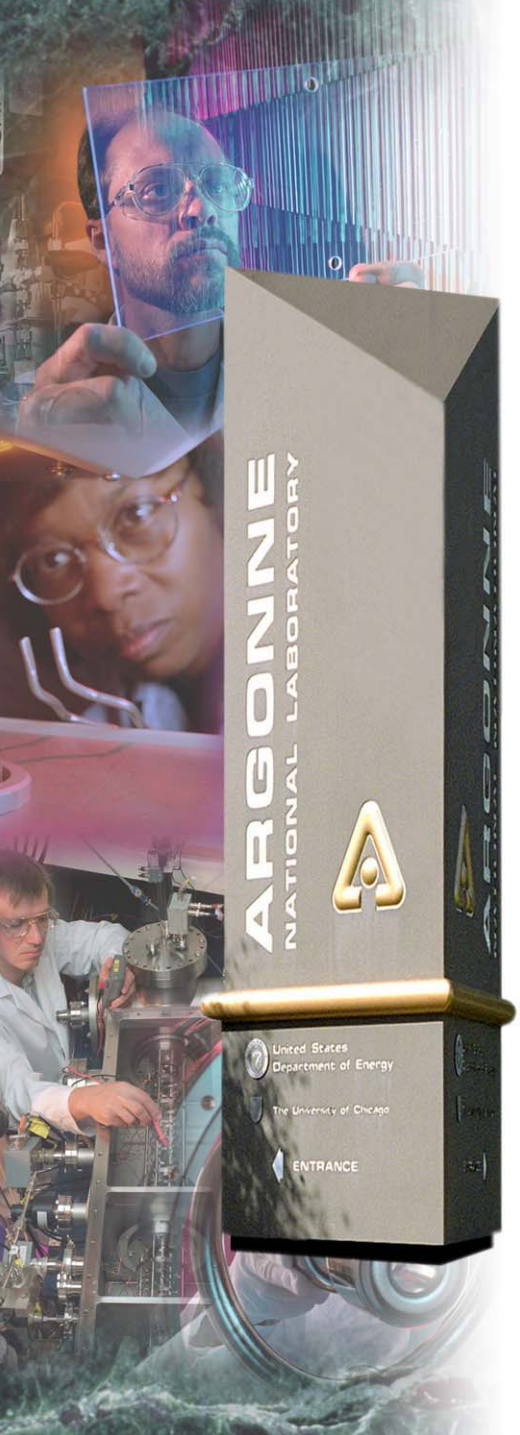


H2A Delivery Scenario Model and Analyses

Marianne Mintz and Jerry Gillette

DOE Hydrogen Delivery Analysis and High Pressure Tanks R&D Project Review Meeting

February 8, 2005

Argonne National Laboratory

Office of Science
U.S. Department of Energy

A U.S. Department of Energy
Office of Science Laboratory
Operated by The University of Chicago

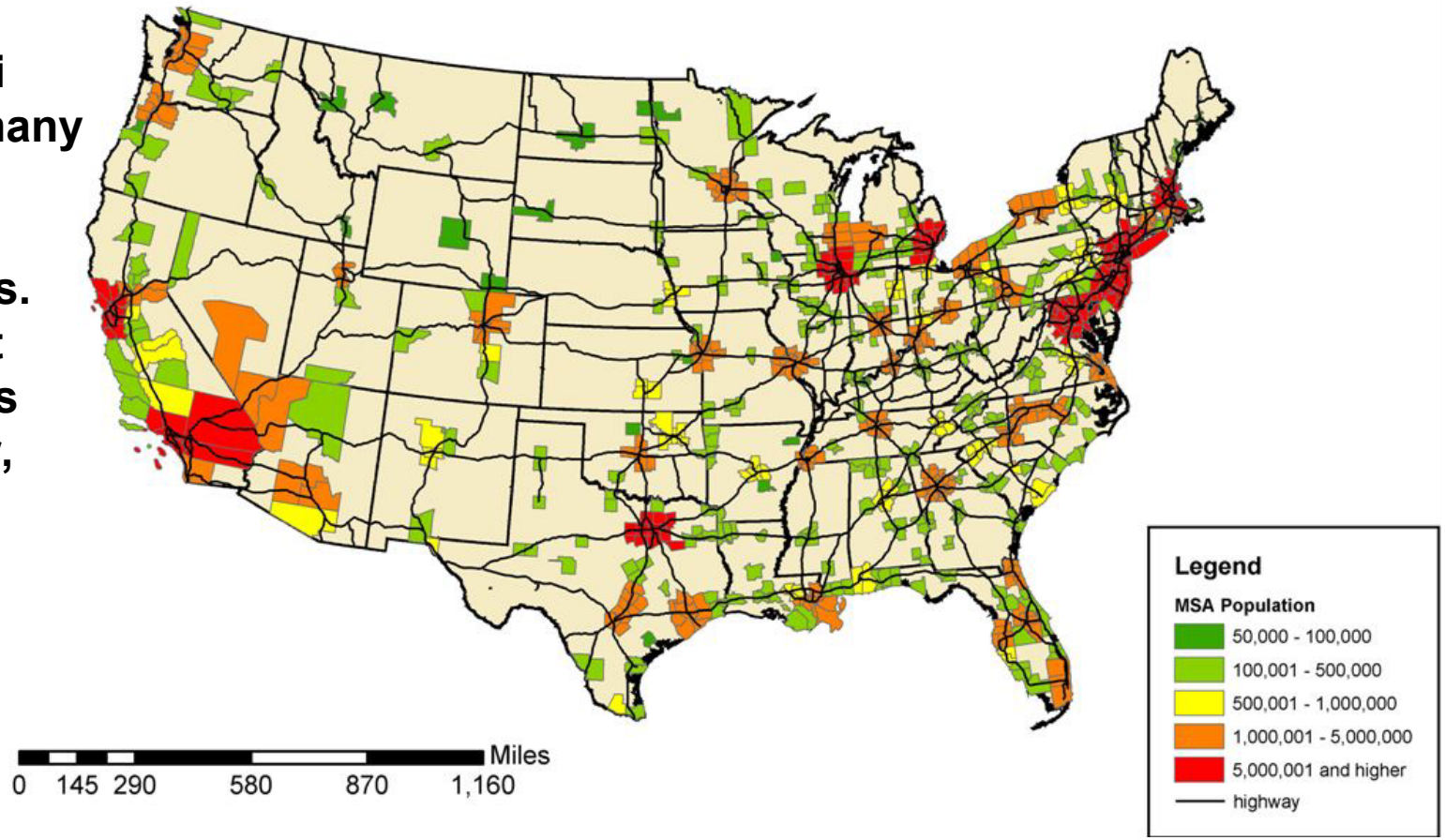
Topics

- **Delivery Scenarios**
  - Current status
  - Future scenarios
- **Delivery Scenarios model**
  - Approach
  - Structure
  - Current status
  - Results
- **Pipeline modeling**
  - Approach
  - Key assumptions
  - Results
- **Next Steps**

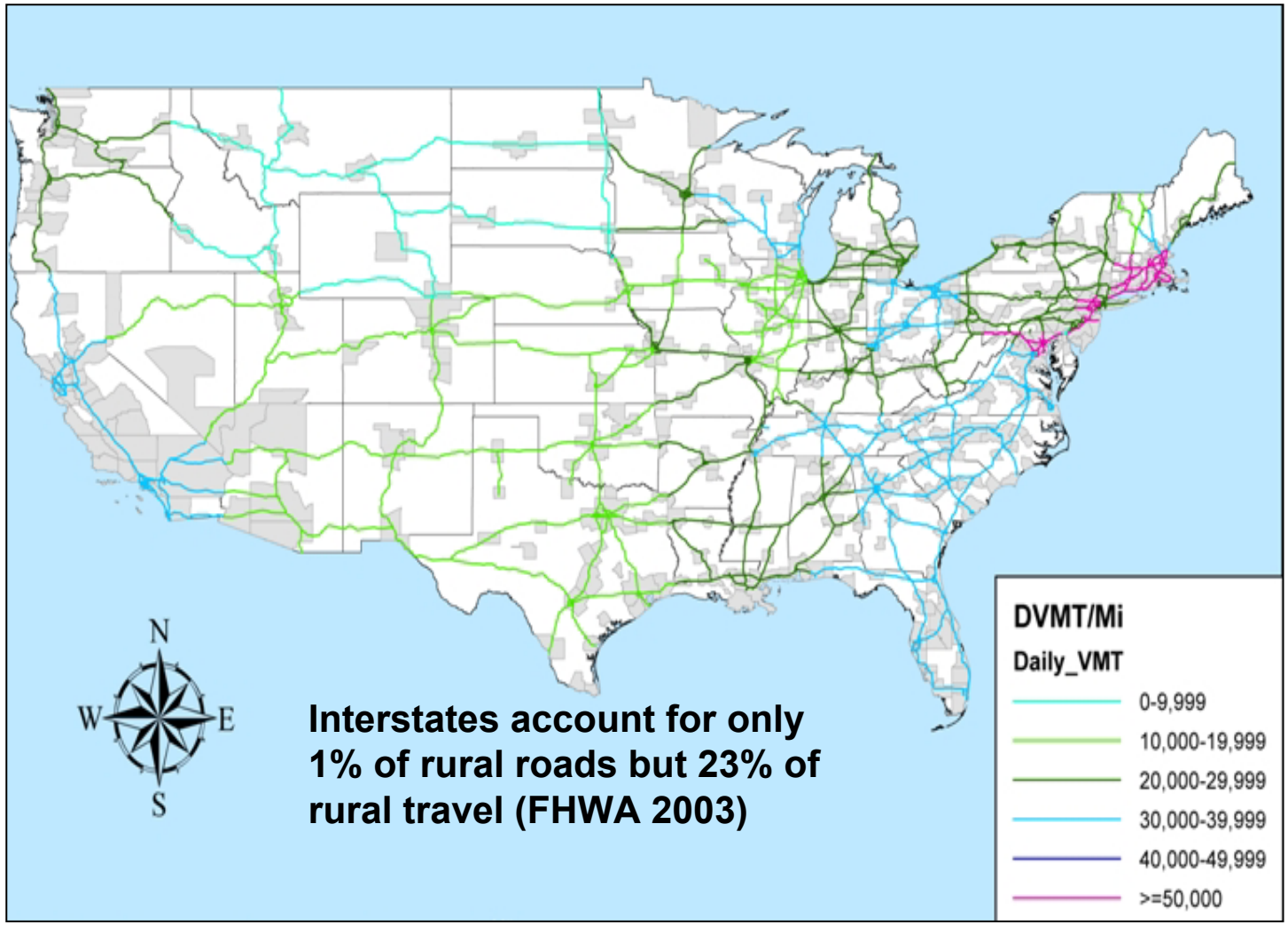
Delivery Scenarios

Three-Quarters of the US Population Reside in Urbanized Areas

East of the Mississippi there are many large, proximate urban areas. In the West urban areas are smaller, fewer and more dispersed.



In Rural Areas Travel Demand Is Concentrated on Interstate Highways

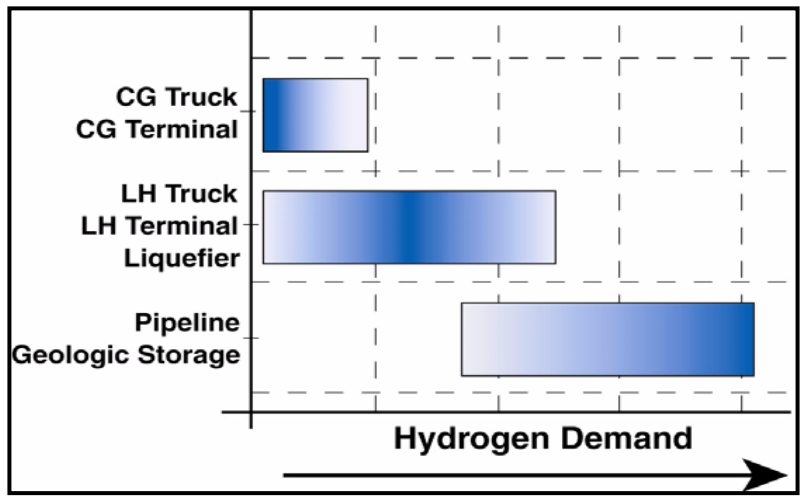


Interstates account for only 1% of rural roads but 23% of rural travel (FHWA 2003)

Hydrogen Can Take Many Paths from "Well-to-Pump"

Since transport unit cost declines with increasing shipment size, bulk modes become more attractive at higher demand levels ---

But where is the tipping point, and which paths are most likely?



