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A method for determining the optimal delivered hydrogen pressure for fuel cell electric vehicles☆

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HIGHLIGHTS

- A 700 bar DHP is a robustly better choice for most circumstances.
- 300 or 500 bar can be recommended in some Cluster Strategy circumstances.
- Tradeoffs among station utilization, availability and pressure are necessary.
- Even higher pressures (> 700 bar) are desirable if technologically viable.
- Consumer heterogeneity is an important factor.

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ABSTRACT

Fuel cell electric vehicles (FCEVs) are considered an important part of a portfolio of options to address challenges in the transportation sector, including energy security and pollution reduction. The market success of FCEVs depends on standardization of key vehicle and infrastructure parameters, including the delivered hydrogen pressure (DHP). This study developed and utilized the Hydrogen Optimal Pressure (HOP) model to systematically identify the optimal DHP among 350, 500, and 700 bar toward the lowest total consumer cost and analyze how the optimal DHP may be affected by attributes of drivers, vehicles, and hydrogen refueling stations. The DHP of 700 bar a robustly better choice than 350 bar or 500 bar for Region Strategy, regardless of fuel availability, FCEV adoption, driver types, time values, and fuel economies. A DHP of 300 or 500 bar can the winner in Cluster Strategy if combined with certain assumptions of driving patterns and time value. the optimal pressure is found to be very sensitive to fuel availability, fuel economy, driving pattern and time value. The appeal of a higher DHP such as 700 bar (or even higher) is more obvious during the early market stages, when the number of hydrogen stations is limited and early FCEV consumers likely have higher time value, and thus may be willing to pay more for the increased range with higher DHP. Future research on mixed DHPs within a station and across stations is suggested.

1. Introduction

Fuel cell electric vehicles (FCEVs) are considered an important part of a portfolio of options to address challenges in the transportation sector, including energy security and pollution reduction [1]. Compared to other zero emission vehicle technologies, FCEVs have some distinct advantages, including short refueling time and long driving range, both of which are related to the onboard hydrogen storage

Abbreviations: ALC, Average & Long Commute; ASC, Average & Short Commute; DHP, delivered hydrogen pressure; FLC, Frequent & Long Commute; FSC, Frequent & Short Commute; FCEVs, Fuel cell electric vehicles; HOP, Hydrogen Optimal Pressure; MLC, Moderate & Long Commute; MSC, Moderate & Short Commute; NWP, nominal working pressure; ZEV, Zero Emissions Vehicles

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system and the underlying storage capacity and pressure. The goal of an onboard hydrogen storage system is to provide fuel safely, efficiently, and effectively for a sufficient driving range. A key challenge for hydrogen storage is the low volumetric energy density, relative to conventional liquid hydrocarbon fuels.

The need for increased driving range and the associated volumetric energy density has motivated the automotive manufacturers to explore various storage solutions including compressed gas, cryogenic, and material-based (e.g. ammonia borane with catalyst) hydrogen storage systems [2–6]. Automotive manufacturers seem to have reached a consensus on the nominal working pressure (NWP) of 700 bar for compressed hydrogen as the most suitable storage system for near term FCEV applications [7,8]. While NWP is used as the associated rating of the safe operation pressure level of the onboard storage tank, it is not the maximum operating pressure[1] for the tank, nor the delivered hydrogen pressure (DHP), which is defined as the actual pressure of delivered hydrogen at the end of the refueling process and affects the delivered hydrogen cost. While NWP has been largely agreed upon and affects vehicle design, DHP is still an open issue for discussion and more relevant to hydrogen infrastructure planning.

This study focuses on identifying the optimal DHP for a fleet of FCEVs with an onboard tank of 700 bar NWP. The hypothesis is that a lower DHP could reduce the cost of the hydrogen delivery infrastructure, although it could also reduce the driving range and increase refueling frequency, all ultimately affecting consumer acceptance of FCEVs. If different DHPs are available from stations, DHP could represent a daily refueling decision by the consumer to accept a reduced driving range even though their onboard storage tank had a higher-pressure capability, capped by its NWP. When the DHP level of the station equals the onboard tank NWP, the vehicle is able to achieve a full fill and maximize the driving range.

