2007 DOE Hydrogen Program

System Dynamics: HyDIVE™ (Hydrogen Dynamic Infrastructure and Vehicle Evolution) Model

Cory Welch
National Renewable Energy Laboratory
May 16, 2007

Project ID: ANP3

Overview

Timeline

- Project start date: 10/2005
- Project end date: 09/2007
- Percent complete: ~80%

Budget

- Total project funding
  - $260K (DOE)
- Funding received in FY 2006
  - $70K
- Funding for FY 2007
  - $190K ($50K from systems analysis, $140K from technology validation)

Barriers

- Barriers addressed
  - "Understanding the behavior and drivers of the fuel and vehicle markets is necessary to determine the long-term applications. Another major issue is the **hydrogen supply, vehicle supply, and the demand for vehicles and hydrogen are all dependent and linked**. To analyze various hydrogen fuel and vehicle scenarios, models need to be developed to understand these issues and their interactions." (MYRDDP, 4.0-11)

Partners

- Varying degrees of collaboration with and/or feedback from:
  - GM, Ford, DaimlerChrysler, RCF Economic Consulting, NERA Economic Consulting, PA Government Services, Knowledge Networks, Massachusetts Institute of Technology

Objectives

- Quantify and better characterize the nature of the "chicken-and-egg" barrier of hydrogen stations and hydrogen vehicle demand
- Identify high leverage strategies and policies for the development of the hydrogen transportation market through spatial, temporal simulation

Approach

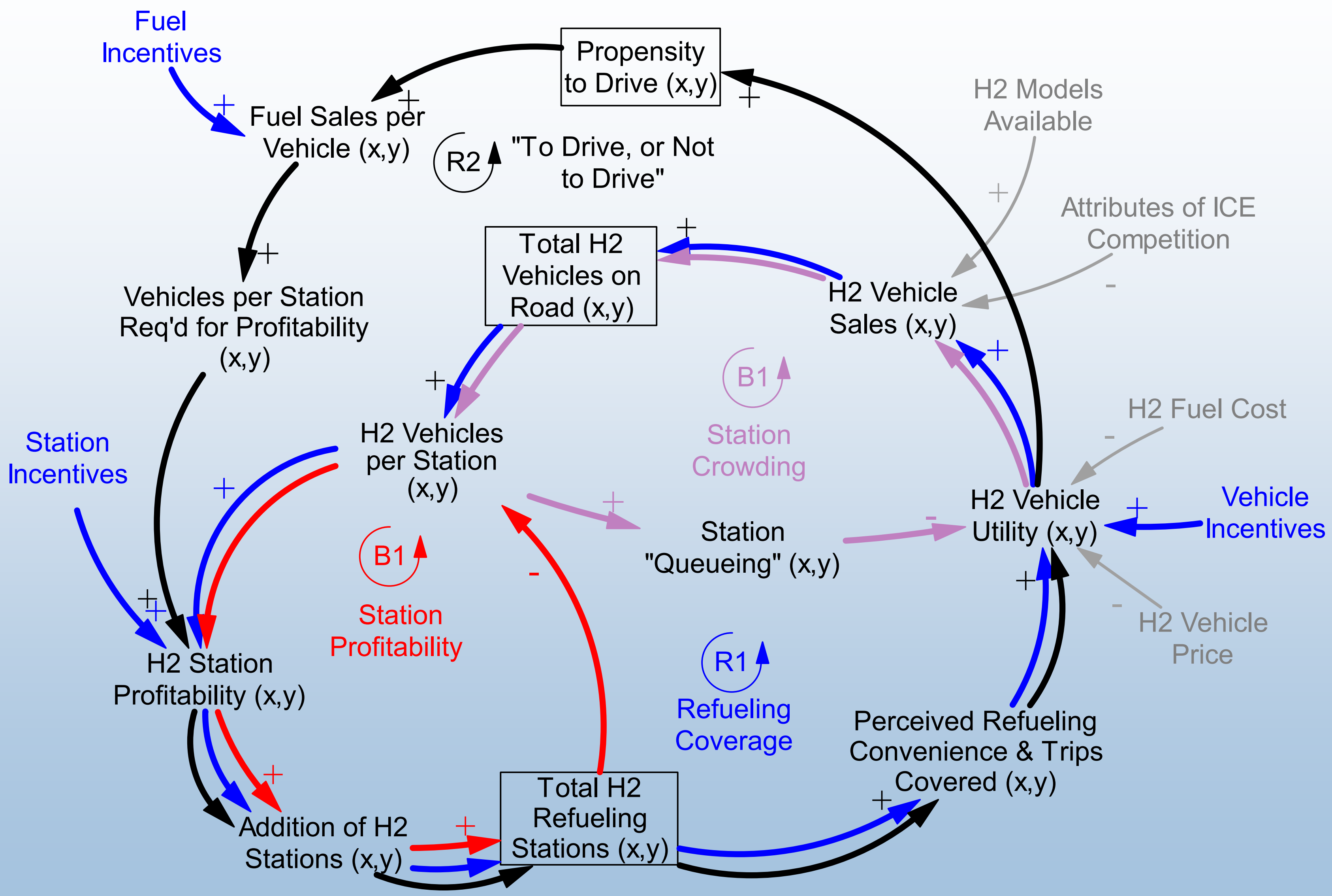
System Dynamics

- HyDIVE is a dynamic, spatial, and behavioral market simulation model (NOT an *optimization* model)
- System behavior results from decision-making processes of individuals (e.g., vehicle owners, refueling station owners)
- Spatial resolution is relevant to vehicle and station owners (current regional focus is southern California)

Discrete Choice Analysis

- HyDIVE vehicle choice model parameters are quantified via discrete choice analysis
- Data were obtained from respondents in southern California with a controlled design of experiment

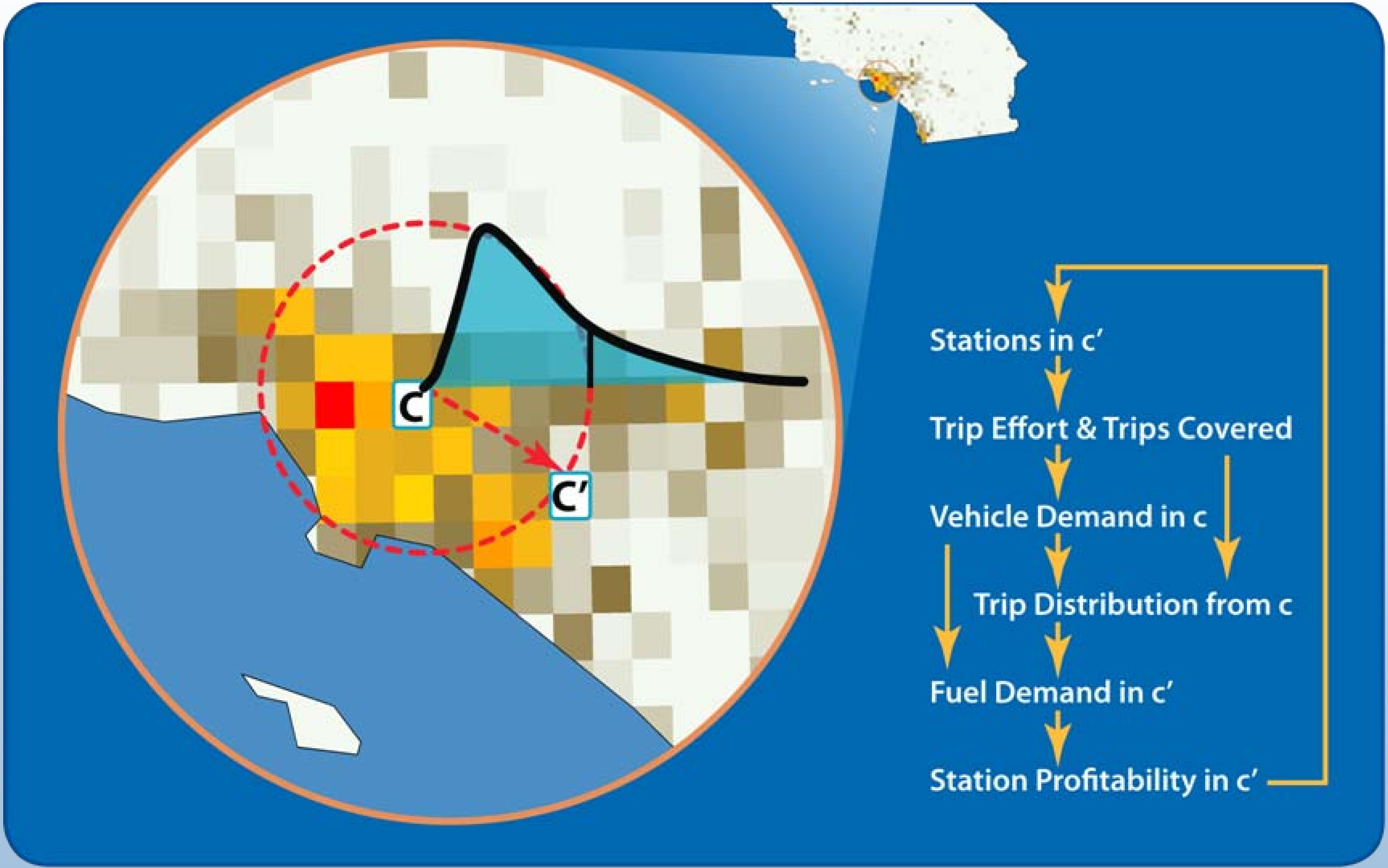
Approach: Main Feedback in HyDIVE (1)(2)