32 Scenarios Are Defined by Market, Penetration and Delivery Mode in Version 1 of Model

Penetration / Market	1%	10%	30%	70%
Large urban	CG Truck	LH Truck Pipeline	LH Truck Pipeline	LH Truck Pipeline
Small urban	CG Truck	LH Truck Pipeline	LH Truck Pipeline	LH Truck Pipeline
Intercity – long segment	---	CG Truck LH Truck Pipeline	CG Truck LH Truck Pipeline	CG Truck LH Truck Pipeline
Intercity – short segment	---	CG Truck LH Truck Pipeline	CG Truck LH Truck Pipeline	CG Truck LH Truck Pipeline

Key Demand Assumptions by Market and Penetration, Version 1

Market \ Penetration	1%	10%	30%	70%
Small Urban				
Population	100,000	100,000	100,000	100,000
Vehicles	116,000	116,000	116,000	116,000
H_2 fueled vehicles	1,160	11,600	34,800	81,200
H_2 fuel stations	12[a]	6[b]	17[b]	39[b]
H_2 demand (tpd)	1	8.3	2.5	58
Large Urban				
Population	1,000,000	1,000,000	1,000,000	1,000,000
Vehicles	890,000	890,000	890,000	890,000
H_2 fueled vehicles	8,900	89,000	267,000	623,000
H_2 fuel stations	86[a]	43[b]	128[b]	298[b]
H_2 demand (tpd)	9	83	250	580
Rural/Intercity[c]				
Travel density (vmt/mi/d)	--	17,000	17,000	17,000
H_2 fueled travel density	--	1,700	5,100	11,900
H_2 fuel density (kg/km/d)	--	18.5	55.5	129.5
H_2 fuel stations	--	4[d]	11[d]	26[d]
Ratio H_2 to gasoline stns	--	.09	.25	.60

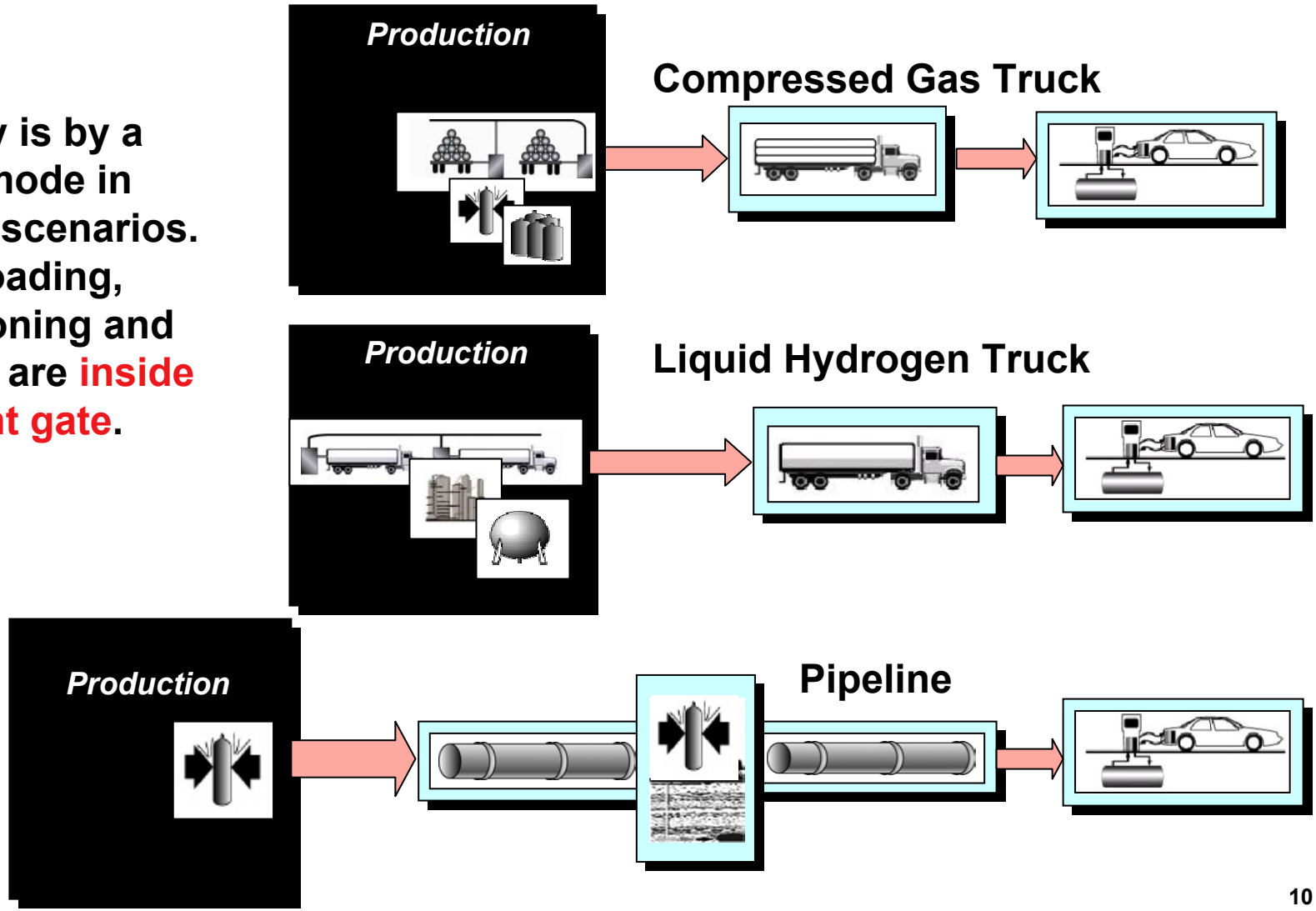
[a]100 kg/d stations.
[b]1500 kg/d stations.
[C]160 km case.
[d]Size varies with demand.

Hydrogen Delivery Scenarios Include:

- **Production Site**
  - Compression
  - Gaseous storage
- **Liquid Distribution**
  - Liquefaction
  - LH_2 terminals
  - LH_2 storage
  - LH_2 trucks
- **Gaseous Distribution**
  - Compression
  - Geologic storage
  - Pipelines
  - Compressed gas terminals
  - Compressed gas storage
  - Compressed gas trucks
- **Forecourt (Refueling Station)**
  - Storage
  - Compression (if applicable)

Current Delivery Scenarios Assume Three Pathways or Delivery Modes

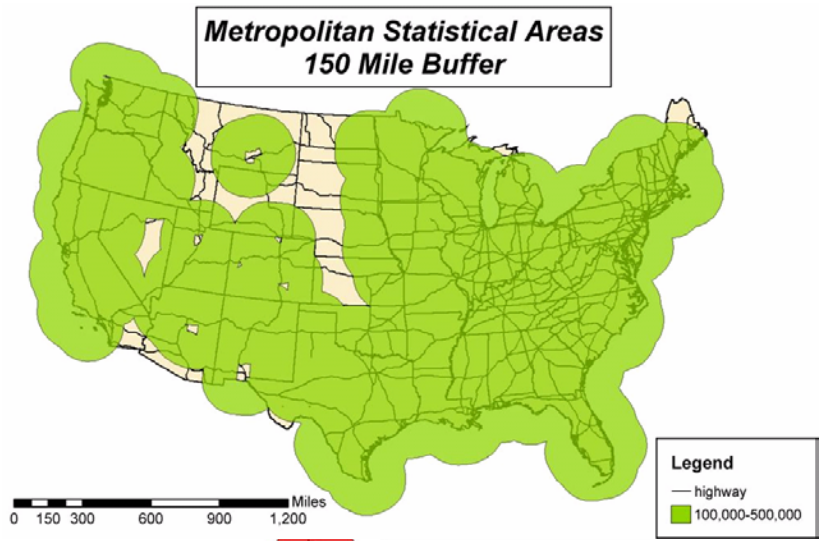
Delivery is by a single mode in current scenarios. Thus, loading, conditioning and storage are inside the plant gate.



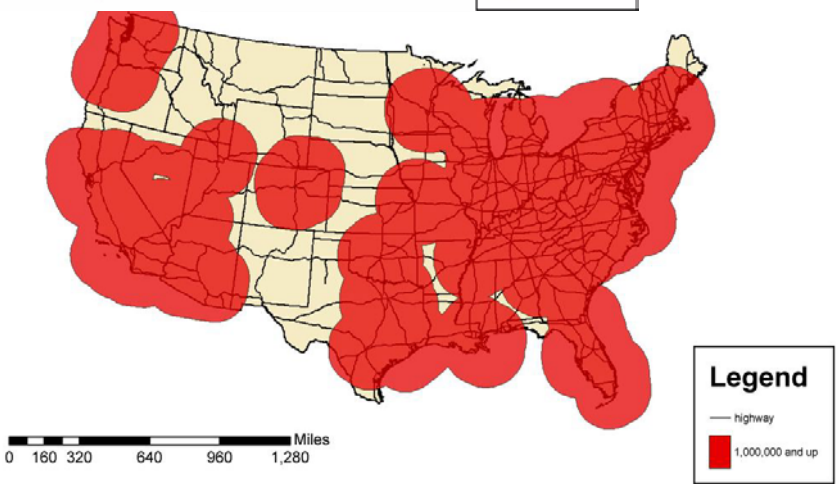
Future Delivery Pathways Will Be More Complex

Component	Pathway						
Pipeline	X	X	X			X	X
Geologic storage	X	X					
Liquefier	X				X	X	
LH Rail (?)					X		
LH Terminal	X				X	X	
LH Truck	X				X	X	
GH Rail (?)				X			X
GH Terminal		X	X	X			X
GH Truck		X	X	X			X
HPGH Truck		X	X	X			X

Rural/Interstate Market May Be Served Via Same Infrastructure as Urban Markets



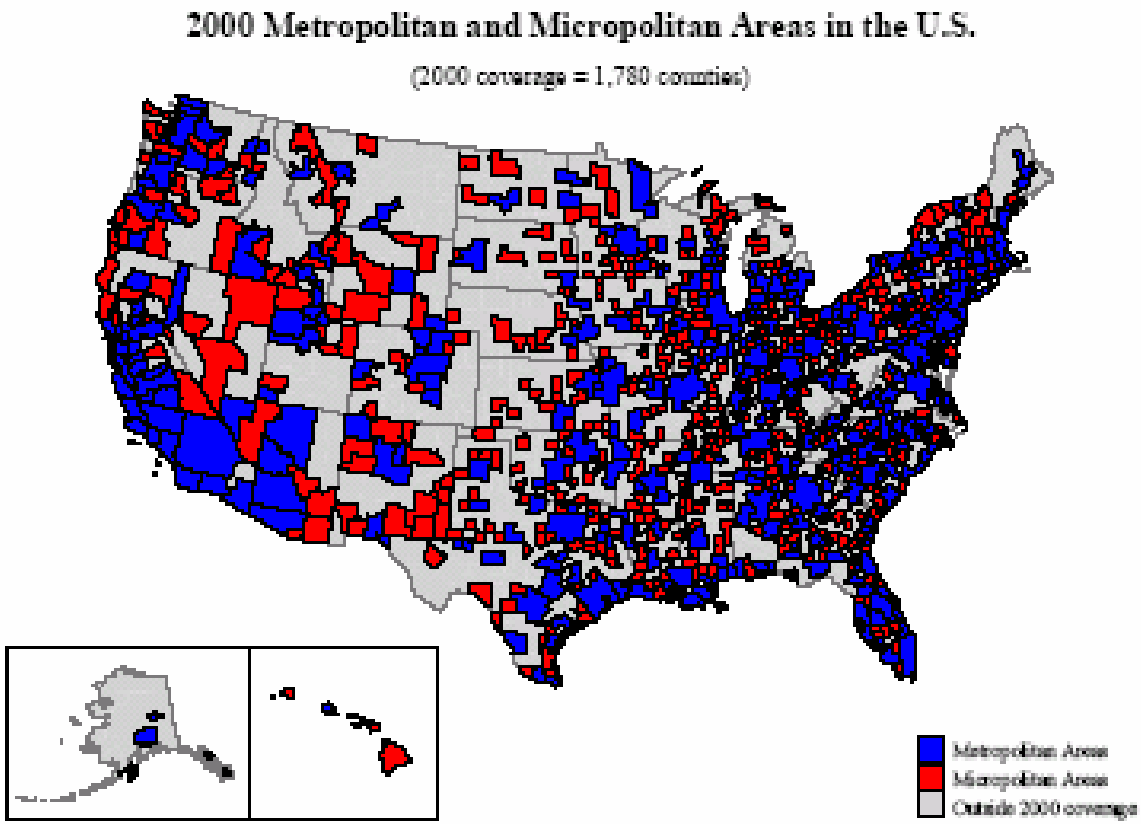
Most of the Great Plains and Mountain States are within 200 highway miles (320 km) of smaller urban areas



Nearly all of the country East of the Mississippi and West of the Rockies is within 200 highway miles (320 km) of large urbanized areas

Alternatively, Rural/Interstate Demand may be Served from Small Towns or "Micropolitan" Areas

There are many "micropolitan" areas in the Great Plains and rural West -- but not necessarily along Interstate highways.



