SA033

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

MANAGED BY UT-BATTELLE FOR THE DEPARTMENT OF ENERGY

Overview

Timeline
• Start date: Oct, 2012
• End date: Oct 2015*
• % 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) • FY14: $100k received • FY15: $100k expected • Total: $200k	**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

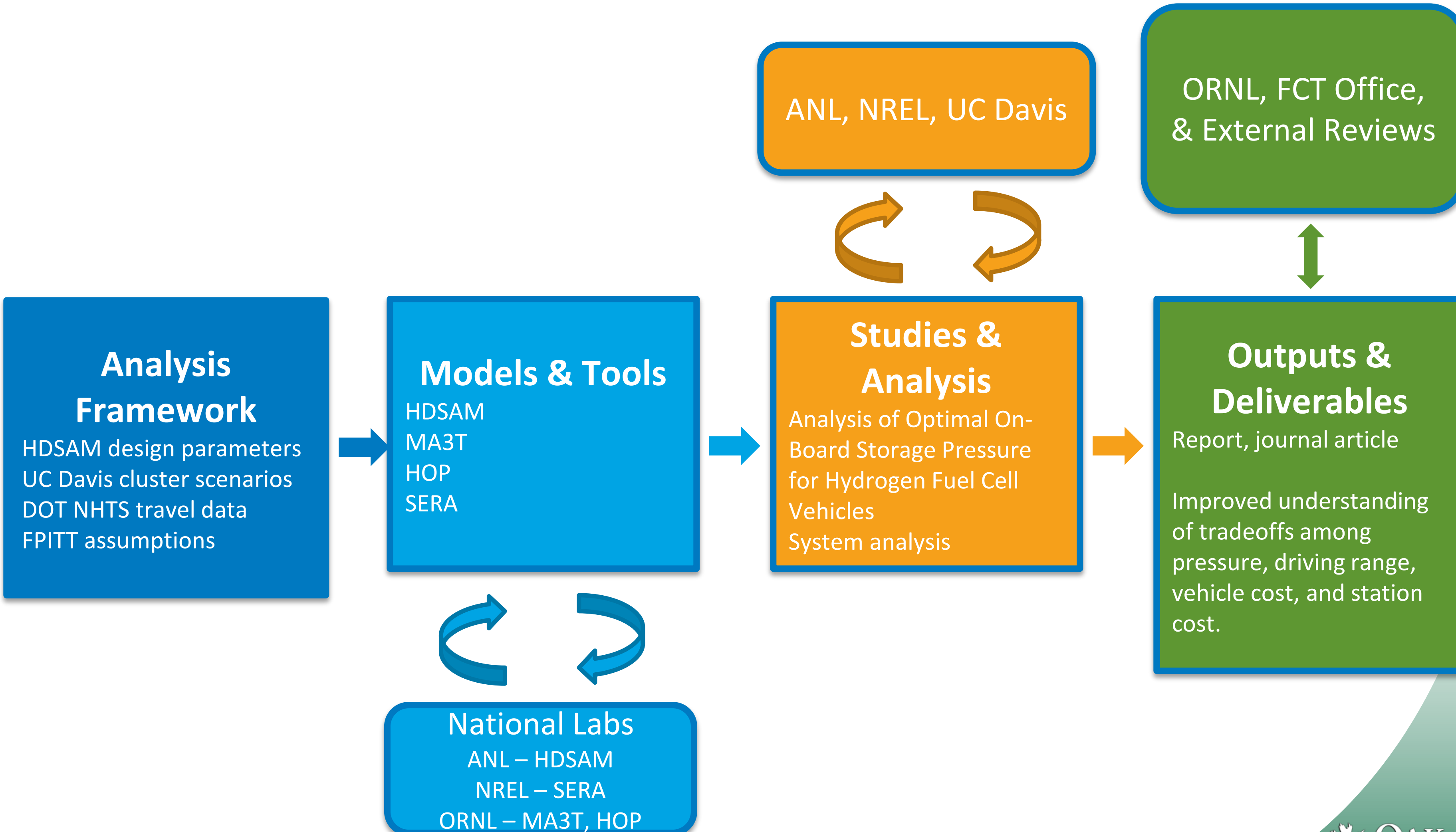
- **Overall Objectives**
  - Develop a method to optimize the onboard hydrogen pressure by integrating a wide range of factors.
  - Conduct case studies and provide useful insights for the industry and R&D planning.
  - Identify the optimal pressure that reduce system cost, increase market acceptance, 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
- **Highlights**
  - FY13: methodology framework, California case studies, found 700bar to be more desirable in many region-strategy scenarios
  - FY14: expand and improve methodology, California ZEV compliance scenarios, both region- and cluster-strategies, found 350bar can be better for certain cluster-strategy scenarios
  - FY15: focus on value of range, ZEV credit effect and mixed pressures, as well as some directions recommended by AMR reviewers