(1) See Struben, 2006a for exposition and analysis of the original model foundation

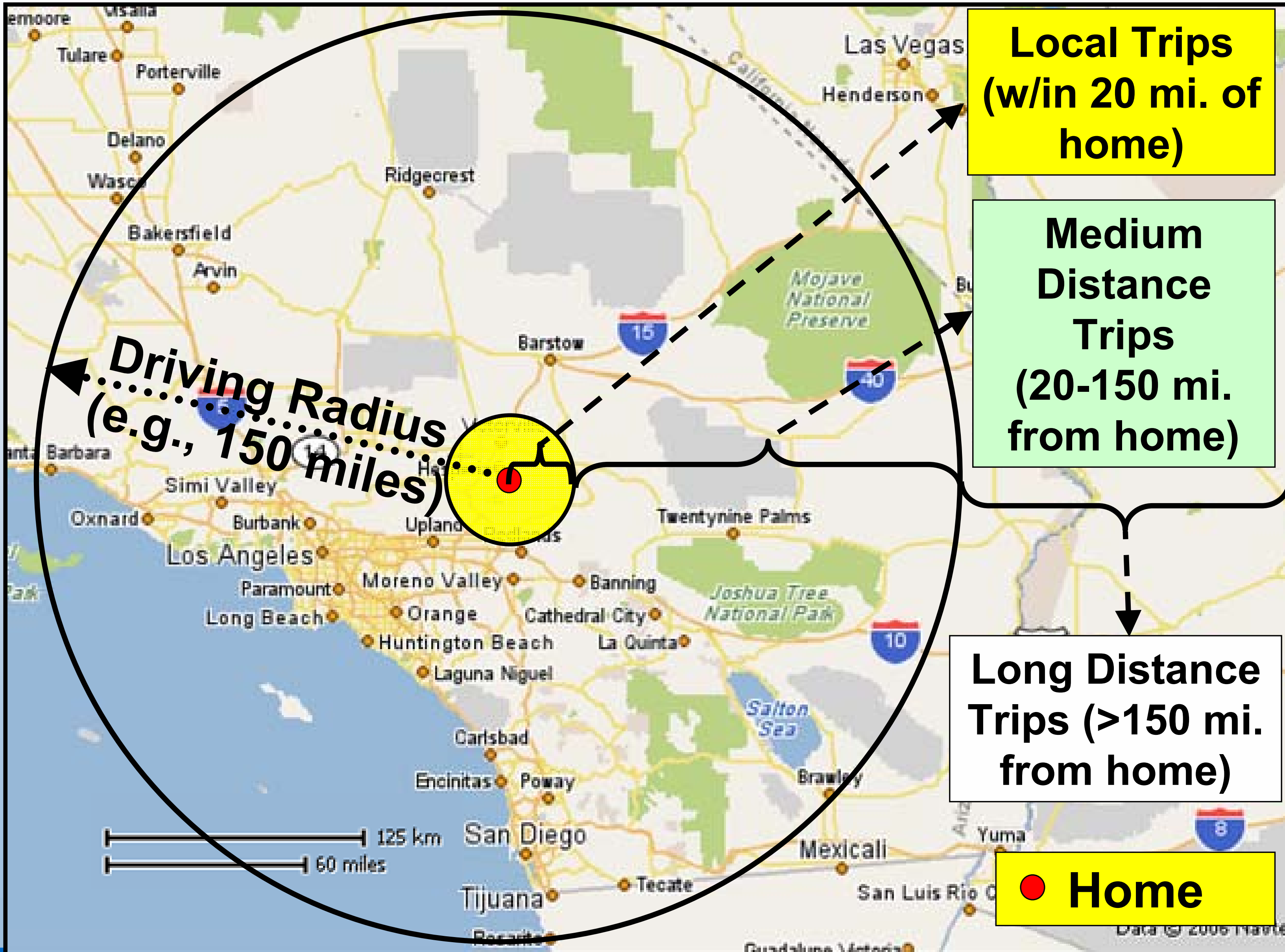
(2) Research at NREL is envisioned to be part of a larger model including additional relevant dynamics

Approach: Spatial, Dynamic Interdependence



Adapted from Struben, Welch, Sterman (2006)

Approach: Spatial Characterization for Discrete Choice Analysis



Approach: Example Discrete Choice Analysis Screen

	Gasoline Vehicle (Similar to Honda Accord)	Alternative Fuel Vehicle A (Similar to Honda Accord)	Alternative Fuel Vehicle B (Similar to Honda Accord)
Click on the attributes for definitions		Virtually NO oil used or imported	
		No smog emissions	
		30%-70% fewer Greenhouse Gas emissions	
Extra Time (one-way) to Local Stations	0 minutes	3 minutes	10 minutes
Driving Radius	Same as your Honda Accord (typically ~200 miles)	150 miles	150 miles
Medium Distance Trips with No Advance Planning	100%	50% no planning	90% no planning
Long Distance Trips that are Possible	100%	50% possible	50% possible
Fuel Cost ($/month)	$110	$110	$165
Purchase Price	$32,000	$27,200	$32,000
Vehicle you are MOST likely to purchase	○	○	○
Vehicle you are LEAST likely to purchase	○	○	○

