Transition Strategies for Alternative Transportation Fuels and Vehicles

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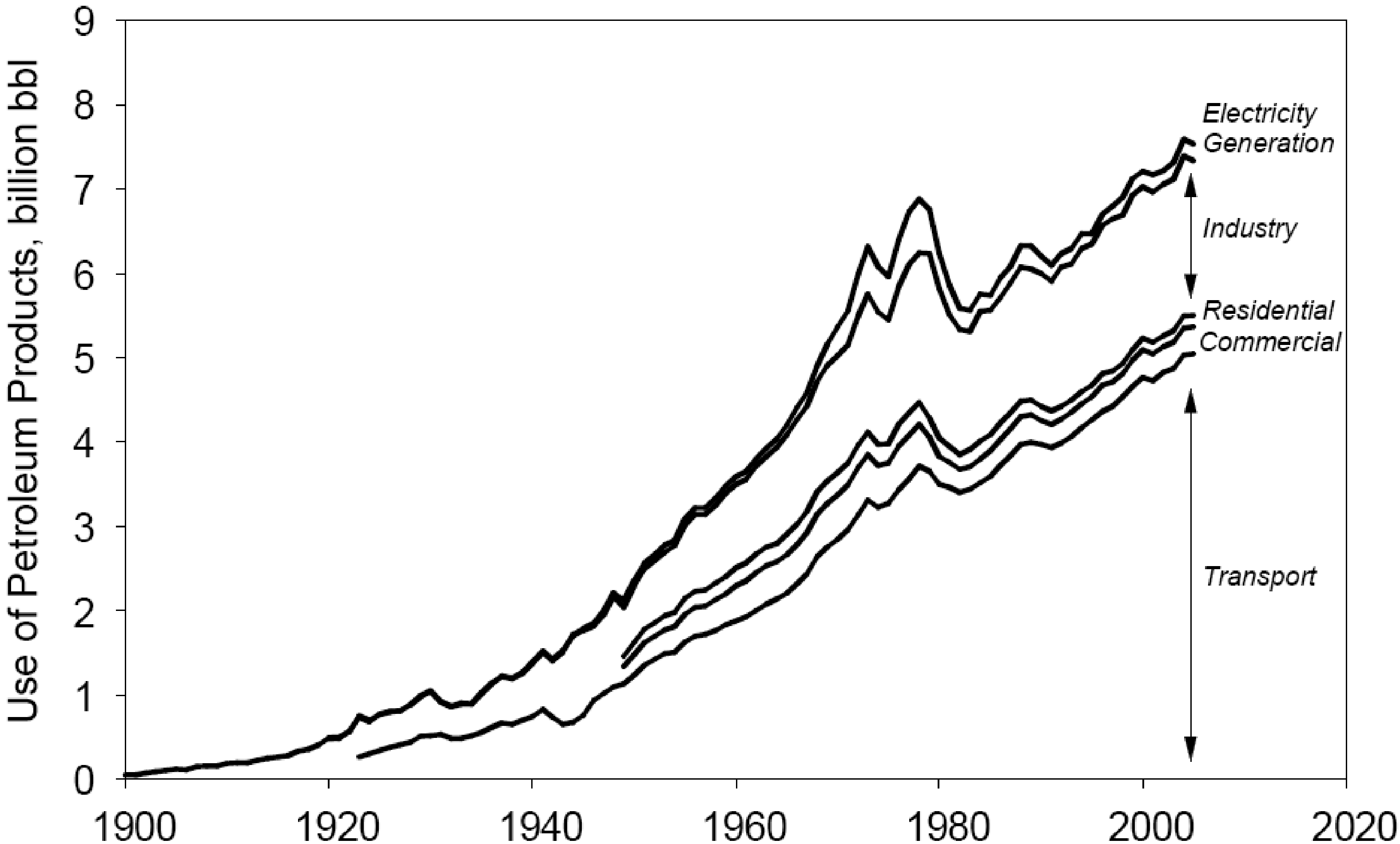
Summary

- **Report latest results from the MIT alternative energy and transportation transition model**
  - New model enhancements
    - Additional AFV platforms
    - Upstream fuel supply chains
    - Enhanced consumer behavior
    - Enhanced representation of OEM R&D, learning, technological spillovers
    - Carbon Capture and Storage
  - Analysis of platform and fuel diffusion
    - Fuel availability and price uncertainty
    - Impact of consumer and OEM responses to carbon prices
    - Impact of consumer and OEM responses to early/late breakthroughs with 2G biofuels and/or CCS

- **Purpose is to**
  - Further develop our conceptual models on transportation transition challenges and opportunities
  - Improve simulation model
  - Explore further critical questions

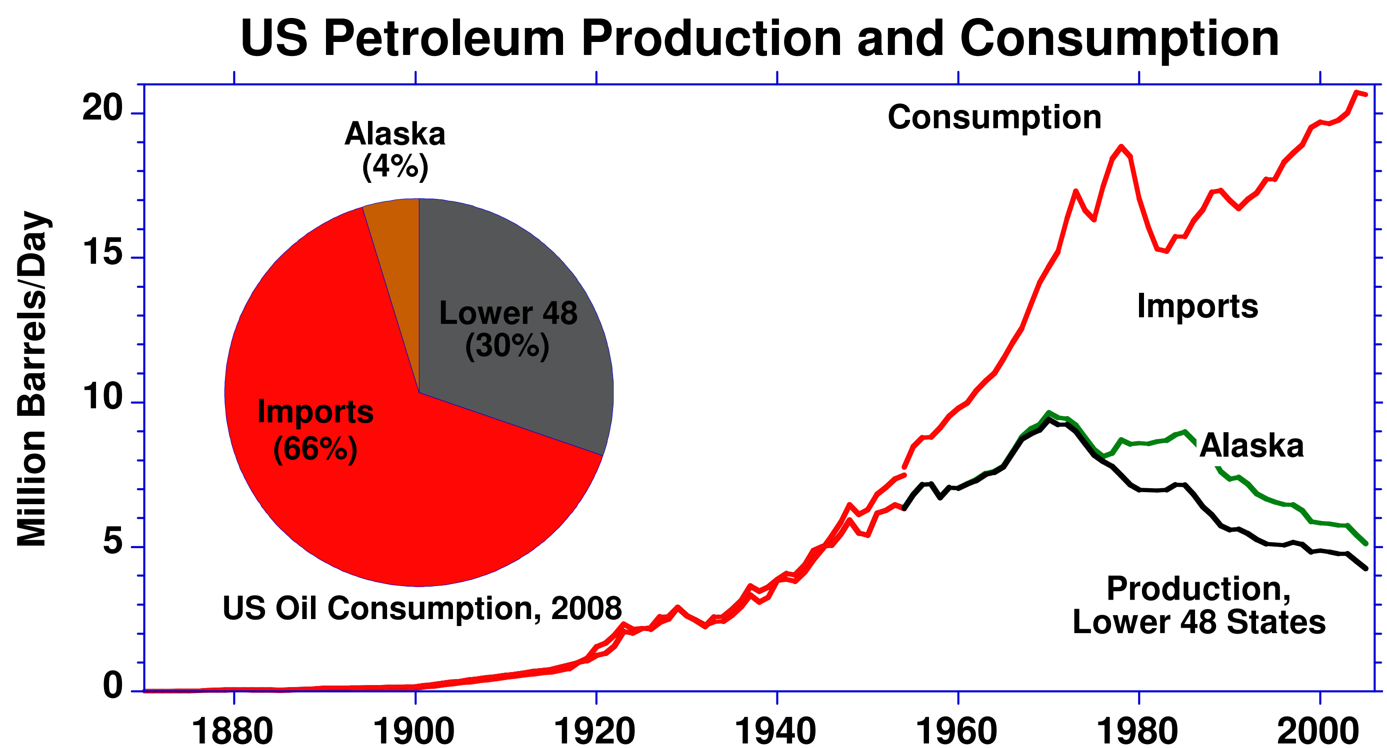
2/3rds of <u>all the world's petroleum</u> is used by transportation



Use of petroleum product by sector in the US, 1900 – 2005. Data source: US Department of Commerce, 1975. Historical Statistics of the United States, Colonial Times to 1970, Bureau of the Census, Washington, DC. US Energy Information Administration, 2007. Annual Energy Review 2006, Estimated Petroleum Consumption by Sector, US Department of Energy, Washington, DC. (From Schafer et al., MIT Press, forthcoming)

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



The current transportation model does not scale:

If the projected world population of 9 billion people in 2050 lived the way Americans do today...

