X.1 Analysis of Optimal Onboard Storage Pressure for Hydrogen Fuel Cell Vehicles

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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) 2014 Objectives

- Include onboard storage cost in optimization
- Optimize with cluster infrastructure strategy
- Update station costs
- Represent refueling annoyance
- Capture early adopter preferences
- 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:

(B) System Cost

(F) Codes and Standards

(K) System Life-Cycle Assessments

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

(B) High hydrogen fuel infrastructure capital costs for polymer electrolyte membrane fuel cell applications

Contribution to Achievement of DOE 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 2014 Accomplishments

- Developed the hydrogen optimal pressure and its user interface as an Excel Visual Basic for Applications tool that solves for optimal pressure under a wide range of user-specified market and technological parameters.
- Expanded the optimization to reflect onboard storage capital cost, refueling annoyance, and cluster strategy. Analyzed optimality within the pressure span of 350-700 bar.
- Found lower pressure (350 or 500 bar) more desirable for certain cluster strategy scenarios and higher pressure (700 bar) generally more desirable for connector stations.
- Recommended 700 bar even with a cluster strategy for early adopters due to their possible higher time value.
- Recommended continued improvement of onboard storage technologies to facilitate deployment of higher pressure that enables longer driving range.
- Quantified tradeoffs between fuel availability and driving range, which have important implications for fuel cell vehicle design and hydrogen infrastructure deployment.
- Found most sensitive factors of optimal pressure: time value, driving intensity and city density (time to nearest station).

- Identified needs for further research that focuses on consumer segmentation and integration with consumer choice models.

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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. 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 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 method is formulated to reflect tradeoff between consumer refueling convenience, onboard storage cost and infrastructure costs. Higher pressure increases hydrogen storage and driving range between hydrogen refills, but increases the cost of delivery and storage infrastructure (therefore increase the cost of hydrogen) and the capital cost of the onboard storage system. Both region-wide optimal infrastructure roll-out strategies and cluster strategies are considered.