73% complete

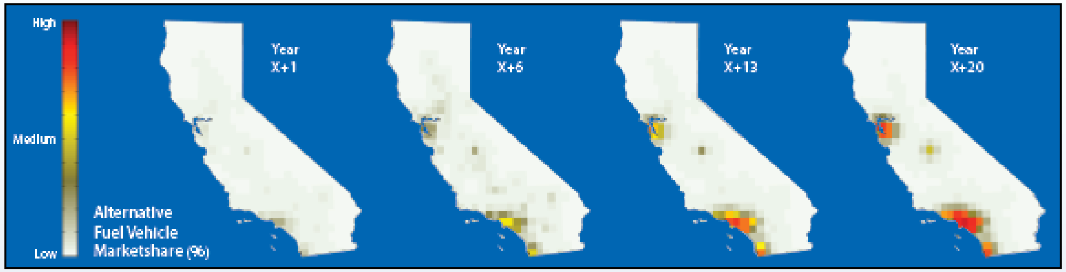
Next Question

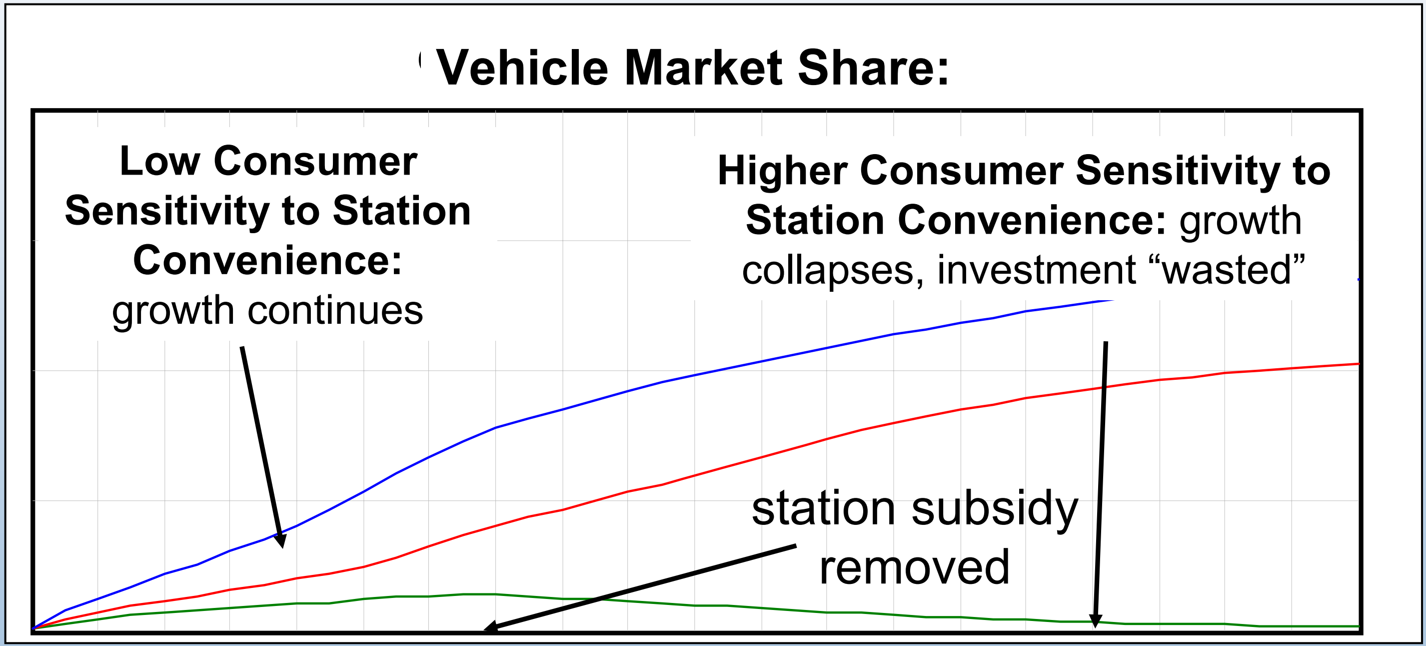
Technical Accomplishments/Progress/Results

- **Initial HyDIVE model developed, capturing key interactions b/w vehicle demand and station coverage**
- **Early dynamic runs revealed that consumer sensitivity to station convenience is a key driver of dynamics**
  - **Based on above analysis, model structure modified to better characterize station convenience**
- ***Discrete choice analysis* experiment designed to quantify consumer sensitivity to station convenience & other metrics**
- **Analysis of early discrete choice analysis data completed**
- **Parameters from discrete choice analysis input to HyDIVE**
- **Spatial, STATIC* analysis conducted to forecast market share for two different station configurations**
  - **Parametric analysis done to quantify effects of fuel cost, vehicle price, and vehicle model availability**

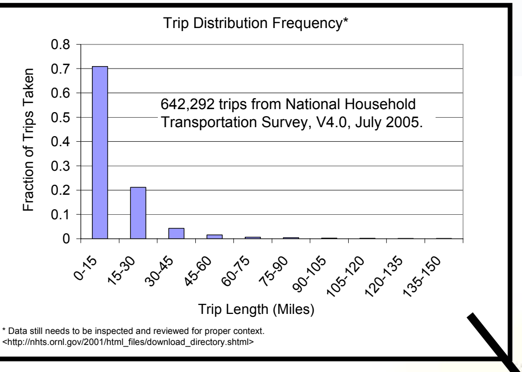
*While HyDIVE is a dynamic model, the scope of this task was limited to static market share forecast analysis. Future work would include dynamic analyses.

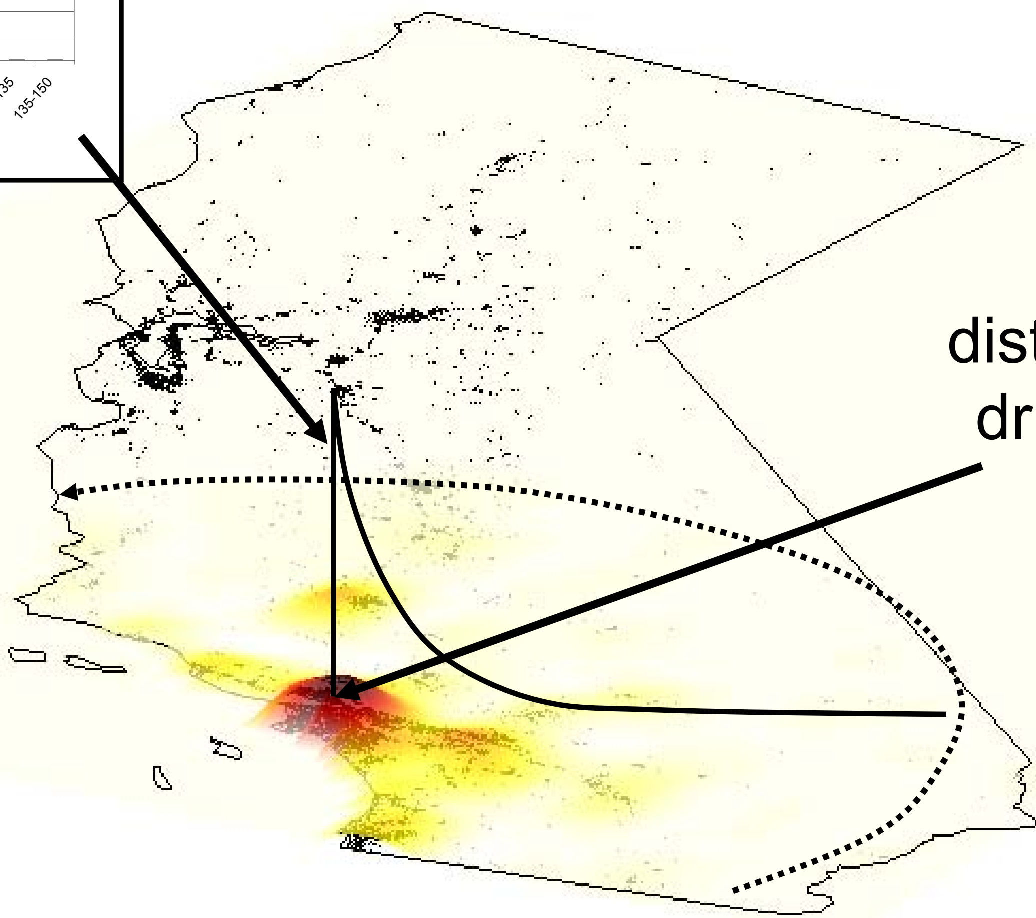
Accomplishments: Early Dynamic Analyses Reveal Key Sensitivities and Spatial Behavior