- **There would be 7.6 Billion motor vehicles on the roads**
- **Transportation alone would consume 440 million barrels of oil per day**
  - *Total* world oil production today is **82 million** bbl/day
- **CO_2 emissions from transportation alone would be 62 billion metric tons/year**
  - *Total* world emissions from fossil fuels today ≈ **28 billion** tons CO_2/year
- **The current model of development and transportation cannot scale to a world of 9 billion, all of whom aspire to live the way we do**
  - New energy supply technologies are necessary but not sufficient
  - End-use efficiency improvements are necessary but not sufficient
- **A new transportation system is coming.**
  - What pathway?How will be a leader?
  - Note only of company but also of national Interest: leadership essential to preserve and enhance domestic innovation, investment, and job creation.

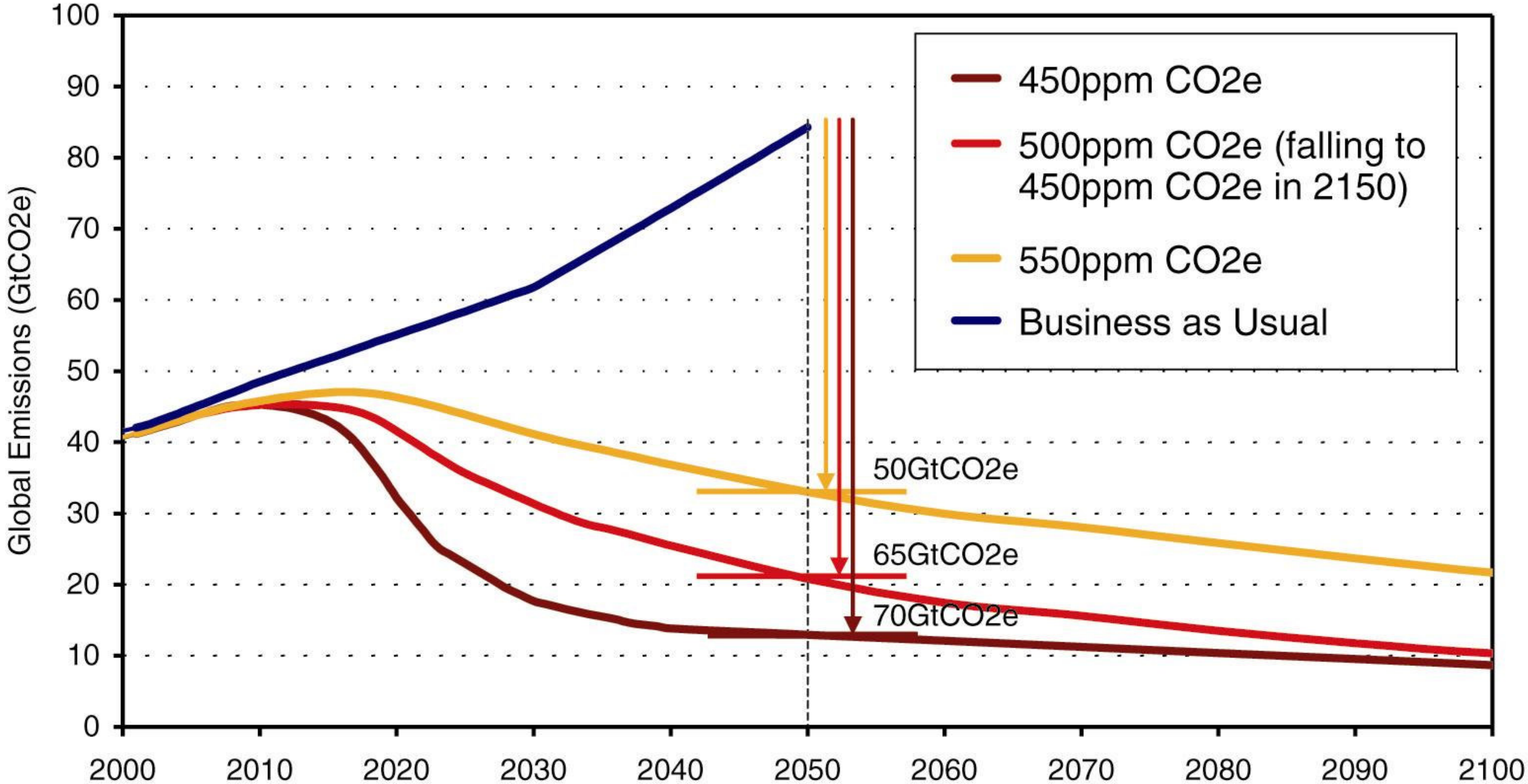
Adapted from: MIT Transportation Initiative, Profs. Barnhart, Jaillet, Sheffi, Sterman, Waitz, Zegras

Mass mobility wave in motion

The Tata Nano: a $2500 car made for a market of one billion people.

Source: MIT Transportation Initiative, Profs. Barnhart, Jaillet, Sheffi, Sterman, Waitz, Zegras

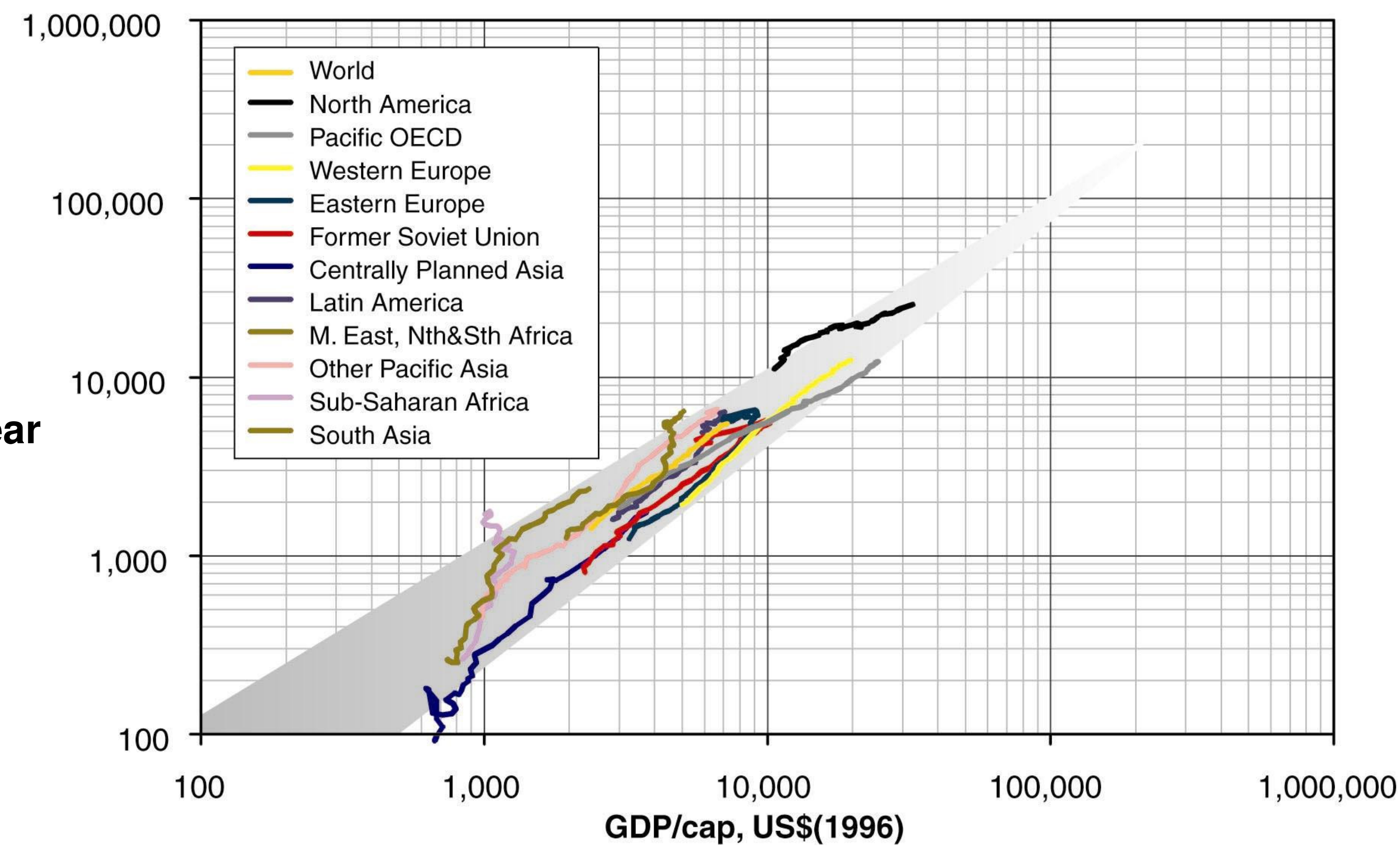
Cutting greenhouse gas emissions enough to stabilize atmospheric concentrations…



