AN033

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

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Center for Transportation Analysis

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Oak Ridge National Laboratory

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Overview

Timeline
 	
• Start date: Oct, 2012
• End date: Oct 2014*
• % completed: 80%
**Project continuation and direction determined annually by DOE*
	Barriers*
	
	• Barriers of Storage
	  • B. System Cost
	  • F. Codes and Standards
	  • K. System Life-Cycle Assessments
	• Barriers of Market Transformation
	  • B. High hydrogen fuel infrastructure capital costs for PEM fuel cell application
	**from 2011-2020 FCTO MYPP*

Budget (DOE share) • FY13: $80k received • FY14: $100k expected • Total: $180k	**Partners/Collaborators** • Fuel Pathway Integration Tech Team members: • Air Products, ExxonMobil, Phillips 66, Shell, Chevron • Argonne National Laboratory • National Renewable Energy Laboratory • University of California, Davis

Relevance

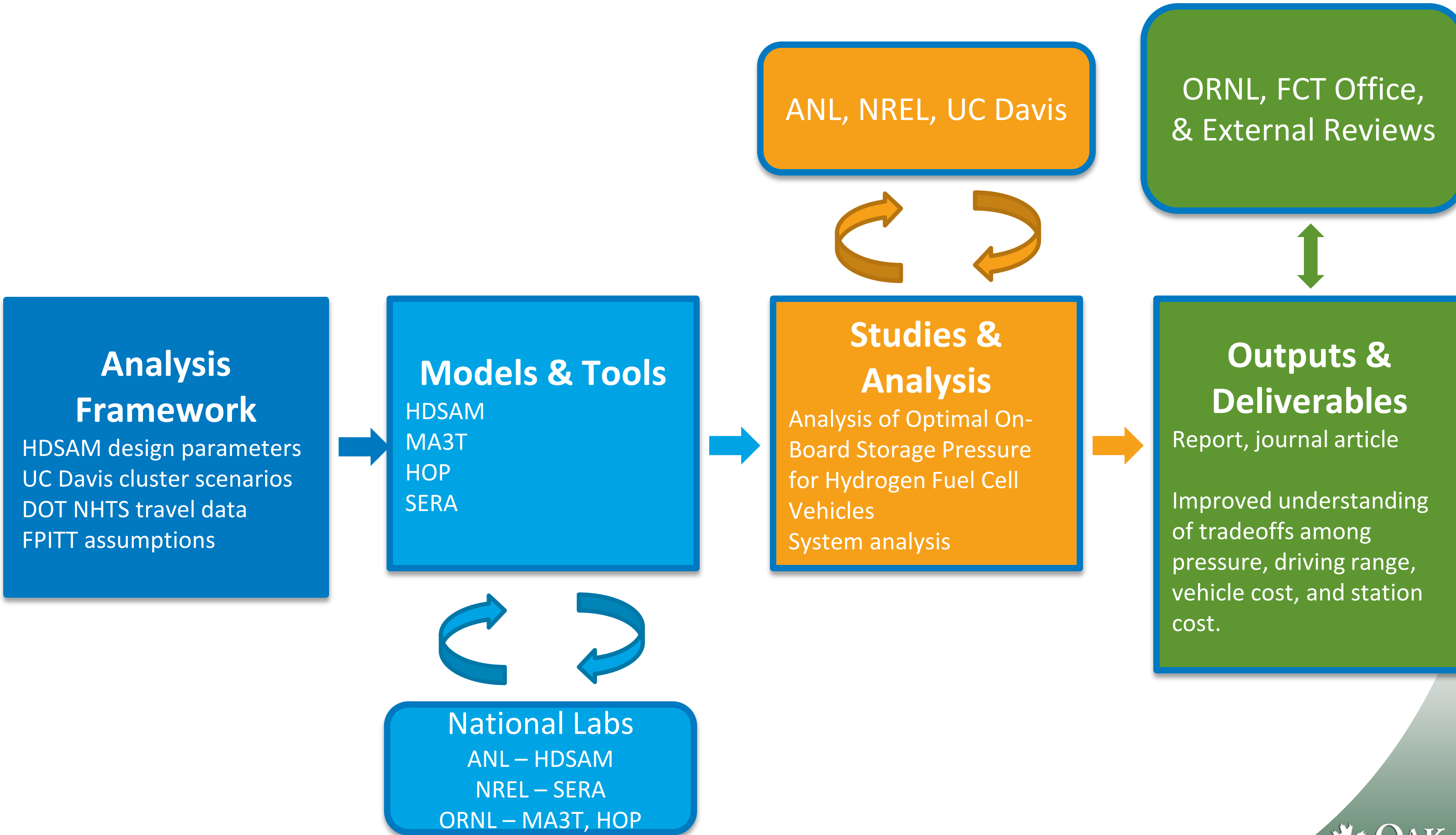
- **Overall Objectives**
  - Develop a method to optimize the onboard hydrogen pressure by integrating a wide range of factors.
  - Conduct case studies and provide useful insights for the industry and R&D planning.
  - Identify the optimal pressure that reduce system cost, increase market acceptance, or both.
- **Directly addressed barriers**
  - “Storage” B: System Cost
  - “Storage” F: Codes and Standards
  - “Market Transformation” B: High hydrogen fuel infrastructure capital costs for PEM fuel cell application
- **Status before this period**
  - Developed the optimization method based on station cost and fuel accessibility cost
  - Completed sensitivity analysis
  - Completed a California case study and recommended 700 bar at least for near-term infrastructure deployment
- **FY13 AMR Key reviewer recommendations**
  - Consider on-board storage cost
  - Consider cluster roll-out strategy
  - Consider refueling annoyance
- **Key FY14 Tasks (%completed)**
  - Include onboard storage cost in optimization (100%)
  - Apply optimization with cluster infrastructure strategy (100%)
  - Update station costs (100%)
  - Represent refueling annoyance (100%)
  - Capture early adopter preferences (100%)
  - Case studies (30%)
  - Reporting and publication (0%)