Accomplishments: Modeling of Driving Patterns -- Combining Theory and Data

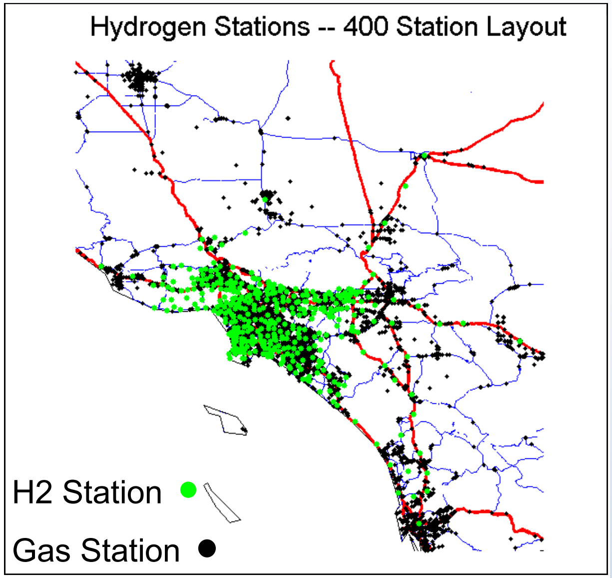


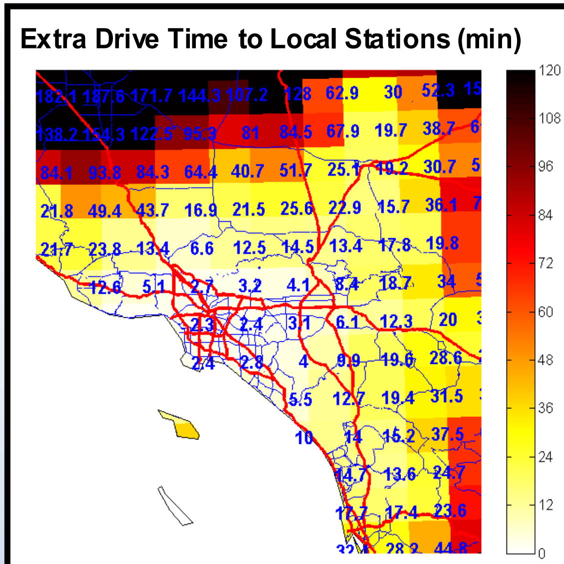


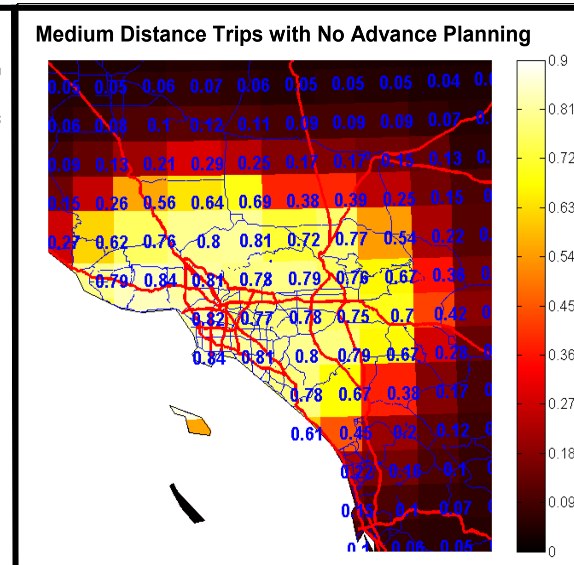
Example trip distribution for one driver living here

Consumer driving patterns model structure improved (important to understand station convenience)

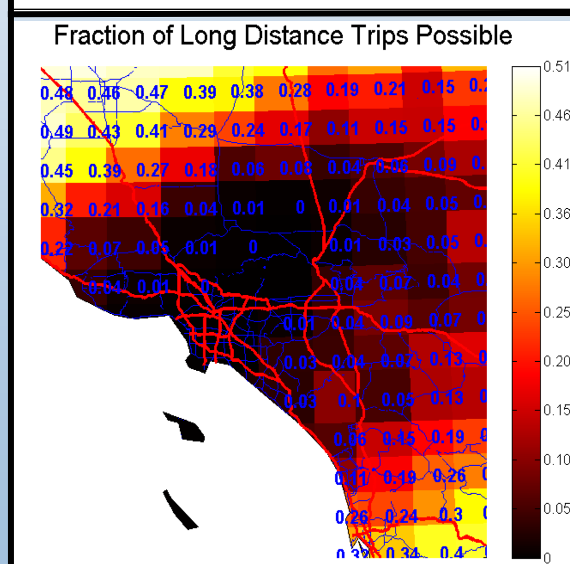
Accomplishments: Analysis of a 400-Station Layout Scenario, Spatial Attribute Calculation and Forecast Market Share

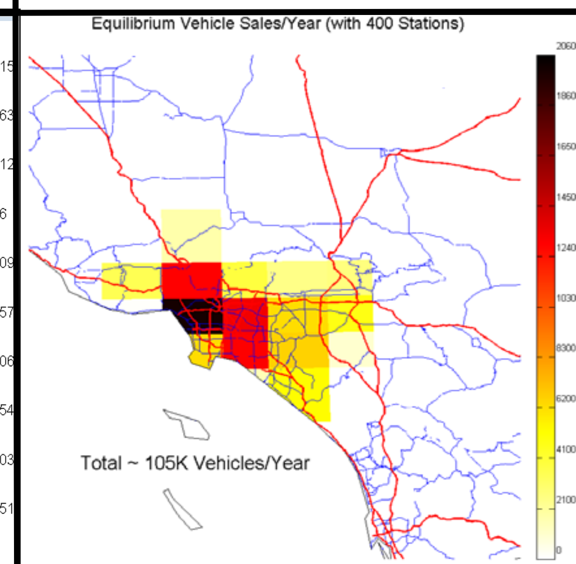






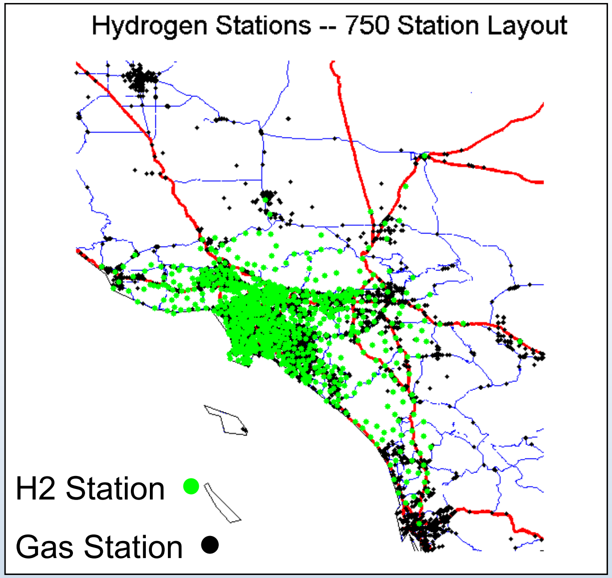
Source: Welch, C., "Using HyDIVE™ to Analyze Hydrogen Scenarios," NREL/TP-560-41363, Golden, CO: National Renewable Energy Laboratory, Forthcoming 2007.

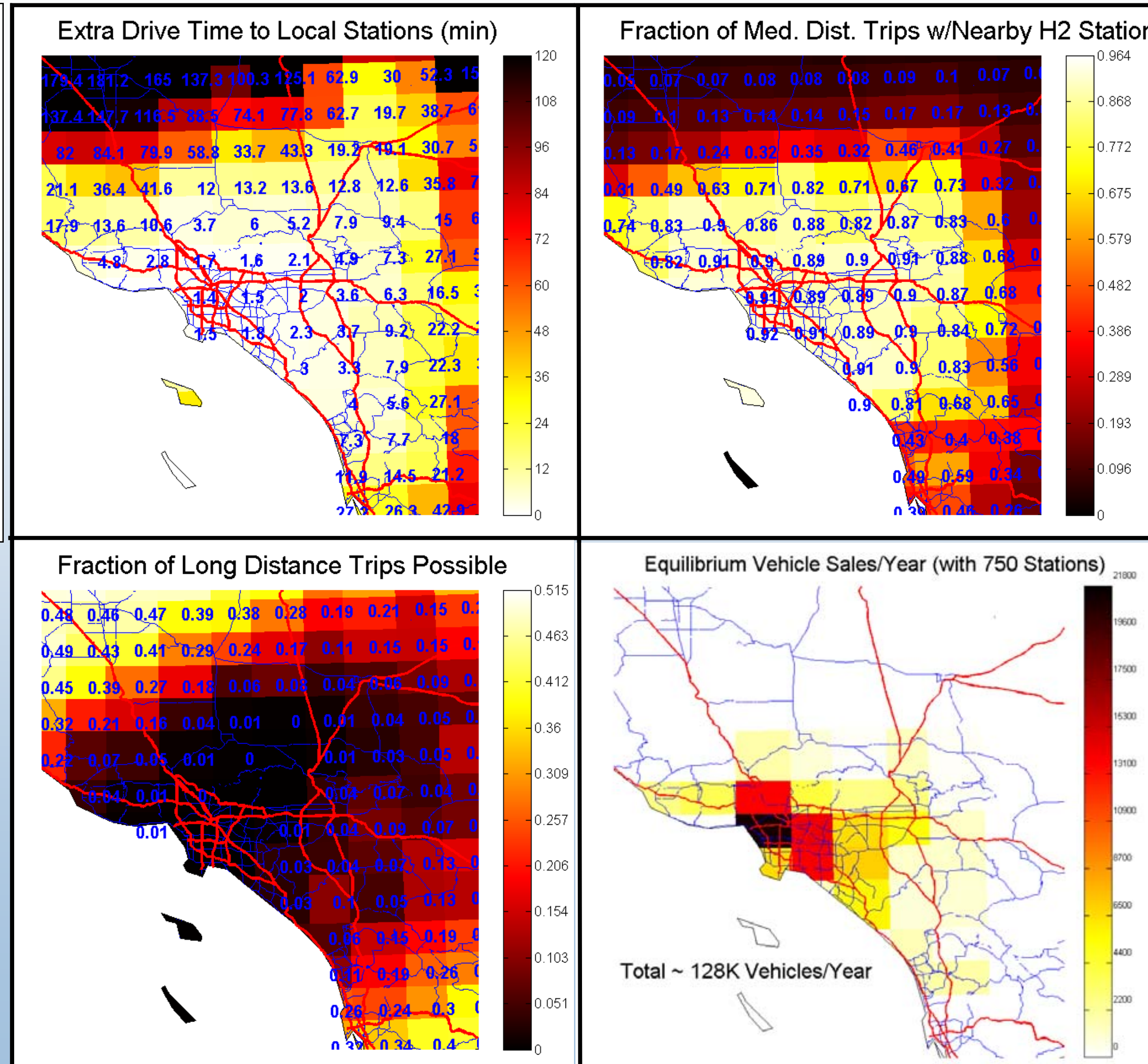




Fueling convenience attributes and equilibrium sales forecast (400-station case). Ten hydrogen FCV models; $3.00/kg hydrogen (before taxes); vehicle price same as equivalent gasoline ICE

Accomplishments: Analysis of a 750-Station Layout Scenario, Spatial Attribute Calculation and Forecast Market Share





Source: Welch, C., "Using HyDIVE™ to Analyze Hydrogen Scenarios," NREL/TP-560-41363, Golden, CO: National Renewable Energy Laboratory, Forthcoming 2007.

