Transition Strategies for Alternative Transportation Fuels and Vehicles

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March 10, 2011
Research Overview

• **Market Emergence**
  – Historic analysis of Alternative Fuel Vehicle (AFV) diffusion
  – Market shifts in nutritional food consumption
  – Market-level coordination

• **Analysis of contemporary AFV Transitions**
  – Models to understand transition challenges and strategies
  – Empirical analysis for parameter estimation
Motivation

Our transportation system does not scale:
If the projected world population of 9 billion in 2050 lived the way Americans do today...

• There would be 7.7 Billion motor vehicles on the roads
• Transportation alone would consume 375 million barrels of oil/day
  – Total world oil production today is 73 million bbl/day
• CO₂ emissions from transportation would be 59 billion metric tons/yr
  – Total world emissions from fossil fuels today ≈ 30.5 billion tCO₂/yr
• Current models for development and transportation cannot scale to a world of 9 billion
  – Research should focus on the design and implementation of systems for sustainable accessibility to the goods, services, people and opportunities needed to promote human welfare while preserving and restoring the environment.

Adapted from: MIT Transportation Initiative, Profs. Barnhart, Jaillet, Sheffi, Sterman, Waitz, Zegras
Reducing Petroleum Consumption a Vital US National Interest

- Declining domestic production
- High and rising import dependence
- Vulnerability to supply disruption, geopolitical instability
- Local air pollution and health effects
- Greenhouse gas emissions
Cutting greenhouse gas emissions enough to stabilize atmospheric concentrations...

Source: Stern Review, Fig. 8.4
Alternative Fuel Vehicle Transition Models

• **Host of integrative transition models exist**
  – AFV markets
    • Greene et al. 2007; Alkemade Frenken et al 2009; Van Vliet et al. 2010;
  – Focus on Plug-In Electric Vehicles (PHEVs)
    • Yeh et al. 2008; 2010; Karplus et al. 2009; Lemoine 2010

• **Dominant analytical focus is on understanding cost-benefit of alternative pathways**
  • Cost (Offer et al 2011), long-term carbon emission reduction impact (Yeh et al. 2008), minimizing integration with the grid (Lemoine et al 2008), maximizing the consumer take-up rate (Lemoine 2010), or combinations (Greene 2007).
Many programs to introduce Alternative Fuel Vehicles (AFVs) fail

- **Compressed Natural Gas**
  - So far so good: Argentina
  - Low penetration: Italy
  - Sizzle and fizzle: Canada, New Zealand
  - Stalled: California, Europe (excl Italy)

- **Diesel**
  - High/self-sustaining: Austria, Germany, France
  - Sizzle and fizzle: USA
  - Low penetration: Sweden, Ireland

- **Ethanol**
  - Sizzle and fizzle: Brazil (100% ethanol)
  - So far so good: Brazil (flex fuels)

- **Gas-electric hybrid (HEV)**
  - So far so good: USA (Prius, Honda Insight, Ford Escape,…)

- **Electric (EV)**
  - Sizzle and Fizzle: USA: EV1, other pure electrics
  - Too soon to tell: Global (Betterplace, Coulomb)

- **Plug-in Hybrids (PHEVs)**
  - Too soon to tell: Various (Ford, Toyota, Chevy Volt)
 Canonical Diffusion Examples versus Nested Technologies

Technological improvements

Consumer acceptance

Complement product or market

Regulation

Fuel supply & infrastructure

Service

Repair

Conversion

Stationary applications

Alternative Fuel Vehicle

Color television

Laser printer

Refrigerator

Walkman

VHS player

Document reader/writer
Methodology

• Suite of spatio-temporal behavioral simulation models of AFV introduction, diffusion, competition

• Broad model boundary to avoid unanticipated “side effects”
  – Integration of vehicle technology, competition among AFVs and with ICE, fuel supply technology, consumer behavior, government policies, other key actors and factors
  – Thought Experiments and Counterfactual analysis

• Grounded in empirical studies, quantitative and qualitative data

A Broad Boundary

Consumers
- Vehicle replacement
- Platform consideration
- Platform choice
  - new/used, car/truck
- Trip choice
- Refueling choice
- Topping-off behavior