Analytical framework needed for complicated relationships between on-board H2 pressure and range, costs, consumer acceptance, and industry risks

- Complexity
  - Lower-pressure H2 reduces vehicle range, but requires less expensive stations and onboard storage systems.
  - Reduced range can be compensated with more stations, but then lower station utilization will increase H2 costs.
  - Station utilization can be increased by reducing station sizes, but diseconomy of scale leads to higher hydrogen costs.
- Issues of interest
  - What is the optimal pressure (OP)* under what circumstances? What is the theoretical pattern of OP changing with other factors?
  - What is the realistic OP, e.g. by considering California's roll-out plan?
  - How significant is pressure optimization and under what circumstances?
  - better or worse: compensate low-pressure inconvenience vs pay for high-pressure high cost?
  - What is the recommended pressure for near-term deployment?
  - What is the optimal strategy for station deployment, timing, size, location, delivery pressure?
  - What are the implications for consumer acceptance, industry risks, R&D and deployment policies?
- Issues important but outside the project scope
  - Safety, equipment reliability and durability, equipment availability

* acronyms are listed and defined in technical backup slides.

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



Optimal pressure (OP) minimizes sum of pressure-affected costs on fuel providers and consumers.

- **Minimize {H(p)+S(p)+R(p)}**
  - **p**: delivered H2 pressure, decision variable
  - **H**: H2 station cost (i.e. delivered H2 cost); increase w/ p
  - **S**: onboard storage cost; increase w/ p
  - **R**: refueling inconvenience cost; decrease with p
  - **[** $-(\partial S/\partial p + \partial R/\partial p)$**]** is the marginal consumer net benefit (MCNB)
- **H2 station cost (H) is a function of:**
  - pressure (p), driving intensity, station size, H2 demand (affect station utilization)
  - scaling factor of 0.608 reflecting economy of scales and incremental cost 0.08%/bar reflecting cost impact of pressure; both calibrated to H2A
- **Onboard storage cost (S) is a function of:**
  - pressure (p), tank capacity
- **Refueling inconvenience cost is a function of:**
  - pressure (p), tank capacity, driving intensity, tank utilization, value of time, annoyance multiplier, filling speed, fuel availability (% of stations), deployment strategy (region vs cluster)
- **Analyses of interest**
  - How OP is affected by FCV market share, station deployment, station cost, value of time, and city density, etc.?

Technical Targets and Program Interactions

Optimal Pressure
- Consumer-supplier system efficiency
- Station, onboard storage, refueling convenience

Storage & Infrastructure
- Reduce system cost but maintain certain consumer convenience
- Provide guidance for codes and standards
- Facilitate accurate lifecycle assessments

Market
- Recognize consumer tradeoff and market competition
- Insights for optimal design of both vehicles and infrastructure
- Quantify technology bottlenecks against market success

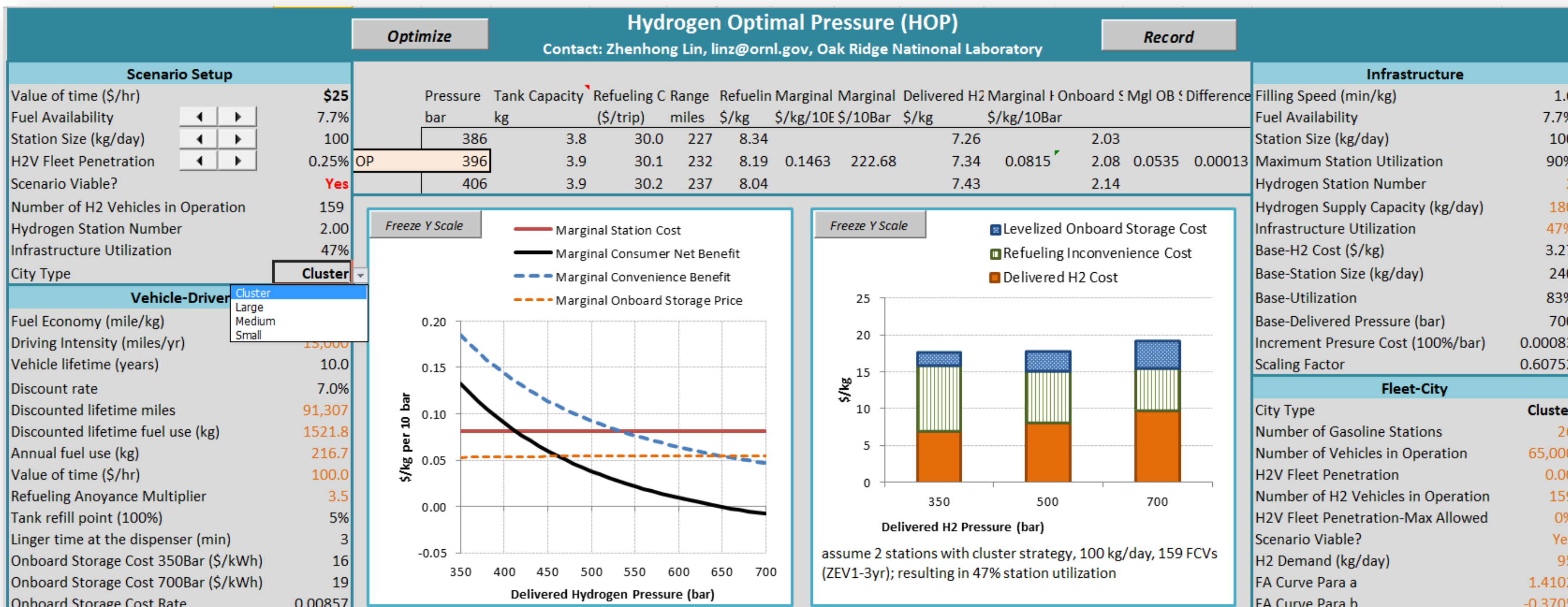
- **Guided by FCTO's MYPP, this project integrates ORNL's system analysis capabilities with data and modeling outputs from other labs and with insights and information from the industry.**

