IX.11 Analysis of Optimal On-Board Storage Pressure for Hydrogen Fuel Cell Vehicles

Zhenhong Lin (Primary Contact), Changzheng Liu
Oak Ridge National Laboratory
2360 Cherahala Boulevard
Knoxville, TN 37932
Phone: (865) 946-1308
Email: linz@ornl.gov

DOE Manager
Fred Joseck
Phone: (202) 586-7932
Email: Fred.Joseck@ee.doe.gov

Project Start Date: October 1, 2012
Project End Date: Project continuation and direction determined annually by DOE

Overall Objectives

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

Fiscal Year (FY) 2015 Objectives

- Represent the ZEV (zero emission vehicle) mandate in optimization
- Consider mixed storage pressure
- Consider travel pattern daily variation and driver heterogeneity
- Quantify range limitation cost
- Conduct California case studies

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 (MYRDDP):

(B) System Cost

(G) Codes and Standards

(X) System Life-Cycle Assessments

This project also addresses the following technical barrier from the Market Transformation section of the Fuel Cell Technologies Office MYRDDP:

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

Contribution to Achievement of DOE Hydrogen Storage and 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 MYRDDP:

- Hydrogen Storage 3.3: Transportation: Complete economic evaluation of cold hydrogen storage against targets. (4Q, 2015)
- Hydrogen Storage 3.6: Update early market storage targets. (4Q, 2017)
- Hydrogen 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 2015 Accomplishments

- The Hydrogen Optimal Pressure (HOP) model was upgraded to include range limitation cost and ZEV credits in its objective function. Six types of daily driving patterns were derived to represent California drivers and on which to base the quantitative analysis of range limitation costs.
- The pressure of 700 bar is found to be especially valuable for consumers with frequent long-distance and away-from-station-cluster trips. These consumers may still face range limitation even with a 300-mile driving range.
- The value of the ZEV credits for 700-bar tanks (enabling >300-mile range) is significant enough to overshadow other determining factors.

✧ ✧ ✧ ✧ ✧

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. Higher hydrogen pressure allows more hydrogen to be stored on board, 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. 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 may encourage investment activities in developing more stations, resulting in better refueling convenience for consumers.

The objectives of this project are to:

- 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 motivation of optimization is to maximize 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 model is formulated to reflect tradeoff between consumer refueling convenience, onboard storage cost, infrastructure costs, range limitation cost, and ZEV compliance value. Higher pressure increases hydrogen storage volume, driving range, and time between hydrogen refills, but increases the cost of delivery and storage infrastructure (thereby increasing the cost of hydrogen) and the capital cost of the onboard storage system. Long driving range decreases the chance of needing a substitute vehicle for long-distance trips. A driving range exceeding 300 miles is eligible for maximum ZEV credits, based on the current ZEV policy. Both region-wide optimal infrastructure roll-out strategies and cluster strategies are considered.

Specifically, the optimal pressure is solved for by equating the marginal value of increased range due to increased pressure to the sum of the marginal H_2 delivered cost and the marginal onboard storage capital cost, also due to increased pressure. This approach is equivalent to minimization of combined costs of refueling inconvenience, onboard storage system, and stations. The marginal value of increased range due to higher pressure includes three components—the reduced need for using a backup vehicle for long and away-from-station trips, the increased units of ZEV credits, and the reduction of net present value of total refueling time over five years. Refueling time includes access time to station (depends on availability), refueling time at station, and annoyance amplification. The marginal cost of increased pressure includes the resulting increased cost of pumps, tanks, and energy use. Based on discussions with the Fuel Pathways Integration Technical Team (FPITT) of the United States Driving Research and Innovation for Vehicle efficiency and Energy sustainability (U.S.DRIVE) partnership, the published work by University of California, Davis, the DOE's Hydrogen Analysis (H2A) model, and the National Household Travel Survey 2009, the following parameter assumptions are used for the baseline: mid-sized fuel cell electric vehicles (FCEVs) with fuel economy of 60 miles per gallon gasoline equivalent; a representative driver who drives 13,000 miles per year and values refueling travel time at $50/hour; a dispenser linger time of 2.4 minutes; hydrogen filling rate of 1.6 kg/min; $3.27/kg delivered hydrogen cost at 700 bar at 200 kg/d and $2.21/kg at 350 bar at 200 kg/d, both with full utilization (based on H2A models); and Southern California as the regional context and the city of Santa Monica in California as the cluster strategy context.

RESULTS

The optimal pressure found from the study has evolved during the three project years due to modification of optimization scope and context. In summary, FY 2013 results found 700 bar to be more desirable in many region-strategy scenarios. FY 2014 results show that 350 bar or 500 bar can be more competitive in reducing system cost in certain cluster-strategy scenarios. FY 2015 results show strong preferences for 700 bar over 350 bar or 500 bar, because 700 bar is the only one among three pressure levels to enable an over 300-mile range required for maximum ZEV credits. The ZEV credit, based on available credit trading information, is so valuable that the ZEV credit value becomes a dominating factor in the optimization, regardless of driver types.

The pressure of 700 bar can be valuable for consumers with frequent long-distance and away-from-station-cluster trips. To capture driving pattern and driver heterogeneity, six types of drivers and their driving patterns are derived to represent California drivers, as shown in Figure 1, based on the 2009 National Household Travel Survey. In our calculation, 350 bar and 700 bar result in 210 miles and 360 miles of driving range, respectively. For most drivers, they are both adequate in meeting daily travel needs. For FSC (frequent and short commute) drivers who concentrate a substantial portion of the annual 31,100 miles on long-distance trips and require a rental car (an equivalent concept for a substitute vehicle) at $50/day, it could result in a significant penalty, i.e., range limitation cost (which is usually a concern for short-range battery electric vehicles), as much as $205/year for 700 bar and $1,428/year for 350 bar.