Source: Stern Review, Fig. 8.4

Is incompatible with this:

Annual
Travel
per Capita
(kilometers/year
per person)

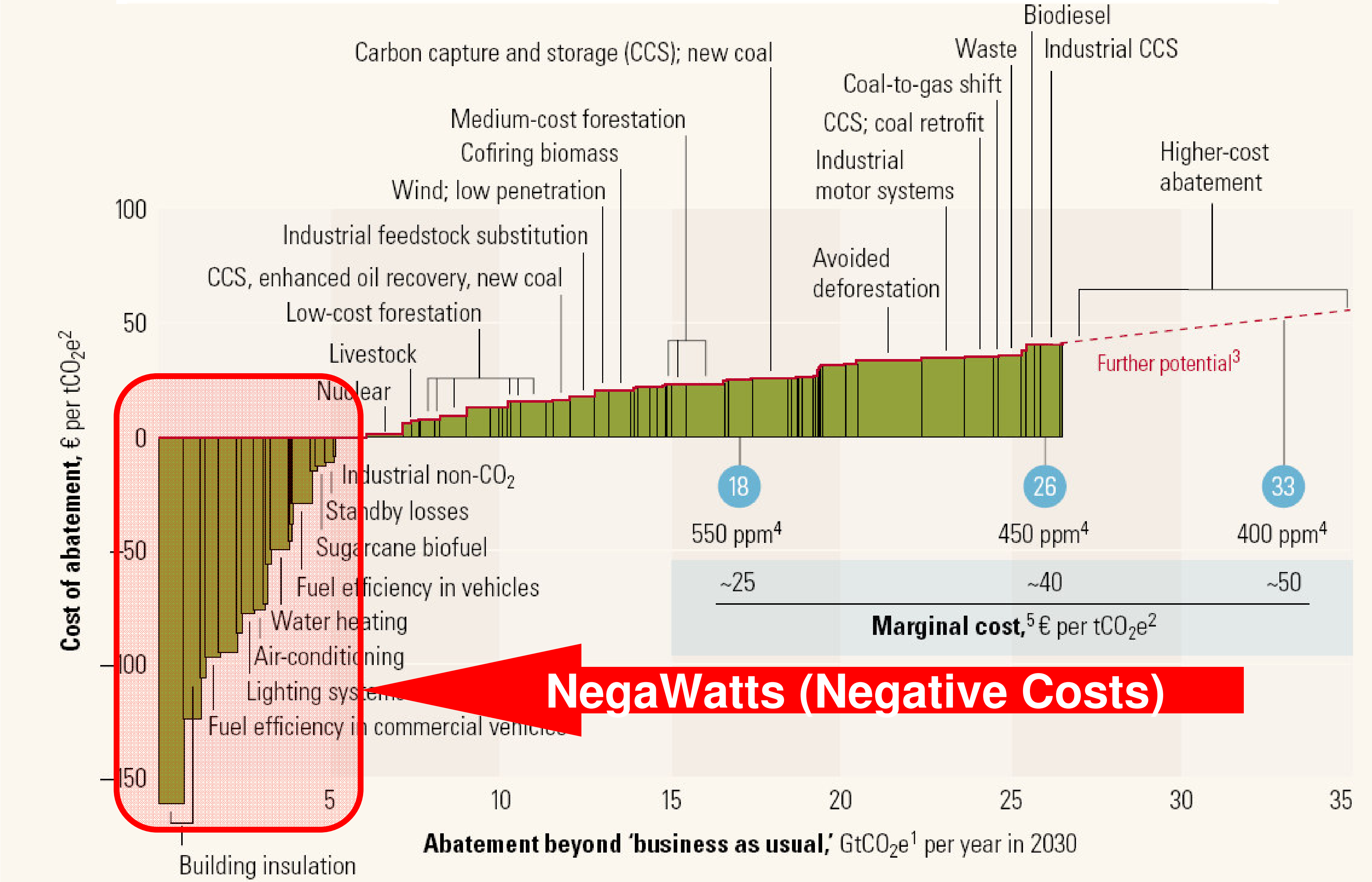


accessibility

…unless we dramatically innovate in ~~transportation~~

Source: MIT Transportation Initiative, Profs. Barnhart, Jaillet, Sheffi, Sterman, Waitz, Zegras

Cost of GHG Abatement

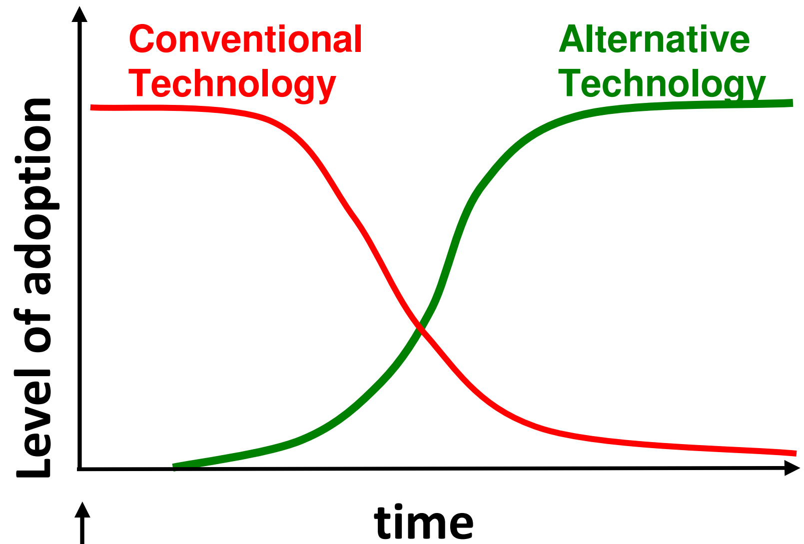


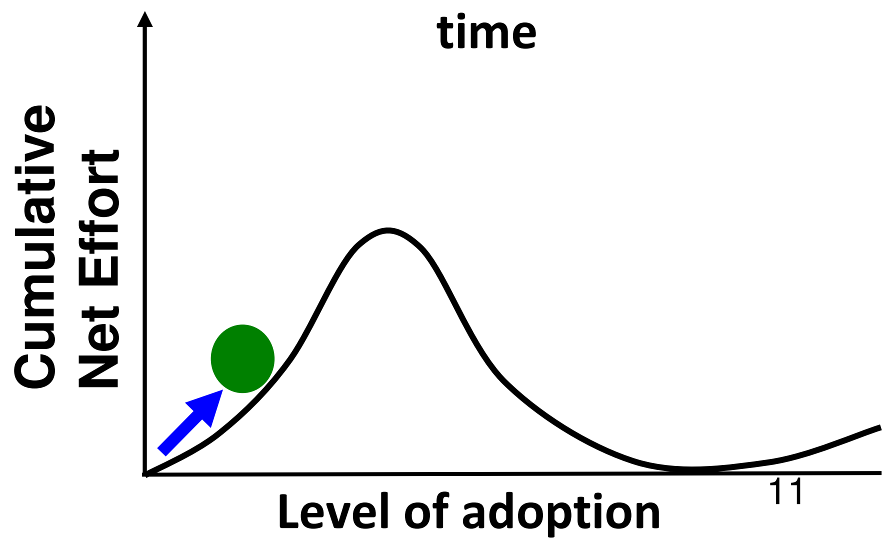
Many opportunities exist. Why not widespread?