Automotive Producers
- Platform portfolio
- Production capacity
- Experience from R&D and spillovers
- R&D investment, incl. fuel efficiency
- Marketing

Fuel Retailing
- Entrance/exit
- Location selection
- Fuel station capacity

Fuel Suppliers & Producers
- Entrance/exit
- Price Setting
- Experience
- CCS Investment
- Electric Power Mkt

Policy makers
- Supply subsidies/taxes
- Demand subsidies/taxes
- Campaigns
- Pilot programs
- CO2 taxes/price

Socio Economic Sector Interactions

Stacked boxes imply multiple vehicle and fuel platforms (Internal combustion engines, HFCVs, hybrids; gasoline/biodiesel/electricity etc.)
**Principal feedbacks**

**Vehicle Choice Attributes**
- Purchase price
- Performance
- Driving Convenience
- Safety
- Operating Cost
- Ecological impact

**Graphical Representation**

- Share of Vehicles in Use
- Consumer Consideration
- Automotive Manufacturer Capabilities
- Vehicle Attractiveness
- Vehicle Choice
- Social Exposure
- Vehicle Sales
- Automotive Economies of Scale, Scope, RD
- Fuel Availability
- Fuel Consumption
- Fuel Supply Chain Capabilities
- Institutional Coevolution
- Vehicle Discards

**Graphical Elements**

- Red line: Success
- Green line: Stagnation
- Time axis
- Arrows indicating feedbacks and influences
Creating an AFV market: California as Laboratory for Experimentation

- **Focus on Central/Southern California**
  - 13.5 Million households
  - 13 Million ICE vehicles
  - 6,500 gasoline fuel stations

- **Behavioral Dynamics**
  - Willingness to consider an AFV in purchase decision depends on marketing, social exposure to AFVs, word of mouth from others (favorable and unfavorable)
  - AFV purchase decision also conditioned by inconvenience of fuel search and risk of no fuel
  - Drivers will go out of their way for fuel – up to a point
  - Drivers worried about fuel availability may top off tanks
Trip Choice: Spatial Representation

- Household density in $z$
- Trip generation to $z$ to $z'$
- Trip choice $z z'$
- Station density in $s$
- Trips $z z'$ refueling in $s$
- Adoption fraction in $z$
### Consumer Driving Decision Tree

#### Overview of decision structure

- **Vehicle choice**
  - AFV sales share
  - Utility to drive

- **Trip choice**
  - Trip weight
  - Trip fraction
  - Trip utility

- **Route choice**
  - Route weight
  - Route share
  - Route utility
  - Route effort

- **Refueling choice**
  - Refueling weight
  - Refueling location share
  - Propensity to fuel
  - Refueling effort

#### Choice function (MNL)

- \( \sigma_{iz} = \frac{u_{iz}}{\sum_j u_{jz}} \)
- \( u_{iz} = u_{iz}^0 \frac{\sum_i \frac{a_{iz}}{a_i}}{a_i} \)
- \( u_{iz}^t = \left( \sum_{z' \in Z} w_{zz} u_{iz', t} \right) \frac{1}{\mu^t} \)
- \( u_{iz'} = u_{iz'}^0 \frac{\sum_{o_{z'} \in \Omega_{z'}} \sigma_{o_{z'}} u_{i o_{z'}, t} \mu^o}{\mu^o} \)
- \( u_{iz'} = u_{iz'}^t \frac{\sum_{o_{z'} \in \Omega_{z'}} \sigma_{o_{z'}} u_{i o_{z'}, t} \mu^o}{\mu^o} \)

#### Aggregate utility and effort function (CES)

- \( a_i^t = a_i^{t_0} + \phi_i a_i^{f_0} \)
- \( a_i^f = \sum_{s \in \omega_{z'}} a_i^s \)
- \( \sigma_{i o_{z'}, s} = \frac{\varphi_{i o_{z'}, s}}{\sum_{s' \in \omega_{z'}} \varphi_{i o_{z'}, s'}} \)
- \( \varphi_{i o_{z'}, s} = r_{o_{z'}, s} e^{\sigma_{i o_{z'}}} \frac{a_{i, s'}}{a_{i, s}} \)
- \( a_{i, s}^f = a_{i, s}^f \)
Two thought experiments