Delivery Scenarios Model

Scenario Model Has Several Objectives

- **Allow user to quickly and easily define scenarios of interest**
- **Efficiently display input and output**
- **Provide a link between appropriate component tabs**
- **Provide structure for efficiently examining**
  - New technologies
  - Additional delivery pathways (e.g., mixed mode)
  - Additional demand scenarios (e.g., combined urban & interstate demands; multiple urban areas from single terminal)

Approach Builds on Past/Current Efforts and Common Analytical Tools

- **To allow maximum flexibility, the Scenario Model:**
  - Is based on Microsoft EXCEL programming
  - Will be put on World Wide Web for downloading by users

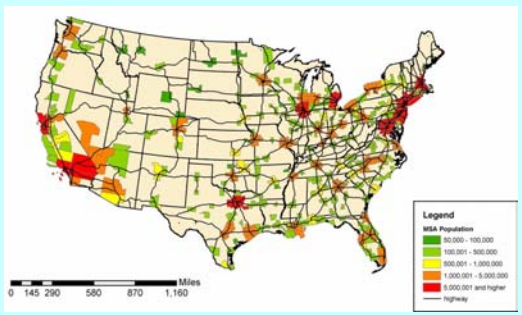
- **Building blocks have been/are being developed within the H2A Program**
  - Delivery Components Model
  - Forecourt model
  - Discounted cash flow analysis
  - Demand definition/analysis

Scenario Definition

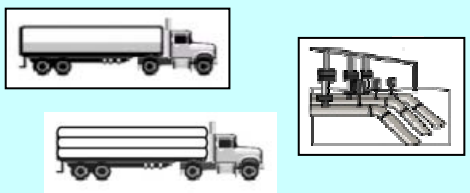
Penetration

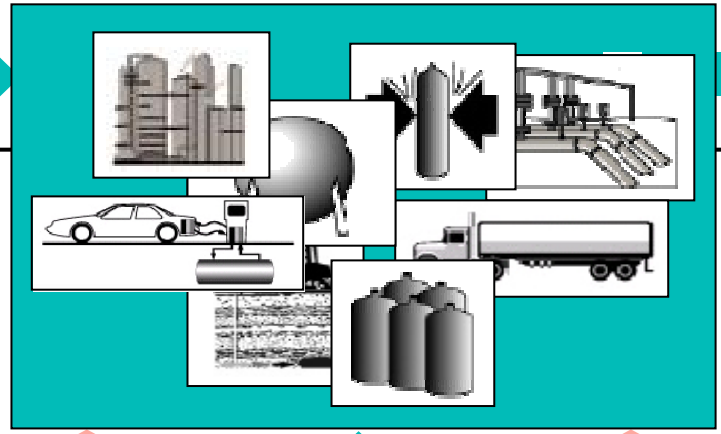
0 25 50 75 100

Market



Mode





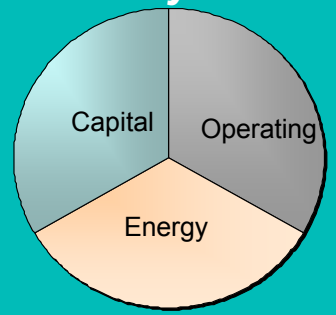
Inputs

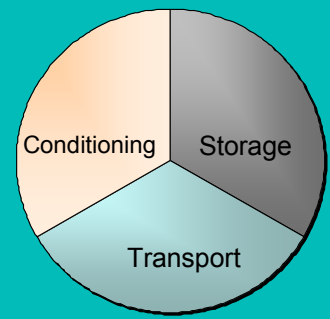
Pipeline Model

Truck Models

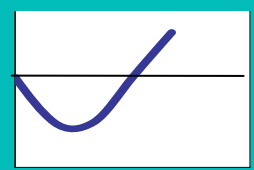
Results

Delivery Cost





Cumulative Cash Flow



Current Scenario Model is Version 1

- **Predefined demands based on**
  - Urban or interstate market
  - City size
  - Penetration of hydrogen-fueled LDVs
- **Delivery mode defined by user**
  - Pipeline with geologic storage
  - Liquefied hydrogen via terminal and truck
  - Compressed hydrogen gas via terminal and truck (for urban cases currently allowed only for very low penetration rate)
- **Target is to have complete working model of Version 1 by end of February and on WWW by June 1**

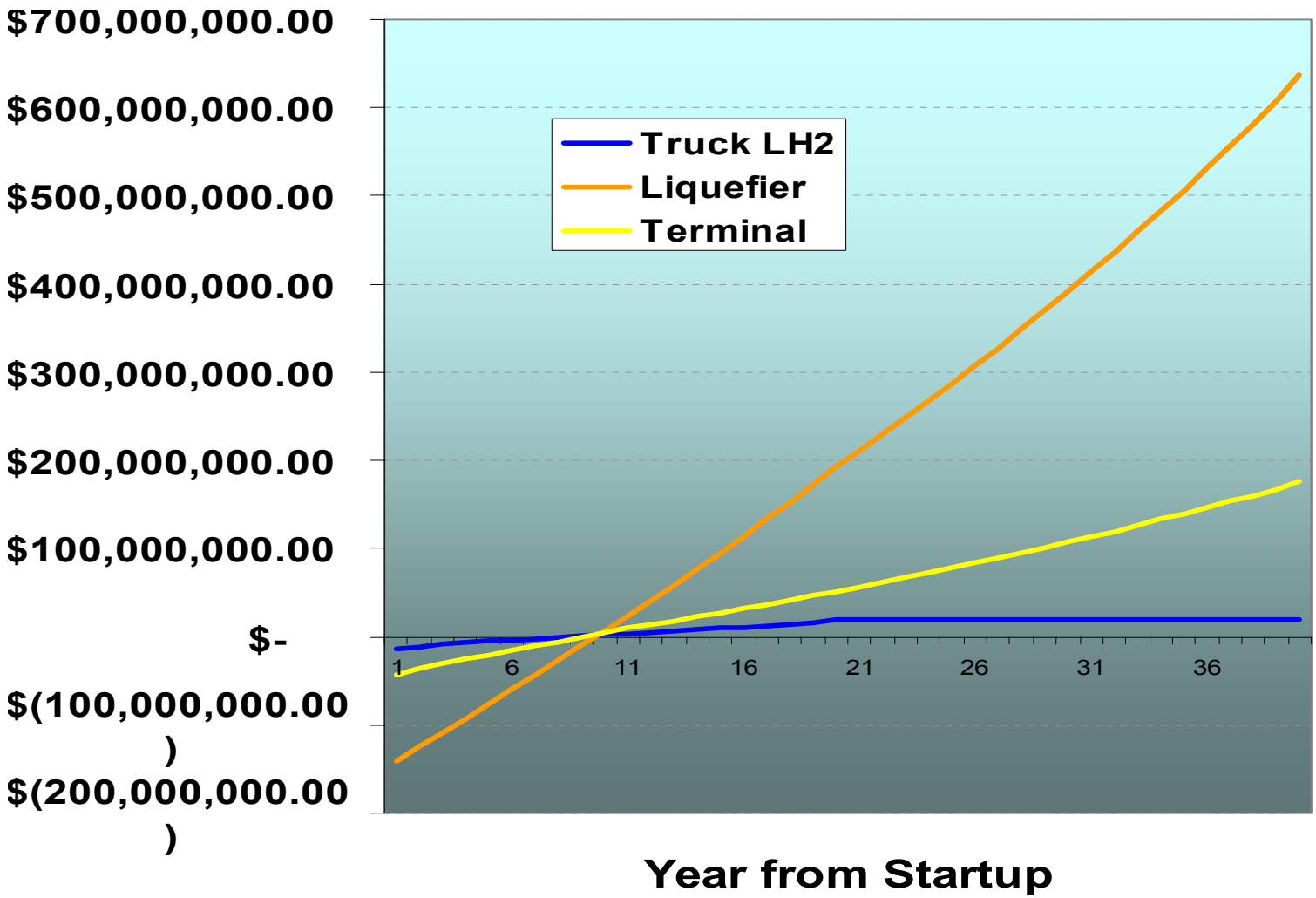
Components Tabs Being Linked So Pathway Capacities Reflect Losses and Availabilities

- **Examples for Small City, 30% Penetration**
  - Hydrogen purchased by consumers – 25,000 kg/day (average)
  - Assume that storage at refueling stations provide for peak demand
- **Liquid H_2 Delivery**
  - Truck – 26,600 kg/day
  - Terminal – 33,200 kg/day
  - Liquefier – 35,500 kg/day
- **Pipeline H_2 Delivery**
  - Pipeline – 28,100 kg/day
  - Geologic Storage – 28,500*days kg/day

Intermediate Results Tab Details Costs for Each Major Component

	Truck LH2	Liquefier	Terminal	Sum
Capital Cost	$ 2.70	$0.25	$0.07	$ 3.02
Energy/Fuel	$ 0.00	$0.12	$ -	$ 0.12
Other	$ 0.26	$0.12	$0.04	$ 0.42
Total	$ 2.96	$0.50	$0.11	$ 3.56

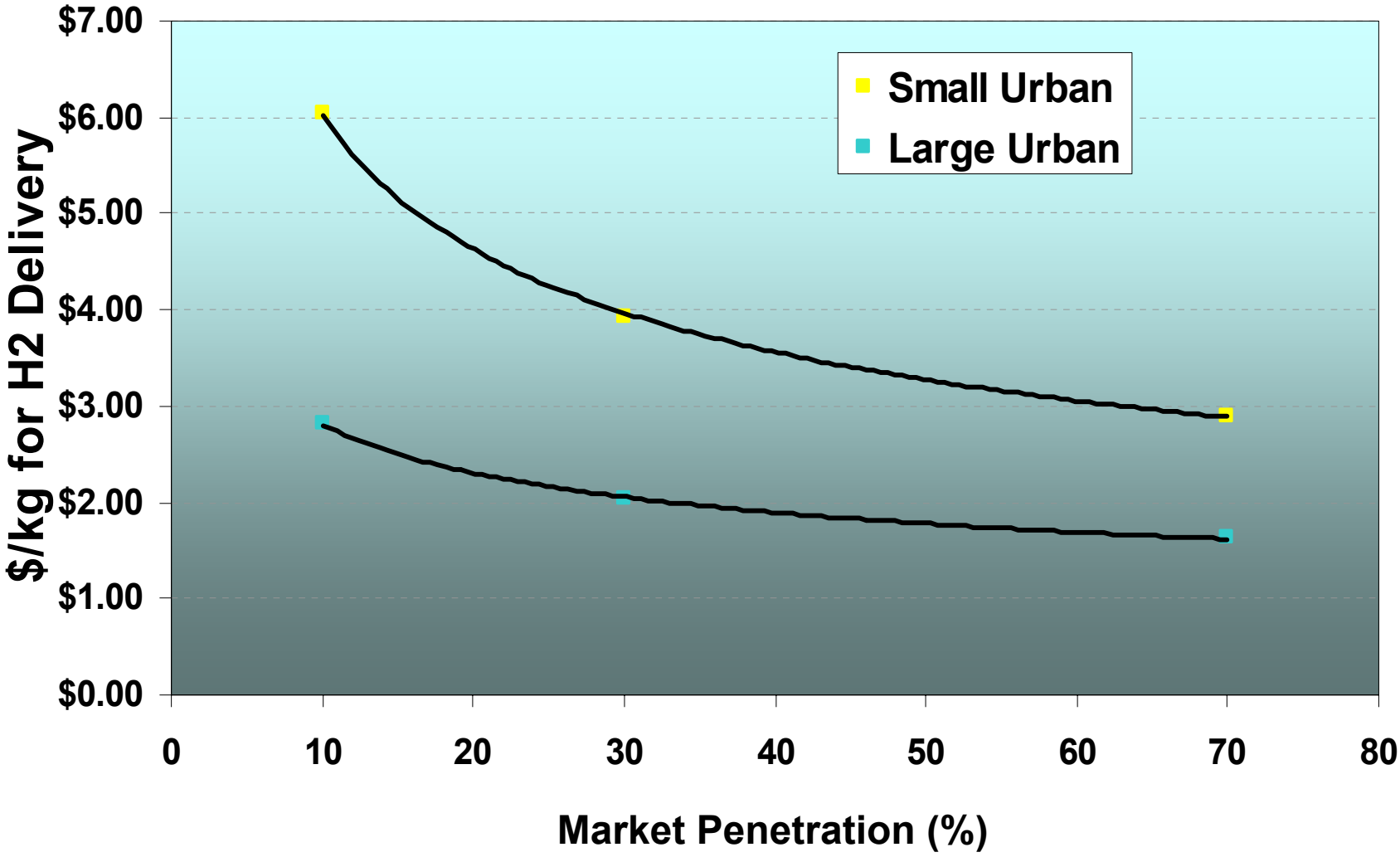
Intermediate Results Tab Shows Cumulative DCF for Each Major Component (Real 2000$)