FY14 Milestone, Tasks and Status

FY14 AOP Milestone	Due Date	Sub-task	Status (% completed)
Model Upgrade and Update	03/31/ 2014	Include onboard storage cost in optimization	100%
		Represent cluster deployment strategy	100%
		Update station costs	100%
		Represent refueling annoyance	100%
		Capture early adopter preferences	100%
Case Study	06/30/ 2014	Preliminary results	100%
		AMR and other presentations	30%
		Respond to comments	0%
Reporting	09/30/ 2014	Submit for peer-review publication	0%

The main project product, Hydrogen Optimal Pressure (HOP), is Excel/VBA model that solves for OP under a wide range of user-specified market and technological parameters.

- Three groups of inputs: Vehicle-Driver, Infrastructure, and Fleet-City.
- Users can use the “Scenario Setup” interface to examine in real-time how the marginal cost curves (left chart) shift up and down and how cost components of 350, 500 and 700 bar (right chart) vary, against changes of any scenario parameter.
- Click on “Optimize” to find OP; click on “Record” to output the OP and associated scenario parameters.
- Users can specify extreme parameter value (e.g. what if no travel time value, what if no difference in onboard storage cost between different pressure) to examine the coherence of HOP.

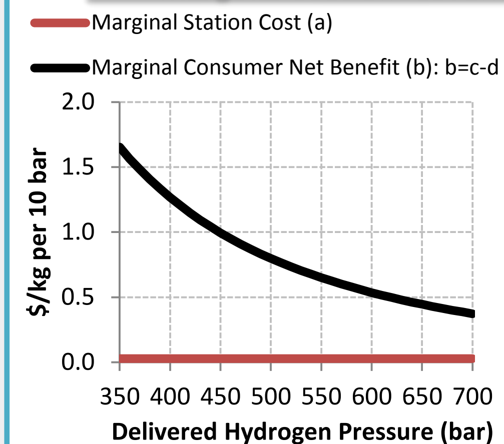


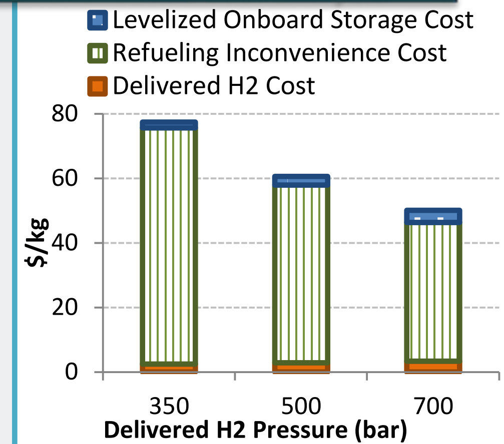
With same numbers of stations and FCVs, cluster strategy means lower pressure.

- The optimal pressure (OP) is where marginal station cost equals marginal consumer net benefit.
- 3 stations and 1000 FCVs, if spread out in a large metropolitan region, would demand 700bar or higher. 3 stations in a large region is too inconvenient and the value of longer range from higher pressure exceeds the cost over the 350-700bar span.
- The same 3 stations and 1000 FCVs, if clustered in a small city, would lead to the OP at 350 bar. 3 stations in a small city is convenient enough so that the additional cost of higher pressure fails to justify the additional convenience benefit of longer range.
- **Cluster strategy allows a small number of stations to achieve a high level of refueling convenience and thus avoids the situation of many underutilized or scale uneconomical stations.**