• AFV and infrastructure fuel station coevolution
  – Illustrative Example: Hydrogen Fuel Cell Vehicles (HFCVs) and Hydrogen

• The impact of shocks on AFV Diffusion
  – Illustrative Example: PHEVs under Oil Shock
Liquid/gas fossil

gasoline, ethanol, diesel

conventional ICE/gasoline, hybrid

Consumer Acceptance

fuel-cell

hydrogen

OEM reinvestment, learning, scale, scope

$ $ $ $ $ $
HFCV Diffusion Experiment Setup

- **2006 ICE/Gasoline Technical Parameters**
  - **Hydrogen Fuel Cell Vehicles compared to current ICE:**
    - $35,000 production cost
    - Equal Initial performance
    - 35 mi/gge fuel economy
    - 6 gge tank capacity
    - **Max Range**: 210 miles
  - **Initial** | **Mature**
    | $35,000 production cost | 2.25 | 1 |
    | Equal Initial performance | 1 | 1.25 |
    | 35 mi/gge fuel economy | 1.67 | 3 |
    | 6 gge tank capacity | 0.3 | 0.5 |

- **Hydrogen Fuel Stations**
  - H₂ Produced at Station Forecourt via Steam Reformation of Natural Gas
  - $2.10 variable cost per gge H₂ output (~$9/mcf natural gas, 70% efficiency)
  - Selection, permitting, construction delays total 2 years

- **Aggressive, coordinated, and persistent policies across the system:**
  - Intensive 15 yr marketing program to build awareness
  - Fleet program involving 500,000 vehicles
  - *Full subsidy of HFCV vehicle price difference with ICE*
  - Intensive R&D programs to lower AFV cost and boost performance prior to roll out
  - Fuel station rollout totaling about 800 stations
  - Fixed $2.50 gge alt fuel retail markup for 10 years, gradual deregulation thereafter
  - $0.50/gallon additional gasoline tax
  - Cost of R&D, marketing program, fleet program, AFV subsidies, fuel station rollout shared between government, auto OEMs and fuel providers

- **Assume no Hindenburgs**
Base Case

Adoption Fraction

- ICE
- HFCV

Spatial snapshot

Fuel Stations
(Max Scale = 23,000 stations)

- Gasoline
- Hydrogen

Rollout Stations

<table>
<thead>
<tr>
<th>Total</th>
<th>Urban</th>
<th>SubUrban</th>
<th>Rural</th>
</tr>
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<tbody>
<tr>
<td>785</td>
<td>87%</td>
<td>5%</td>
<td>8%</td>
</tr>
</tbody>
</table>

Fuel Station openings

5,700

Spatial snapshot

Market collapses after subsidies end

Hydrogen Fuel Cell Vehicles on the Road

Chicken and Egg Problem

Fuel Availability

Fuel Demand

Hydrogen Fuel Stations

Fuel Station openings
Some adoption in urban areas, but poor rural, exurb fuel availability leads to market collapse.
Underlying Mechanism: Topping Off

We examine the following behavioral assumptions for driver refueling behavior:

1. **Rigid**
   - refill at buffer
   - buffer fixed

2. **Flexible**
   - refill on average at buffer
   - buffer fixed

3. **Adaptive**
   - refill on average at buffer
   - buffer adapts to perceived fuel availability
AFV Driver “Topping off” Creates Self-Reinforcing Fuel Shortages

Gas line and policy response during 1979 crisis
Successful Policy: Subsidize fuel stations in rural areas

Base Case

Adoption Fraction
- ICE
- HFCV

Rollout Stations
- Total: 785
- Urban: 87%
- SubUrban: 5%
- Rural: 8%

Fuel Stations (Max Scale = 23,000 stations)
- Gasoline
- Hydrogen

Fuel Station Rollout, Rural Emphasis

Adoption Fraction
- ICE
- HFCV

Rollout Stations
- Total: 785
- Urban: 33%
- SubUrban: 26%
- Rural: 41%

Fuel Stations (Max Scale = 23,000 stations)
- Gasoline
- Hydrogen

Spatial snapshot
AFV Adoption Fraction in 2030

Base Case

Base Case with Rural Fuel Station Rollout Emphasis
Experiment 2: The Effect of (Oil) Shocks on AFV (PHEV) Diffusion
Exploring PHEV Introduction: Basic Assumptions and Data

