2006 DOE Hydrogen Program Review
Hydrogen Transition Modeling and Analysis
HyTrans v. 1.5

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Project ID AN7
Overview: Our Overall Goal is to Identify and Evaluate Transition Scenarios

Timeline
- Start: 10/1/2004
- Finish: 10/31/2007
- Status: 60% completed

Barriers
- Transition Scenarios
  - “By 2007, identify and evaluate transition scenarios, consistent with developing infrastructure and hydrogen resources, including an assessment of timing and sequencing issues.” p. 4-1

Budget
- FY05 - $450K
- FY06 - $XXXXK

Partners
- ANL – Pipelines & delivery
- NREL & H2A – Production & delivery, spatial demand
- UC Davis, others - Expert review
Objectives:
Model the market transition to a H2 vehicle system in a way that is useful for R&D planning, cost-benefit analysis, policy analysis and envisioning.

- Integrates all main H₂ market components
  - Hydrogen Production
  - Hydrogen Delivery
  - Vehicle Production
  - Consumer Choice
  - Hydrogen Use

- Determines a market equilibrium solution
  - Maximizes total consumption benefit minus production, distribution, and other costs
  - Estimates amounts and timing of costs, benefits, levels of investment and activity, production and consumption, key environmental impacts.
  - Sensitive to technological goals and supporting policies.
Our method is economic modeling via non-linear optimization.

- Production pathways: cost functions
- Vehicle production: cost functions
- Consumer demand: NMNL
- 3 fuel demand density regions
- Key dynamic elements:
  - Learning-by-doing
  - Technological change
  - Scale economies
  - Fuel availability
  - Diversity of vehicle choices
- Generalized Algebraic Modeling System
HYTRANS integrates all major components

- H₂ Feedstock Supply Curves
- H₂A H₂ Production Models
- PSAT ASCM Vehicle Attributes
- H₂A H₂ Delivery Systems Models
- Hydrogen Infrastructure Investment
- Hydrogen Availability
- Price of Hydrogen
- Vehicle Supply Model Tech. Change Learning Scale Econ.
- Vehicle Choice Model
- Vehicle Sales by Technology
- Vehicle Stock & Fuel Use
- Non-Transport Hydrogen Use

AEO Energy Scenarios

Make & Model Diversity

LDV Sales

GREET

Costs

GHG Emissions

Vehicle Attributes

Vehicle Supply Model

Technology

Costs

GHG Emissions
A H2 Supply Pathway comprises three parts.

**Production**
- Centralized SMR
- Coal Gasification
- Biomass, etc.

**Delivery**
- Compression/Liquefaction + Storage + Dispensing + Transporting + Storage + Compression/Vaporization

**Forecourt**
- Pipeline
- Truck Compressed Gas
- Truck Liquefied
- Retailing of Compressed Gas

**Forecourt SMR**
**Forecourt Electrolysis**
**Many Others...**
Accomplishments: Enhancements to allow more realistic modeling of the early transition to hydrogen.

- Added representation of West-coast (region 9) and rest of U.S.
- Added representation of supply from existing H2 production facilities in R9.
- Developed method for solving year-by-year in the early years
- Develop accurate reduced-form representation of the H2A Delivery Model
- Add more regions & metropolitan areas
- Expand representation of regional feedstock supply
- Improve representation of existing H2 supply, extend to all U.S.
- Improve representation of manufacturers’ decision making, introduction of makes & models
- Improve representation of fuel availability
- Link to/establish consistency with NREL detailed GIS analysis
Two recent FY 2006 achievements.

- Development of a method for solving year-by-year in the early years.
  - Connects to 5-year solution periods in future
  - Allows greater realism and detail in early years
  - Facilitates moving window of limited foresight

- Development of an accurate reduced-form representation of the H2A Delivery Model
  - Predicts unit costs with 1-2% accuracy
  - A function of total H2 demand, city area, station size
  - Required reformulating how we represent the geographical evolution of demand and supply
For better market transition analysis, we needed a more precise representation of the small numbers of the early transition.

Case of H2-FCV Introduction Program 3, Followed by $1.5K Subsidy for FCVs

But we seek to connect it with these ultimate outcomes

Decision-makers are very interested in this region!
Increased resolution in early period while maintaining connection to long-term future at 5-year intervals.