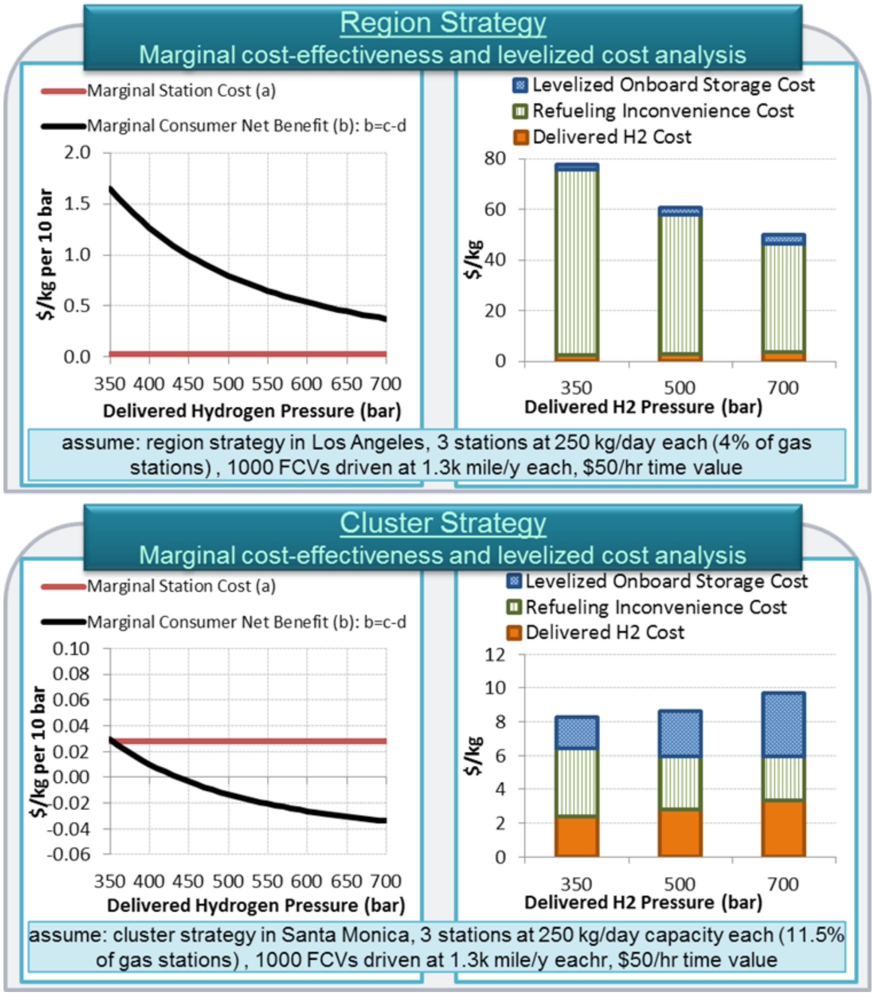
Specifically, the optimal pressure is solved for by equating the marginal value of increased range due to increased pressure to the sum of the marginal hydrogen delivered cost and the marginal onboard storage capital cost, also due to increased pressure. This is equivalent to minimization of combined costs of refueling inconvenience, onboard storage system and stations. The marginal value of increased range due to higher pressure is measured by 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 of U.S.DRIVE and the published work by University of California, Davis, the DOE's H2A model and the National Household Travel Survey 2009, these parameter assumptions are assumed for the baseline: mid-size fuel cell vehicles (FCVs) with 60 miles per gasoline gallon equivalent (mpgge), a representative driver who drives 13,000 miles per year and values refueling travel time at $50/hour, a dispenser linger time at 2.4 minutes, hydrogen filling rate at 1.6 kg/min, $3.27/kg of delivered hydrogen cost at 700 bar at 200 kg/day and $2.21/kg at 350 bar at 200 kg/day, 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 is found to be lower with the cluster strategy than with the region roll-out strategy. Cluster strategy allows a small number of stations to achieve a high level of refueling convenience and thus increases tolerance for a low-pressure-caused short driving range and avoids the situation of many underutilized or scale uneconomical stations. As shown in Figure 1, three stations and 1,000 FCVs, if spread out in a large metropolitan region, would demand 700 bar or higher. Three stations in a large region is too inconvenient and the value of longer range from higher pressure exceeds the incremental cost from 350 to 700 bar. The same three stations and 1,000 FCVs, if clustered in a small city, would lead to the optimal pressure around 350 bar. Three stations in a small city is convenient enough so that the additional cost of higher pressure fails to justify the additional convenience benefit of a longer range.

Improvement of onboard storage is needed for higher hydrogen pressure and longer driving range. High-pressure onboard storage is more expensive due to the higher per-kWh cost and a larger amount of hydrogen stored. Optimal pressure for one 150-kg/day station supporting 150 FCVs in Santa Monica is estimated to be 374 bar, or 540 bar if onboard storage cost is ignored (Figure 2). Reducing onboard storage cost (from R&D progress) can lead to higher optimal pressure (a, c unchanged, d curve shifting down and b curve up on Figure 2) and longer driving range.

Higher pressure may be more desirable for early adopters possibly with high time value. Higher pressure enables longer driving range, reduces refueling frequency, and thus saves annual refueling time. Refueling inconvenience cost is proportional to value of time, which may vary greatly among consumers. Assuming one 150 kg/day station supporting 150 FCVs driven in Santa Monica, optimal pressure changes