Analytical framework needed for complicated relationships between on-board H_2 pressure and range, costs, consumer acceptance, and industry risks

- Complexity
  - Lower-pressure H_2 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 H_2 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)+L(p)-Z(p)}*
  - **p**: delivered H_2 pressure, decision variable
  - **H**: H_2 station cost (i.e. delivered H_2 cost); increase w/ p
  - **S**: onboard storage cost; increase w/ p
  - **R**: refueling inconvenience cost; decrease with p
  - **L**: range limitation cost, decrease with p
  - **Z**: value of eligible ZEV credits, increase discretely with p
- **H_2 station cost (H) is a function of:**
  - pressure (p), driving intensity, station size, H_2 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, storage, convenience, range value, ZEV value

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.**

FY15 Milestone, Tasks and Status

FY15 AOP Milestone	Due Date	Sub-task	Status (% completed)
Model Upgrade and Update	06/30/ 2015	Characterization of value of range	100%
		Implement logics to allow mixed pressure	50%
Case Study	06/30/ 2015	Preliminary results	90%
		Respond to comments	80%
Reporting	09/30/ 2015	Report or publication manuscript	30%

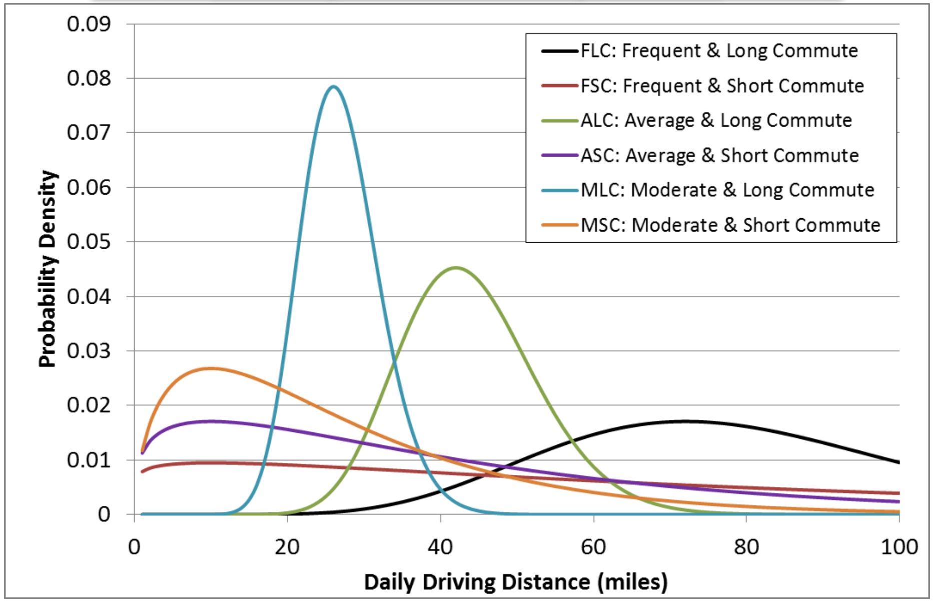
Two upgrades of Hydrogen Optimal Pressure (HOP)—range value and ZEV credit value.

- The HOP allows users to change 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.
- Interface includes an “Optimize” button to find OP; “Record” button 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.

