III.21 Range Optimization for Fuel Cell Vehicles

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Objectives

- Develop the fuel cell vehicle (FCV) range optimization model.
- Compare onboard storage technologies.
- Support the DOE integrated analysis on storage and range issues.

Technical Barriers

This project addresses the following three barriers from the Fuel Cell Technologies Program Multi-Year Research, Development and Demonstration Plan [1]:

(A) System Weight and Volume from the Storage section
(B) System Cost from the Storage section
(B) Stove-piped/Siloed Analytical Capability from the System Analysis section

Technical Targets

This project optimizes the driving range for FCVs. Insights gained from the study can be applied toward assessment and planning of research and development (R&D) activities on onboard hydrogen storage in meeting the following DOE 2010 hydrogen storage targets [1]:

- Cost: $4/kWh net
- Specific energy: 1.5 kWh/kg
- Energy density: 0.9 kWh/L

Accomplishments

- Baseline analysis suggests that the optimal FCV range for the very near term is estimated to be 297-544 miles, depending on up to 10% variation on key parameters.
- Sensitivity analysis demonstrates the robustness of the optimization. A 10% variation on each of 16 key parameters results in -5.7% to +6.2% of change in the optimal range and the optimal onboard usable fuel capacity.
- Quantified the functional relationship between optimal range, storage cost, storage density, and fuel availability. In general, the optimal range is found to increase with lower storage cost or higher storage density, but decrease with better fuel availability.
- Based on the range optimization model, several storage technologies are compared in the transitional market context based on an integrated consumer value metric.
- Demonstrated the benefit of range optimization in informing policy making. Compared to the optimal range, the standard range assumption leads to an overestimate of FCV commercialization barrier by over $8,000 per vehicle. Such a significant overestimate of this transition barrier can seriously mislead policy making but can be corrected by range optimization.

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Introduction

The driving range of FCVs needs to be properly determined for accurately assessing the market barriers and cost-effectiveness of this vehicle technology [2-5]. While an overestimated range means an overestimated cost of onboard storage, an underestimated range leads to exaggeration of refueling hassle especially in the early transition period when fuel availability is very limited. Either overestimation or underestimation of the driving range leads to exaggeration of commercialization barrier for FCVs and could mislead policies.

If FCVs become commercialized, it is logical and likely that the private sector will design the range to maximize the value for FCV customers. This suggests optimization of FCV range for proper representation of FCVs in analyses where various vehicle technologies are compared and the future vehicle market is projected. Currently, the FCV range commonly assumed in many analyses is based on engineering constraints and simple analogy to conventional vehicles [6], but not on optimization that reflects the storage technology status and fuel availability for FCVs. It is unclear to what extent the ongoing non-optimal range assumptions affect the FCV barrier assessment. It is necessary to revisit the issue by optimizing the FCV range in the context of transitional markets.

Approach

The FCV range is optimized from the perspective of maximizing consumer value or minimizing total vehicle ownership cost. As a benefit to consumers, increasing the FCV range reduces the stress and time of accessing hydrogen stations, the wasted fuel in searching for stations and the time at the station. On the cost side, a longer FCV range results in loss of legroom or cargo space and higher storage system cost and vehicle price. The optimal range is defined as one where the marginal benefit equals the marginal cost. In preparation for the optimization, the stress and time of refueling are estimated based on calibration to 5,850 light-duty vehicles and appear to be more consistent with survey estimates than conventional analytical methods that consider only travel time cost [7]. Refueling travel time is calculated by assuming optimal station locations [8,9]. Onboard storage technologies are characterized based on published information from the hydrogen storage projects funded by U.S. DOE [1,10]. Value of vehicle interior space is currently based on published estimate that is based on statistical analysis of vehicle design and pricing data [11].

Results

- The baseline analysis shows the optimal FCV range for the very near term ranging from 297 to 544 miles, depending on up to 10% variation on key parameters. The baseline case is intended to represent the near term characterized by very limited hydrogen station deployment and current technology status for onboard storage. For hydrogen availability, the percentage of stations providing hydrogen is assumed to grow from 1% at the present to 10% in 10 years. Onboard storage technology is assumed to be available at \$15.6/kWh and 0.6 kWh/L.
- The barrier of limited range and fuel availability is described by the extra range cost relative to conventional gasoline vehicles, including storage hardware cost, loss of interior space, refueling travel stress and time, wasted fuel, dispensing time and station time overhead. The baseline case results show the extra range cost for a near-term FCV owner is more than \$20k (Figure 1). Storage system cost, loss of interior space and refueling travel stress and time contribute to most of the extra range cost.
- Sensitivity analysis demonstrates the robustness of the optimization. A 10% variation on each of 16 key parameters results in -5.7% - +6.2% change in the optimal range and the optimal onboard usable fuel capacity (Figure 2).