Fueling convenience attributes and equilibrium sales forecast (750-station case). Ten hydrogen FCV models; $3.00/kg hydrogen (before taxes); vehicle price same as equivalent gasoline ICE

Accomplishments: Parametric "Equilibrium" Analysis for a 400-Station Scenario

Los Angeles Area: Forecast Hydrogen FCV Sales and Scenario Targets			HyDIVE Equilibrium Upper Bound Sales/Year[16]	Target Sales/Year (2020)[17] Scenario Number[18]		
# Vehicle Models[19]	Vehicle Price (rel. to gas ICE)[20]	H2 Price ($/kg, before taxes)[21]	w/ 400 Stations (seeFigure 6)	1 105 stations	2 372 stations	3 386 stations
10	-15%	$2.00	130K	55K	130K	160K
10	-15%	$3.00	123K	55K	130K	160K
10	-15%	$4.00	117K	55K	130K	160K
10	0%	$2.00	112K	55K	130K	160K
10	0%	$3.00	105K	55K	130K	160K
10	0%	$4.00	99K	55K	130K	160K
10	15%	$2.00	94K	55K	130K	160K
10	15%	$3.00	87K	55K	130K	160K
10	15%	$4.00	81K	55K	130K	160K
15	-15%	$2.00	163K	55K	130K	160K
15	-15%	$3.00	155K	55K	130K	160K
15	-15%	$4.00	147K	55K	130K	160K
15	0%	$2.00	141K	55K	130K	160K
15	0%	$3.00	133K	55K	130K	160K
15	0%	$4.00	124K	55K	130K	160K
15	15%	$2.00	118K	55K	130K	160K
15	15%	$3.00	110K	55K	130K	160K
15	15%	$4.00	102K	55K	130K	160K
20	-15%	$2.00	191K	55K	130K	160K
20	-15%	$3.00	181K	55K	130K	160K
20	-15%	$4.00	172K	55K	130K	160K
20	0%	$2.00	165K	55K	130K	160K
20	0%	$3.00	155K	55K	130K	160K
20	0%	$4.00	145K	55K	130K	160K
20	15%	$2.00	138K	55K	130K	160K
20	15%	$3.00	129K	55K	130K	160K
20	15%	$4.00	119K	55K	130K	160K

16 This static forecast is considered to be an upper bound, equilibrium level per HyDIVE calculations. See Section 4.2.4 for the caveats associated with using this equilibrium value. Hydrogen FCV performance is assumed to be equivalent to gasoline ICEs. For this initial estimate, Hydrogen FCVs compete only with gasoline ICEs (i.e., not with gas-electric hybrids). Competition with gas-electric hybrids would reduce these forecast sales volumes somewhat, depending on the success level of hybrid vehicles.

17 All the forecast vehicle sales correspond with convenience levels afforded by having 400 fueling stations in the Los Angeles area and **do not necessarily correspond with the year 2020**, since delays (see Section 4.2.4) in achieving the upper bound equilibrium sales forecast for the given level of station coverage have not yet been taken into account. The comparison to DOE's 2020 targets was made since in 2020, the number of stations required for *capacity* only is less than or roughly equal to 400 stations (per HyTrans calculations received from ORNL, 386, 372, and 105 stations are required for capacity only, assuming the *cumulative* target sales volumes for each scenario are achieved).

18 DOE Hydrogen FCV sales growth scenarios.

19 For calculating equilibrium vehicle sales, FCVs are assumed to be offered in vehicles similar to the top *X* (e.g., 10, 15, 20) selling gasoline ICE models (see 3.0). If offered in less popular models, forecast sales would be lower. Hydrogen FCV range is assumed to be 300 miles.

20 Price difference (including incentives) is relative to that of an equivalent performance gasoline ICE.

21 The actual price paid at the pump, for the purpose of forecasting, is assumed to include an additional $0.55/kg for state and federal taxes (about $0.55/gal for gasoline in California). The gasoline price, which affects the relative fuel cost savings and therefore hydrogen FCV sales, is assumed to be $2.64/gal, including taxes, per AEO's "High Price" scenario for 2020. A fuel economy ratio of 2.4 is assumed (per DOE guidance) for hydrogen FCVs over conventional gasoline ICEs (again, hybrid competition is not yet included).

Source: Welch, C., "Using HyDIVE™ to Analyze Hydrogen Scenarios," NREL/TP-560-41363, Golden, CO: National Renewable Energy Laboratory, forthcoming 2007

Accomplishments: Parametric "Equilibrium" Analysis for a 750-Station Scenario

Los Angeles Area: Forecast Hydrogen FCV Sales and Scenario Targets			HyDIVE "Equilibrium Upper Bound" Sales/Year[26]	Target Sales/Year (2022)[27] Scenario Number[28]		
# Vehicle Models[29]	Vehicle Price (rel. to gas ICE)[30]	H2 Price ($/kg, before taxes)[31]	w/ 750 Stations (see Figure 16)	1 229 stations	2 592 stations	3 698 stations
10	-15%	$2.00	155K	85K	150K	210K
10	-15%	$3.00	148K	85K	150K	210K
10	-15%	$4.00	141K	85K	150K	210K
10	0%	$2.00	135K	85K	150K	210K
10	0%	$3.00	128K	85K	150K	210K
10	0%	$4.00	120K	85K	150K	210K
10	15%	$2.00	115K	85K	150K	210K
10	15%	$3.00	107K	85K	150K	210K
10	15%	$4.00	100K	85K	150K	210K
15	-15%	$2.00	195K	85K	150K	210K
15	-15%	$3.00	186K	85K	150K	210K
15	-15%	$4.00	177K	85K	150K	210K
15	0%	$2.00	170K	85K	150K	210K
15	0%	$3.00	161K	85K	150K	210K
15	0%	$4.00	151K	85K	150K	210K
15	15%	$2.00	144K	85K	150K	210K
15	15%	$3.00	135K	85K	150K	210K
15	15%	$4.00	125K	85K	150K	210K
20	-15%	$2.00	228K	85K	150K	210K
20	-15%	$3.00	218K	85K	150K	210K
20	-15%	$4.00	207K	85K	150K	210K
20	0%	$2.00	199K	85K	150K	210K
20	0%	$3.00	188K	85K	150K	210K
20	0%	$4.00	177K	85K	150K	210K
20	15%	$2.00	169K	85K	150K	210K
20	15%	$3.00	158K	85K	150K	210K
20	15%	$4.00	147K	85K	150K	210K

[26] This static forecast is considered to be an upper bound, equilibrium level per HyDIVE calculations. See Section 4.2.4 for the caveats associated with using this equilibrium value. Hydrogen FCV performance is assumed to be equivalent to gasoline ICEs. For this initial estimate, H2 FCVs compete only with gasoline ICEs (i.e., not with gas/electric hybrids). Competition with gas–electric hybrids would reduce these forecast sales volumes somewhat, depending on the success level of hybrid vehicles.

[27] All the forecast vehicle sales correspond with convenience levels afforded by having 750 fueling stations in the Los Angeles area and **do not necessarily correspond with the year 2022**, since delays (see Section 4.2.4) in achieving the upper bound equilibrium sales forecast for the given level of station coverage have not yet been taken into account. The comparison to DOE's 2022 targets was made since in 2022, the number of stations required for *capacity* only is less than or roughly equal to 750 stations (per HyTrans calculations received from ORNL, 229, 592, and 698 stations are required for capacity only, assuming the *cumulative* target sales volumes for each scenario are achieved).