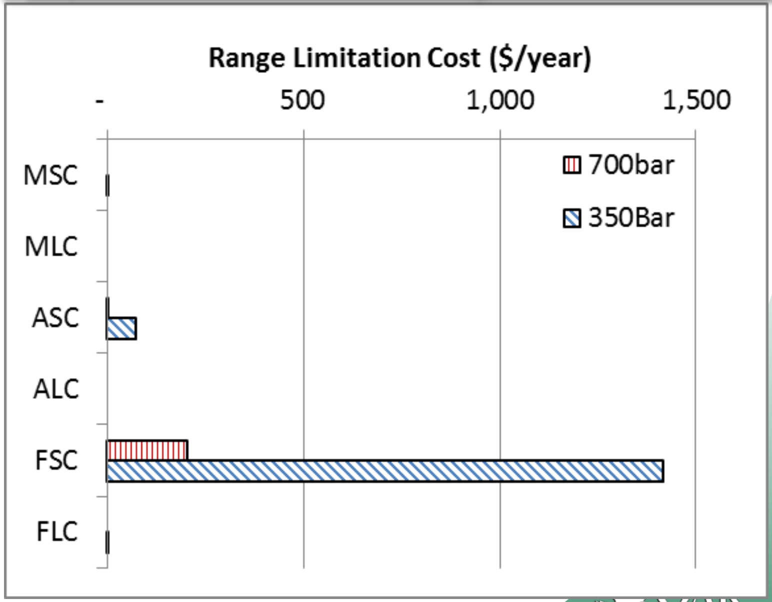
700bar can be valuable for consumers with frequent long-distance & away-from-station-cluster trips

- Some consumers may still face range limitation even if with a 300-mile driving range.
- Value of FCV range depends on pressure, H_2 availability as well as daily driving pattern and access to a backup vehicle.
- 6 types of drivers are examined; assume $50/day of range limitation cost. 700bar found valuable for frequent (high annual VMT) & short-commute drivers.
- Method from: Lin, Z. , 2014. Optimizing and Diversifying Electric Vehicle Driving Range for U.S. Drivers, *Transportation Science* 48(4), 635-650

Heterogeneous Driving Pattern



Impact of Pressure on Range Limitation Cost



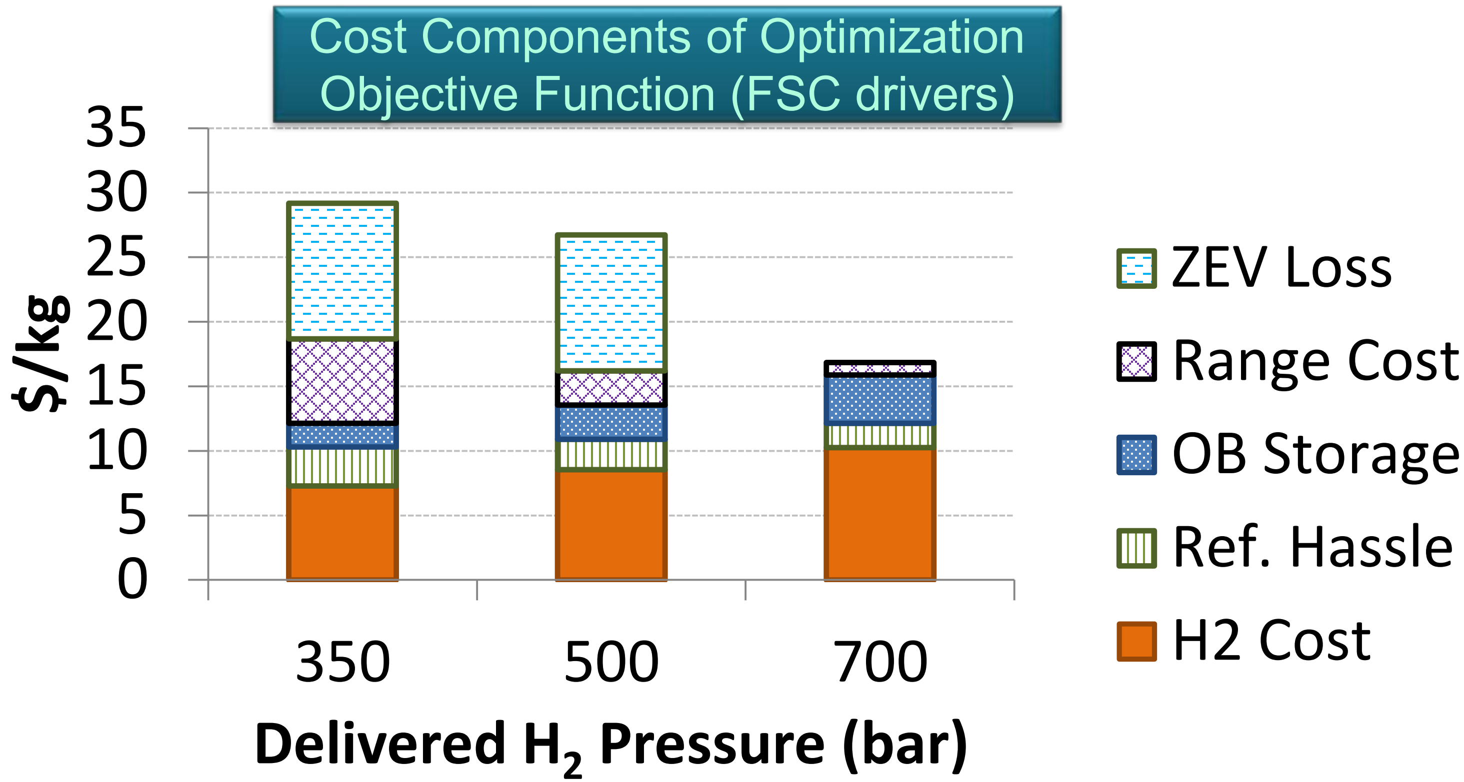
ZEV relevance to H_2 pressure—a discrete incentive for certain high pressures?