- Launch in California

- Initial PHEV costs high (realistic), but...
  - Charge-at-home capability
  - Extensive PHEV R&D, marketing. Funding from various parties.
  - Multistakeholder commitment to deploying PHEVS

- Parameters calibrated to established sources
  - Fuel supply chain and PHEV data from Ford and Shell Hydrogen
  - PHEV efficiency potential based on Kromer and Heywood (2007)

- For illustrative purposes: electricity predominantly derived from fossil inputs (natural gas; coal)
Base Case: Successful PHEV Diffusion

Platform Market Share

- Dimensionless
- Conventional Vehicles
- PHEVs

Years: 2005 to 2040
Conditions favor successful PHEV diffusion

PHEVs use existing fuel infrastructure

Sustained diffusion through self-reinforcing learning, scale effects
Sensitivity of PHEV Diffusion to Major Uncertainties

• How is PHEV adoption affected by an oil shock?

• Scenario:
  – Real price of Oil rises 100% in 2010, remains constant thereafter
Hypothesis: Higher oil prices improve relative attractiveness of PHEVs

PHEV Sales increase because of higher cost to drive conventional vehicle. PHEV can built scale and experience faster, speeding diffusion.
High Oil Prices Increase PHEV Adoption, but, the Effect is Small

Platform Market Share

- PHEVs
- PHEVs + Oil Shock

Conventional Vehicles

PHEVs
Overcoming an Established and Resilient Transportation System
Real Petroleum Price, 2007$/bbl
Market Responses to Oil Prices: Consumers

<table>
<thead>
<tr>
<th>Year</th>
<th>Real Oil Price</th>
<th>Road Vehicle Miles (Trillions/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1980</td>
<td>20</td>
<td>0.5</td>
</tr>
<tr>
<td>1990</td>
<td>40</td>
<td>2.5</td>
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Market Responses to Oil Prices: Automotive OEMS

New vehicle sales weight and performance decrease (increase), with a lag, following an increase (decrease) in oil prices, as consumers adjust model selection and OEMs adjust models and portfolio.

Transportation Energy Data Book, Ed. 26-2007 Table 4.6, Autodata and Ward's
Vehicle average fleet efficiency responds to real prices with a very long delay. Prices jump in 1973, but efficiency remains nearly constant until 1980. Prices fall to about $20/bbl by 1986 and efficiency gains stall in 1992 as automakers use technical improvements to boost performance instead of mileage, and as consumers switch to larger vehicles and SUVs.
Higher fuel prices lead consumers to choose smaller, more efficient vehicles.
Fuel Economy of Conventional Vehicles: Depends on Competition and Oil Price

Fuel Economy of Installed Base (Conventional ICE)

- **Base Case**
- **PHEVs**
- **PHEVs + Oil Shock**

**Cars**

**Small Trucks**

120$/barrel

100% Oil price increase

[Graph showing fuel economy trends over time for different scenarios.]
Consumers respond to adjust VMT, lowering operating costs.
Higher real oil prices raise real prices of electric power (direct & through cross-elasticity)

Electricity Retail Price

- **Base Case**
- **PHEVs**
- **PHEVs + Oil Shock**

100% Oil price increase

Cents/Kwh

2005 2010 2015 2020 2025 2030 2035 2040
Examining the Importance of a broad model boundary: cutting behavioral feedbacks
Ignoring behavioral feedbacks leads to overestimation of AFV diffusion

PHEV Installed Base Share (relative to ICE 2010)

- **PHEVs**
- **PHEVs + Oil Shock**

**Reduced Feedback Model**
- Vehicle size choice
- Efficiency improvement response to Oil Prices
- Electricity Price response to Oil Prices

**Broad Feedback Model**

![](chart.png)
Behavioral Feedbacks Strongly Reduce Estimated PHEV Adoption Benefit from Oil Shock

PHEV Installed base Share (2040)

Reduced Model

Full Model

Compensating Feedback Effects

Vehicle Size 33%

Efficiency 44%

Electricity Price 23%

PHEV

PHEV + Oil

PHEV

PHEV + Oil

+23%

+20%

+11%

0.4
Reduced Feedback Model Overestimates PHEV Adoption *and* Gasoline Consumption

Automotive Gasoline Consumption

- **Base Case**
- **PHEV Introduction**
- **PHEV Introduction, Reduced Feedback Model**

