XI.4 Analysis of Optimal Onboard Storage Pressure for Hydrogen Fuel Cell Vehicles

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Project End Date: September 30, 2013

Overall/Fiscal Year (FY) 2013 Objectives

- Optimize delivered H_2 pressure
- Analyze sensitivity of optimal pressure
- Compare different pressure options for California

Technical Barriers

This project addresses the following technical barriers from the Hydrogen Storage section of the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan:

(B) System Cost

(F) Codes and Standards

(K) System Life-Cycle Assessments

This project also addresses the following technical barriers from the Market Transformation section:

(B) High hydrogen fuel infrastructure capital costs for Polymer Electrolyte Membrane (PEM) fuel cell applications

Contribution to Achievement of DOE Hydrogen Storage/Market Transformation Milestones

This project will contribute to achievement of the following DOE milestones from the Hydrogen Storage and Market Transformation sections of the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan:

- Storage 3.3: Transportation: Complete economic evaluation of cold hydrogen storage against targets. (4Q, 2015)
- Storage 3.6: Update early market storage targets. (4Q, 2017)
- Storage 3.7: Transportation: Complete analysis of onboard storage options compared to ultimate targets. (4Q, 2020)
- Market Transformation 1.13: Deploy, test, and develop business cases for renewable hydrogen energy systems for power, building, and transportation sectors. (1Q, 2015)

FY 2013 Accomplishments

- Developed a spreadsheet tool to determine the optimal onboard hydrogen pressure in a regional context.
- Explained interactions between pressure, station size, and station number.
- Recommended 700 bar for Southern California after comparing the combined costs of infrastructure and refueling inconvenience resulting from 350, 500, and 700 bar, assuming 100 stations and 50,000 fuel cell electric vehicles (FCEVs) on the road as the California Fuel Cell Partnership 2017 deployment plan envisions.
- Analyzed sensitivity of optimal pressure against high-pressure incremental cost, value of time, FCEV market share, vehicle efficiency, and driving intensity.

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INTRODUCTION

The pressure of hydrogen delivered to hydrogen vehicles can be an important parameter that has great impact on the delivered cost of hydrogen and the range limitation obstacle of hydrogen vehicles. On one hand, higher hydrogen pressure allows more hydrogen to be stored onboard, enabling a longer driving range between hydrogen refills, but the cost of hydrogen supply infrastructure, and therefore the delivered cost of hydrogen, will be higher. However, while lower hydrogen pressure shortens the driving range and results in higher refueling frequency, the delivered hydrogen cost can be lower. Also importantly, the lower capital cost of low-pressure stations will encourage investment activities in developing more stations, resulting in better refueling convenience for consumers.

The objectives of this project are:

- Develop an optimization model to identify the delivered pressure of hydrogen that reflects tradeoff among hydrogen cost, infrastructure capital cost requirement, driving range, refueling frequency, and refueling convenience. The objective of optimization is maximization of consumer acceptance of hydrogen vehicles.
- Analyze and recommend the delivered hydrogen pressure as a function of technology cost, regional geography, hydrogen demand, and driving patterns.

APPROACH

The optimization method is formulated to reflect tradeoff between consumer refueling convenience and infrastructure costs. Higher pressure increases hydrogen storage and driving range between hydrogen refills, but increases the cost of delivery infrastructure and the cost of hydrogen. To simplify the problem, FCEVs are assumed to be equipped with high-pressure-capable tanks. A region-wide optimal infrastructure roll-out scheme, as opposed to cluster strategies, is implicitly assumed. That is, hydrogen stations are implicitly assumed to be optimally located to minimize the expected refueling travel time of a random motorist.

Specifically, the optimal pressure is solved for by equating the marginal value of increased range due to increased pressure to the marginal H_2 delivered cost due to increased pressure. This is equivalent to minimization of combined costs of refueling inconvenience and stations. The marginal value of increased range due to higher pressure is measured by reduction of net present value of total refueling time over 5 years. Refueling time includes access time to station (depends on availability) and refueling time at station. The marginal cost of increased pressure includes the resulting increased cost of pumps, tanks, and energy use. Based on discussions with the Fuel Pathway Integration Technical Team of U.S. DRIVE, these metrics are assumed for the baseline: a mid-size FCEV car with 60 miles per gasoline gallon equivalent fuel economy; a representative driver who drives 12,800 miles per year and values refueling travel time at $50/hour; a dispenser linger time of 2.4 minutes; hydrogen filling time of 1.6 kg/min; $4.50/kg delivered hydrogen cost at 700 bar and $4.00/kg at 350 bar, both with full utilization (based on H2A models); and Southern California as the regional context.