Type	Definition	2012-2014 eligible credits	2015-2017 eligible credits
Type III ZEV	100+ mile range and fast refueling capable or 200 mile range	4	4
Type IV ZEV	200+ mile range and fast refueling capable	5	5
Type V ZEV	300+ mile range and fast refueling capable	7	9

Source: http://www.arb.ca.gov/msprog/zevprog/zevregs/1962.1_Clean.pdf
Value of each ZEV credit <= $5000

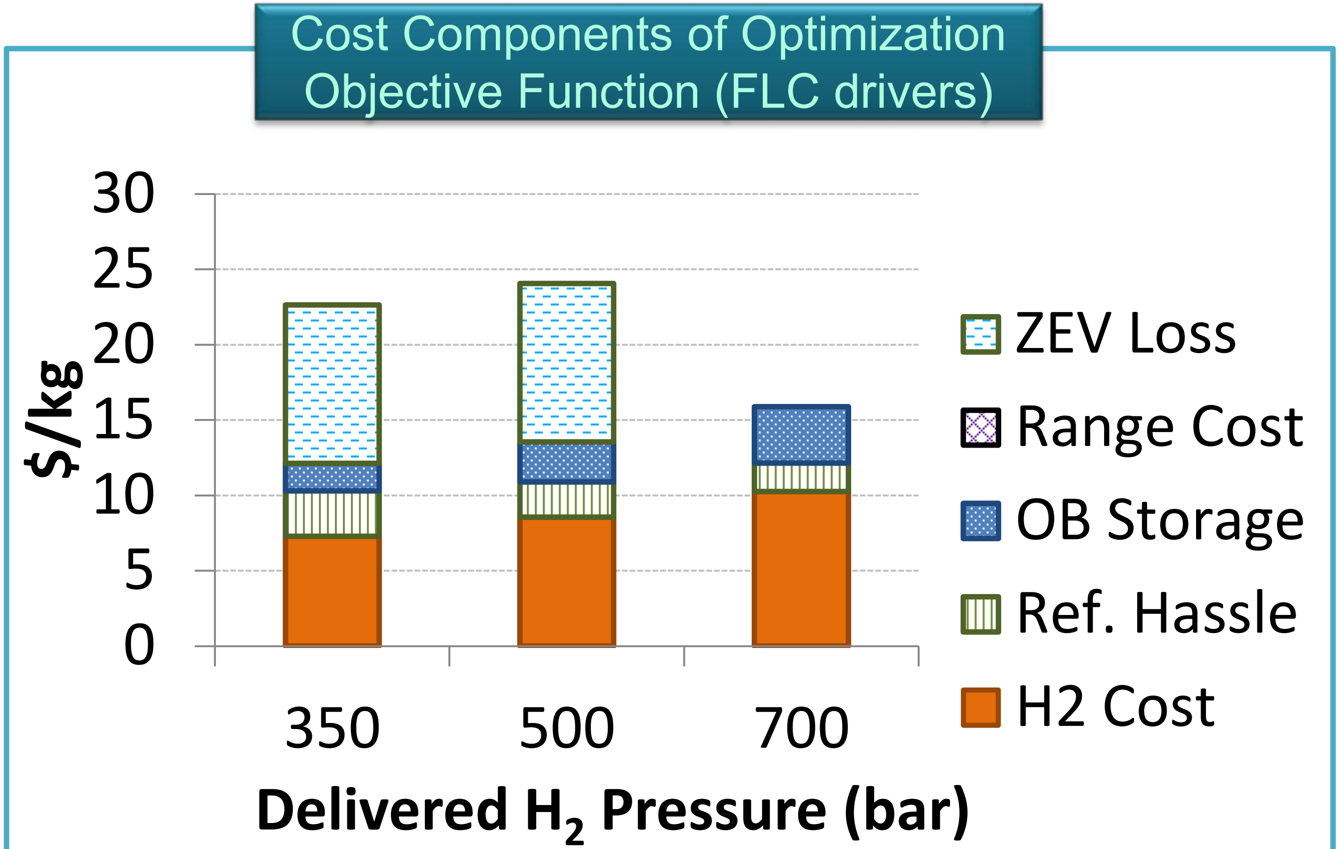
For FSC drivers, range value is significant due to frequent long-distance trips. ZEV value of 700bar is significant