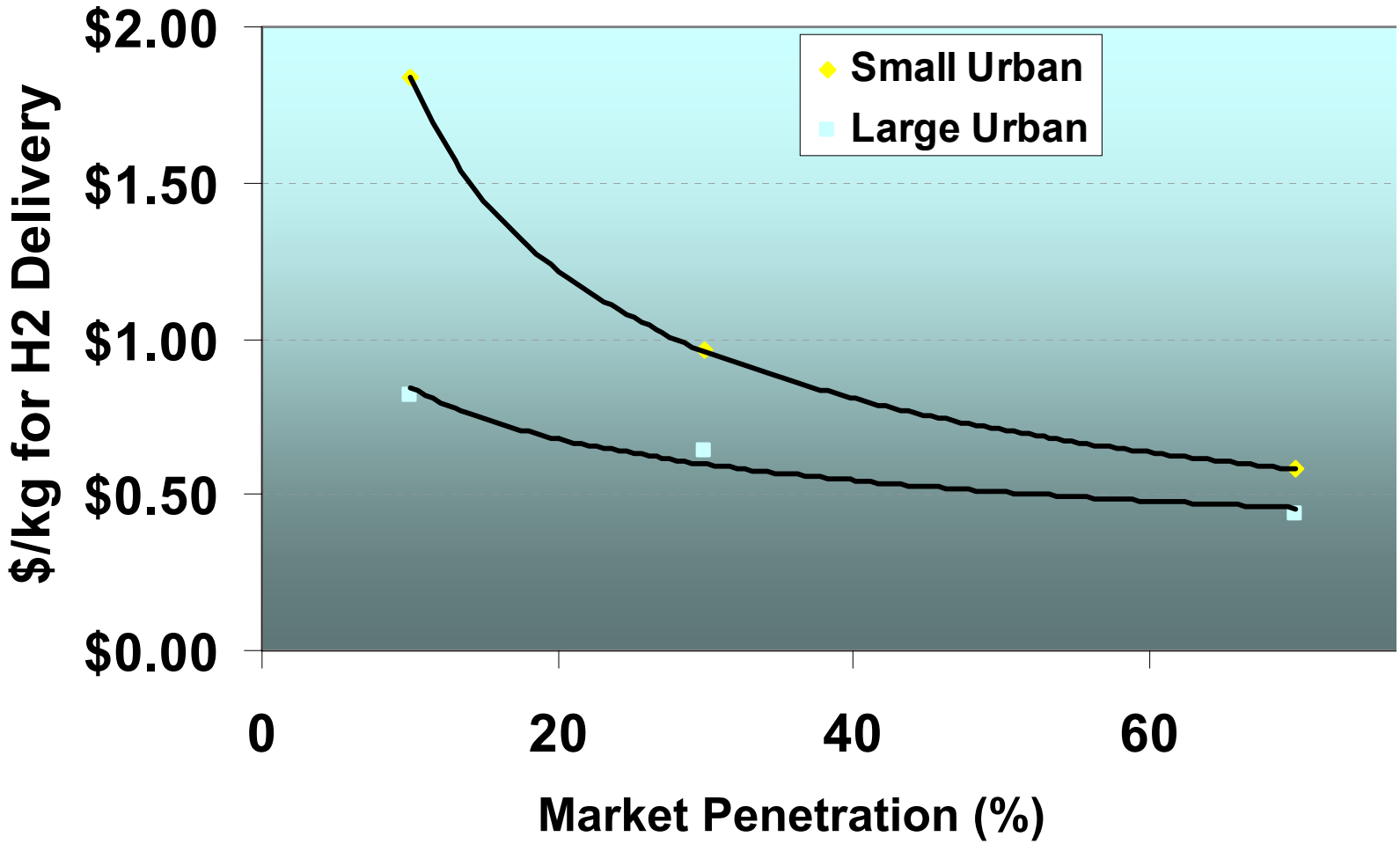
Preliminary Results that Follow Are NOT Based on Fully Integrated Model

- Not based on detailed financial analysis
- Intended to illustrate types of analyses to be conducted
- Illustrate types of comparisons that can be made
- Provide very preliminary hints as to what conclusions might be drawn

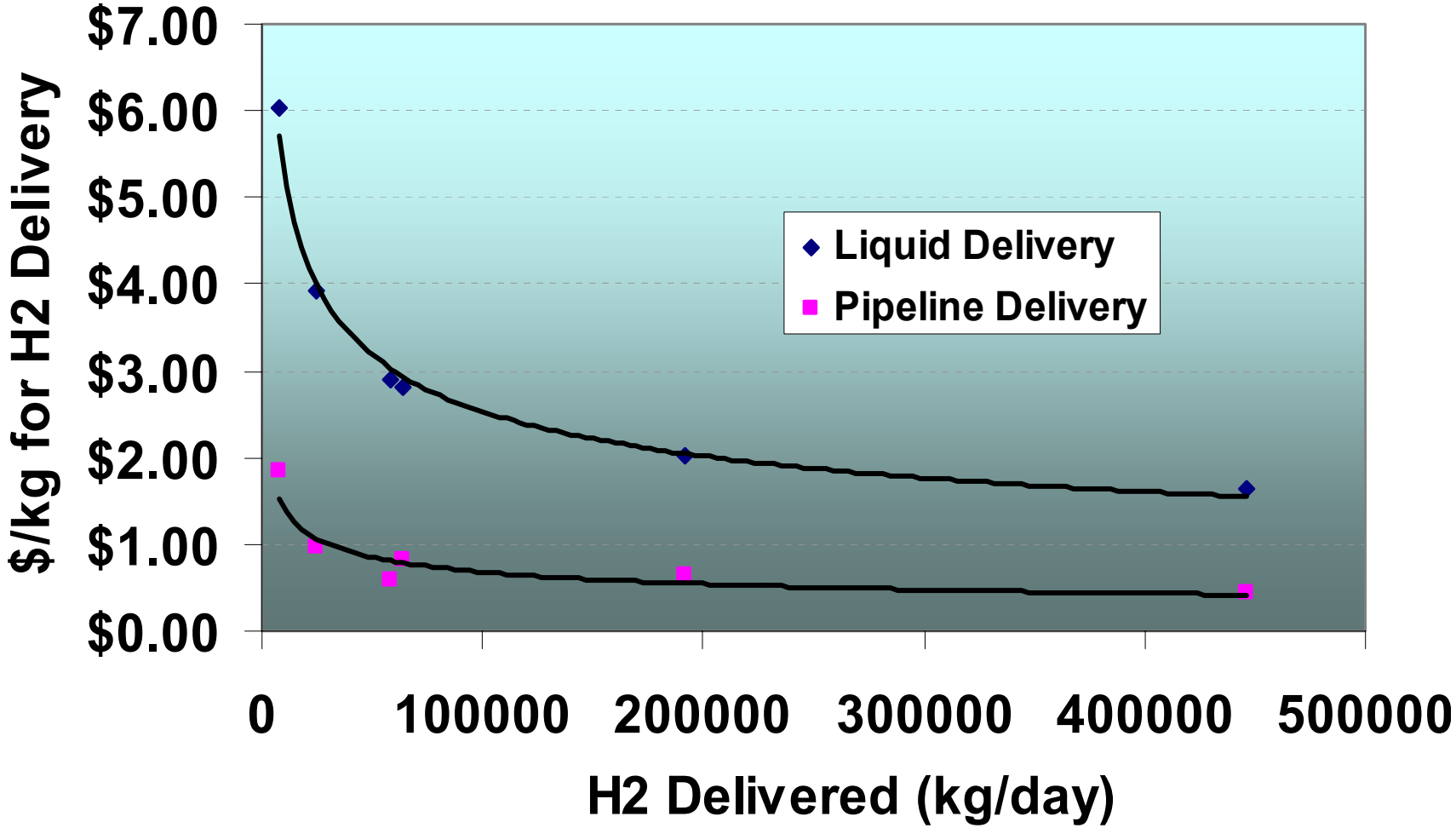
Liquid Delivery Costs Are Dependent on Market Penetration



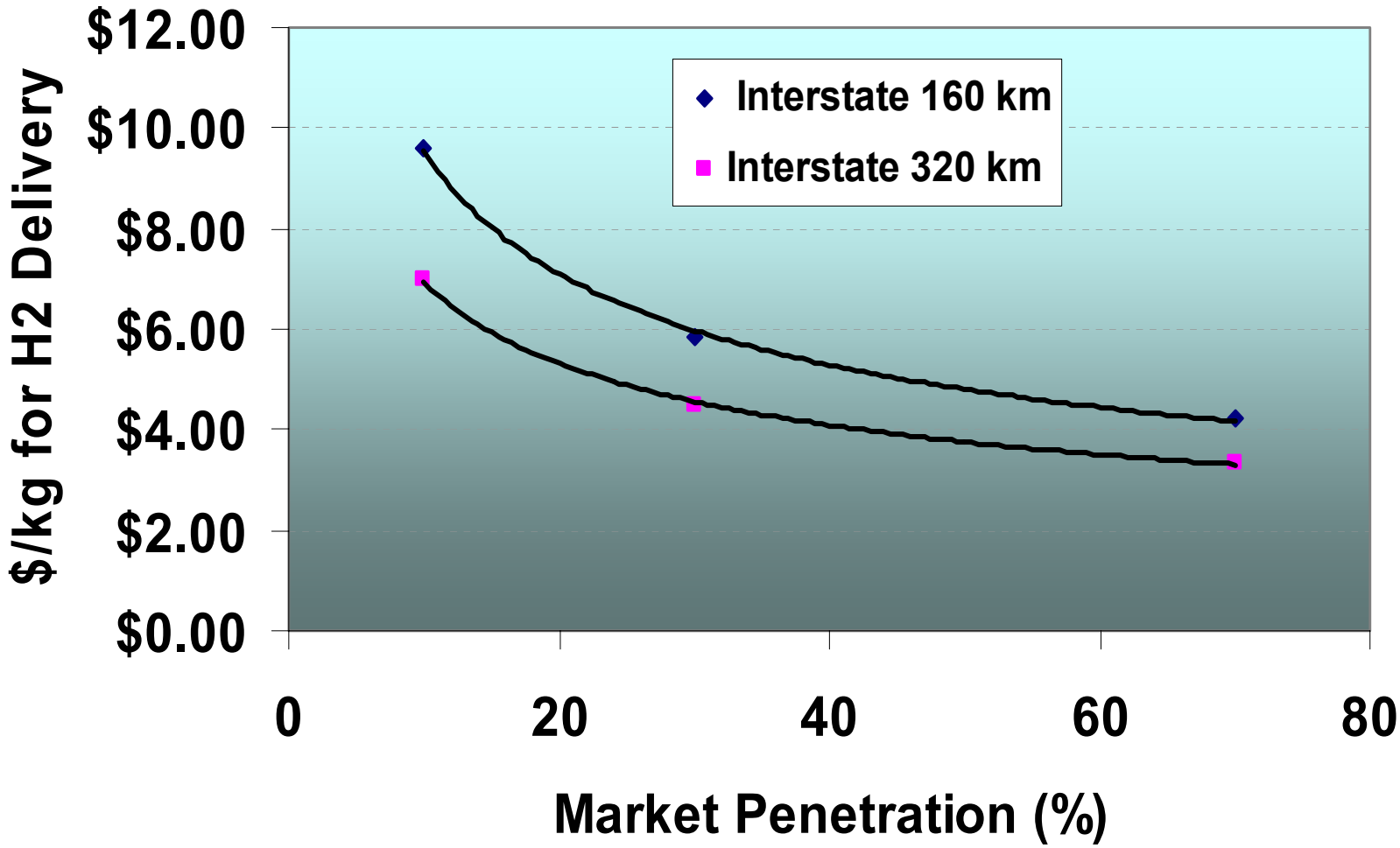
Pipeline Costs Are Also Highly Dependent on H_2 Market Penetration