Technology Disruptions: Traditional Perspectives

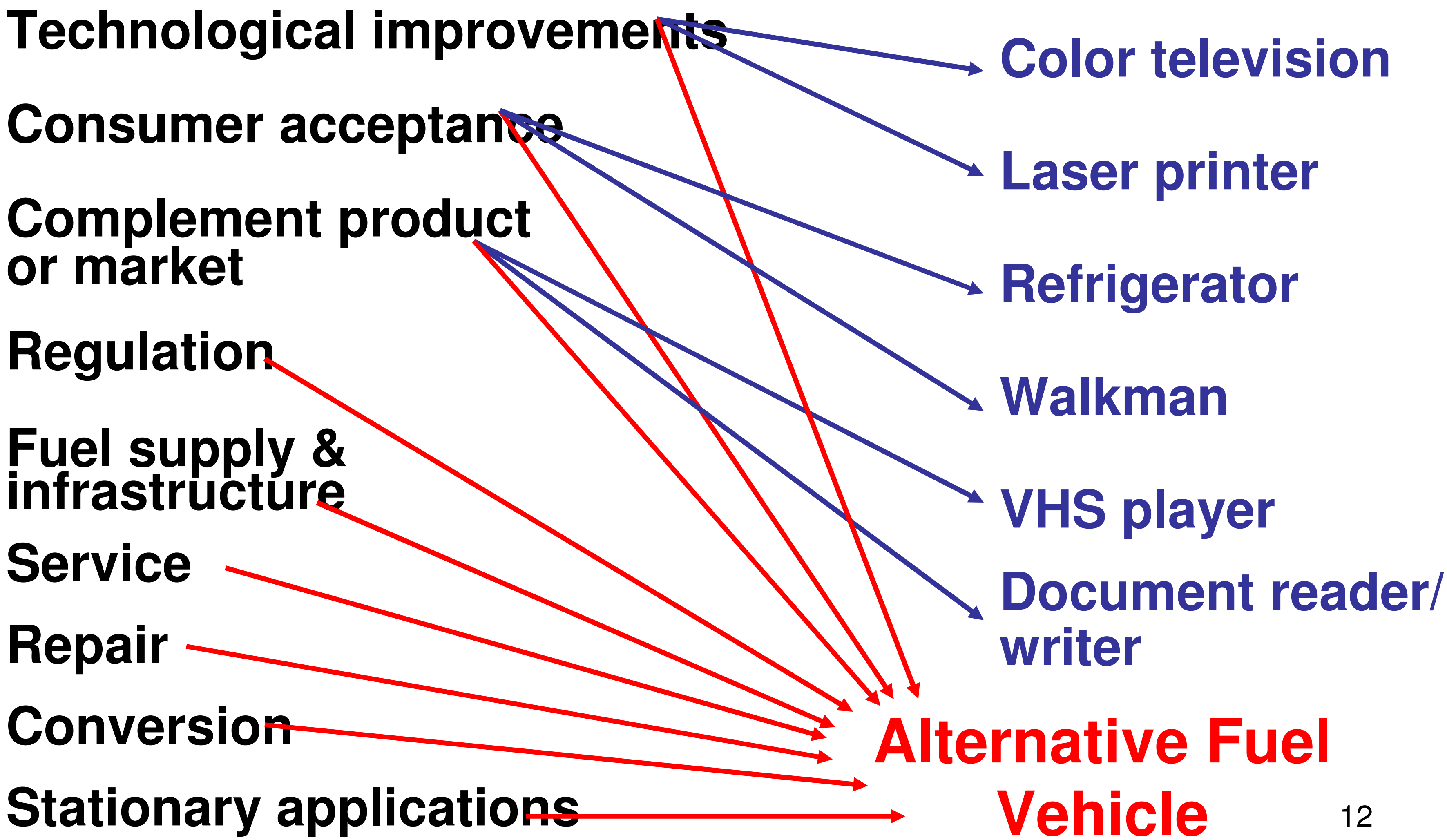
Personal Stereo

Cameras

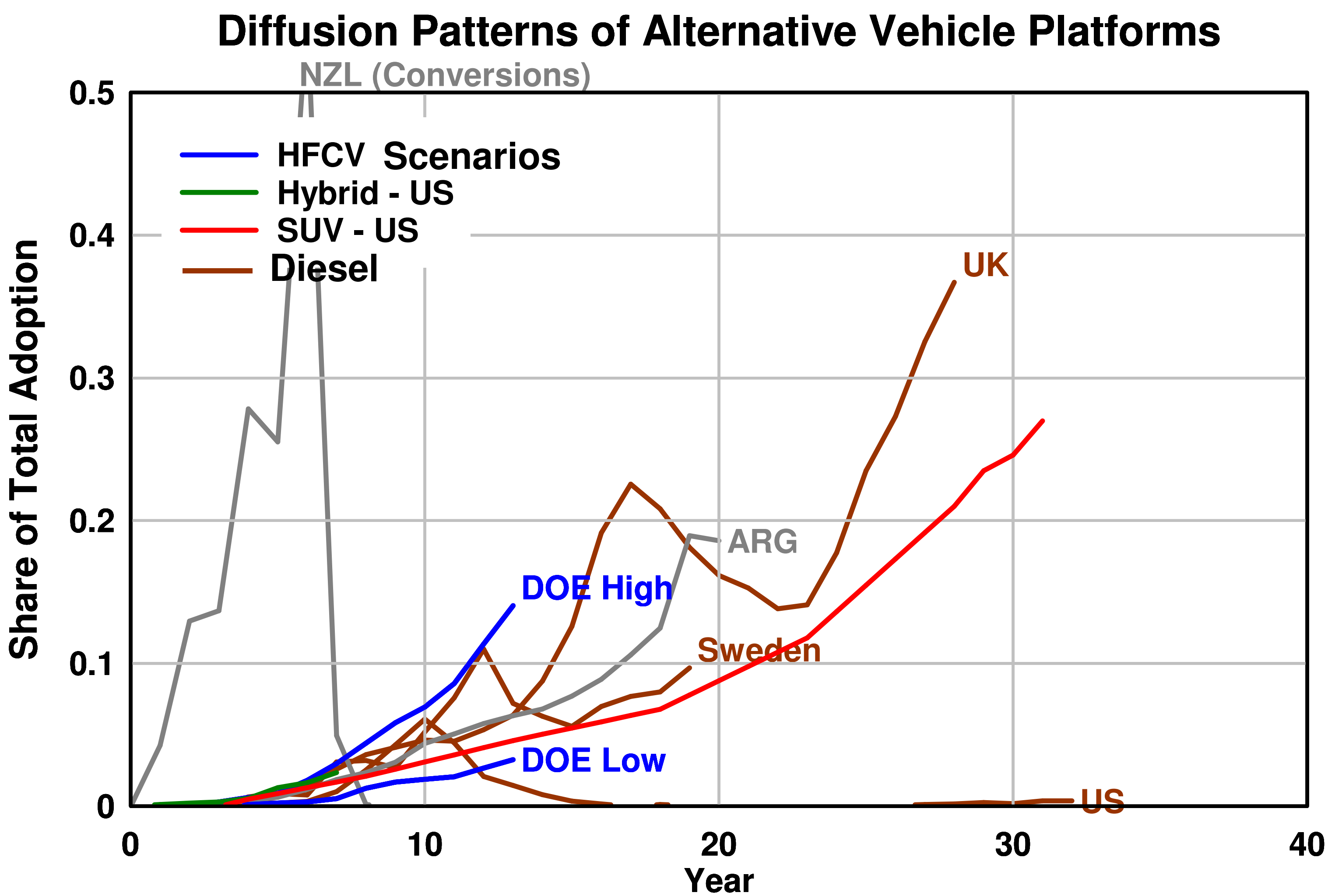




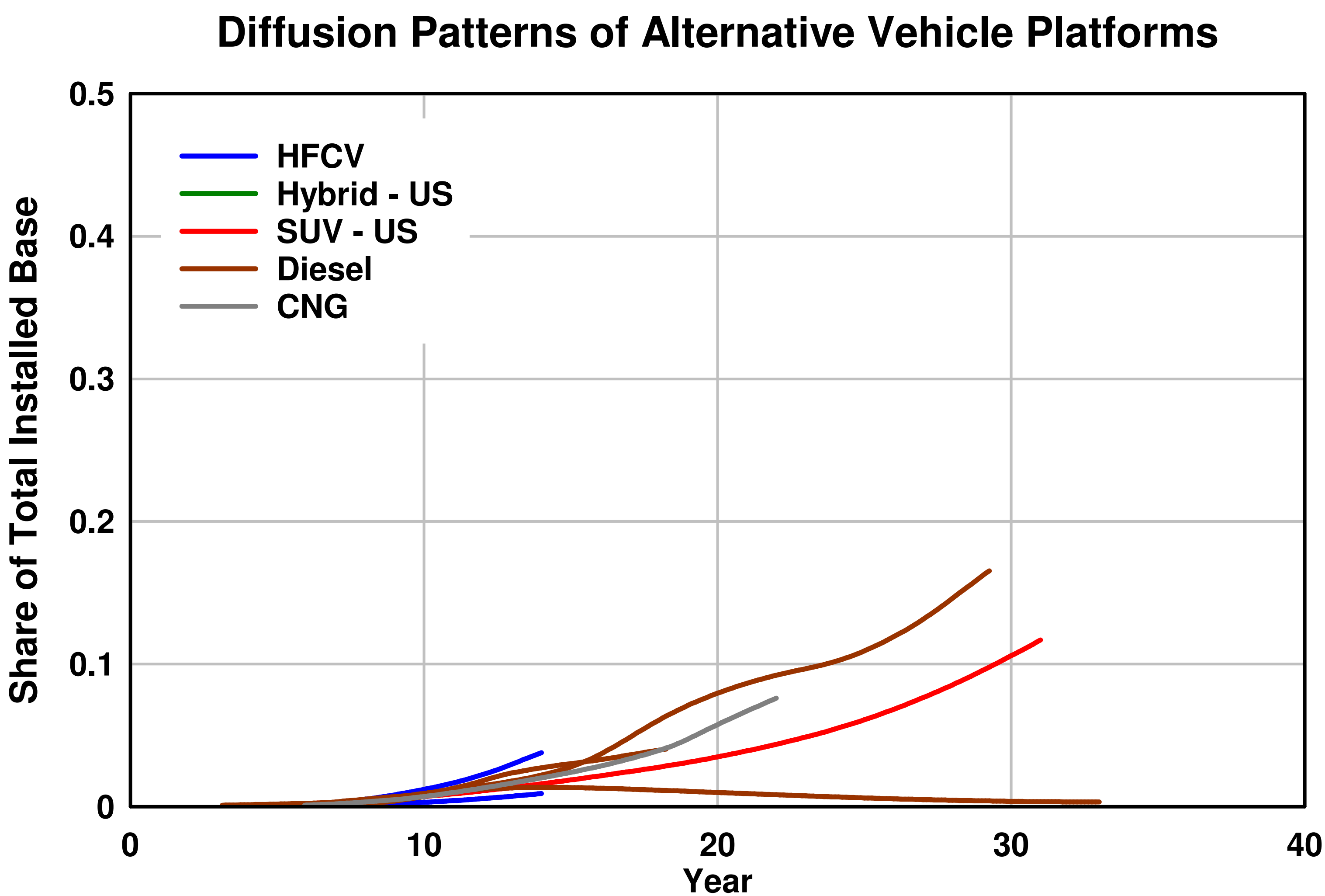
Canonical Diffusion Examples versus Network Technologies



Alternative Fuel Vehicle Diffusion: Slow and Fragile



Alternative Fuel Vehicle Diffusion: Slow and Fragile



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 (e.g. Prius)**
  - So far so good USA
- **Electric**