Region Strategy

Marginal cost-effectiveness and levelized cost analysis

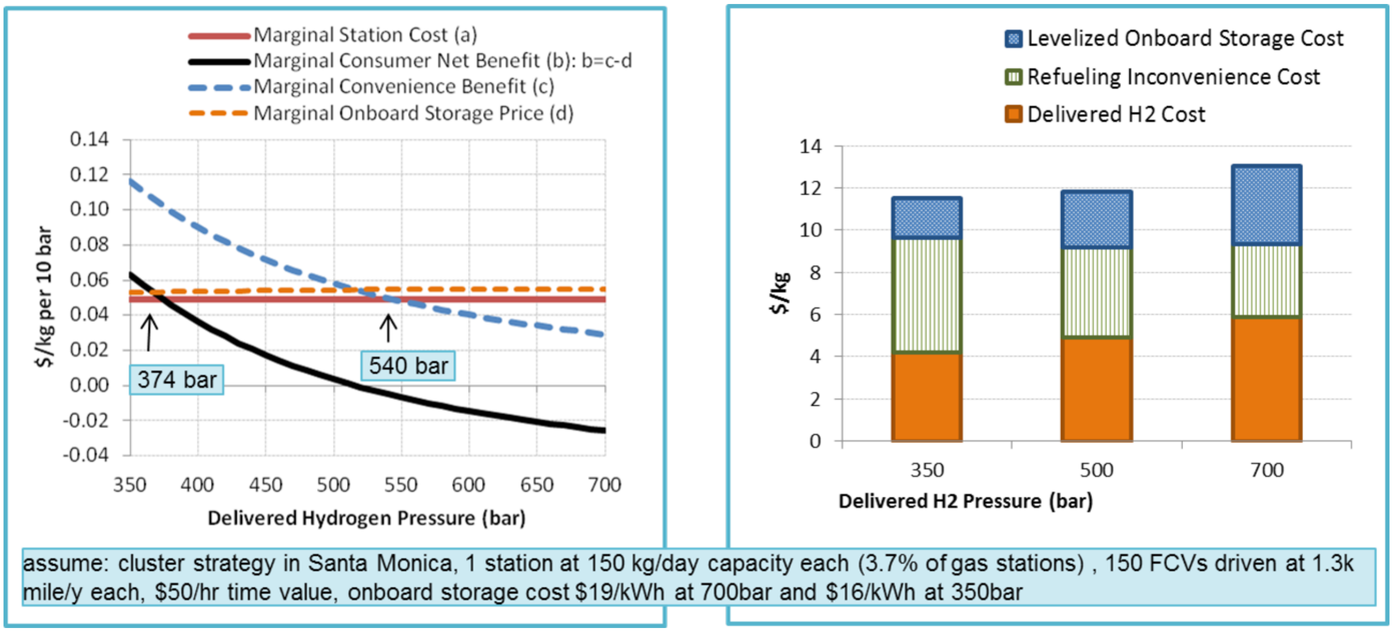
assume: region strategy in Los Angeles, 3 stations at 250 kg/day each (4% of gas stations) , 1000 FCVs driven at 1.3k mile/y each, $50/hr time value

Cluster Strategy

Marginal cost-effectiveness and levelized cost analysis

assume: cluster strategy in Santa Monica, 3 stations at 250 kg/day capacity each (11.5% of gas stations) , 1000 FCVs driven at 1.3k mile/y eachr, $50/hr time value

FIGURE 1. Optimize Pressure for Region and Cluster Strategies



assume: cluster strategy in Santa Monica, 1 station at 150 kg/day capacity each (3.7% of gas stations) , 150 FCVs driven at 1.3k mile/y each, $50/hr time value, onboard storage cost $19/kWh at 700bar and $16/kWh at 350bar

FIGURE 2. Effect of Onboard Storage Cost on Optimal Pressure

from 375 bar to over 700 bar when refueling travel time value increases from \$50/hour to \$200/hour (Figure 3). This illustrates the importance of segmenting early adopters by income and other demographic attributes that may affect time value.