**Stable Oil Price**

**Oil Shock**

- **Reduced Mileage**
- **Smaller Vehicles**
- **More Efficient Vehicles**
- **Gasoline / Electricity Substitution**
- **Further Efficiency Gains (Spillovers)**
- **Further (Increased) Reduced Mileage**

<table>
<thead>
<tr>
<th>Year</th>
<th>Million Quads/Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005</td>
<td>5</td>
</tr>
<tr>
<td>2010</td>
<td>10</td>
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<tr>
<td>2015</td>
<td>15</td>
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<td>2020</td>
<td>20</td>
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<tr>
<td>2025</td>
<td>25</td>
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<tr>
<td>2030</td>
<td>30</td>
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<tr>
<td>2035</td>
<td>35</td>
</tr>
<tr>
<td>2040</td>
<td>40</td>
</tr>
</tbody>
</table>
GHG Emissions Reductions from Oil Shock are Suppressed under PHEV scenario (due too Limited Elasticity in Electricity Usage)
Other Analysis Performed, in Progress, and Planned

- Extensive model testing
- Further PHEV analysis
  - Base scenario using: CAFE, (CA) renewable fuel standards, Senate Bills, etc..
  - Sensitivity to technical, economic, behavioral uncertainties (e.g. CCS, biofuel commercialization timing, Carbon prices)
  - Policy analysis
- Competition with and interactions between PHEV & other AFVs
  - Alternative PHEV technologies
  - Conventional hybrids
  - Biofuels/biodiesel
  - HFCV, H-ICE
  - Pure electric (e.g. BetterPlace)
- Fuel supply chain scenarios:
  - Biofuels: 2nd Generation (cellulosic; waste inputs)
  - H₂ from sustainable sources (e.g. Nocera process, biofuels)
  - Electricity peak and base load, battery supply chains, storage
- Interactions among all items above
- Other regions
- Factor Explaining HEV adoption in the US (2000-2010)
Factors Explaining HEV Diffusion
Collaborators: David Keith and John Sterman, Demetrios Vakratsas

Observation: Wide variation of HEV adoption within the US

"Quarter 2, 2001"
Spatial Variation in Demographic Attributes

**Household Income**

- California
- Utah

[Map: Household Income](http://creativeclass.com/whos_your_city/maps/#The_Income_Map)

**Gasoline Prices**

- Map showing gasoline prices across the US

[Map: Gasoline Prices](http://www.gasbuddy.com)

**Political Preferences**

- Map showing political preferences across the US

**Federal, State, OEM Incentives**

[Map: Federal, State, OEM Incentives](http://www-personal.umich.edu/~mejn/election/2008/)

**Prius Market Share of New Vehicle Sales**

- Line graph showing Prius market share from 2000 to 2009

- California
- Utah
How do Spatial and Network Interactions affect HEV Consideration?

- We examine how consumers are influenced by:
  - Material Exposure (of Vehicles in Use)
    - Local
    - Regional (drive patterns)
  - Social Exposure
    - Local
    - Regional (work, other travel patterns, media)
    - National - clustered (travel)
    - National – mixed (media)
AFV Diffusion: Counterintuitive Dynamics

- Focusing initial fuel station rollout on urban areas, where initial AFV demand likely highest, leads to urban focus, market failure.

- More costly exurb/rural focus builds sustainable, profitable AFV and alt fuel market, with greater urban market share, larger NPV for all key actors (Auto OEMs, fuel providers, consumers, government and environment).

- A more efficient AFV can slow or prevents adoption due to negative impact of lower fuel demand on alt fuel profitability and infrastructure investment.

- Plug-in Hybrids not vulnerable to infrastructure dynamics; diffusion more rapid and durable, assuming technical risks overcome.

- Success rapidly reduces gov’t fuel excise tax revenues; fuel tax must rise over time to maintain revenues (and compensate for drop in world oil price induced by lower consumption).

- Faster AFV sales leads to surplus used conv. vehicles. Low used car prices limit AFV diffusion. Early decommissioning of conventional cars (Cash for Clunkers) a high-leverage policy.

- Others...
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