United States has been the lack of success in the marketing the few natural gas vehicle models that have been offered for sale. Annual sales of the Honda Natural Gas (GX) Civic were only 2198 vehicles in 2013 and only 781 in 2014. This leads Honda to discontinue sales of the GX Civic after 2015. These vehicles were retrofits of gasoline fueled Honda Civic models to accommodate natural gas as the fuel. Because the volume of the natural gas tank is much larger than the gasoline tank, part of the trunk of the retrofitted vehicle is taken up by the natural gas tank. Even then, the range of the natural gas vehicle is significantly less

* Corresponding author. Tel.: +1 530 752 9812.
E-mail address: afburke@ucdavis.edu (A. Burke).

http://dx.doi.org/10.1016/j.retrec.2015.10.005
0739-8859/

than that of the gasoline fueled model. In addition, the price of the natural gas model was significantly higher ($5–6 K) than the standard gasoline model. Hence it was not surprising that sales of the natural gas model were very low.

The questions addressed in this paper are whether light-duty vehicles designed from the ground-up to use gaseous fuels could be marketed successfully as natural gas vehicles and further how they would compare in the near-term with hydrogen fuel cell vehicles using the same chassis design to accept hydrogen storage tanks. In this way, natural gas vehicles could serve as a bridge to public acceptance and the mass marketing of fuel cell vehicles in the United States and Europe as their price becomes lower and the hydrogen infrastructure is developed. The wide availability of natural gas and its projected relatively low price (U.S. EIA, 2013) into the future compared to gasoline makes the strategy of marketing natural gas vehicles a reasonable possibility. As discussed in Cannon (2012), Hefner (2009), Parish (2005), Lee, Zinman, and Logan (2012), there are synergies between fueling stations for compressed natural gas and hydrogen, which should reduce the cost of providing the hydrogen infrastructure especially in the early stages of the introduction of fuel cell vehicles. For example, both stations would require the delivery via a pipeline of natural gas and a means of compressing and storing the gaseous fuel at high pressure.

In this paper, detailed comparisons are made between various types of light-duty vehicles fueled with natural gas and hydrogen. The natural gas vehicles are designed as charge sustaining hybrid vehicles (HEV) and the hydrogen fueled vehicles (FCV) are powered by a fuel cell. All the vehicles have a range of 400 miles between refueling stops. Schematics of the powertrain of the CNG hybrid and hydrogen fuel cell vehicles are shown in Fig. 1. Both vehicles are electrified and use a small battery to increase the driveline efficiency. In the charge sustaining hybrid vehicle, the battery state-of-charge is maintained in a near range do to charging from the generator connected to the engine. Hence both vehicles are fueled by the gaseous fuels and not from the wall-plug.

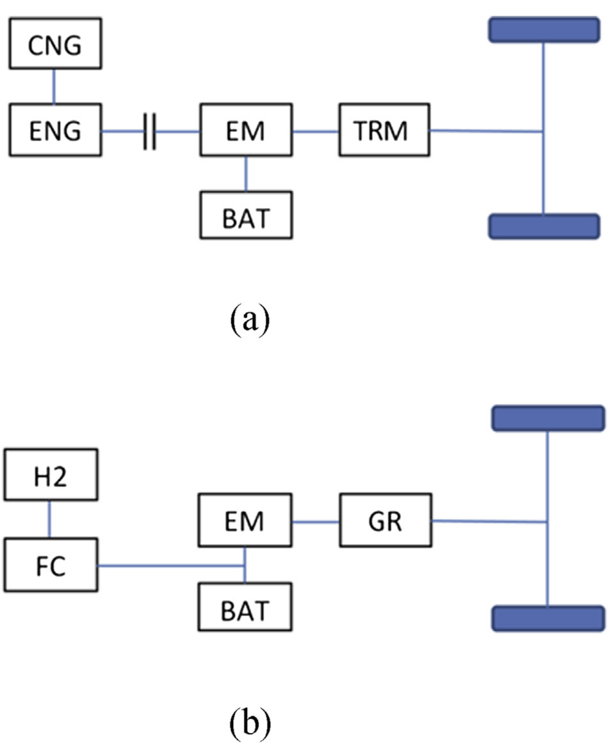

Fig. 1. Powertrain schematics of the CNG and fuel cell vehicles. (a) Natural gas charge sustaining hybrid (HEV), (b) Hydrogen fuel cell vehicle.