Region Strategy

Marginal cost-effectiveness and levelized cost analysis

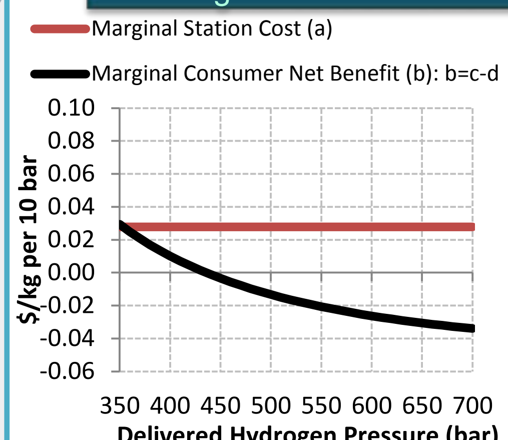


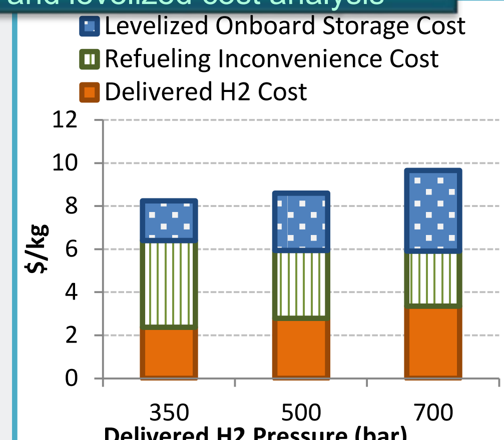


assume: region strategy in Los Angeles, 3 stations at 250 kg/day each (4% of gas stations) , 1000 FCVs driven at 1.3k mile/y each, $50/hr time value

Cluster Strategy

Marginal cost-effectiveness and levelized cost analysis

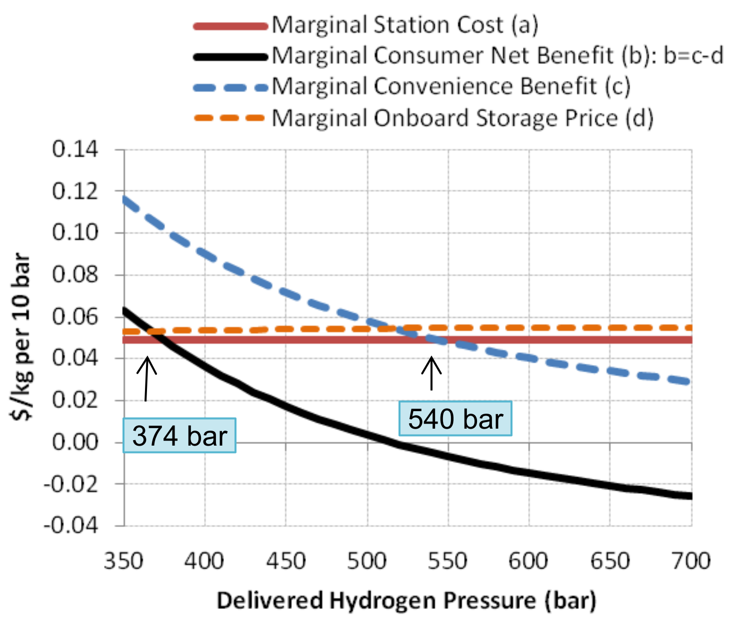


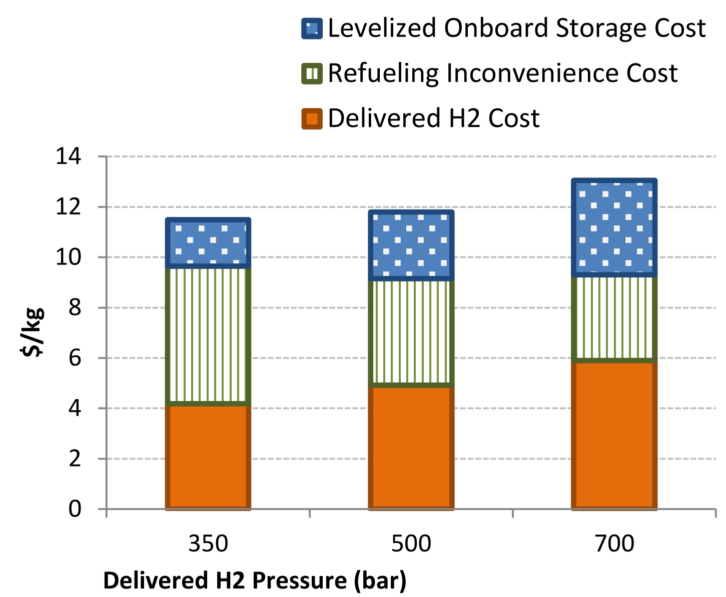


assume: cluster strategy in Santa Monica, 3 stations at 250 kg/day capacity each (11.5% of gas stations) , 1000 FCVs driven at 1.3k mile/y eachr, $50/hr time value

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.
- OP of the shown example is 374 bar; 540 bar if onboard storage cost is ignored.
- Reducing on-board storage cost (from R&D progress) will lead to higher OP (a, c unchanged, d curve shifting down and b curve up) and longer driving range.