The newly added value component on ZEV credits seems to be the dominating factor for the optimal pressure level. A 700 bar pressure enables a driving range of 360 miles, making the vehicle eligible for nine ZEV credits, while driving ranges for vehicles with 350 bar and 500 bar

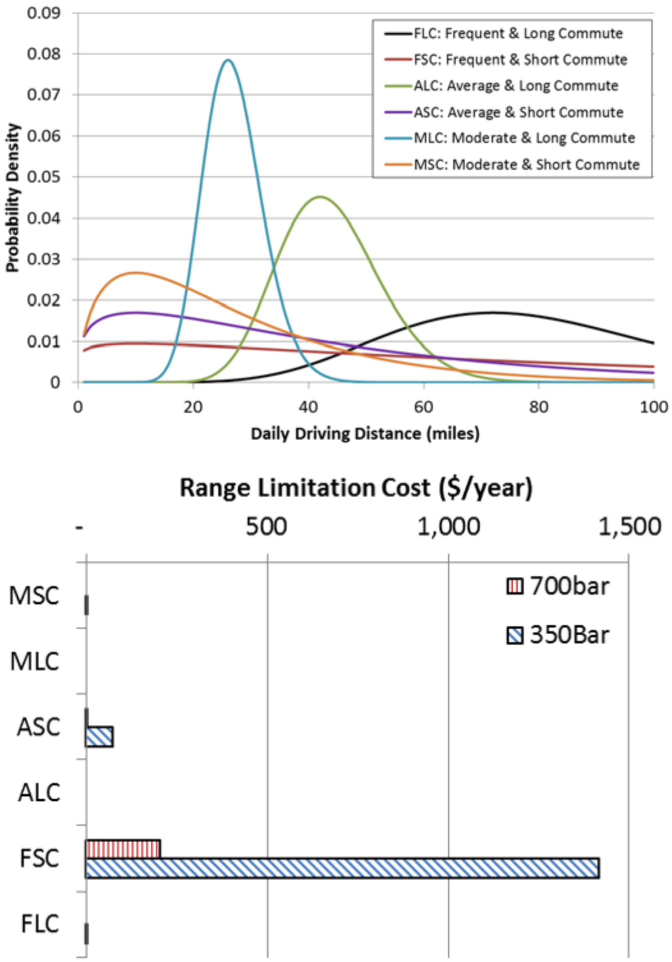
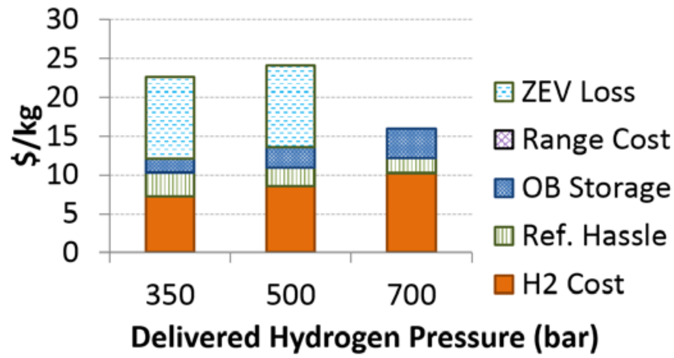


FIGURE 1. Range limitation cost of heterogeneous drivers

tanks are 200–300 miles qualifying the vehicles for only five ZEV credits. If $4,000 is assumed for the value of each ZEV credit, the four-credit gap means $16,000 in revenue lost per vehicle for original equipment manufacturers. This is a significant advantage of 700 bar. As shown in Figure 2, without considering ZEV credits, 350 bar would result in the lowest system cost among the three pressure levels with the cluster strategy for station roll-out, for the FLC (frequent & long commute) drivers. Using nine ZEV credits as the reference and assuming $4,000 as the value of each ZEV credit, we found significant ZEV loss (due to not gaining the full nine ZEV credits) for 350 bar and 500 bar. As a result, 700 bar is a clear winner of the three.



assume cluster strategy in Santa Monica, 1x12 kg/day station (5% fuel availability), 130 FCEVs, $100/hr time value
OB – Onboard

FIGURE 2. Cost components of optimization objective function (FLC drivers)

CONCLUSIONS AND FUTURE DIRECTIONS

The HOP model was upgraded to include range limitation cost and ZEV credits in its objective function. Six types of daily driving patterns were derived to represent California drivers and on which to base the quantitative analysis of range limitation costs.

The pressure of 700 bar is found to be especially valuable for consumers with frequent long-distance and away-from-station-cluster trips. These consumers may still face range limitation even with a 300 mile driving range.

The ZEV value of 700 bar (enabling >300-mile range) is significant enough to overshadow other determining factors.

In-depth optimal pressure analysis for early adopters and integration with consumer choice models is recommended. More research is needed on identifying the optimal pressure for early adopters, for maximizing FCEV market acceptance, and for standardization concerns. Uncertainty of key parameters also requires more analysis.

FY 2015 PUBLICATIONS/PRESENTATIONS

1. Zhenhong Lin, Changzheng Liu, Analysis of Optimal On-Board Storage Pressure for Hydrogen Fuel Cell Vehicles. Presented at the 2015 DOE Annual Merit Review meeting.