RESULTS

The optimal pressure is found to decrease with availability of more hydrogen stations or larger stations. As shown in Figure 1, the optimal pressure decreases from over 700 bar to 350 bar when the hydrogen availability increases from 2.5% to 6%. With more stations, consumers spend less

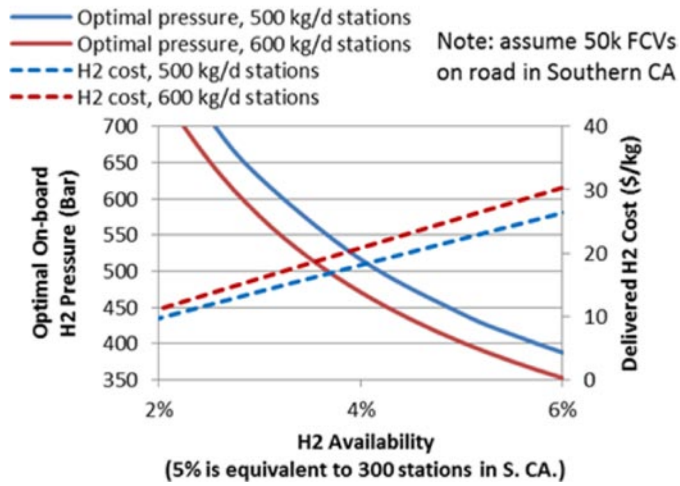
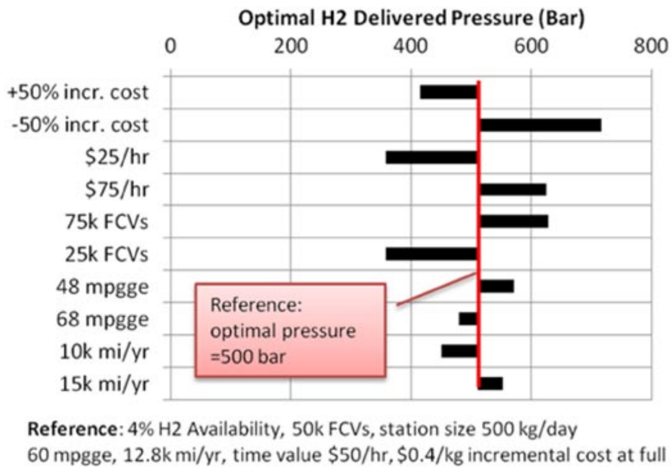


FIGURE 1. Response of Optimal Pressure and Hydrogen Cost

time on the road to refueling each time they need a refill. A shorter driving range becomes more tolerable, allowing lower hydrogen pressure. But because the number of FCEVs, 50,000 in this example, is held constant, higher hydrogen availability results in lower infrastructure utilization and thus higher hydrogen cost. But with the same number of stations and FCEVs on the road, smaller stations (from 600 kg/d to 500 kg/d in Figure 1) allow higher utilization and lower the delivered hydrogen cost, making room for higher pressure to raise the driving range.

The optimal pressure is found to be sensitive to the high-pressure incremental cost, value of refueling travel time and the number of FCEVs on the road. The reference case for the sensitivity analysis is based on the assumptions of 4% hydrogen availability; 50,000 FCEVs on the road; an average station size of 500 kg/day; an average vehicle fuel economy of 60 miles per gasoline gallon equivalent; an average 12,800 miles of annual driving distance; a time value at $50/hour; and $0.4/kg incremental cost of hydrogen from 350 bar to 700 bar. The resulting optimal pressure is about 500 bar. As shown in Figure 2, a 50% decrease in the incremental cost of hydrogen would drive the optimal pressure up to about 700 bar. Reducing the time value to $25/hour or the number of FCEVs to 25,000 would reduce the optimal pressure to about 350 bar.

Three pressure levels are compared to find the best for Southern California based on the near-term FCEV and infrastructure deployment scenario envisioned by California Fuel Cell Partnership. The pressure of 700 bar is found to be the best among the three. The comparison is based on the assumptions of 100 stations, each 350 kg/day, and 50,000 FCEVs on the road. The three levels of pressure being compared are 350, 500, and 700 bar. In all cases involving variation of time value from $25 to $75 per hour and the incremental cost from $0.2 to $0.6 per kg H_2, as shown on Figure 3, the pressure level 700 bar results in lowest