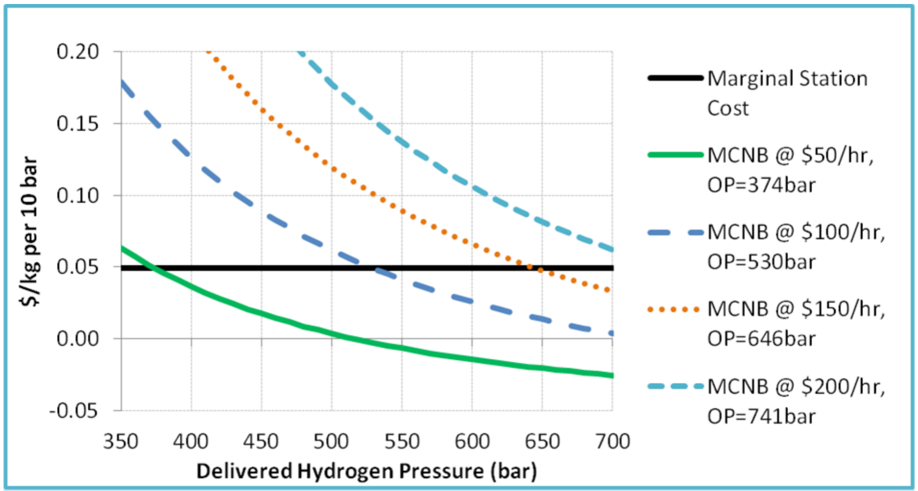
Under scenarios constructed to reflect compliance with the zero-emission vehicle (ZEV) mandate in California, lower pressure is found to be desirable for the cluster strategy and higher pressure for the region strategy. For three 3-year periods, 636, 3,442 and 25,000 FCVs are assumed to be adopted, supported by 8, 12, and 48 stations at 100, 200, and 350 kg/day, respectively (Table 1). In the region strategy, these vehicles and stations are assumed to spread over the Southern California region. In the cluster strategy, they are assumed to concentrate in 4, 6, and 12 Santa Monica-like areas during the three periods, respectively. Even though the total numbers of vehicles and stations are the same, the refueling convenience differs between the two roll-out strategies, which leads to difference in optimal pressure. In Figure 4, cluster and region roll-out strategies are compared in terms of the optimal pressure, the best of three (350/500/700 bar) and the non-optimality regret of choosing one of the three, for the three ZEV mandate compliance periods. Optimal pressure under the region strategy is found to be well over 700 bar for all three periods. Under the cluster strategy, optimal pressure is estimated to be 412, 525 and 503 bar, respectively. If limited to the above three pressure levels, the best choice appears to be 350 bar during the 1st period and 500 bar during the 2nd and 3rd periods under the cluster strategy, and 700 bar during all three periods under the region strategy. The non-optimality regret is found between \$0.1/kg and \$1.7/kg hydrogen under the cluster strategy, depending on which non-optimal pressure is chosen, but is more significant with the region strategy, ranging from \$2.6/kg to \$41/kg hydrogen.

TABLE 1. ZEV Compliance Assumptions

	ZEV-Year1-3	ZEV-Year4-6	ZEV-Year7-9
FCVs on road	636	3,442	25,000
Average Station Size (kg/d)	100	200	350
Station Utilization	47%	85%	88%
Cluster Strategy			
Clusters	4	6	12
FCVs On Road/Cluster	159	574	2,083
Stations/Cluster	2	2	4
Percent of Gas Stations	7.7%	7.7%	15.4%
Region Strategy			
Stations in the region	8	12	48
Percent of Gas Stations	0.13%	0.20%	0.80%

Sensitivity analysis of optimal pressure is completed on seven parameters—time value, driving intensity, time to nearest station, onboard storage cost, station cost, pressure incremental station cost, and station scaling factor. Each parameter is varied by 20% at either direction from the reference case, for which assumptions include:

- Cluster strategy, 574 FCVs and two stations at 200 kg/day each
- Time value (\$100/hour)
- Driving intensity (13,000 mile/yr)
- Time to nearest station (3.6 min)



assume: cluster strategy in Santa Monica, 1 stations at 150 kg/day capacity each (3.7% of gas stations) , 150 FCVs driven at 1.3k mile/yr each, onboard storage cost \$19/kWh at 700bar and \$16/kWh at 350bar. Refueling travel time value varies from \$50/hour to \$200/hour, which is further multiplied by a refueling annoyance factor of 3.5.