[28] DOE hydrogen FCV sales growth scenarios.

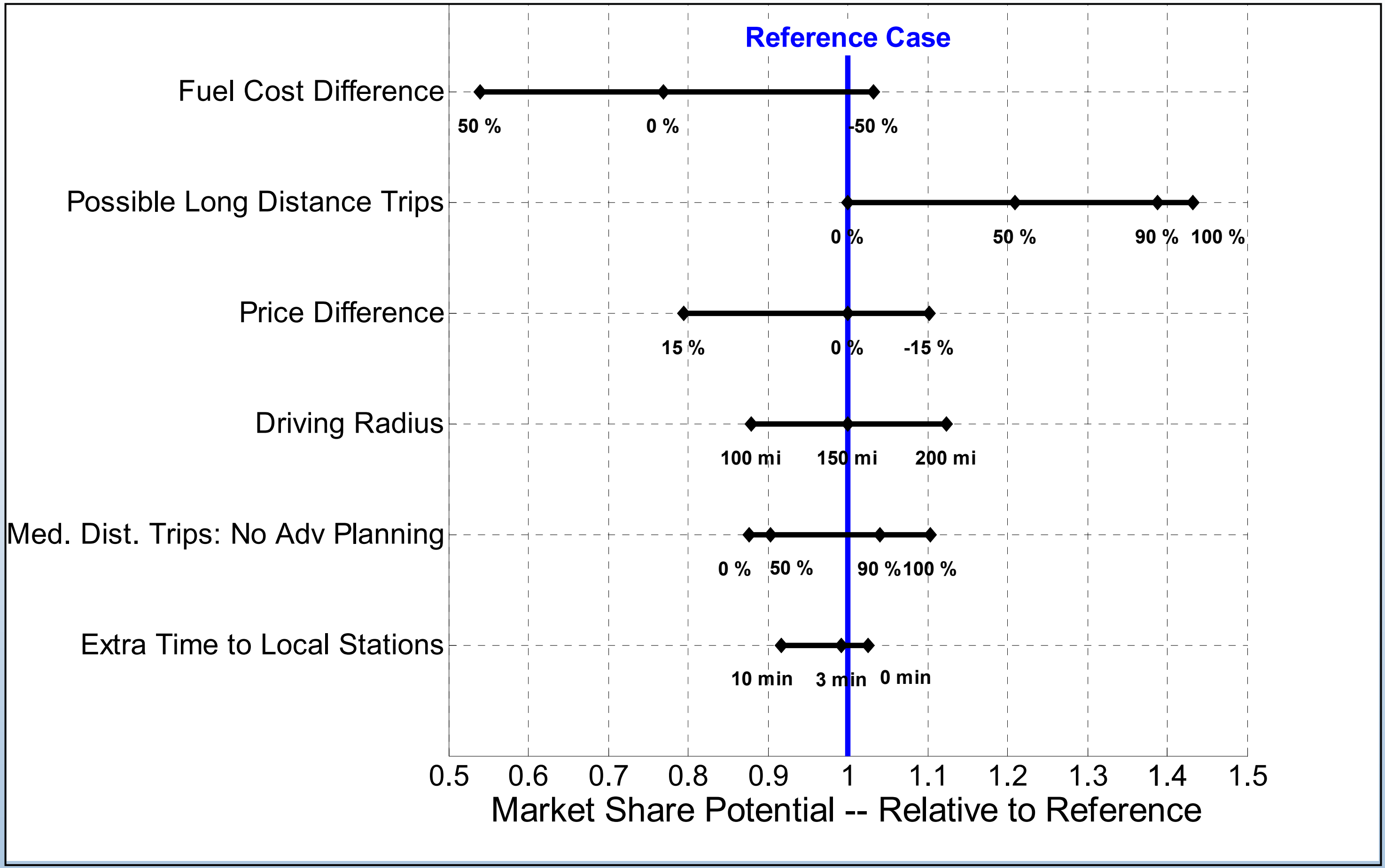
[29] For calculating equilibrium vehicle sales, FCVs are assumed to be offered in vehicles similar to the top *X* (e.g., 10, 15, 20) selling gasoline ICE models. If offered in less popular models, forecast sales would be lower. Hydrogen FCV range is assumed to be 300 miles.

[30] Price difference (including incentives) is relative to that of an equivalent performance gasoline ICE.

[31] The actual price paid at the pump, for the purpose of forecasting, is assumed to include an additional $0.55/kg for state and federal taxes (about $0.55/gal for gasoline in California). The gasoline price, which affects the relative fuel cost savings and therefore hydrogen FCV sales, is assumed to be $2.67/gal, including taxes, per AEO's "High Price" scenario for 2022. A fuel economy ratio of 2.4 is assumed (per DOE guidance) for hydrogen FCVs over conventional gasoline ICEs (again, hybrid competition is not yet included).

Source: Welch, C., "Using HyDIVE™ to Analyze Hydrogen Scenarios," NREL/TP-560-41363, Golden, CO: National Renewable Energy Laboratory, forthcoming 2007

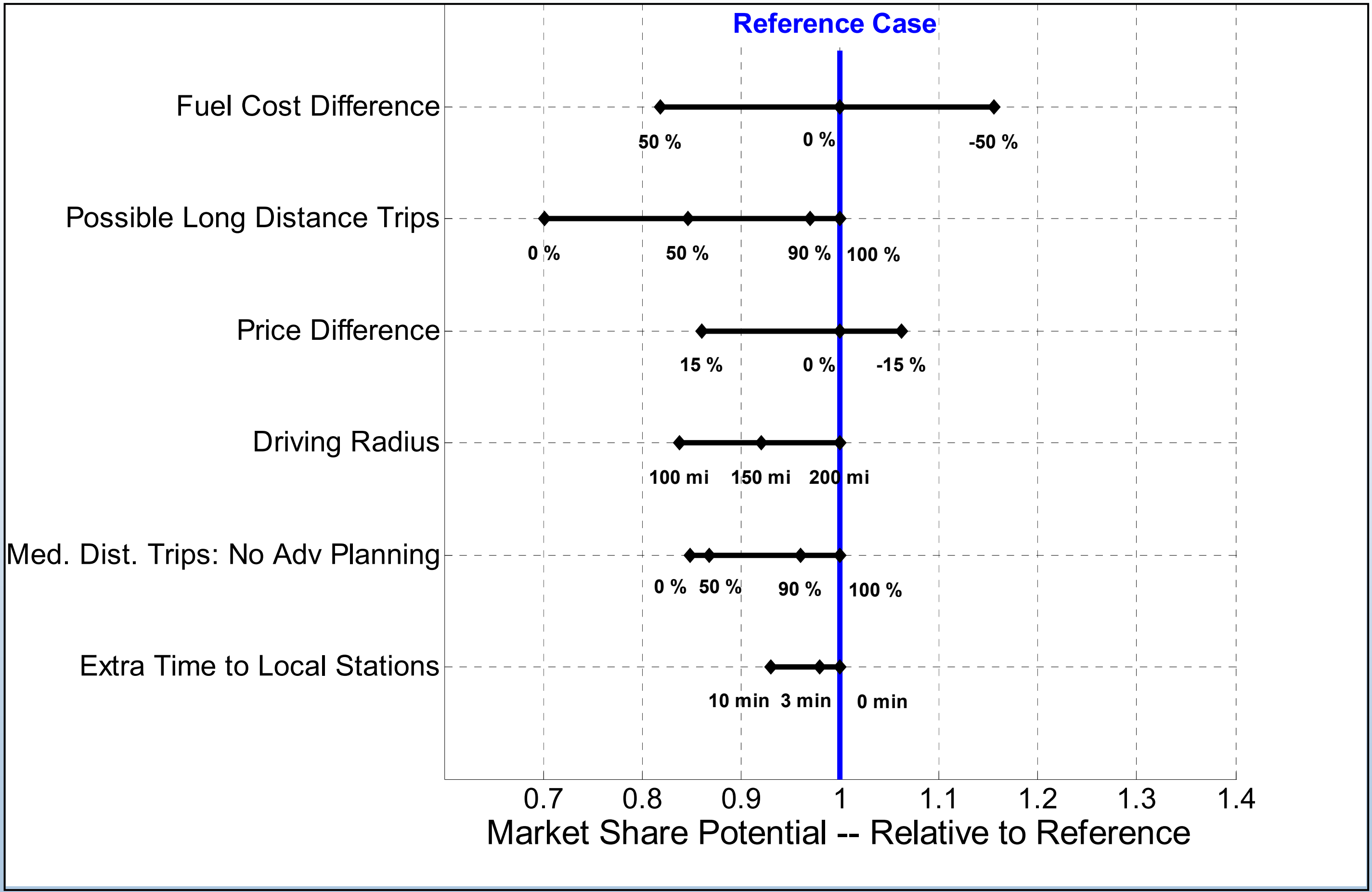
Accomplishments: Sensitivity Analysis of Forecast Market Share to Various Attributes