  - Sizzle and Fizzle USA: EV1, other pure electrics
- **Plug-in Hybrids**
  - Too soon to tell Various (Ford, Toyota, Chevy Volt)

Creating a Market That Does Not Exist: Research Question

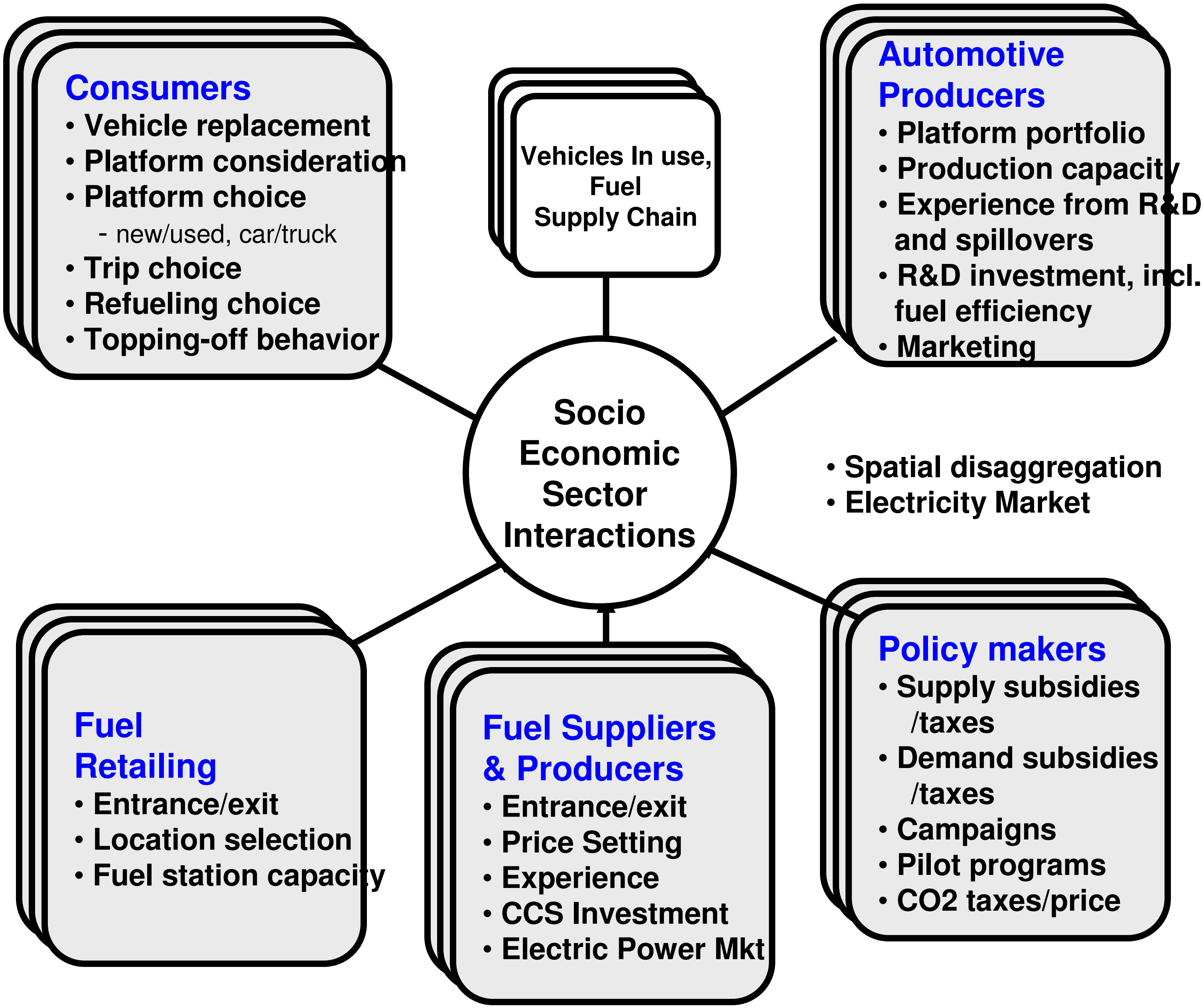
- **How do AFVs enter the market, gain traction, and sustain themselves?**
  - What are viable pathways?
  - Where are important pitfalls?
  - Where lie important policy leverages?
  - What level of coordination is needed ? Who? What kind of coordination? How long?
  - What portfolios to build?