DHP represents a decision variable of the FCEV's vehicle-infrastructure system for balancing the delivered hydrogen cost and consumers' vehicle operating inconvenience (e.g. the frequency of refueling or using alternative travel means to destinations far away from hydrogen stations). The latter can be seen as a function of driving range, number of fueling stations, vehicle fuel economy and fueling time. Since a change in DHP can lead to both desirable and undesirable outcomes, determining a proper DHP naturally becomes an optimization problem. A few previous studies attempted to evaluate the optimal DHP. Cohen et al. [9] compared different types of equipment and techniques for hydrogen refueling design and suggested different DHPs in various situations. Harty et al. [10] investigated the best DHP in the FCEVs by comparing some parameters (precooling temperature, types of tank materials, infrastructure cost and location, and safety requirements). Hua et al. [11] built a performance model to assess the optimal DHP for automotive application by evaluating the costs (including the carbon fiber for tank material, balance of plant components, infrastructure, manufacturing process), durability and life requirements. The Hydrogen Analysis (H2A) model [12] can be used to estimate the costs of various hydrogen production and delivery technologies for a given vehicle storage pressure. The Hydrogen Delivery Scenario Analysis Model (HDSAM) provides a general engineering economic framework to estimate the levelized cost for a given hydrogen demand [13], although it doesn't consider other perceived costs such as that due to DHP-limited driving ranges. Meanwhile, the driving range of the electric vehicle (EV) has been studied more extensively. Lin [14] developed a method for optimizing the EV driving range by considering tradeoffs among battery cost, electricity cost, and perceived range limitation cost. The driving range was demonstrated to be influential to the types of charging stations and costs of the charging infrastructure [15]. Although range limitation is rarely associated with FCEVs [16], it is relevant because FCEV drivers in early markets may need to drive long distances to regions far away from the very limited number of hydrogen stations and face the range limitation issue. Other literature on hydrogen storage have focused on grid operation [17–19], power level or sizing coordination with other powertrain components [20–22], but have not explicitly consider DHP and the resulting driving range for either powertrain design or vehicle-infrastructure system analysis.

As stated, the objective of this study is to model and find the optimal DHP by considering both infrastructure (supply) and consumer (demand) factors that are of stakeholder interest, and conduct case studies to provide useful insights into DHP strategies that reduce infrastructure cost, increase market acceptance, or both. As indicated, this paper assumes a constant 700 bar NWP onboard tank and only varies the DHP with a focus on three often-considered pressure options (350 bar, 500 bar, 700 bar). Therefore, the DHP pressure among these three options that is closest to the modeled theoretical optimal DHP will be considered the optimal choice. For example, if the resulted optimal pressure is above 700 bar in the model, then this practically means that 700 bar is the optimal choice for DHP.

The second section of the paper describes the DHP optimizing method, which is implemented as the Hydrogen Optimal Pressure (HOP) model in Excel. The baseline case is then defined by a set of parametric assumptions. The third section presents detailed results, starting with the effect of heterogenous driving patterns and sensitivity analysis of 9 other factors, in order to identify key factors for subsequent analysis. Then, detailed results are shown and discussed regarding spatial strategies (Cluster vs. Region), travel time, fuel economy and the evolution of the optimal DHP with reasonable projections of FCEV and infrastructure deployment over time. Contributions, key findings and future studies are summarized in the final section.

2. Problem scope and model formulation

The basic modeling idea, as in Eq. (1), is to find the optimal DHP p by minimizing the sum C(p) of three perceived cost components: delivered H_2 cost H(p), refueling inconvenience cost R(p), and range limitation cost L(p), all as a function of the decision variable – DHP.

$$\min_{p\in[p_{min},p_{max}]} C(p) = H(p) + R(p) + L(p) \tag{1}$$

In Eq. (1), p_{min} and p_{max} define the DHP range of interest, such as 350 bar and 700 bar in this study. C(p) is the DHP-related perceived cost per kilogram of hydrogen ($/kg) consumed over the lifetime of the FCEV. We chose the per-kg measurement, but not the total dollar amount, for readers to easily relate with the hydrogen unit costs or gasoline prices, although both measurements should result in the same DHP solution. H(p) is the delivered hydrogen cost ($/kg). R(p) is the perceived refueling inconvenience cost ($/kg), which is the refueling travel time and hassle cost borne by the driver due to the limited driving range and the limited station availability. L(p) is the perceived range limitation cost ($/kg) due to the occasional needs to use a backup vehicle (or other travel means) for long-distance travel to destinations far from available hydrogen stations. Tax on the final product (e.g., fuel sales tax) and/or credits (e.g., vehicle subsidies) [23] are excluded from this analysis for simplicity.

It is obvious but worth noting that factors beyond the scope of the objective function in Eq. (1) are not addressed or implicitly assumed to be independent of the decision variable DHP, such as safety, reliability, vehicle design, the vehicle onboard tank cost.

Although these three cost components are by definition either directly paid or perceived by FCEV consumers, they are systematically linked to important factors of station and FCEV deployments, as

[1] The maximum operating pressure is typically defined at 1.25× of NWP with a maximum fill temperature of 85 °C to allow for the temperature to rise in the tank during the filling process while maintaining a constant density when the tank temperatures settle to the NWP at 15 °C. The ultimate strength requirement for the tank is defined as the burst pressure which is established by standards at 2.25× the NWP for carbon fiber tanks at the beginning of life.