Reference Case: roughly equivalent to the 400-station scenario with \$3/kg H_2 (before taxes)

Source: Welch, C., "Using HyDIVE™ to Analyze Hydrogen Scenarios," NREL/TP-560-41363, Golden, CO: National Renewable Energy Laboratory, forthcoming 2007

Accomplishments: Sensitivity Analysis of Forecast Market Share to Various Attributes



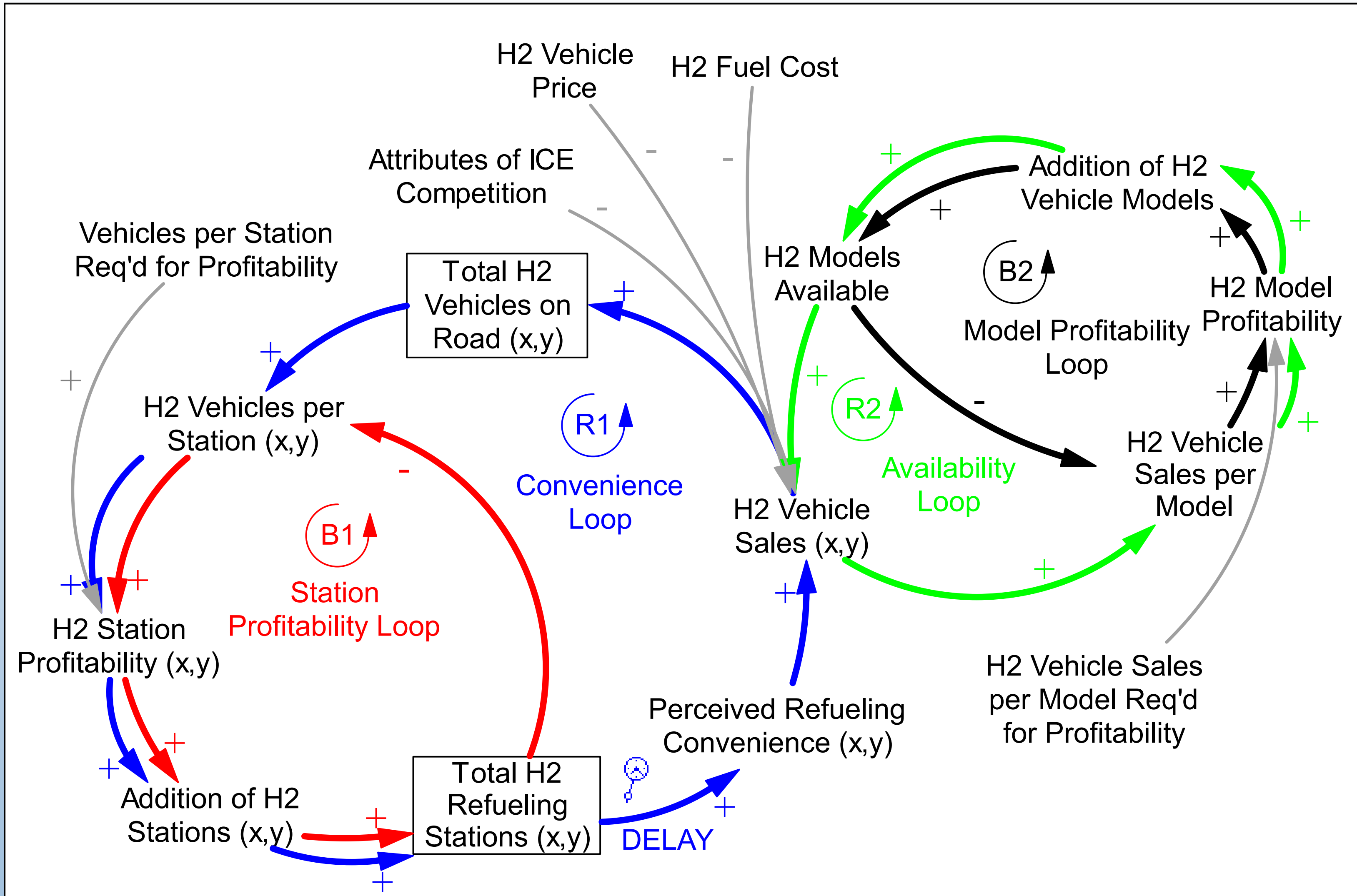
Reference Case: equivalent to 100% H_2 station coverage with equivalent fuel cost (on a $/mile basis)

Source: Welch, C., "Using HyDIVE™ to Analyze Hydrogen Scenarios," NREL/TP-560-41363, Golden, CO: National Renewable Energy Laboratory, forthcoming 2007

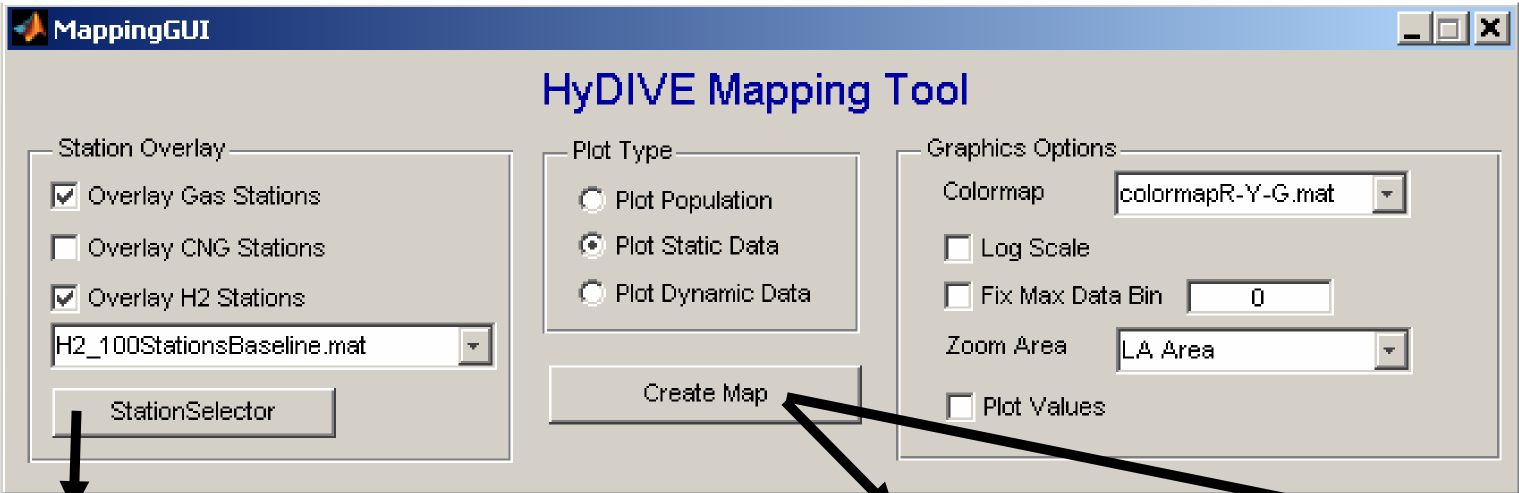
Future Work

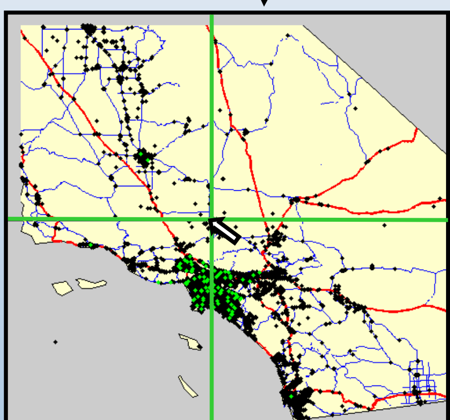
- **FY 2007**
  - Complete NREL technical report (in review when this presentation was submitted; should be complete by merit review date)
  - Complete discrete choice analysis based on final data set … formally document methodology/parameters in separate report
  - Compare HyDIVE with other models (e.g., HyTRANS, RCF CAS model) to determine potential synergies, overlaps, gaps, etc.
- **Beyond FY 2007 (contingent upon funding)**
  - Incorporate additional dynamics and data into HyDIVE (e.g., vehicle availability, diffusion of technology awareness, etc.)
  - Make endogenous H_2 price at station using H2A
  - *Dynamic* strategy/scenario/policy analysis