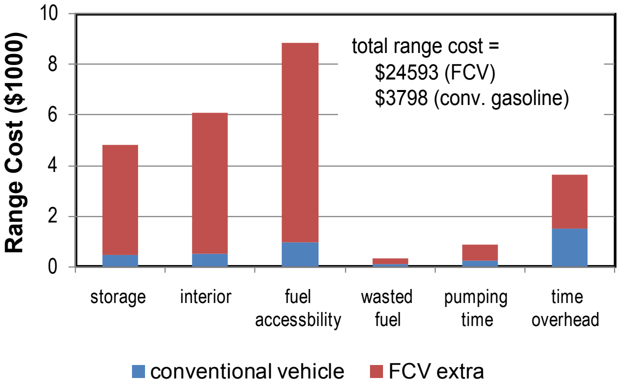

FIGURE 1. FCV range cost by component for the baseline optimal range. Fuel availability is assumed to grow from 1% to 10% in 10 years. Current 350 bar compressed hydrogen is assumed.

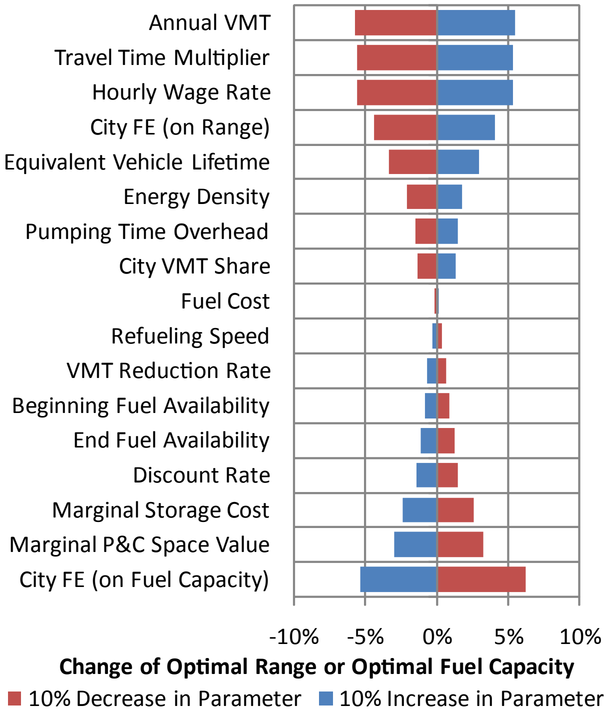

FIGURE 2. Percentage change in optimal range or optimal fuel capacity in response to +/-10% change in each parameter.

- The relationship between optimal range, storage cost, storage density, and fuel availability is quantified. In general, the optimal range is found to increase with lower storage cost or higher storage density, but decrease with better fuel availability.
- Different storage technologies are compared based on range cost and infrastructure cost (Figure 3)

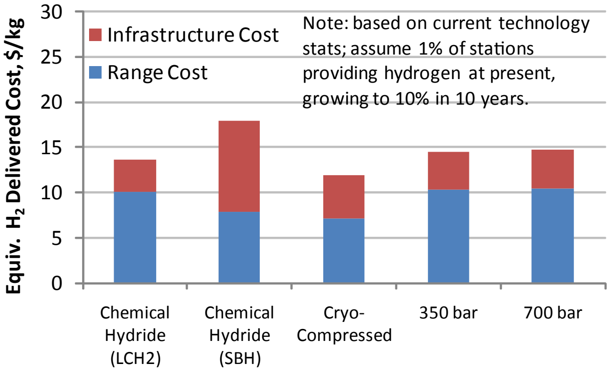

FIGURE 3. Onboard storage technology comparison based on range cost and infrastructure cost.