FIGURE 3. Marginal Cost-Effectiveness by Travel Time Value

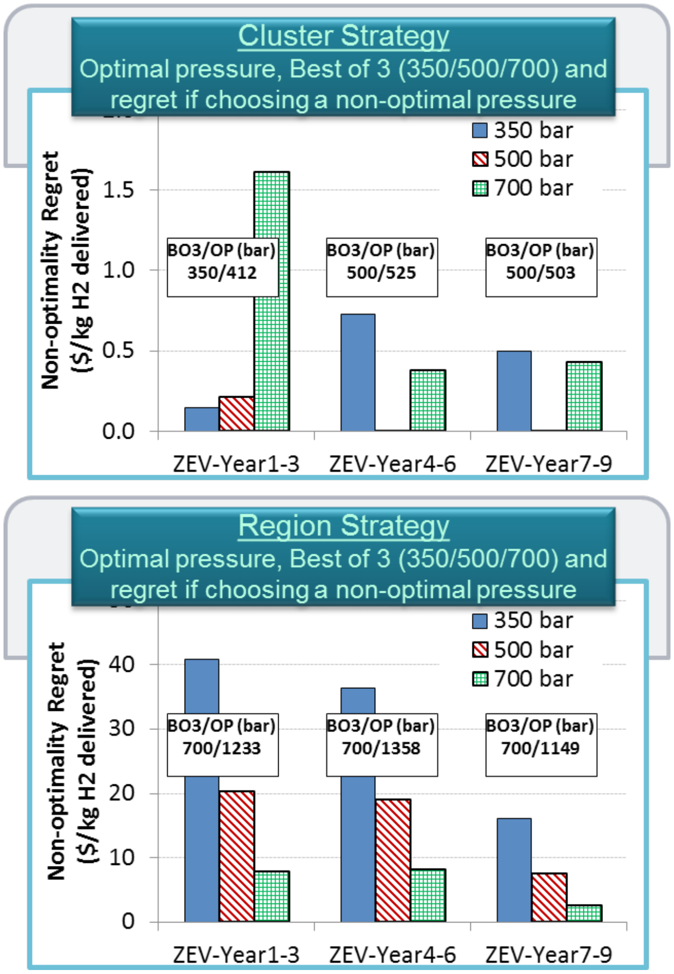


FIGURE 4. Optimal Pressure and Non-Optimality Regret under ZEV

- Onboard storage cost ($16/kg and $19/kg at 350/700 bar)
- Station cost ($3.27/kg at 83% utilization of 240 kg/d at 700 bar)
- Pressure incremental station cost (8.3%/100 bar)
- Station scaling factor (-0.608)

As shown in Figure 5, optimal pressure is most sensitive to time value, driving intensity and time to the nearest station, suggesting needs for consumer segmentation. It is also highly sensitive to onboard storage cost, implying that storage R&D can help adoption of high delivered pressure.

Clearly, there is a tradeoff between delivered pressure and fuel availability. More stations makes each refueling trip shorter and thus can reduce the need for a longer range that is enabled by higher pressure. The contour lines on Figure 6 visualize such tradeoffs between the optimal pressure and the hydrogen fuel availability, under the assumptions of the cluster strategy, 574 FCVs and two stations at 200 kg/day each. As shown, optimal pressure is 500 bar at 15% fuel availability and about 450 bar at 20% fuel availability, assuming $150/hour time value. The contour line shifts downward if lower time value is assumed, meaning lower optimal pressure for the same fuel availability or lower fuel availability for the same pressure.