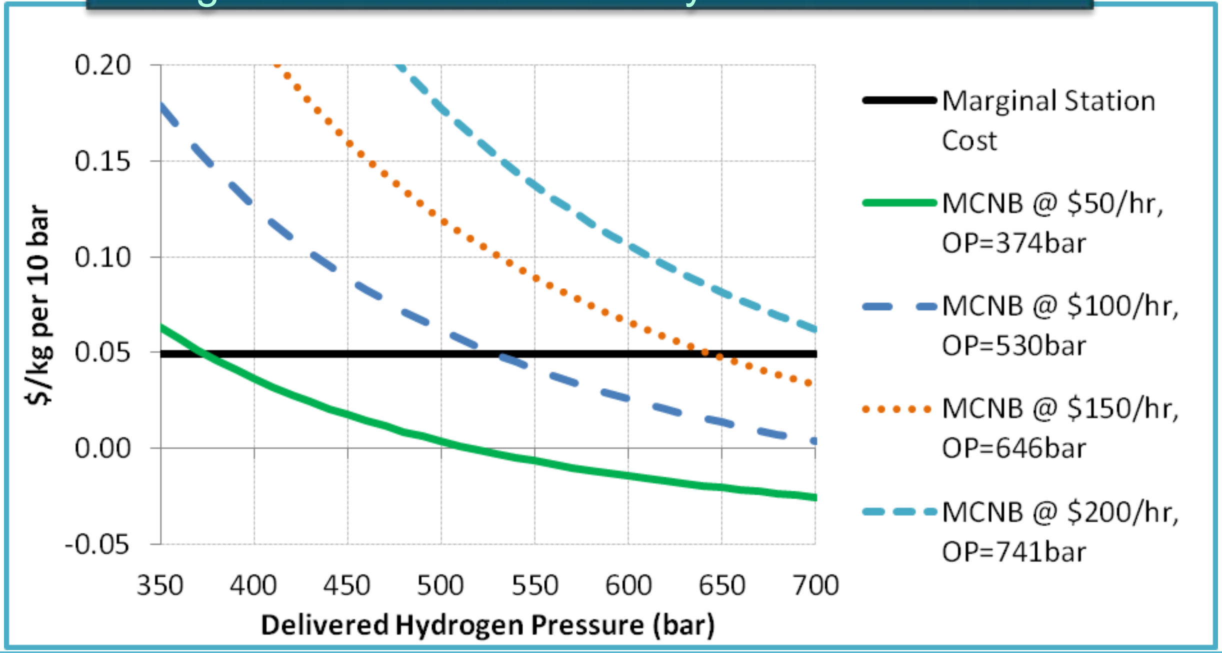


assume: cluster strategy in Santa Monica, 1 station at 150 kg/day capacity each (3.7% of gas stations) , 150 FCVs driven at 1.3k mile/y each, $50/hr time value, onboard storage cost $19/kWh at 700bar and $16/kWh at 350bar

Higher pressure may be more desirable for early adopters possibly with high time value.

- Intersection of the Marginal Station Cost curve and each Marginal Consumer Net Benefit (MCNB) curve indicates the corresponding optimal pressure (OP).
- 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.

Marginal Cost-effectiveness by Travel Time Value



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, 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.

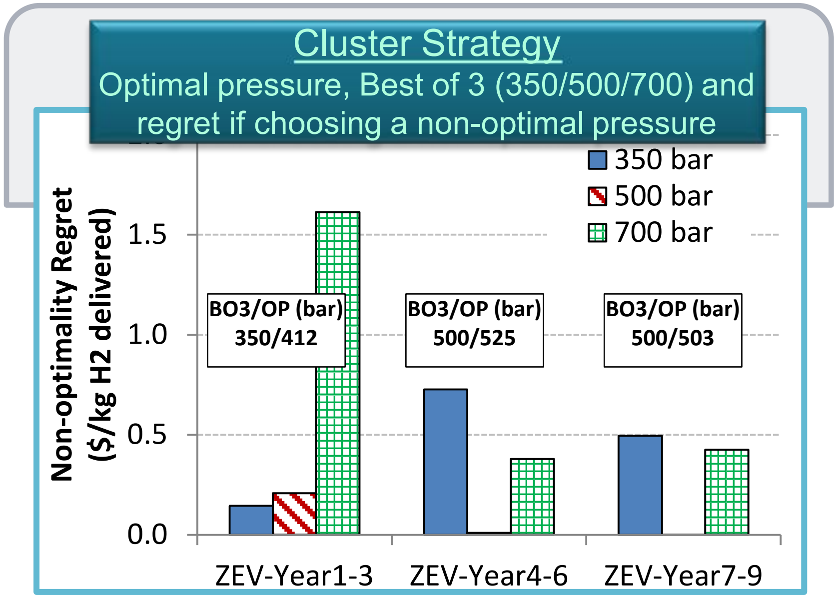
Lower pressure for cluster strategy and higher pressure for region strategy, as suggested by results of ZEV scenarios.

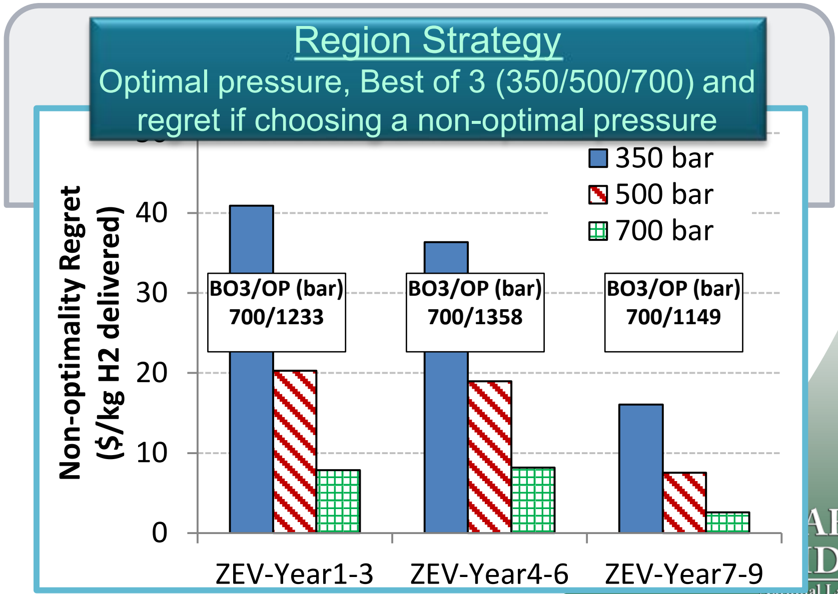
- Cluster and regional roll-out strategies are compared in terms of the optimal pressure, the best of three (350/500/700 bar) and the non-optimality regret of choosing one of the three, for three ZEV mandate implementation periods.