MIT System Dynamics Group Approach

- **Suite of simulation models of AFV introduction, diffusion, competition**
  - Dynamic
  - Spatially explicit
  - Behavioral (realistic depiction of decision making)
- **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
  - Counterfactual analysis
- **Grounded in detailed empirical study, quantitative and qualitative data**
  - Case studies of prior AFV programs and policies

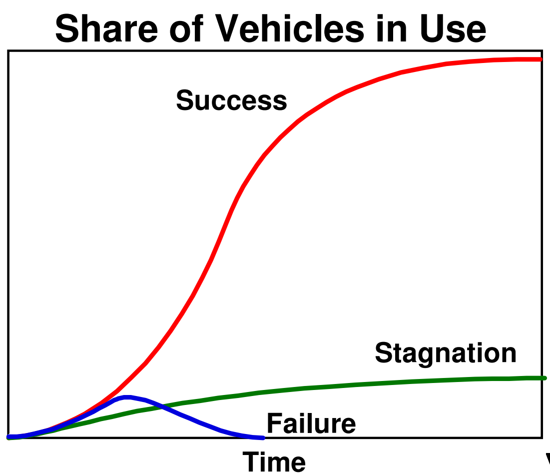
See: Struben J, Sterman J, 2008, "Transition challenges for alternative fuel vehicle and transportation systems" *Environment and Planning B* 35(6) 1070 – 1097