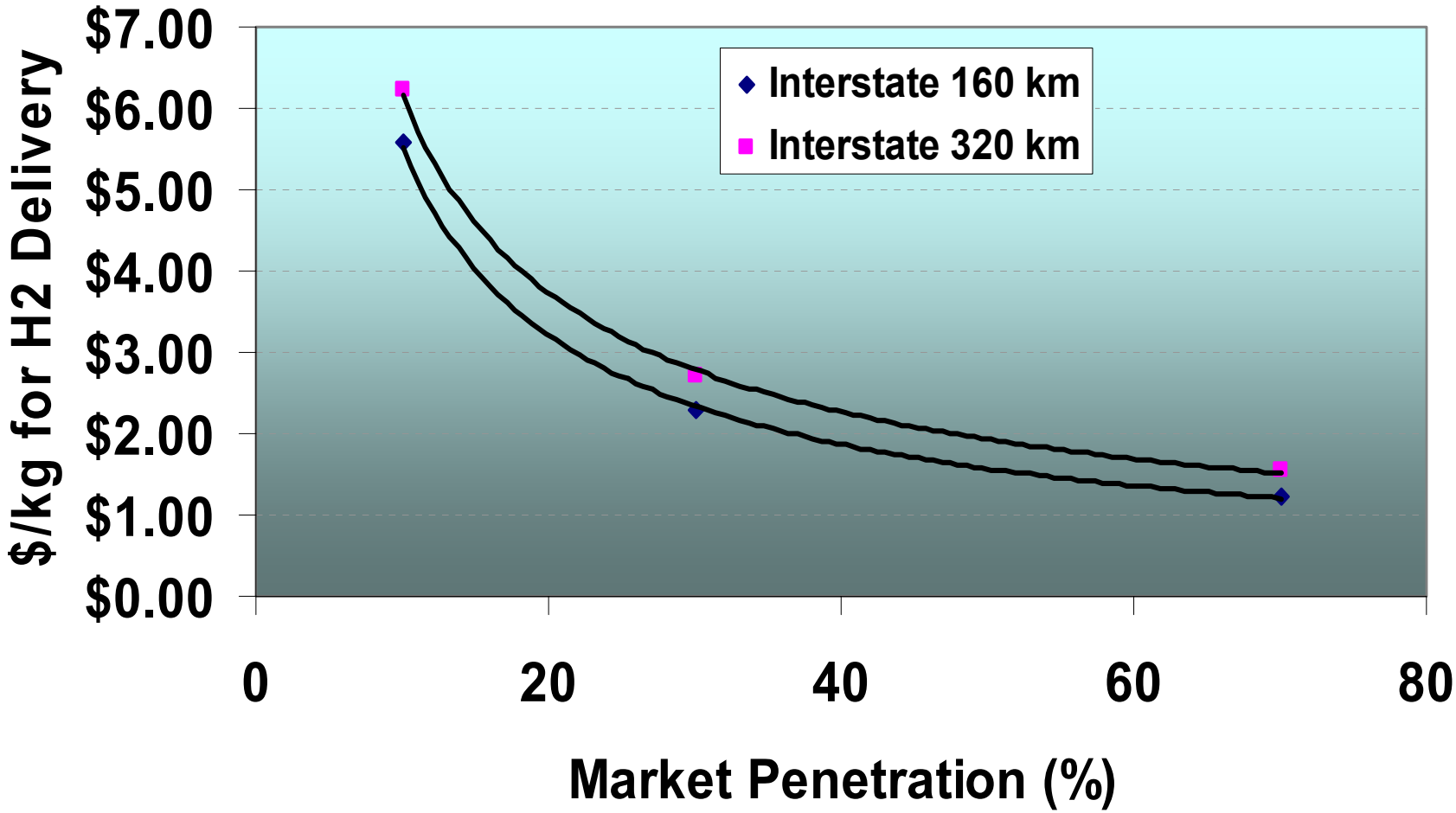
Preliminary Results Show Pipeline Delivery Costs Less than Liquid at Demand Levels Modeled



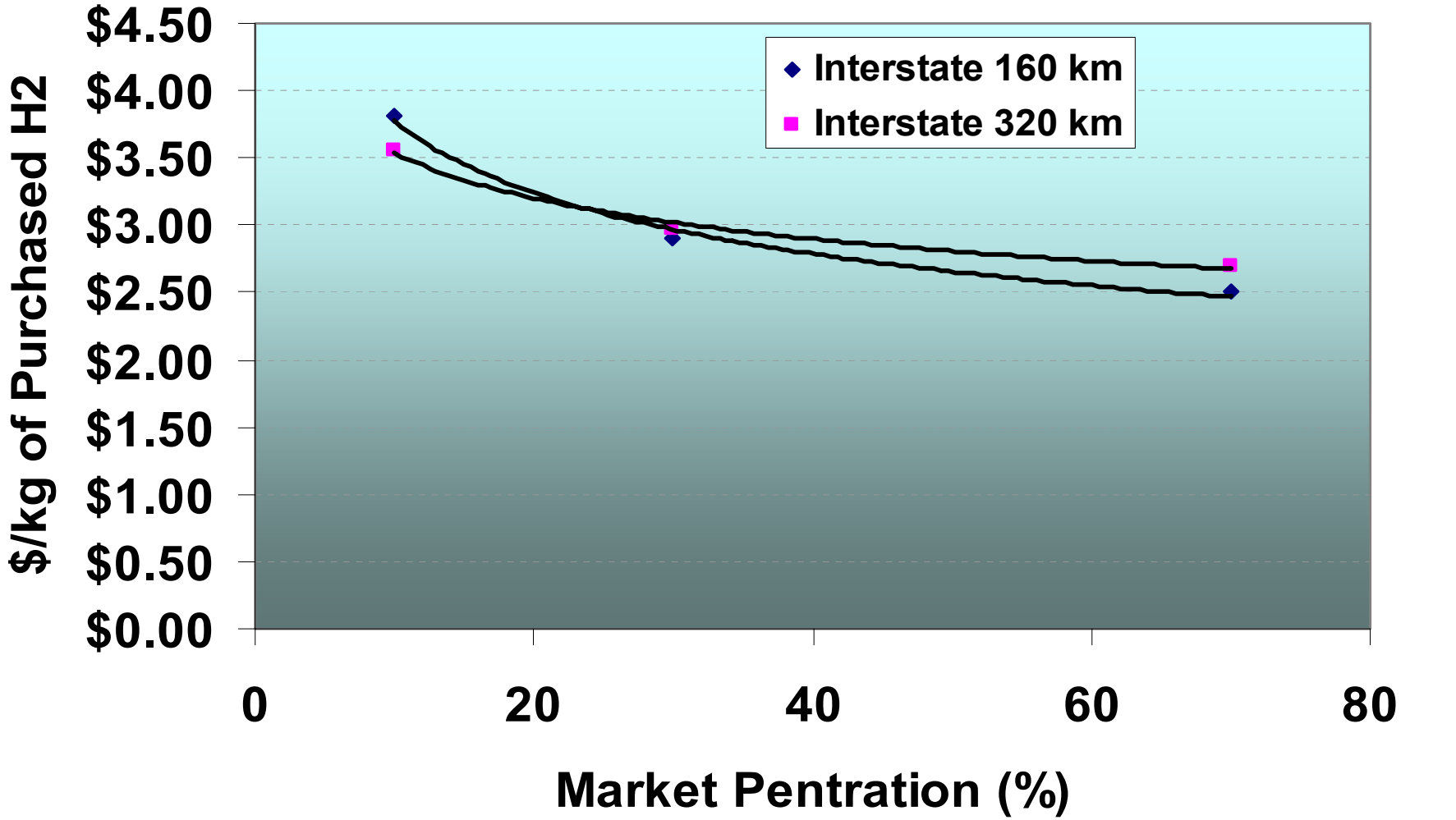
Liquid H_2 Delivery to Interstate Stations Is Expensive



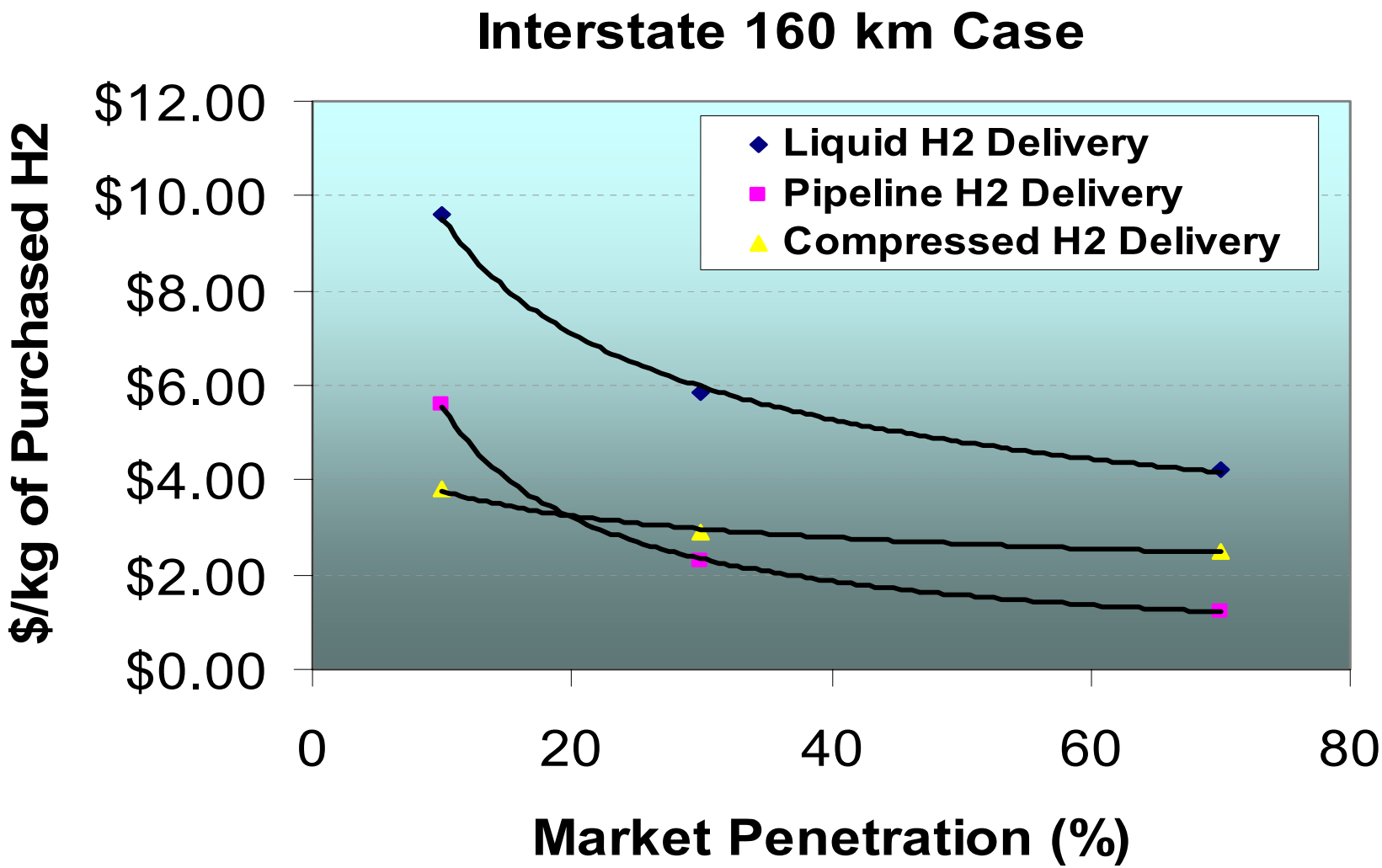
Pipeline Delivery to Interstate Stations Is Highly Dependent on Market Penetration