- Assumptions behind the chart results:

	ZEV-Year1-3	ZEV-Year4-6	ZEV-Year7-9
FCVs on road	636	3442	25000
Avg. station Size (kg/d)	100	200	350
Station Utilization	47%	85%	88%
Cluster Strategy			
Clusters	4	6	12
FCVs on road/cluster	159	574	2083
Stations/cluster	2	2	4
FA (% of gas stations)	7.7%	7.7%	15.4%
Region Strategy			
Stations in the region	8	12	48
FA (% of gas stations)	0.13%	0.20%	0.80%

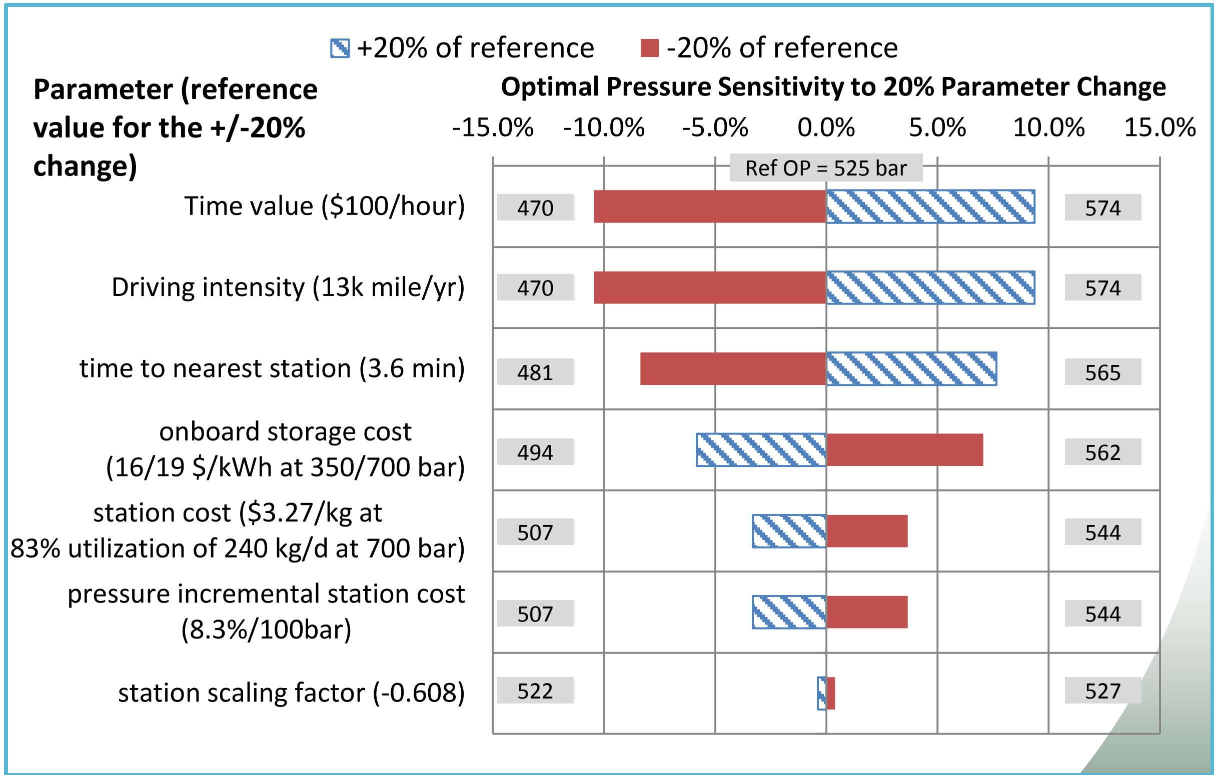
- Others: 0.6kg/day/FCV from 13k mile/yr and 60 mile/kg; travel time value $100/hour; roll-out assumptions consistent with (Ogden and Nicholas 2010).





The relative high sensitivity to time value and driving intensity suggests needs for market segmentation. Storage R&D may help adoption of high delivered pressure.

- Reference case optimal pressure: 525 bar
- Reference case assumptions:
  - cluster strategy, 574 FCVs and 2 stations at 200 kg/day each
  - Time value ($100/hour)
  - Driving intensity (13k mile/yr)
  - time to nearest station (3.6 min)
  - "onboard storage cost(16/19 $/kWh 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%/100bar)"
  - station scaling factor (-0.608)