- **FSC=frequent & short commute**



assume cluster strategy in Santa Monica, 1x200 kg/day station (5% fuel availability) , 130 FCVs, $100/hr time value

For other types of drivers, range value is not significant. ZEV value of 700bar is significant



assume cluster strategy in Santa Monica, 1x200 kg/day station (5% fuel availability) , 130 FCVs, $100/hr time value

Mixed H_2 pressures—it is realistic and necessary?

- **FCV consumers may minimize fuel cost by using low-pressured H_2 for some days and high-pressure H_2 for others.**
- **Mixed pressures can be provided by mixed stations or the same station**
- **The recommendation would depend on the incremental cost of delivered pressure, individual driving pattern and the spatial coordination between cluster and connection stations.**

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 Pathways Integration Tech Team includes Air Products, ExxonMobil, Shell, Chevron	Comments on the method and suggestions on assumptions
Argonne National Laboratory Amgad Elgowainy	Execute the H2A model and provide delivered H_2 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.

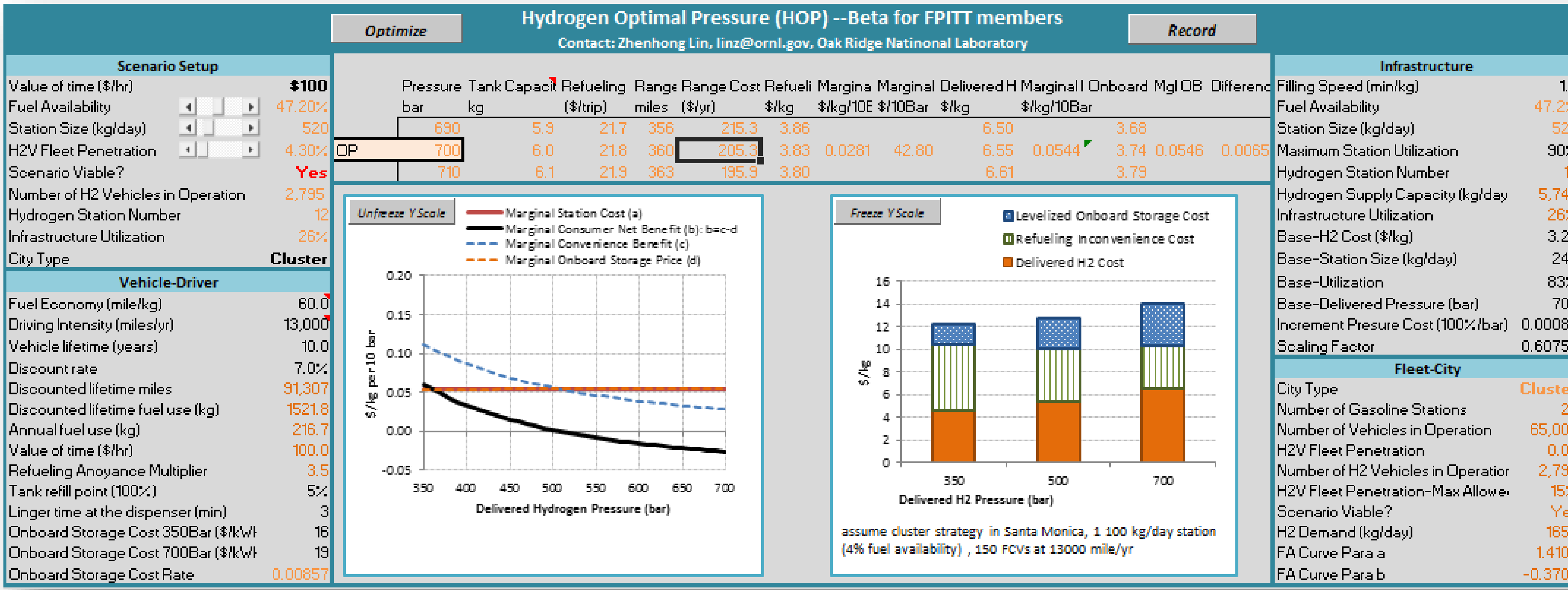
Summary

- FY15 work focuses on range value, ZEV mandate and mixed pressure and found significant effect of range value for certain drivers and significant effect of ZEV mandate that makes 700bar superior.
- 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

Interface of HOP



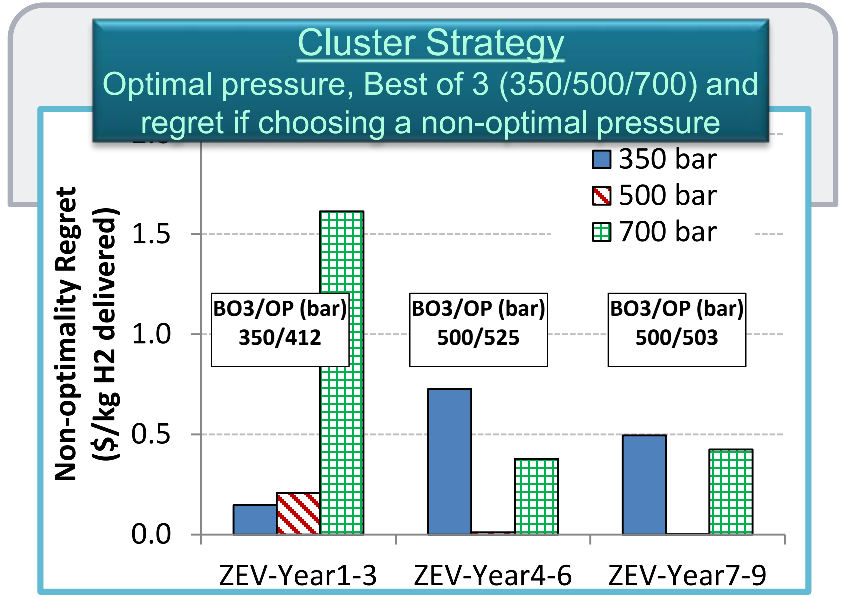
(from last AMR presentation)Lower pressure for cluster strategy and higher pressure for region strategy, as suggested by results of ZEV scenarios.

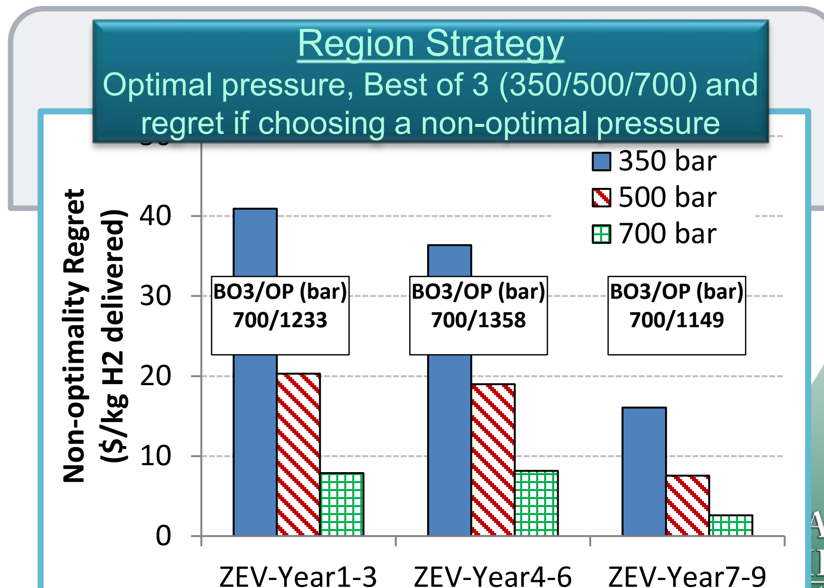
- Cluster and regional roll-out strategies are compared in terms of the optimal pressure, the best of three (350/500/700 bar) and the non-optimality regret of choosing one of the three, for three ZEV mandate implementation periods.