- Increased numerical resolution of key variables at small values (early vehicle sales and fuel production)
- Introduced shorter time steps in early periods (e.g. annual) and variable time step later to keep long planning horizon and modest model size
- Greater geographical resolution in R9 (e.g., LA is LA).
HyTrans is now much more accurate in the period from 2010 to 2025, with annual detail at an acceptable computational cost.
HyTrans is able to evaluate Scenarios with combinations of market introduction strategies and subsidies, with incentives varying over time.

Case of H2-FCV Introduction Option 4, With and Without $1.5K/H2-veh Subsidy after 2025. (HytrV253)
Early H2 Vehicle Sales Match Program (through 2020). 2025 and Beyond, Market Expands Rapidly (With H2 Veh. Subsidy)

Case of H2-FCV Introduction Program 3, Followed by $1.5K Subsidy for FCVs
Production begins with available refinery/merchant capacity, and distributed SMR

Case of H2-FCV Introduction Option 4, With $1.5K/H2-veh Subsidy after 2025. No GHG policy. US Totals. (HytrV253)
Following distributed SMR, full market develops (in this case) from Centralized Coal and Biomass Gasification.

Case of H₂-FCV Introduction Option 4, With $1.5K/H₂-veh Subsidy after 2025. No GHG policy. US Totals. (HytrV253)

Delivery is by mix of pipeline (PP) and cryo-truck (CT), depending on regional density.
Developing Scenarios: E.g. Early H2 Vehicle Program Coupled With Post-2025 Subsidy ($1.5K), H2 Vehicles Can Displace HEVs

Case of H2-FCV Introduction Program 3, Followed by $1.5K Subsidy for FCVs
Vehicle Stock by Type: Transition to H2 Vehicle System Takes over decades, with Hybrid-Electric Vehicle as Intermediate Technology

Total Vehicle Stock by Type

Case of H2-FCV Introduction Option 4, With $1.5K/H2-veh Subsidy after 2025. (HytrV253)
Relative Vehicle Make-and-Model Diversity Varies with New-Vehicle Market Share

Relative Vehicle Model Diversity by Type

- Conv Gaso
- Gaso-Hybrid
- H2-FCV

Case of H2-FCV Introduction Option 4, With $1.5K/H2-veh Subsidy after 2025. (HytrV253)

A measure of broad vehicle platform groups, not detailed models
H2 Vehicle Prices Decline Rapidly Early Under Program (through 2025), Eventually FCVs, Hybrids & Gasoline CV are Priced Near Parity

**Vehicle Prices**

- Conv. Gaso Veh
- Gaso-Hybrid
- H2-FCVs

Case of H2-FCV Introduction Program 3, Followed by $1.5K Subsidy for FCVs
Allowing variable time increments was an important methodological breakthrough.

- Allows greater realism in early period where policies will play a crucial role.
- Facilitates alternatives to perfect foresight formulation:
  - Can move year-by-year window forward in time more realistically representing limited planning horizons.
  - Connect year-by-year window to future represented in 5-year increments. Even if agents imperfectly perceive future, accounting of future stocks, flows necessary.
We have estimated accurate reduced form equations representing the H2A Delivery Systems Model.

- Break each process into cost components.
- Each component depends on "city" demand for H2, city area and station size (capacity utilization = 1).
- Prediction errors of about 1-5% versus ANL spreadsheet model, in most cases 1-2%.
- Forced us to rethink our entire representation of regional demand and supply, but that’s good.
The general functional form is a sum of component costs which vary chiefly with scale and delivery distance (sqrt(area)).

\[
UC = \sum_{i=1}^{n} X_i \left( \sum_{j=1}^{m_i} a_{ij} Y_j^{\alpha_{ij}} \right)
\]

UC = unit cost of hydrogen delivery
\(X_i\) = cost component i
\(Y_j\) = value of variable j
(City H2 Use, City Area, Forecourt Size, Forecourt Capacity Utilization = 1)
The new spatial model of supply and demand is more realistic. Instead of “delivering” to the aggregated (circular) region, only parts of the region are served, and incrementally.
According to EPA data, 2/3 of LDV fuel is used in <10% of the land area.