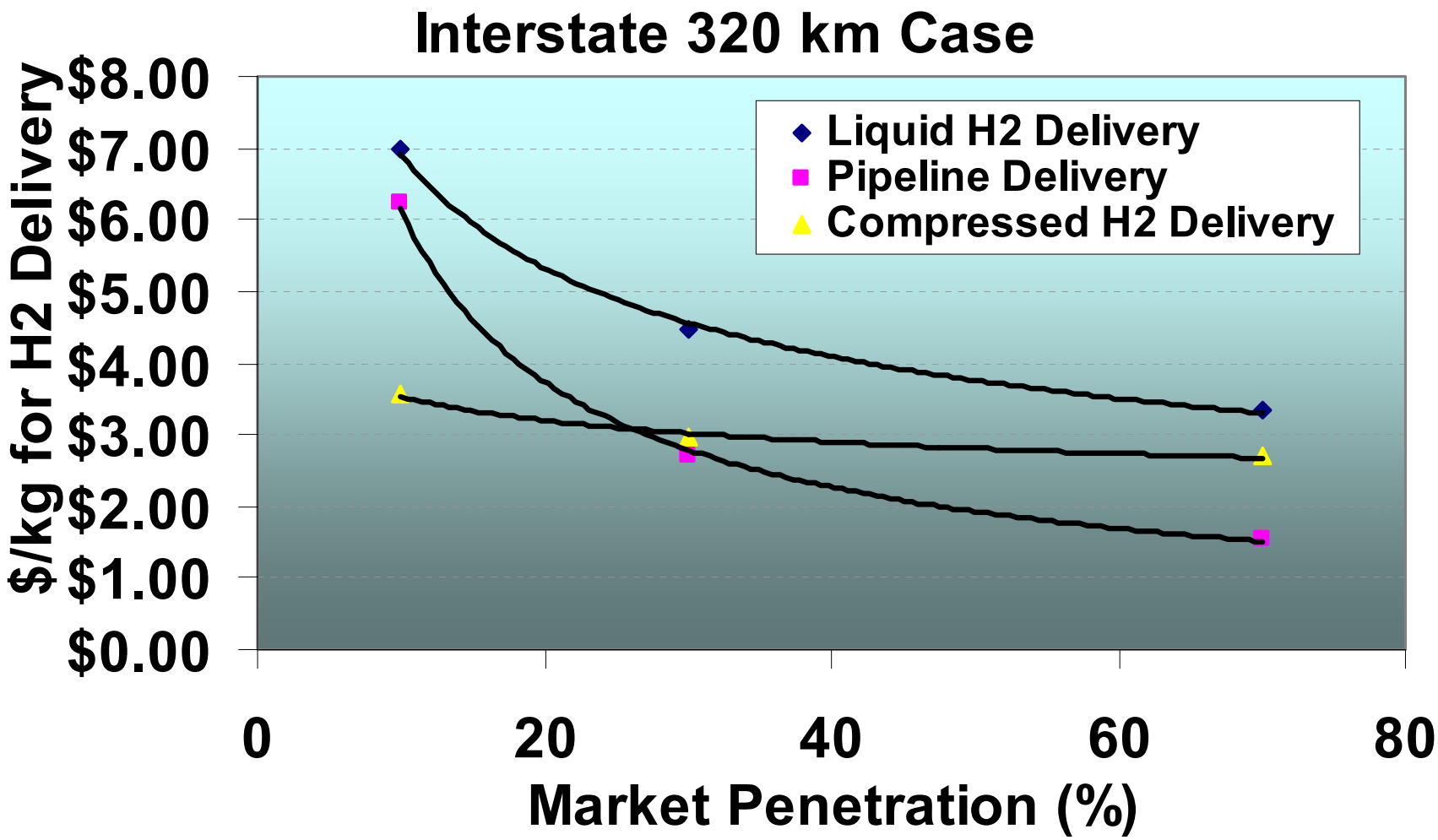
Compressed H_2 Delivery to Interstate Stations Is Less Dependent on Penetration or Length of Haul



Compressed H_2 Delivery to Interstate Stations Is Lowest Cost Option at Low Penetration



Compressed Gas Delivery Is Also Lowest Cost Option for Longer Interstate LOH at Low Penetration



Improvements in Scenario Model Version 2, Now Under Development:

- Mixed delivery pathways (e.g., pipeline to compressed gas terminal)
- Mixed demands/markets (e.g., combining multiple urban areas or combining urban demand with interstate demand)
- Forecourt model
- Additional urban scenarios
- Enhanced interstate scenarios
- High pressure tube trailers
- Determine energy efficiencies
- Estimate CO_2 emissions