The paper discusses the on-board storage of natural gas (3600 psi) and hydrogen (10,000 psi) in terms of the volume, weight, and cost of the tanks required and how fuel storage affects the vehicle design. Detailed computer simulations of the vehicles are presented for several driving cycles and the energy (MJ) and volume (L) of fuel required to meet the 400 mile range target for each vehicle using natural gas and hydrogen are compared.

The costs of the vehicles simulated are projected for 2015–2030. The differences between the costs of the natural gas hybrid vehicles and the fuel cell vehicles are calculated for the various vehicle types as the cost of the fuel cells, batteries and other powertrain components decrease in the future. The annual ownership costs of the vehicles are also calculated. The CO_2 emissions from the CNG hybrid and hydrogen fuel cell vehicles are determined and compared. As a final step, the ways in which the introduction of the natural gas fueled vehicles could be a bridge to the mass marketing and infrastructure for fuel cell vehicles are discussed.

2. Storage of natural gas and hydrogen

Both natural gas and hydrogen are stored on-board the vehicle as a compressed gas. The volumes of the tanks are much greater than the volume of the gasoline tank in a conventional ICE vehicle. The technology for manufacturing storage tanks for compressed natural gas (CNG) is mature and commercial products are available (Worthington, 2015). Both steel and composite carbon fiber tanks are marketed. In the case of hydrogen, the technology for the tanks is still evolving (Dillich, 2009; Hua et al., 2010; Roth, Hu, & Ahluwalia 2013; Wood, 2014) and all the tanks are manufactured using carbon fiber composites. The characteristics of the energy storage tanks for natural gas and hydrogen are summarized in Table 1. The hydrogen is stored at 10,000 psi (680 atm.) and the natural gas at 3600 psi (245 atm.). The tank sizes given in Table 1 are for storing an amount of energy (MJ or kWh) equivalent to that in 5 gallons of gasoline or 5 kg of hydrogen. The tank sizes for storing larger amounts of energy can be calculated from the MJ/L and MJ/kg parameters. Note that the weight and volume of the tanks needed to store hydrogen are significantly greater than to store the same amount of energy with natural gas. This will be true even when the DOE goals for hydrogen storage are met. If both the natural gas and hydrogen tanks are constructed of carbon composite materials, the MJ/L factor for the natural gas tank is about 3x that of the DOE goal for hydrogen. For the same fuel energy storage (MJ), the volume of a natural gas tank is 4x greater and the hydrogen tank 8–9x greater than that of the gasoline tank.

The composite hydrogen tanks are of carbon fiber construction and the present cost of the carbon fiber is quite high. However, considerable R&D (Hua et al., 2010; Roth et al., 2013; Wood, 2014) is being done to reduce the cost so it is expected that the cost of the hydrogen tanks will decrease significantly from their present cost of nearly $10/MJ. The natural gas tanks are metal with a carbon wrap and their present cost is about $3/MJ. The cost of all the tanks will also decrease in volume production for passenger cars.

3. Vehicle designs and simulations

As indicated in the **Introduction**, the gas fueled vehicles being compared are charge sustaining hybrid-electric CNG vehicles and fuel cell hydrogen vehicles. All the vehicles were simulated using the ADVISOR vehicle simulation program that has been extensively modified at UC Davis (Burke and Van Gelder, 2008; Burke, Zhao, & Van Gelder, 2009). ADVISOR models in detail the driveline components and the vehicle road load and calculates the sec-by-sec