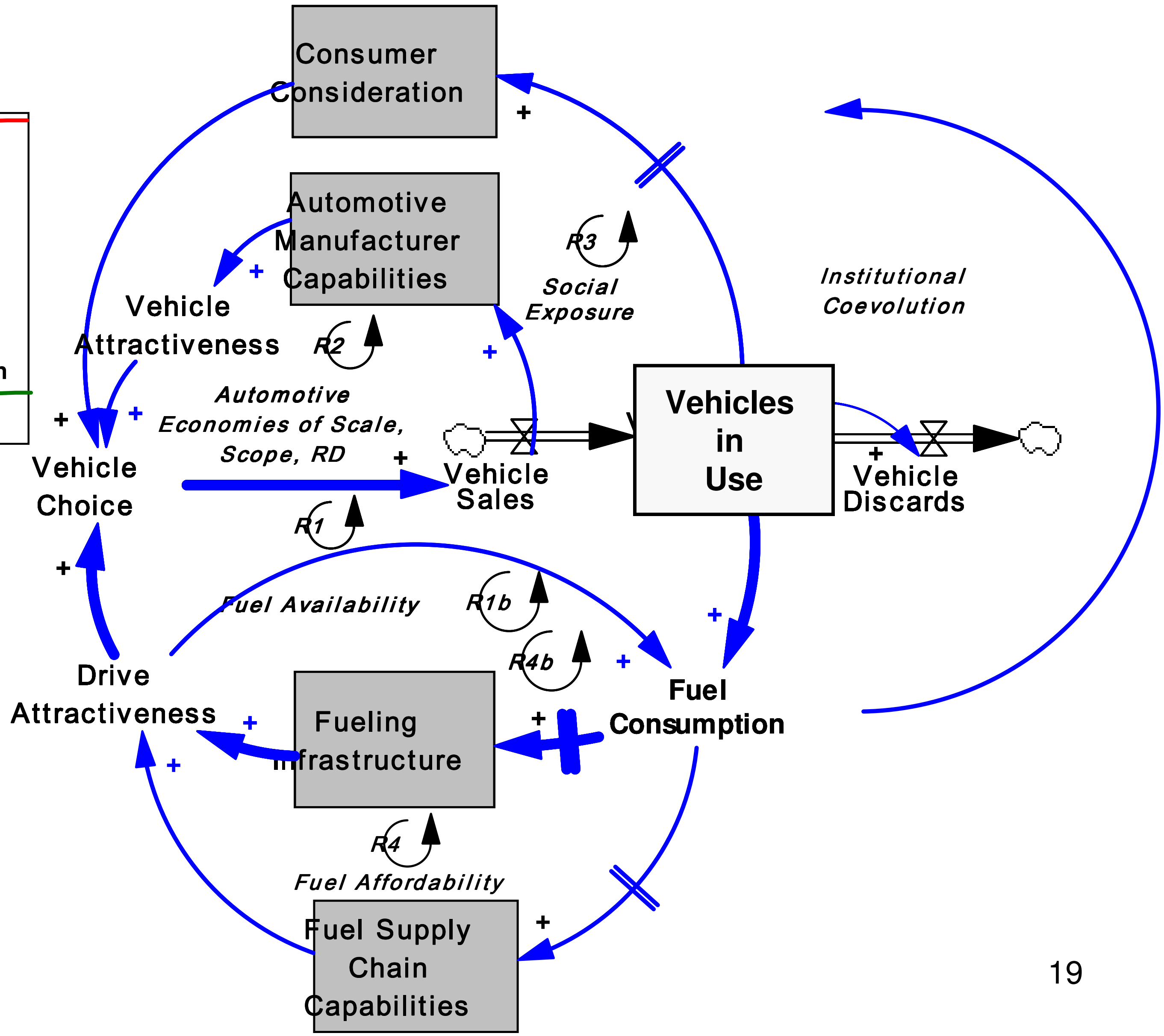
A Broad Boundary



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

Principal feedbacks



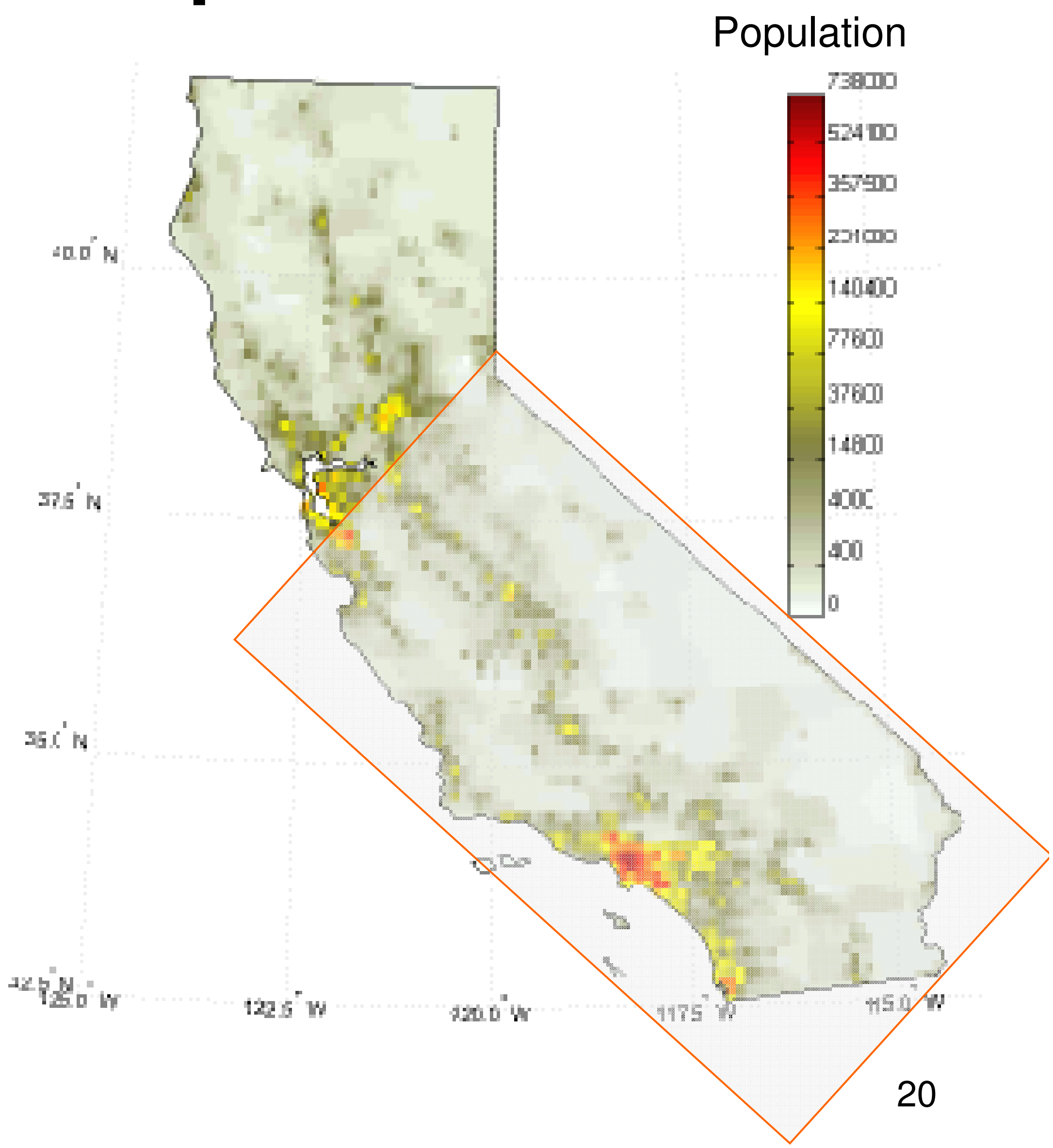


Vehicle Choice Attributes

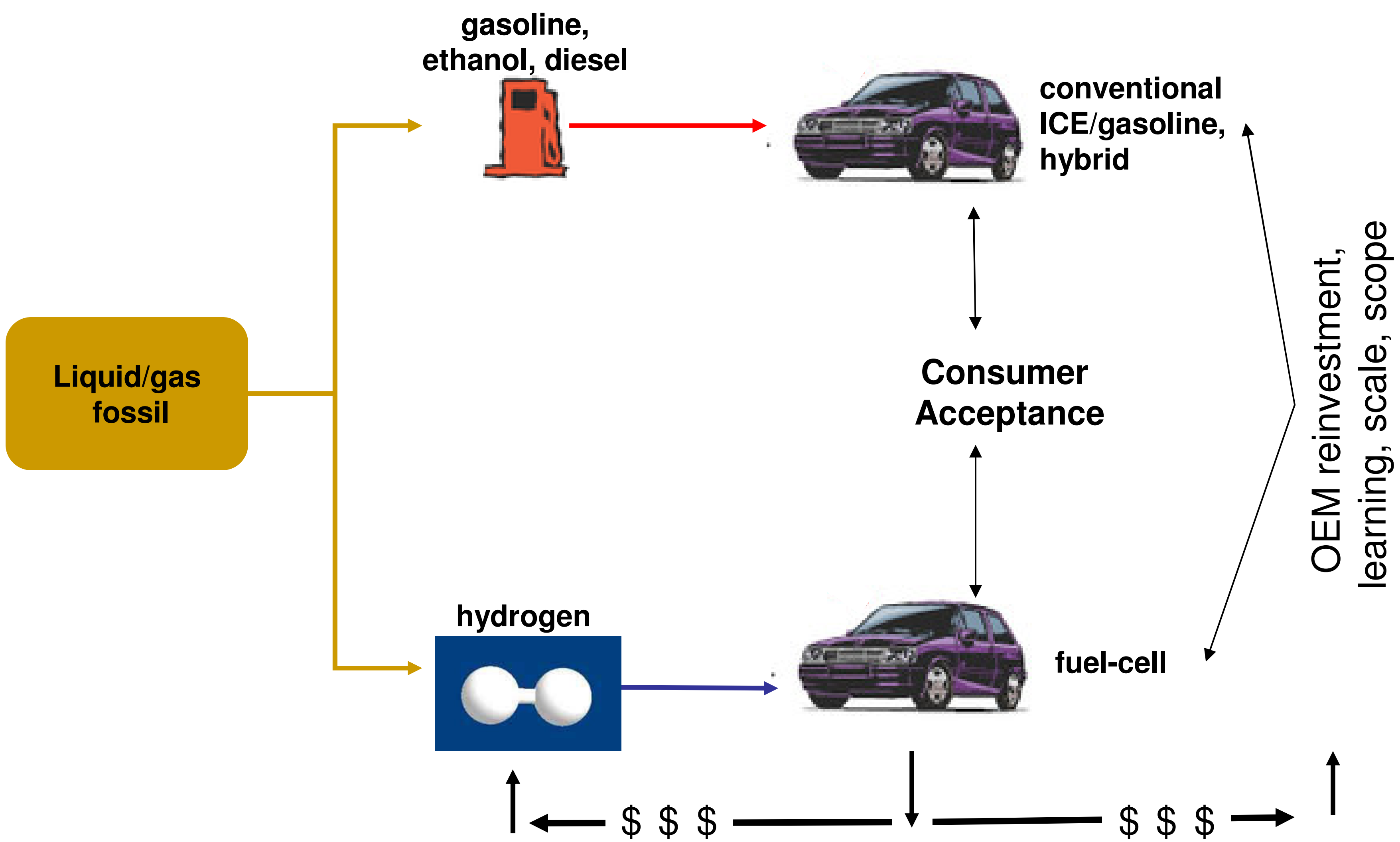
- *Purchase price*
- *Performance*
- *Driving Convenience*
- *Safety*
- *Operating Cost*
- *Ecological impact*

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



Experiment 1: HFCV Diffusion



Example: HFCV

- **2006 ICE/Gasoline Technical Parameters**
- **Hydrogen Fuel Cell Vehicles compared to current ICE:**

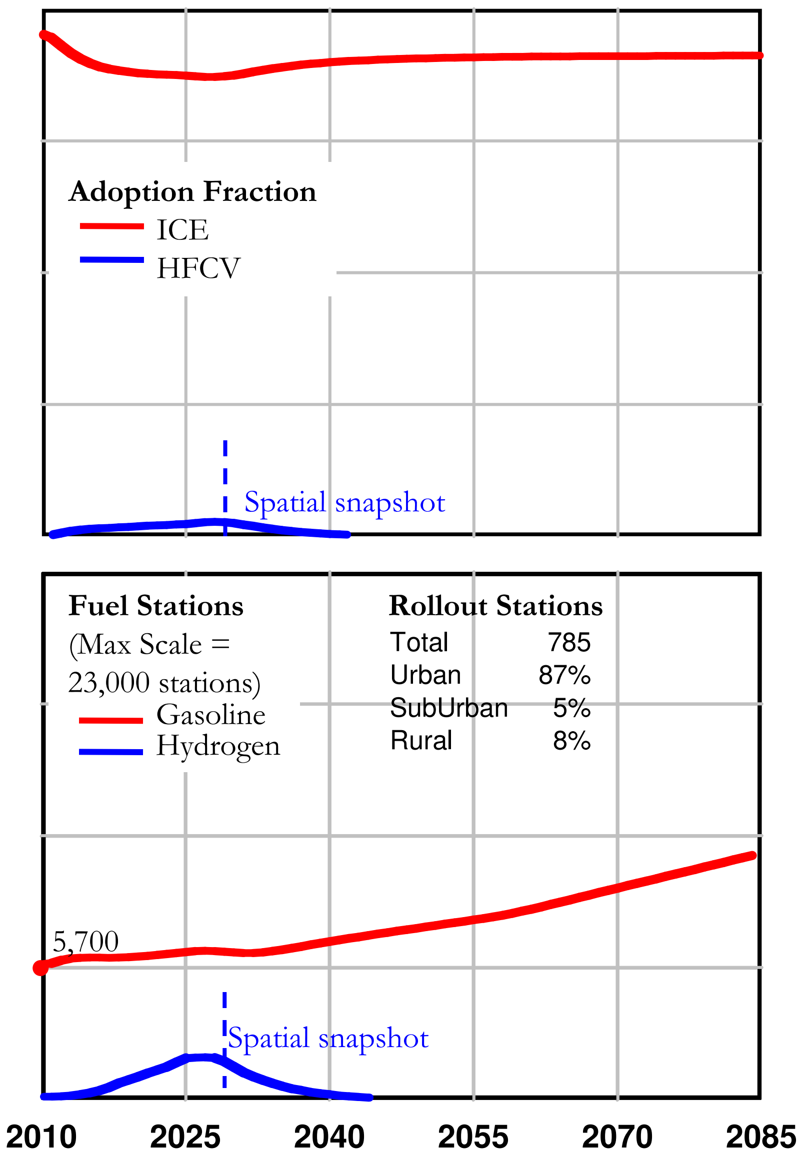
	Initial	Mature
– $35,000 production cost	2.25	1
– Equal Initial performance	1	1.25
– 35 mi/gge fuel economy	1.67	3
– 6 gge tank capacity	0.3	0.5