Plan to have Version 2 on WWW by end of September

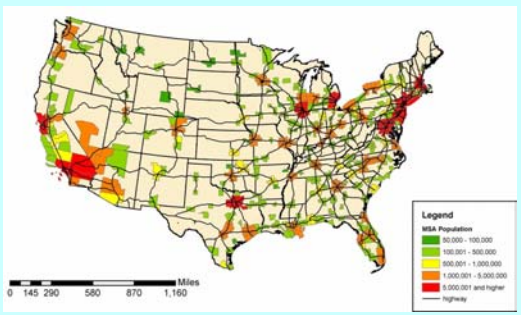
Pipeline Model

Scenario Definition

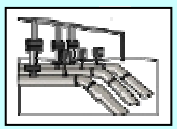
Penetration

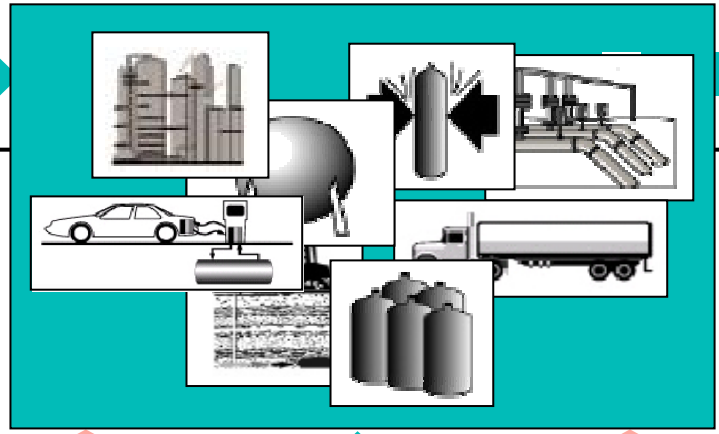
0 25 50 75 100

Market



Mode





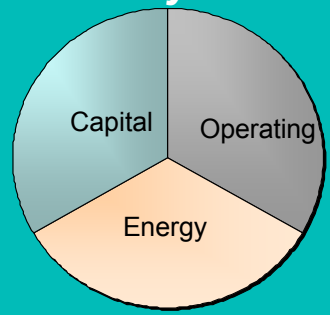
Inputs

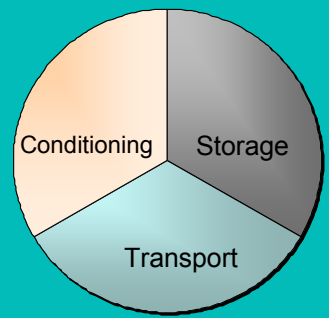
Pipeline Model

Truck Models

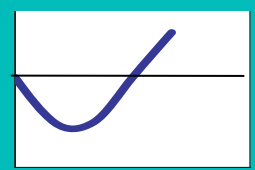
Results

Delivery Cost





Cumulative Cash Flow

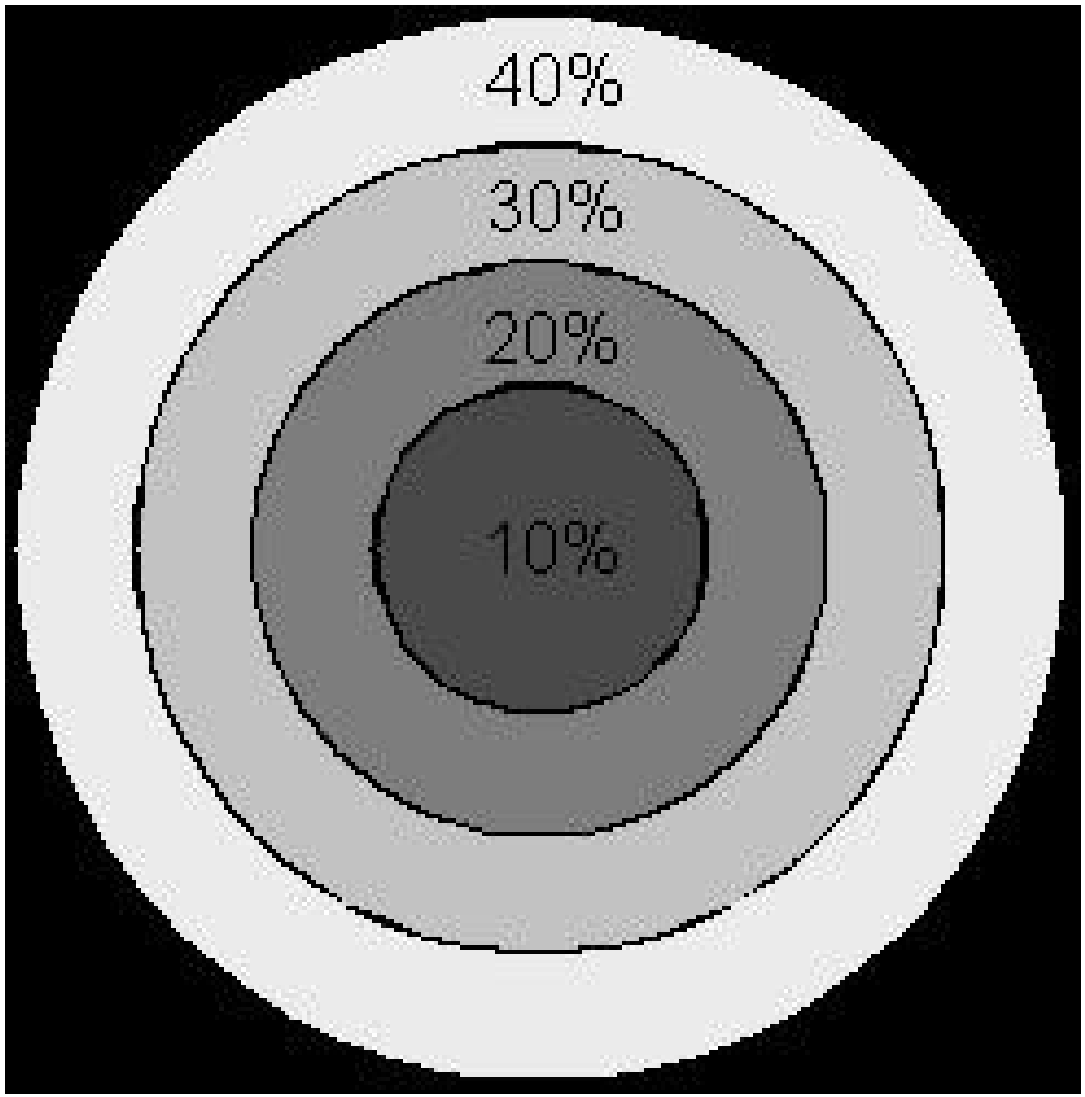


Pipeline Model Approach

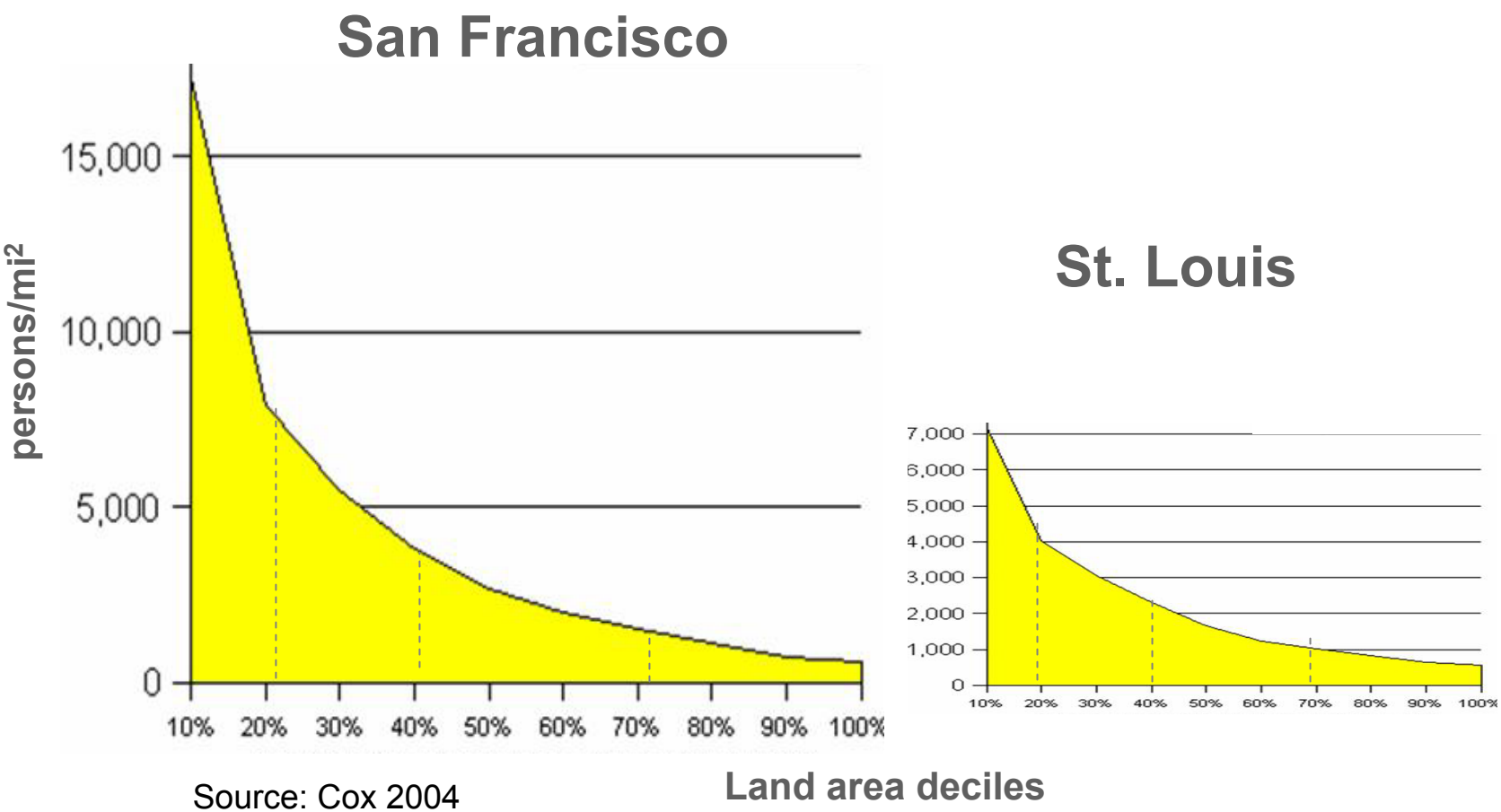
For urban area of population X, the model estimates:

- **Land area and density regions**
  - Population density
  - Density profiles
- **Hydrogen-fueled vehicle density**
  - Density region
  - Vehicle ownership
  - Market penetration
- **Number and location of hydrogen refueling stations**
  - Service ratio (vehicles/station)
  - Minimize service line lengths
- **Pipeline cost and location with respect to centroid**
  - Unit cost by function and diameter
  - Cost minimization heuristic
  - Circuity factors

Urban Land Area Can Be Expressed as a Series of Annular Rings around a Centroid



Population Density Declines Asymptotically with Land Area Decile Regardless of Overall Density



Source: Cox 2004

Vehicle Ownership Is Inversely Related to Population Density

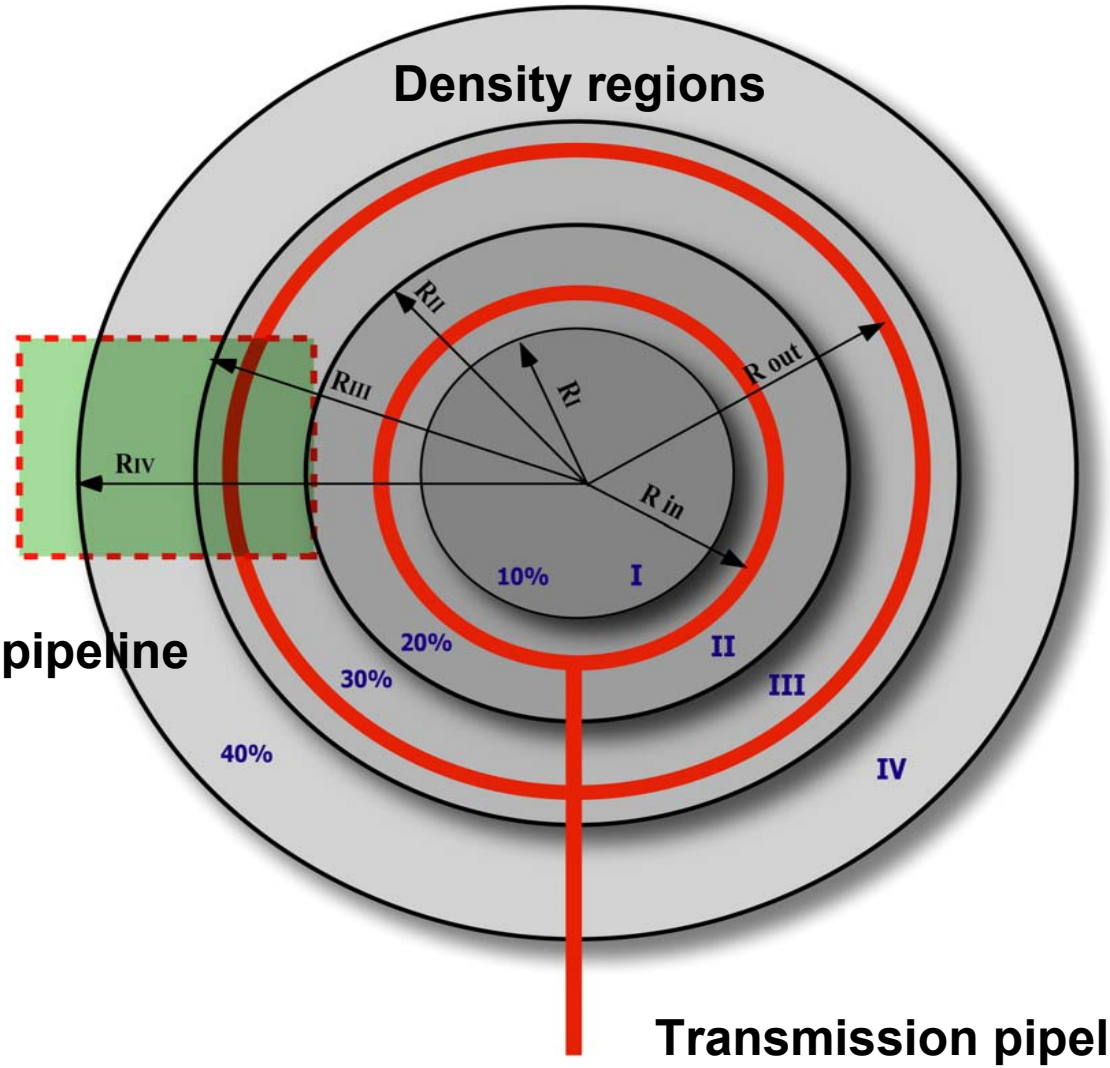
Vehicles per Household	Persons per Square Mile			
	<2000	2000-4000	4000-10,000	>10,000
	Percent of households by number of vehicles			
None	3.9	6.2	8.5	31.0
One	27.3	33.8	38.6	41.7
Two	44.5	42.3	38.6	21.3
Three or More	24.3	17.7	14.4	6.0
Ave. Vehicles	2.9	1.80	1.66	1.05
Household Size	2.51	2.41	2.37	2.33
Vehicles/Person	1.16	0.75	0.49	0.45

Source: NPTS 1995

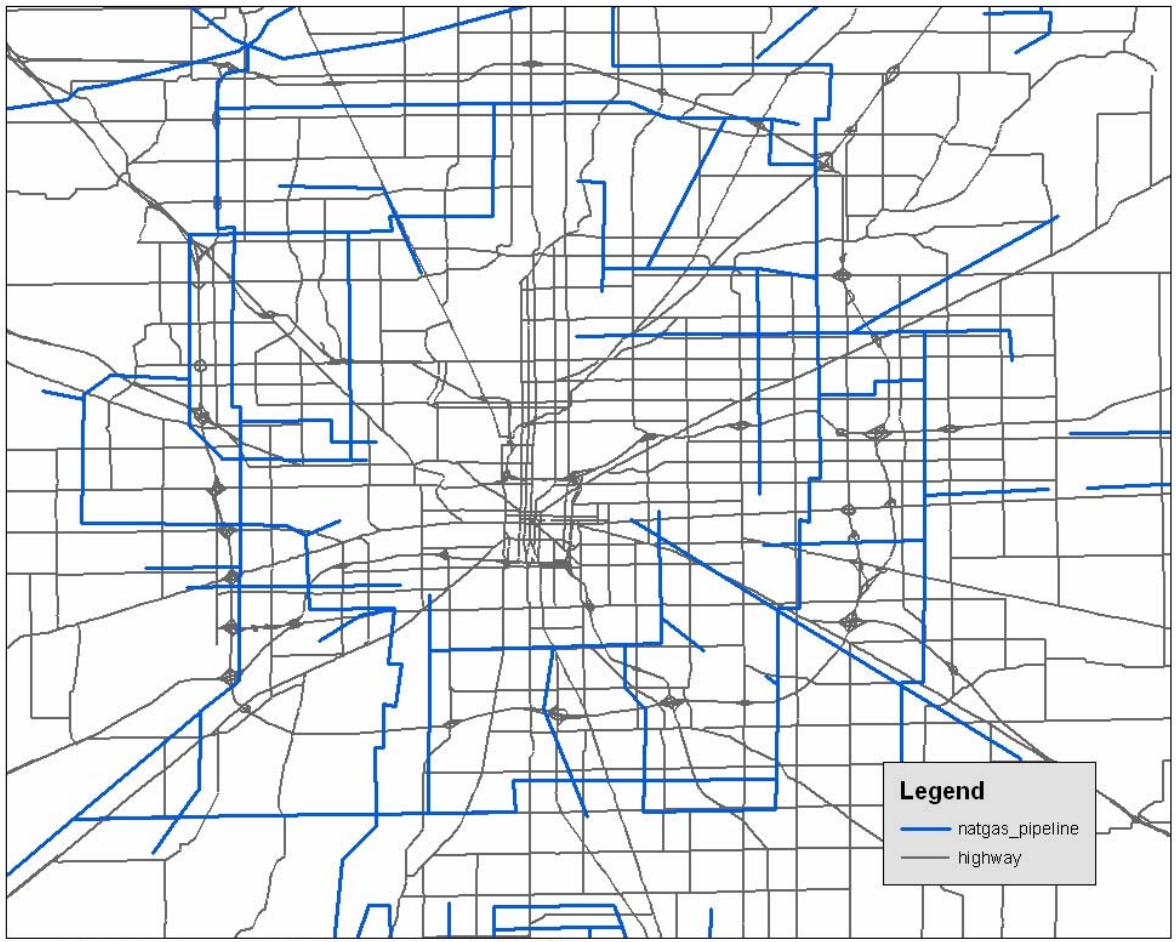
Model Parameters Assuming Moderately Dense Large Urban Area

	Core	1st Ring	2nd Ring	3rd Ring
Outer Radius, mi	3.8	6.6	9.3	12
Area, sq mi	44.8	89.6	134.4	179.2
Density, (persons/sq mi)	7000	3500	1700	800
Population	313,600	313,600	228,480	143,600
Lt Duty Vehicles	154,000	235,000	265,000	167,000
Refueling Stations	77	117	132	83

For Large Urban Areas a Double Ring System (Adjusted for Circuity) Is Least Costly