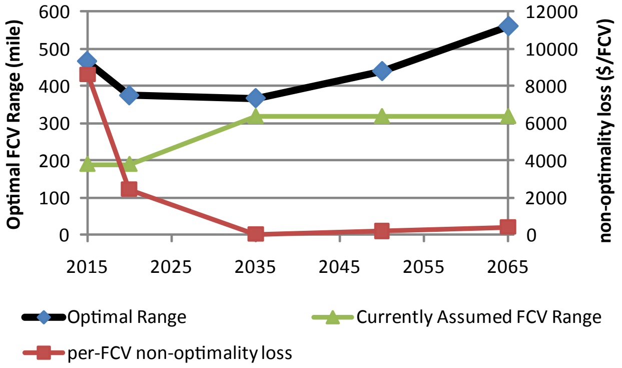

FIGURE 4. Standard range, optimal range and non-optimality loss that describe how much the market barrier can be overestimated if the range is not optimal.

for the near-term scenario. Based on current technology status and near-term infrastructure deployment, cryo-compressed appears to be overall the most cost-competitive, even though its infrastructure cost is higher than compressed gaseous technologies. The chemical hydride technology based on liquid hydrogen carrier (LCH_2) is slightly more cost-competitive than compressed gaseous hydrogen. The two compression technologies, with pressures of 350 bar and 700 bar, do not differ substantially from each other in terms of total range and infrastructure costs. The chemical hydride technology based on sodium borohydride (SBH) has a good balance of storage system cost and density, resulting in a relatively low range cost, but its high infrastructure cost makes it the least cost-competitive among the five technologies. It should be noted that these comparisons reflect the near-term technology and infrastructure status and do not reflect the improvement potential of the technologies.

- The barrier overestimation by non-optimal range design can be significant. Compared to the optimal range, the standard range assumption leads to an overestimate of range cost by over $8,000 per vehicle. Such a significant overestimate of barrier can seriously mislead policy making and should be corrected by range optimization (Figure 4).
- The scenario analysis based on the DOE Scenario 3 shows that the FCV range does not necessarily exhibit a monotonic increase or decrease over time. It decreases initially and grows later in response to the relative development pace of storage technology and infrastructure (Figure 4). In reality, product design constraints and consumer expectation set by previous products may prevent the designed range from significantly decreasing. However, what is important is that by reaching the initial critical level of fuel availability, FCV range can be reduced to save costs if little progress is made on onboard storage. It also suggests that after the critical fuel availability level, a higher FCV range is realistic if onboard storage is significantly improved.

Conclusions and Future Directions

- It is very likely that the non-optimal FCV range currently assumed in analyses has led to exaggeration of this market barrier. Compared to the estimated optimal range, the currently assumed FCV range is found to be too low, which reduces the cost of onboard storage hardware but will require early FCV owners to make more frequent trips to the very few stations that provide hydrogen. The collective effect is a range cost overestimation by over $8,000 per each early FCV owner. In integrated market analyses, such an overestimation would put FCVs into biased disadvantage. It should and can be corrected with range optimization that trades off onboard storage cost with refueling inconvenience.
- The optimal FCV range is found to be a function of fuel availability, onboard hydrogen storage cost and density. The optimal range increases with technological progress of onboard storage, because lower storage cost or higher storage density makes it cost-effective to have additional range in order to reduce refueling frequency. The optimal range decrease with refueling infrastructure deployment, because better fuel availability makes it worthwhile to reduce the range in order to save upfront storage cost.
- The FCV range should be adaptive to the developments of onboard storage technology and refueling infrastructure, for two reasons. First, as we have shown, the optimal FCV range is a function of storage cost, storage density and fuel availability. Second, all these three factors will likely change significantly during the transition period.

- High cost and low density onboard storage and limited fuel availability cause a serious market barrier for FCVs, even if the FCV range is optimized. To eliminate such a barrier, both improving onboard storage and deploying refueling infrastructure will help, but given the uncertainty of technology development and the diminishing contribution to fuel availability of more stations, building up the initial small-scale refueling network should be of higher priority.
- On future study, the methods or observations from this study should be utilized for integrated models. The optimization model can be used to track the progress of onboard storage R&D activities. More research is recommended to better understand the value of vehicle interior space. The optimization model can be expanded to other vehicle technologies, including electric vehicles and plug-in hybrid vehicles. Other factors may also need to be included in optimizing the range, such as weight, efficiency and leakage.

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