CONCLUSIONS AND FUTURE DIRECTIONS

The FY 2014 work of this project has led to new understandings of the issue. The 700-bar pressure level was found by this project during FY 2013 to be more desirable in most scenarios including the California near-term plan. With inclusion of onboard storage cost, the cluster strategy and

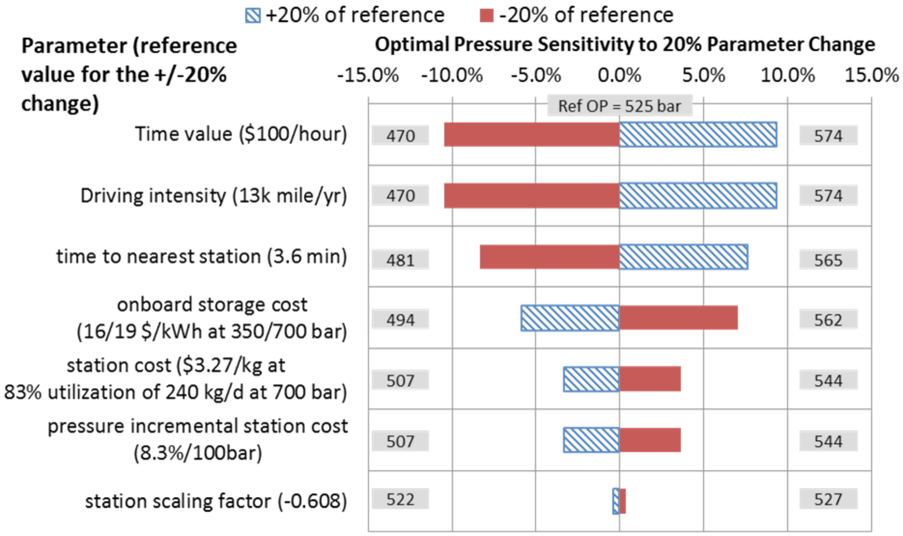


FIGURE 5. Sensitivity of the Optimal Pressure

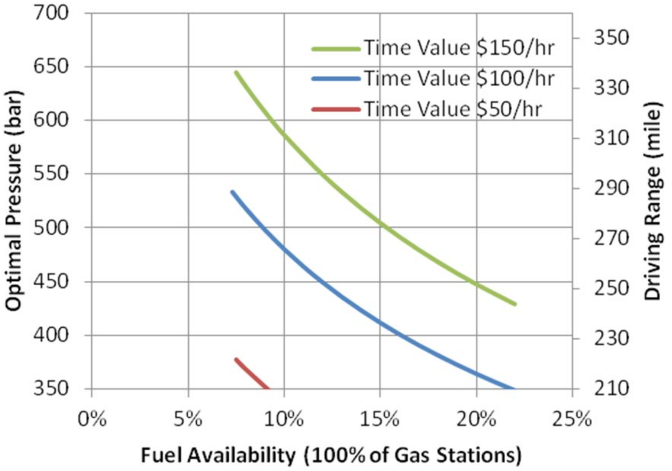


FIGURE 6. Pressure and Fuel Availability Tradeoff

refueling annoyance, the FY 2014 results suggest that 700 bar may not be the optimal, especially under cluster strategy and the current onboard storage cost. 350 bar and 500 bar appear superior in ZEV scenarios with the cluster strategy.

FY 2014 progress includes:

- Added storage cost to the objective function (only including station cost and inconvenience cost in FY 2013)
- Represented both cluster and region strategies
- Developed a friendly user-interface
- Analyzed optimal pressure under cases reflecting ZEV
- Conducted sensitivity analysis

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 FCV market acceptance and for standardization concerns. Uncertainty of key parameters also deserves more analysis.

FY 2014 PUBLICATIONS/PRESENTATIONS

1. Zhenhong Lin, Changzheng Liu, and David Greene. Analysis of Optimal On-Board Storage Pressure for Hydrogen Fuel Cell Vehicles. Presented at the 2014 DOE Annual Merit Review meeting.