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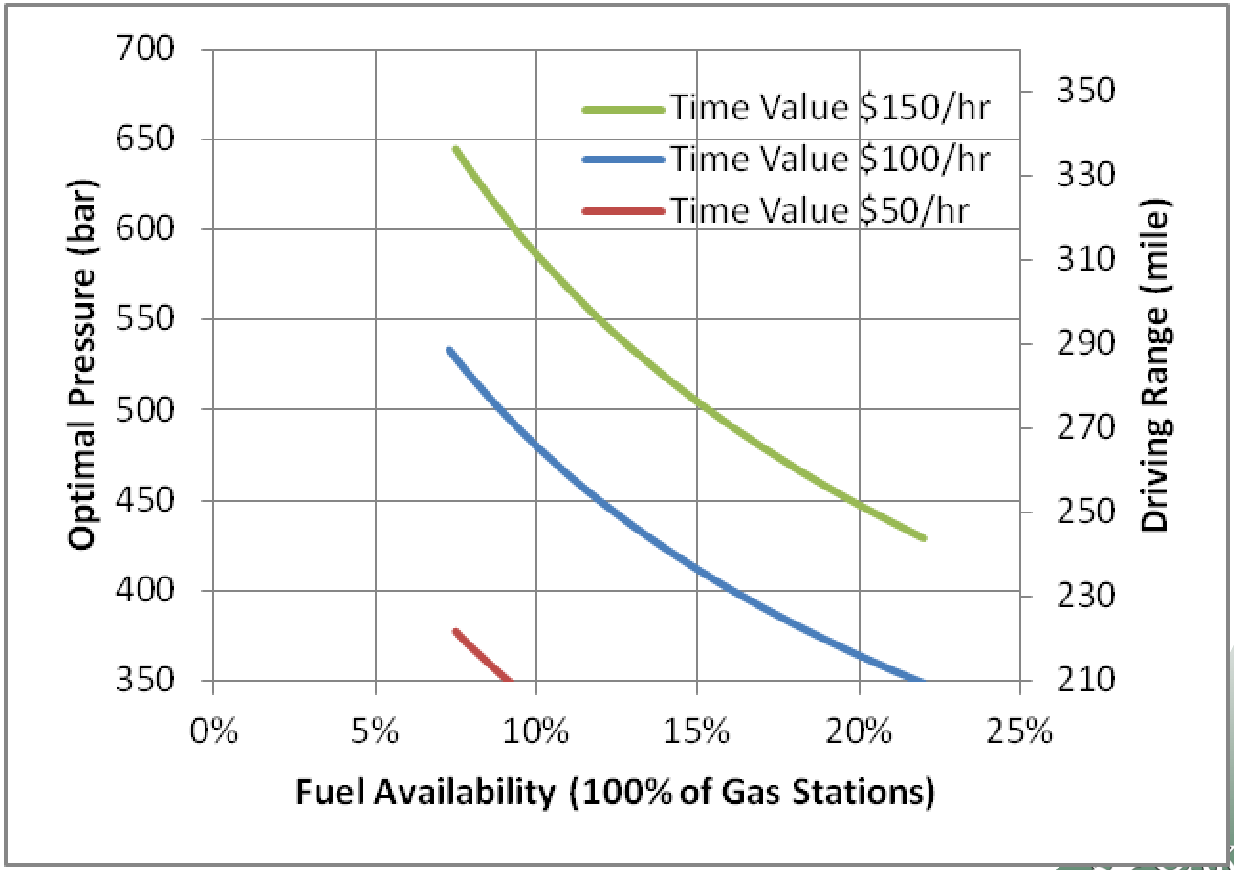
Contour lines indicates tradeoff between fuel availability and driving range, depending on time value.

- Assumptions: cluster strategy, 574 FCVs and 2 stations at 200 kg/day each.
- Similar contour lines can be generated by station cost, market share, and onboard storage cost.



Responding to FY13 AMR reviewer comments, we have restored the refueling annoyance factor, included on-board storage cost, allowed cluster strategy, and will attempt to integrate with consumer choice models.

- Selected FY13 AMR reviewer comments on the project:
  - "The cost approach for system pressure comparisons is rational and straightforwardly executed. However, this approach does not, nor can it, account for the —**annoyance factor** of having to refuel more often when at a low pressure. This factor may be significant, yet it is completely overlooked."
  - "It would have been helpful to tie these results to some actual plans, for example, a closer tie with **California rollout plans**. Using a **cluster strategy** like California's for the station rollout may eliminate some of the inconvenience issues raised."
  - "The project could be improved by more input on financing options, or influence of **station clustering strategies**."
  - "The project would also benefit from more **collaboration** with researchers investigating initial hydrogen infrastructure rollout strategies."
  - "The proposed extension is good, especially for looking at the **cluster strategy**. "
  - The project as explained should be expanded to model hydrogen infrastructure clustering in the initial rollout phase, and should be integrated with **vehicle choice models**.
  - "Modeling **cluster rollout strategies** will require some estimate of the local density of early adopters."
  - "It would be good to see more modeling of hydrogen infrastructure clustering during the early FCEV commercialization phase. The project's modeling should be tied to **consumer choice models** of advanced vehicles to understand how changes in vehicle range can affect vehicle market penetration."

Collaborations

Institution	Role
Oak Ridge National Laboratory (ORNL) Zhenhong Lin (PI), Changzheng Liu, David Greene (retired)	Prime, oversee the project, optimization formulation and implementation, data collection, analysis
Fuel Pathway Integration Tech Team members from Air Products, ExxonMobil, Phillips 66, Shell, Chevron	Comments on the method and suggestions on assumptions
Argonne National Laboratory Amgad Elgowainy	Execute the H2A model and provide delivered H2 costs for various station sizes and pressures
National Renewable Energy Laboratory Marc Melaina, Brian Bush, Yongling Sun, Jennifer Melius	Generate hydrogen station roll-out scenarios at various spatial levels
University of California, Davis Joan Ogden, Michael Nicholas	Provide station costs, generate cluster roll-out scenarios

We propose in-depth OP analysis for early adopters and integration with consumer choice models.