- 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%

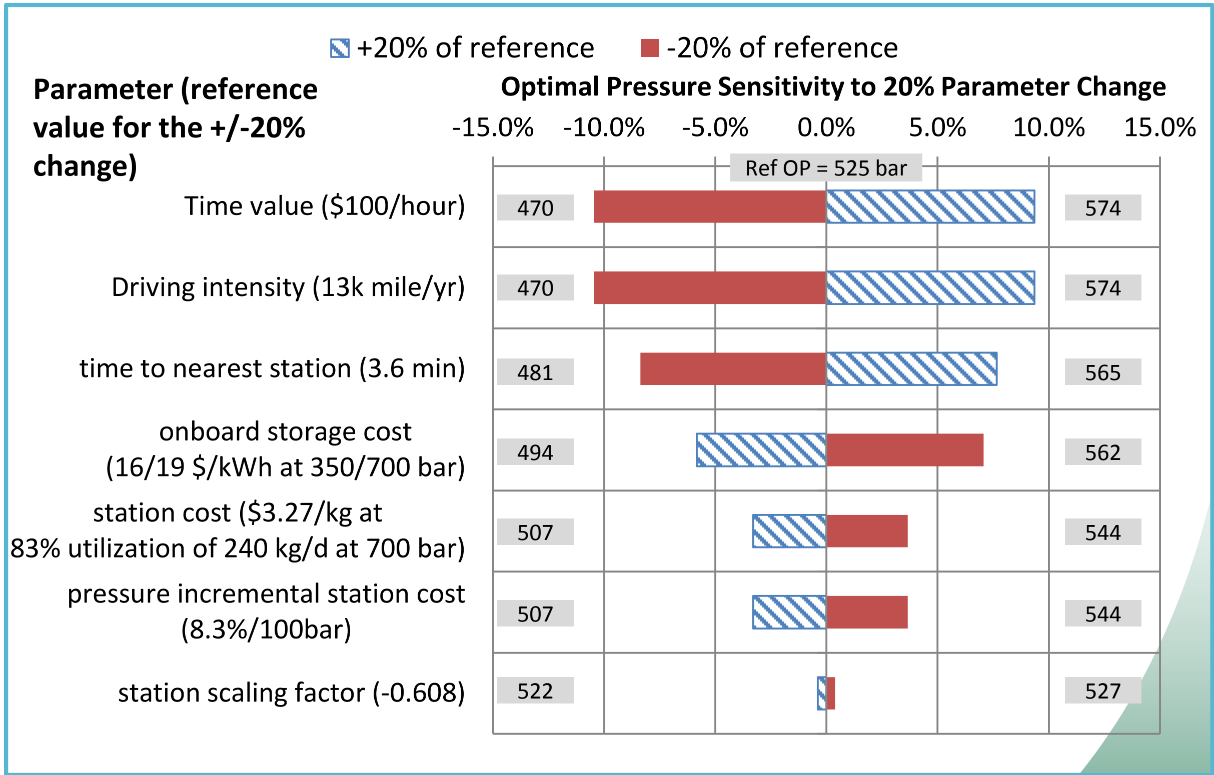
- Others: 0.6kg/day/FCV from 13k mile/yr and 60 mile/kg; travel time value $100/hour; roll-out assumptions consistent with (Ogden and Nicholas 2010).





(from last AMR presentation) 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)



Responding to FY14 AMR reviewer comments, we have presented progress and share HOP to FPITT, and included range value and ZEV value.

- Integrate with choice models
- Questions the flat line of marginal station cost; expect it to be increasing with pressure due to additional cooling and compression
- Share a beta version of HOP with FPITT before its public release
- Need clarification: why 13k miles/yr as opposed to 15k miles/year used by H2A and Macro-System Model.
- incorporating ANL's work on station cost at different fueling pressures to optimize precooling.
- Consider a 10,000 psi tank refueling at lower (cheaper) pressure
- The proposed work (on the AMR presentation) seems too extensive for the time and budget
- Seek comments from FPITT on the user interface
- Option on the interface for station owner to minimize cost
- Seek comments from OEMs
- Consider the station owner perspective

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