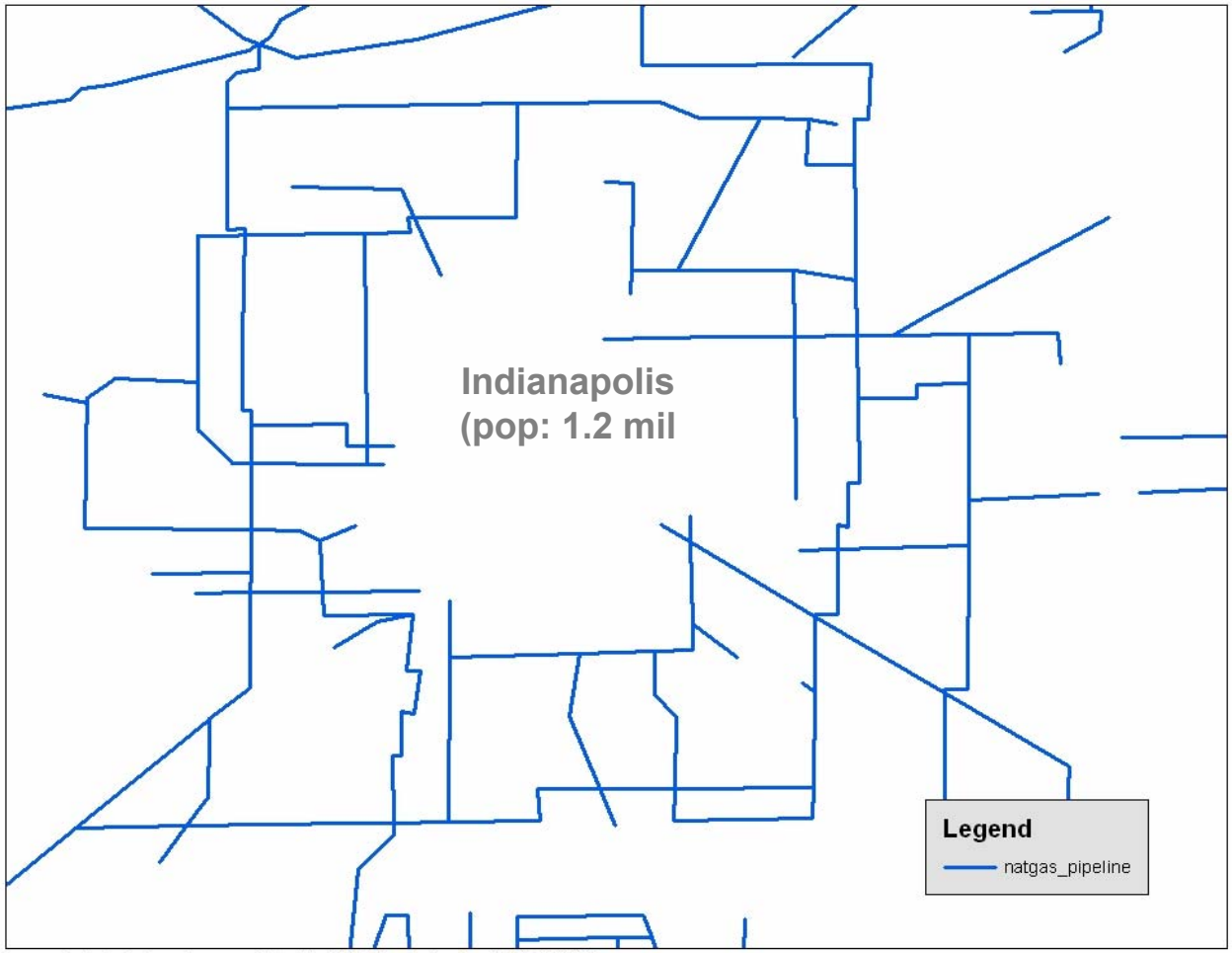


Indianapolis' Pipeline Geometry Reflects Grid and Radial Highway Network



Beltway ~ 13 miles

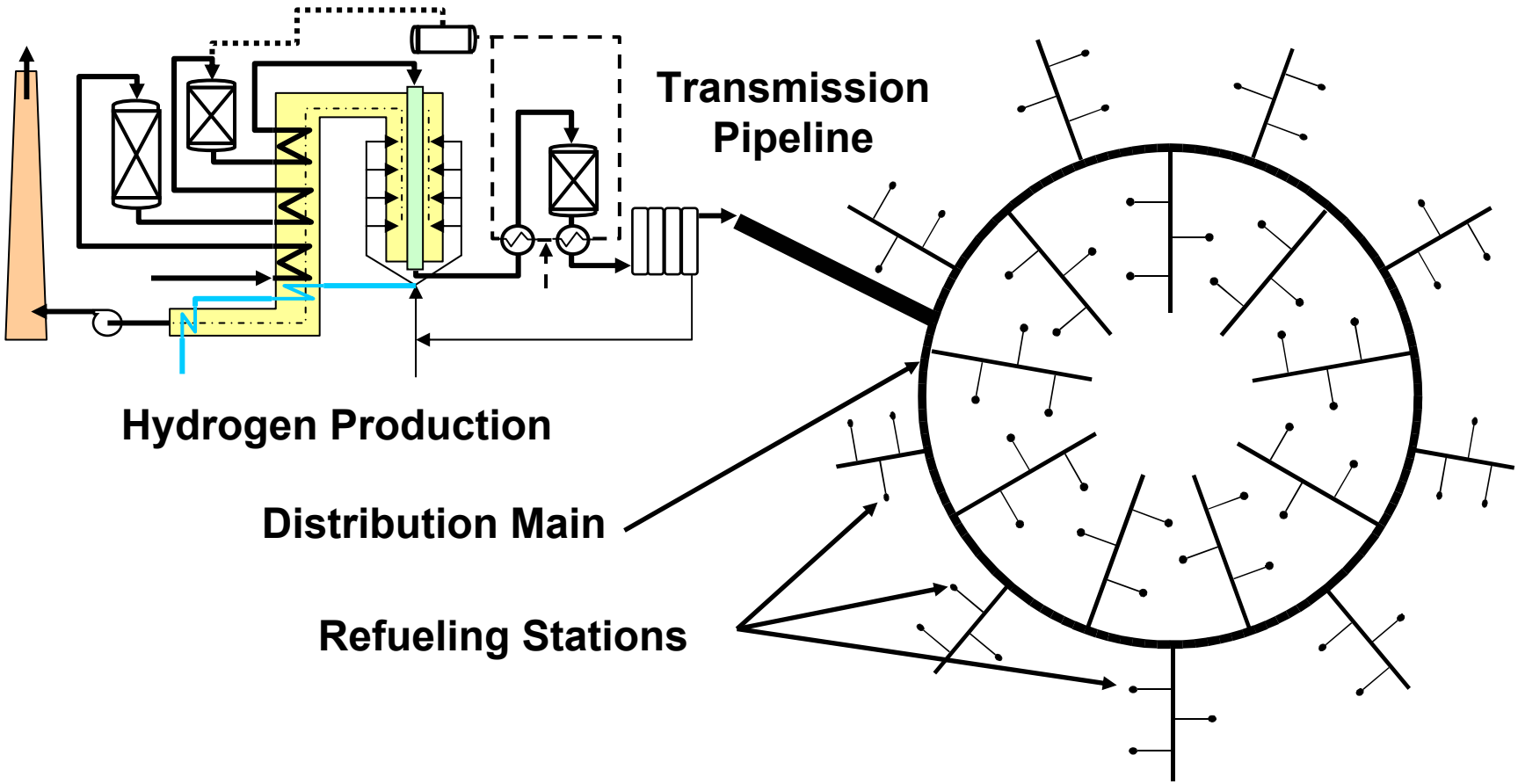
Generic Geometry Compares Well with Observed NG Pipe Geometry for Similar-Sized Urbanized Area



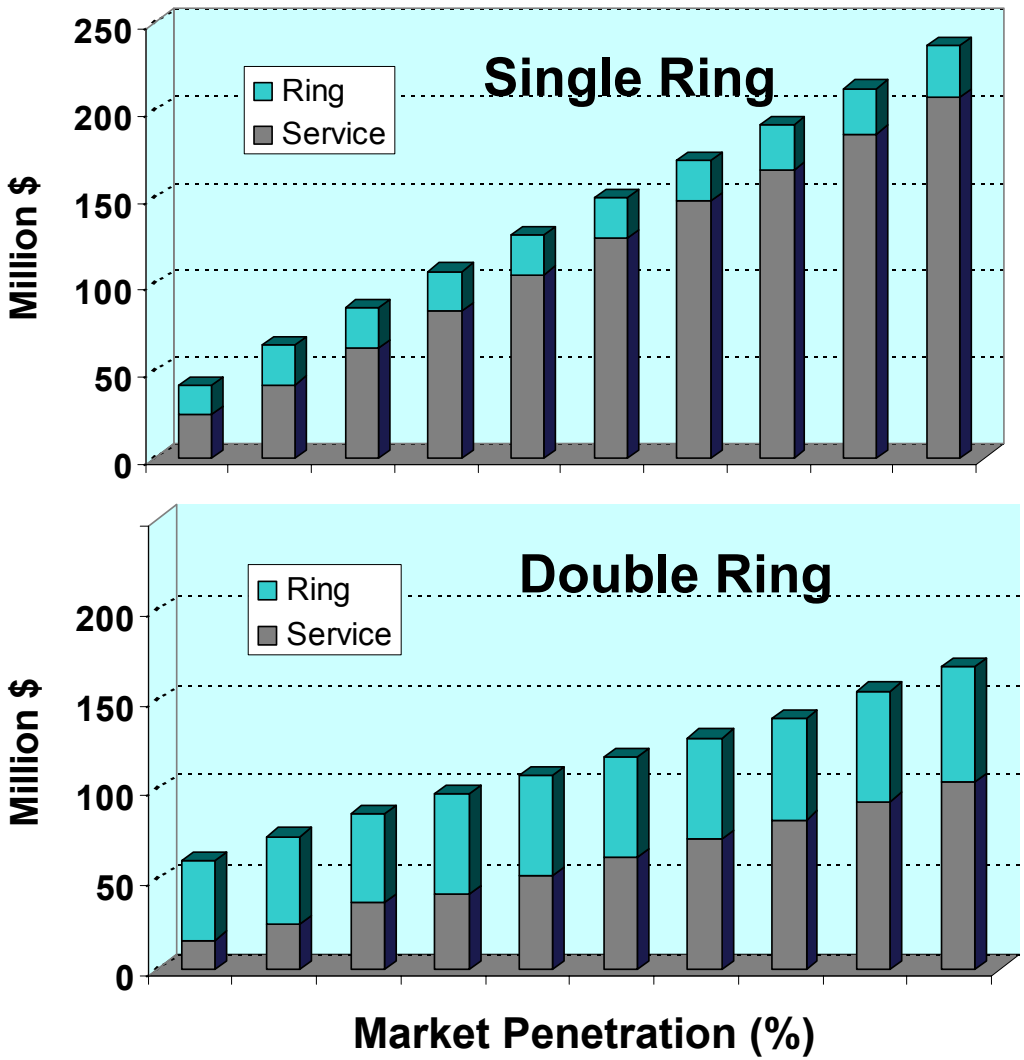
Heuristic Selects Lowest-Cost Locations for Pipeline Mains (Rings) and Service Lines

- Calculates series of ring perimeters and service lines capable of supplying H2 to all stations
- For each set of pipelines, computes capital cost as function of length and required flow rate to satisfy demand (allowing for station dispensing rate and alternative inner pipe diameters)
- Selects lowest cost alternative

For Small Urban Areas a Single "Ring and Spoke" System (with Circuity) Is Least Costly



Service Lines Account for Increasing Share of Pipeline Cost as Penetration Rises



- For 1-ring system, service lines account for 60 to 87% pipeline cost
- For 2-ring system, service lines account for 27 to 62%
- 1-Ring system less costly below 30% penetration
- Lowest cost 2-ring mileage achieved at 40% penetration

Next Steps

Next Steps

- **Complete Scenario Model Version 1**
- **Develop Version 2 with enhancements noted previously**
- **Incorporate pipeline and truck models into Scenario model**
- **Evaluate additional urban compressed gas and hydrogen carrier scenarios**
- **Evaluate impacts of technology improvement**
- **Evaluate impacts of initial overbuilding of delivery infrastructure**
- **Sensitivity analyses**
  - Service ratio
  - Options for reducing service line mileage
  - Dispensing rate, forecourt storage, etc.
  - Geologic vs terminal storage
  - Etc.

Thank You!

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