The US (& region 9) is divided into 3 fuel demand density regions. The delivered cost of hydrogen depends on density via quantity of demand and delivery distance (square root of area).
We added a separate representation of region 9, including existing H2 production. The two high fuel demand density areas in Region 9 are LA and the Bay Area ( >240,000 kg/km²/year).
A spreadsheet model we have distributed to NREL and other colleagues summarizes our reduced form version of the delivery model.
Pipelines with 200km access, costs of 1,500 kg/d forecourts included.
Serving very small forecourts by pipeline is expensive, with costs increasing rapidly with city size and not strongly dependent on market penetration.

**Unit Cost of Hydrogen Delivery by Pipeline**

**Small Size Stations: 100 kg/day**

- **H2 Unit Cost ($/kg)**
  - $0.00
  - $2.00
  - $4.00
  - $6.00
  - $8.00
  - $10.00
  - $12.00
  - $14.00
  - $16.00

- **City H2 Demand (Thousands kg/day)**
  - 40
  - 400
  - 760
  - 1,120
  - 1,480
  - 1,840
  - 2,200
  - 2,560
  - 2,920
  - 3,280
  - 3,640
  - 4,000

- **City Area (Square Miles)**
  - 30
  - 780
  - 1,530
  - 2,280
With station size increased by a factor of 10, costs come down by about $\frac{1}{2}$. 

![Graph showing the unit cost of hydrogen delivery by cryogenic trucks for medium size stations with 1000 kg/day. The graph displays the relationship between city H2 demand (in thousands of kg/day) and the city area (in square miles), with unit cost of hydrogen delivery ranging from $0.00 to $4.00 per kg.](image-url)
Reduced Form Delivery Model Approximation Errors are Quite Small

Prediction errors for gaseous truck delivery are very small, <$0.05/kg.

Liquid truck delivery costs are the most accurate of all, <$0.02/kg

Pipeline delivery cost errors generally less than $0.10/kg (1%-5%)

Small stations, Low demand.

Large stations, High demand.
HyTrans is making significant progress.

- Plausible answers to:
  - Is a stable transition achievable?
  - When?
  - How long will it take?
- Can begin to test key policies
- Produces potentially useful cost and benefit measures
- Close to useful visions of the transition
- Beginning to generate insights about R&D goals
  - Good enough?
  - Effects of competing technologies
Significant improvements to HyTrans will be made in 2006.

- Initial realistic early transition scenarios by June 2006. Coordinate with NREL’s detailed geographical analysis.
- Add more regions, beginning with NE states
  - Add more regional feedstock supply curves.
  - With NREL, add renewable regional feedstock supply curves.
- Complete implementation of delivery model.
- Enhance representation of
  - fuel availability.
  - consumer choice: early adopters. Exclusive meetings with auto manufacturers in CA.
  - technological progress, scale economies, learning-by-doing, manufacturer decision making.
- Incorporate alternatives to complete information.
- Update calibration to AEO 2006
THANK YOU.
Backup Slides
These scenarios are provided for transition analyses as recommended by the National Research Council to evaluate the transition phase and do not represent any specific policy recommendation.

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H2 Market Penetration Starts in Highest Density (Urban) Area, Region 9. Spreads to Medium Density R9, Then Rest of USA

H2 Market Share by Region

USA
USHDENS
USMDENS
USLDENS
US9HDENS
US9MDENS
US9LDENS

Case of H2-FCV Introduction Program 3, Followed by $1.5K Subsidy for FCVs
Previous HyTrans versions with 5-year intervals crudely approximated the four DOE scenarios in which vehicle sales were < 1% of total U.S. sales.
Alternative H2 Pathway Costs: According to H2A, Coal, SMR and biomass can be produced at comparable prices.

Delivered Costs fall to ~$1.75/gge by 2020

H2 Prod. Unit Cost by Path (vers. 1) ($/kg)
Liquid truck transport excluding forecourt costs, plant at city gate.
Adding costs of 1,500kg/d forecourts and 100 km distance to city gate.
Compressed gas trucks (3,000 psi) delivering to 100 kg/d forecourts.