- Daily distance variation and share of miles on home stations vs regional stations
- Combining both cluster and region strategies
- Demographics of early adopters
- Dynamic optimal pressure: uniform OP vs adapted OP
- More comprehensive uncertainty analysis (e.g. with @Risk)
- Optimal strategy for station deployment: timing, size, location, delivery pressure.
- Integrated with HySEB (or other business analytical models) to study the implications for industry risks, R&D and deployment policies.
- Reflecting OP as part of FCV optimal design in consumer choice models to maximize market acceptance
- Respond to FY14 AMR reviewer comments and industry comments

Summary

- FY13 analysis found 700bar superior in most cases, including in the California near-term plan, but was based on region strategy and excluded on-board storage cost.
- FY14 progress including:
  - Added storage cost to the objective function (only including station cost and inconvenience cost in FY13)
  - Represented both cluster and region strategies
  - Developed a friendly user-interface
  - Analyzed optimal pressure under cases reflecting ZEV
  - Conducted sensitivity analysis
- FY14 results suggest that 700bar may not be the optimal under cluster strategy and the current on-board storage cost. 350bar and 500 bar appear superior in ZEV scenarios with cluster strategy.
- 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.

THANK YOU

TECHNICAL BACKUP SLIDES

Travel time to the nearest station for clustered consumers varies among clusters, but generally is lower than that for region-wide random consumers.

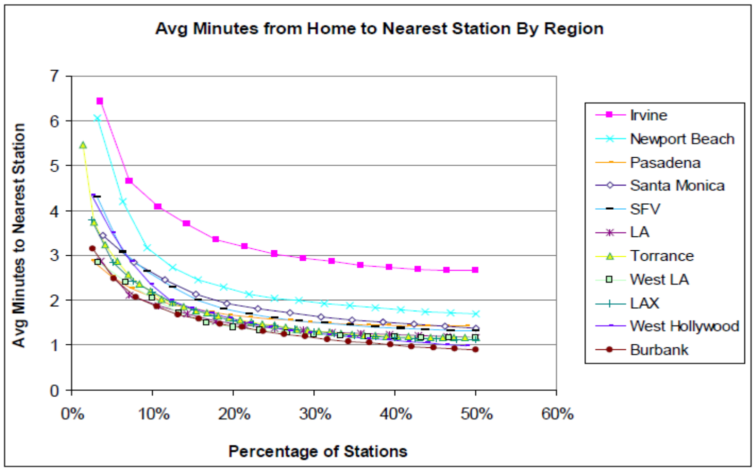
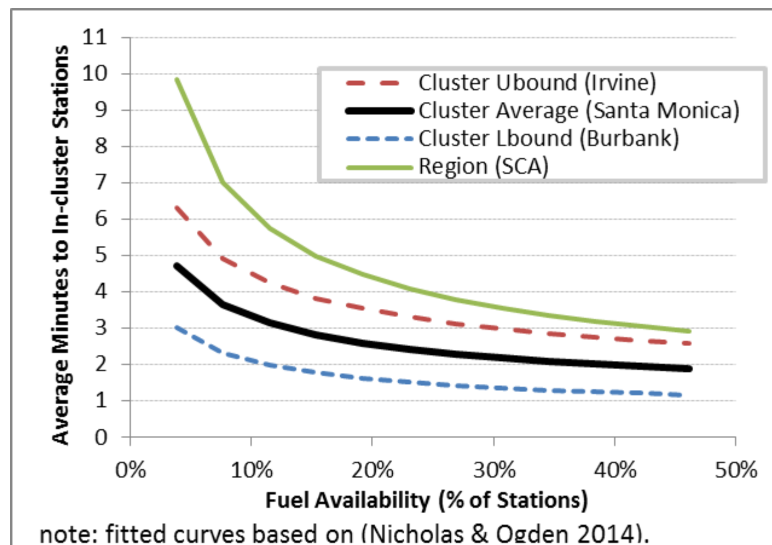


Figure 6 Due to the varying number of stations per cluster, the average minutes to the nearest station is plotted as a function of the percentage of gasoline stations that offer hydrogen. Each dot signifies a hydrogen station. One station is signified by the leftmost dot in each line. Subsequent dots signify additional stations. Irvine, as defined by the cluster boundary, shows poorer access to fuel than other clusters. If there were 50% as many hydrogen stations as gasoline stations, most clusters would average a little over a minute to the nearest station.

Source: J. Ogden, M. Nicholas, 2014. Energy Policy, 39(4), Pg 1923-1938

Home station fuel accessibility cost is a function of fuel availability (% of stations), FA curve that reflects city density, travel time value that reflects income level, and number of FCVs on road.



Acronyms

AOP	Annual Operating Plan
FCV	Fuel cell vehicle
FPITT	Fuel Pathway Integration Tech Team
H2A	Hydrogen Analysis
HOP	Hydrogen Optimal Pressure
HySEB	Hydrogen Station Economics and Business
MA3T	Market Acceptance of Advanced Automotive Technologies
MYPP	Multi-year Program Plan
OP	Optimal pressure
ZEV	Zero-emission vehicle