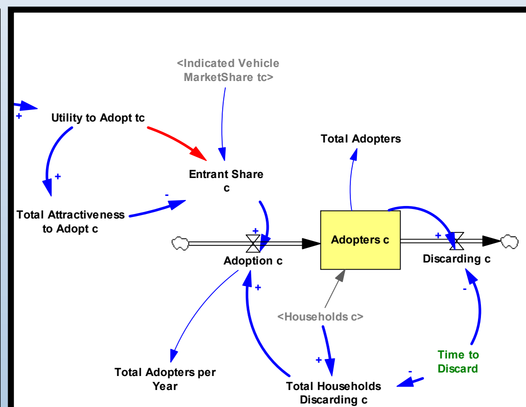
Future Work: Rigorous Modeling of Dynamics of Vehicle Availability

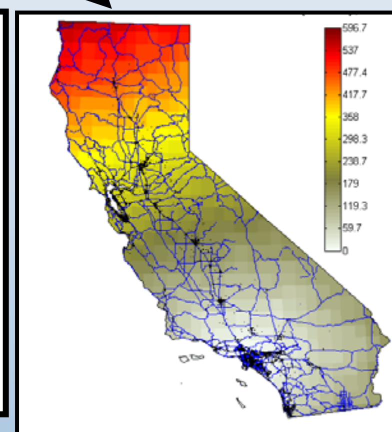


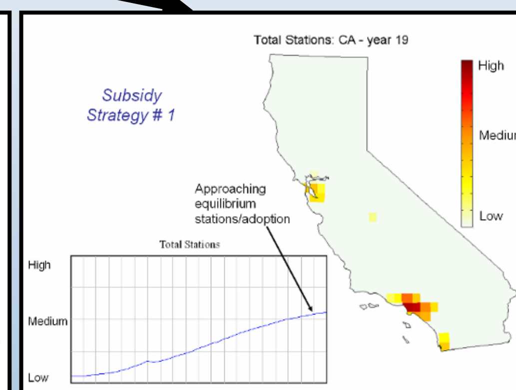
Future Work: Scenario/Strategy Analysis











Initial station "seed"

HyDIVE analysis

Static output (e.g., demand, station profitability, etc.)

Dynamic output (to test strategies/polices)

Summary

Relevance: Characterizes and better quantifies the nature of the H_2 station coverage and vehicle demand chicken-and-egg problem

Approach: Spatial, dynamic, behavioral modeling using system dynamics; discrete choice analysis to quantify key parameters

Accomplishments: Early dynamic results to illuminate key areas to characterize and quantify; discrete choice analysis executed and analyzed; parameters input to HyDIVE to conduct parametric static, spatial analysis of market share for two station scenarios

Proposed Future Work: Include additional relevant dynamics into model; make fuel cost and vehicle availability endogenous; compare HyDIVE with other models to assess similarities, gaps, overlaps

Cory Welch

Cory_Welch@nrel.gov, 303-275-4436

Publications and References

Struben, J., Welch, C. and Sterman, J. "Modeling the Co-Evolutionary Dynamics of Hydrogen Vehicles and Refueling Stations." NHA Annual Hydrogen Conference, Long Beach, CA, 2006.

Struben, J. J. "Identifying Challenges for Sustained Adoption of Alternative Fuel Vehicles and Infrastructure." *MIT Sloan Research Paper No. 4625-06* 2006. Available at SSRN: http://ssrn.com/paper=927012.

Welch, C. "HyDIVE™ (Hydrogen Dynamic Infrastructure and Vehicle Evolution) Model Analysis." Presented at the DOE 2010-2025 Scenario Analysis Meeting, Washington, D.C., August 9-10, 2006. Available at http://www.eere.energy.gov/hydrogenandfuelcells/analysis/pdfs/welch_hydive.pdf.

Welch, C. "Lesson Learned from Alternative Transportation Fuels: Modeling Transition Dynamics." NREL/TP-540-39446. Golden, CO: National Renewable Energy Laboratory, February 2006.

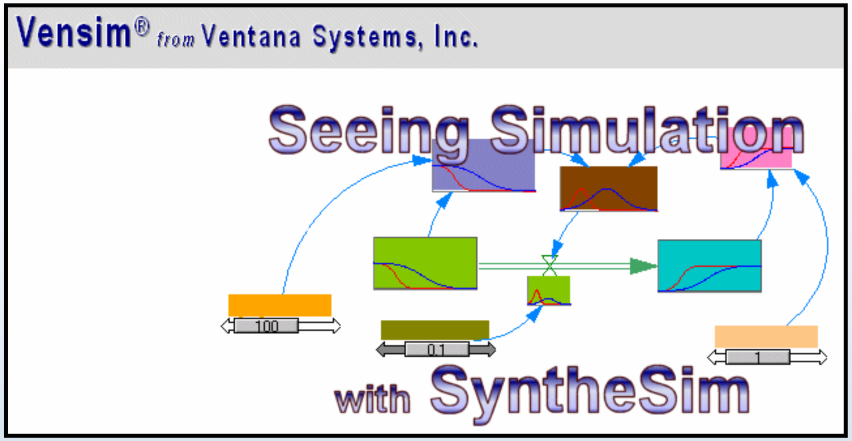
Welch, C. "Discrete Choice Analysis: Hydrogen Fuel Cell Vehicle Demand Potential." Presented at the DOE 2010-2025 Scenario Analysis Meeting, Washington, D.C., January 31, 2007. http://www1.eere.energy.gov/hydrogenandfuelcells/analysis/pdfs/scenario_analysis_welch1_07.pdf

Welch, C. "Using HyDIVE™ to Analyze Hydrogen Scenarios." NREL/TP-560-41363. Golden, CO: National Renewable Energy Laboratory, Forthcoming 2007.

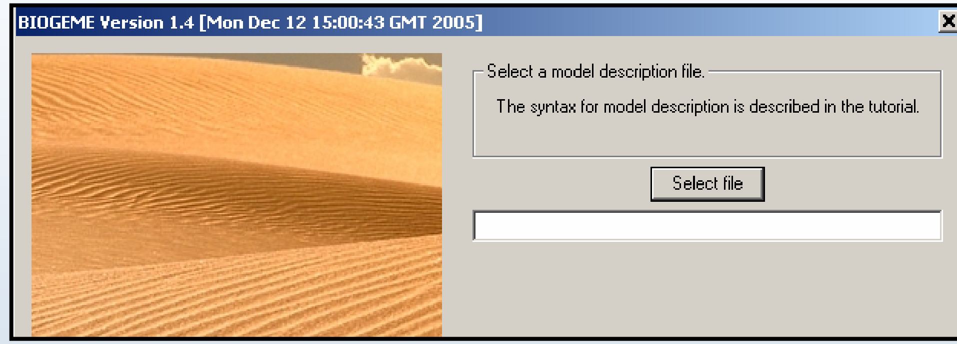
Additional Slides

Analysis Tools Employed

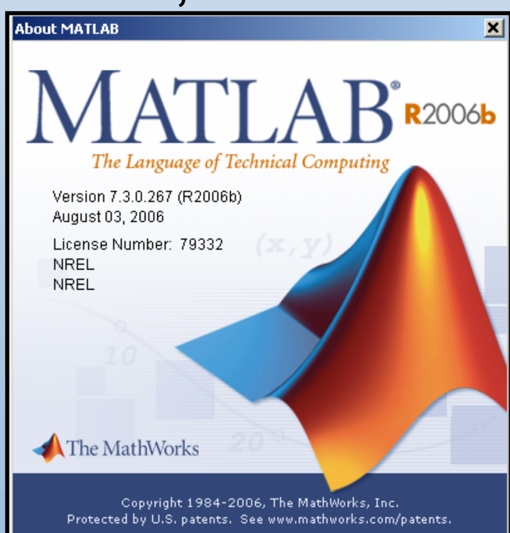
System Dynamics



Discrete Choice Analysis: Parameter Estimation



Mapping, Animation, Station Selection, Tornado Charts



Data Input/Output Interface