FCV - fuel cell vehicle

FIGURE 2. Sensitivity of Optimal Pressure

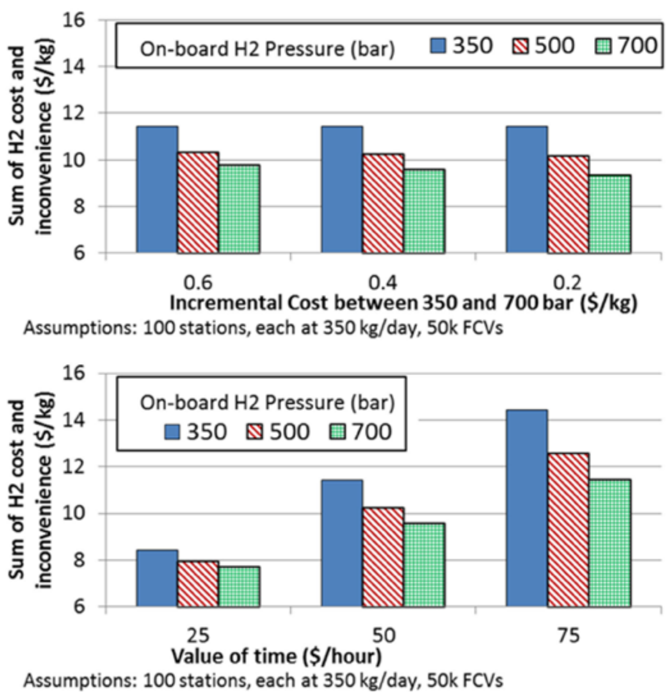


FIGURE 3. Compare Three Hydrogen Pressures for Southern California

combined cost of station and consumer inconvenience, regardless of the incremental cost of hydrogen and the value of time.

CONCLUSIONS AND FUTURE DIRECTIONS

This project determined and analyzed the optimal onboard hydrogen pressure as a function of vehicle and driver attributes, infrastructure availability and cost, and FCEV penetration in a regional context. Key quantitative findings are:

- A sub-optimal pressure leads to a higher combined cost, including infrastructure cost and refueling inconvenience cost, and therefore bigger barriers for market acceptance.
- With everything else held constant, including the number of FCEVs on the road, more hydrogen stations lead to lower onboard pressure and higher delivered hydrogen costs, due to lower infrastructure utilization.
- With everything else held constant, smaller hydrogen stations lead to higher onboard pressure and lower delivered hydrogen costs, due to higher infrastructure utilization.
- The optimal pressure is most sensitive to value of time, incremental cost of hydrogen, and number of FCEVs.
- With 100 stations and 50,000 FCEVs in Southern California, consistent with the California Fuel Cell Partnership 2017 deployment plan, 700 bar offers lower combined costs than either 350 bar or 500 bar. This conclusion is robust against uncertainty of high-pressure incremental costs (0.2-0.6 $/kg for high-pressure upgrade) or value of refueling travel time (25-75 $/hour).

The caveats of this study include:

- No representation of demand response to H_2 cost and pressure
- Limited analysis on uncertainty
- No consideration of cluster roll-out strategy

Thus, we propose an extended study to estimate the optimal delivered pressure that maximizes station profitability and FCEV acceptance and minimizes investment risks, via the following next tasks:

- Define and measure station profitability and investment risk
- Model cluster roll-out strategies
- Integrate with consumer choice models (e.g., MA3T)
- Estimate required subsidy and analyze station business models
- Conduct comprehensive uncertainty analysis
- Expand the study to beyond 100 stations to understand the point when the fueling pressure decreases
- Update the analysis with new station and fueling pressure costs from H2A Delivery Scenario Analysis Model

FY 2013 PUBLICATIONS/PRESENTATIONS

1. Zhenhong Lin, David Greene. Optimal Delivered H_2 Pressure: preliminary results. Presented to the FPITT team, Houston, Texas, Jan. 26, 2013.

2. Zhenhong Lin, David Greene. Impacts of Range and Refueling Pressure. Presented to the FPITT team, Fairfax, Virginia, Mar. 18, 2013.

3. Zhenhong Lin, David Greene. Analysis of Optimal On-Board Storage Pressure for Hydrogen Fuel Cell Vehicles. Presented at the DOE Hydrogen and Fuel Cells Program 2013 Annual Merit Review meeting, Crystal City, Virginia, May 14, 2013.

REFERENCES

1. Karl J. Gross, et al. (2012). Recommended Best Practices for the Characterization of Storage Properties of Hydrogen Storage Materials. H2 Technology Consulting, LLC.

2. The Department of Energy Hydrogen Analysis (H2A) Cost models are available online: http://www.hydrogen.energy.gov/h2a_analysis.html

3. Department of Energy. The Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan.

4. Zhenhong Lin, Joan Ogden, Yueyue Fan, Chien-Wei Chen (2008). The fuel-travel-back approach to hydrogen station siting. International Journal of Hydrogen Energy, 33(2008), 3096 – 3101.