Max Range

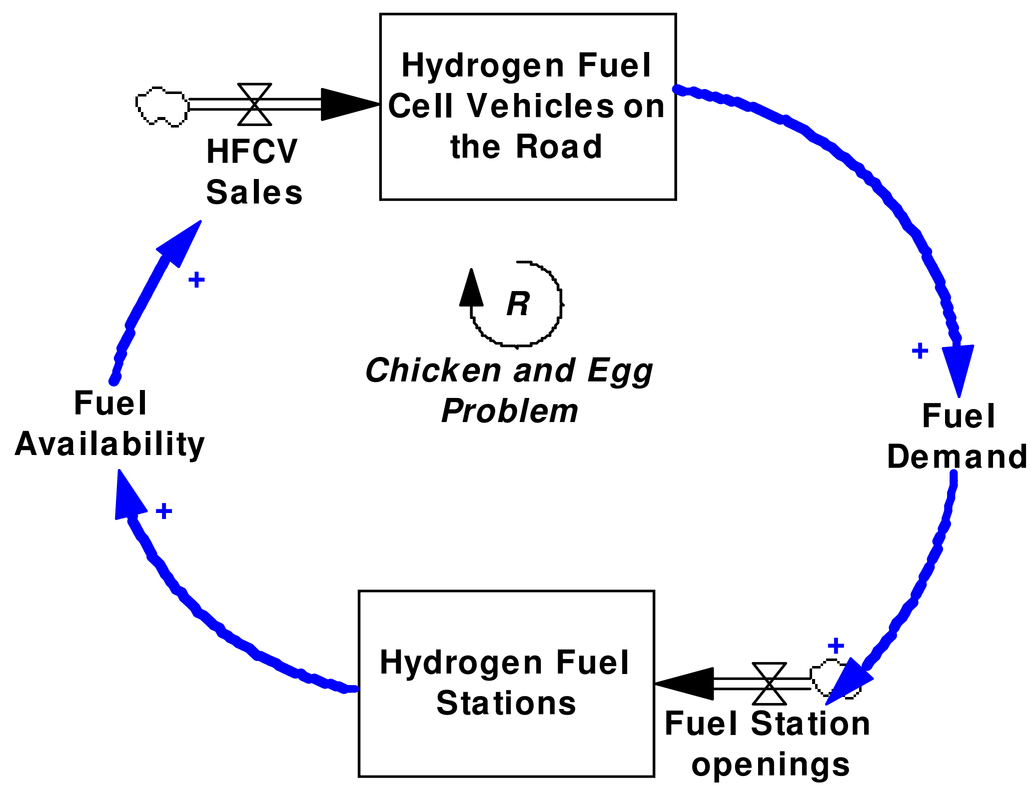
210 miles

- **Hydrogen Fuel Stations**
  - H_2 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**

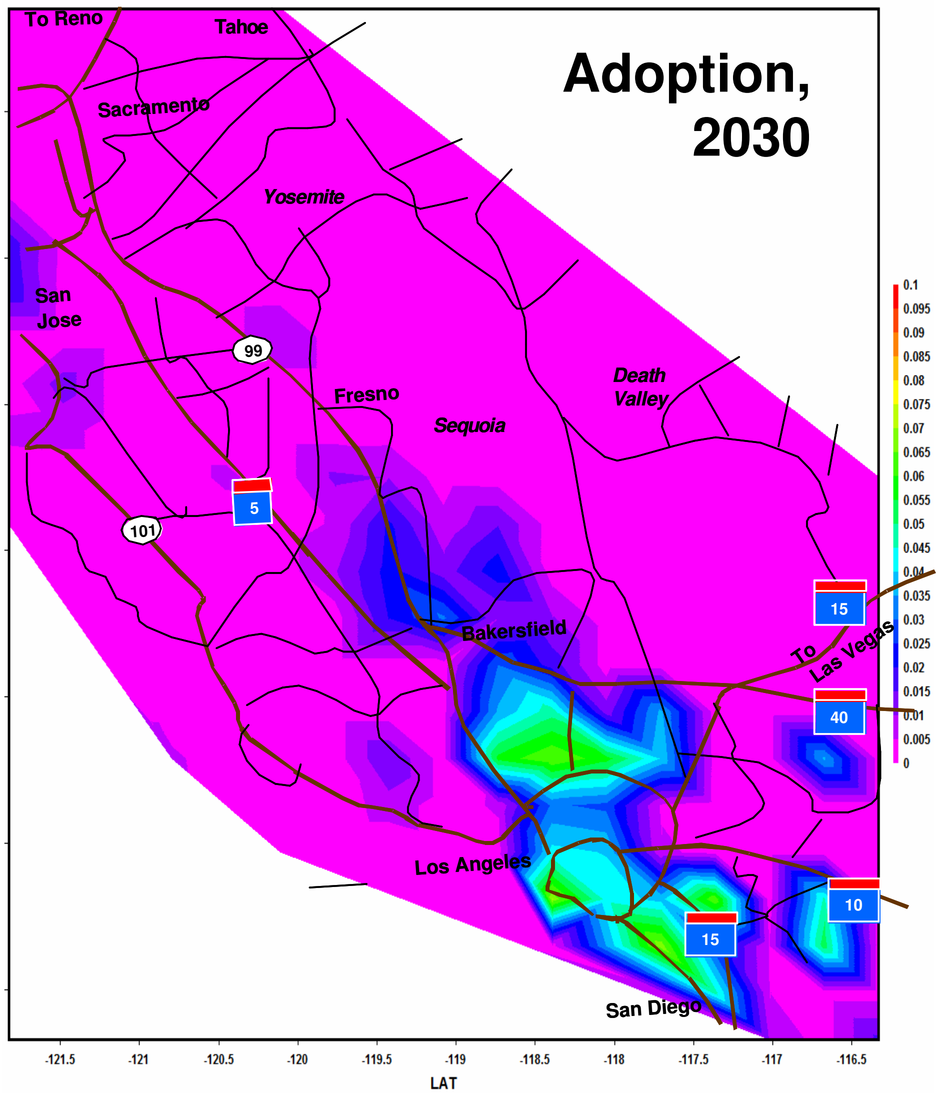
Base Case

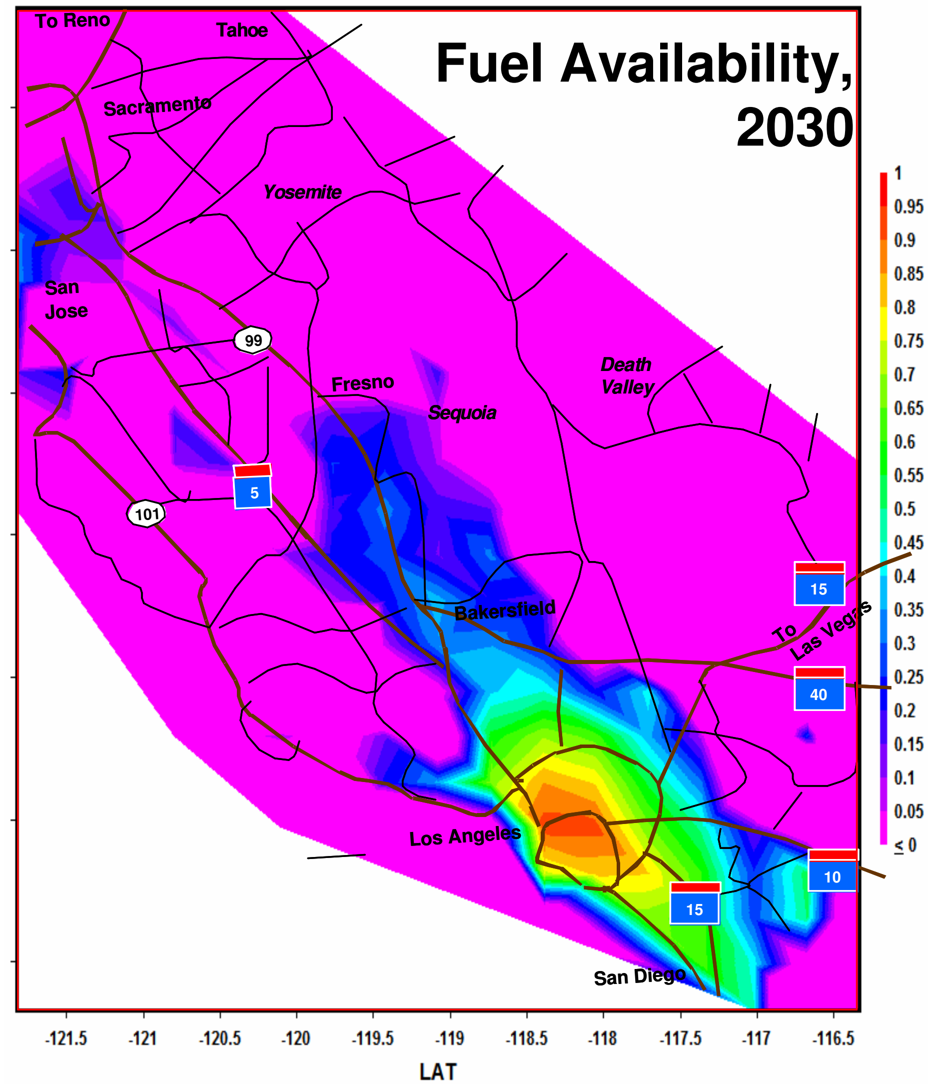


Market collapses after subsidies end

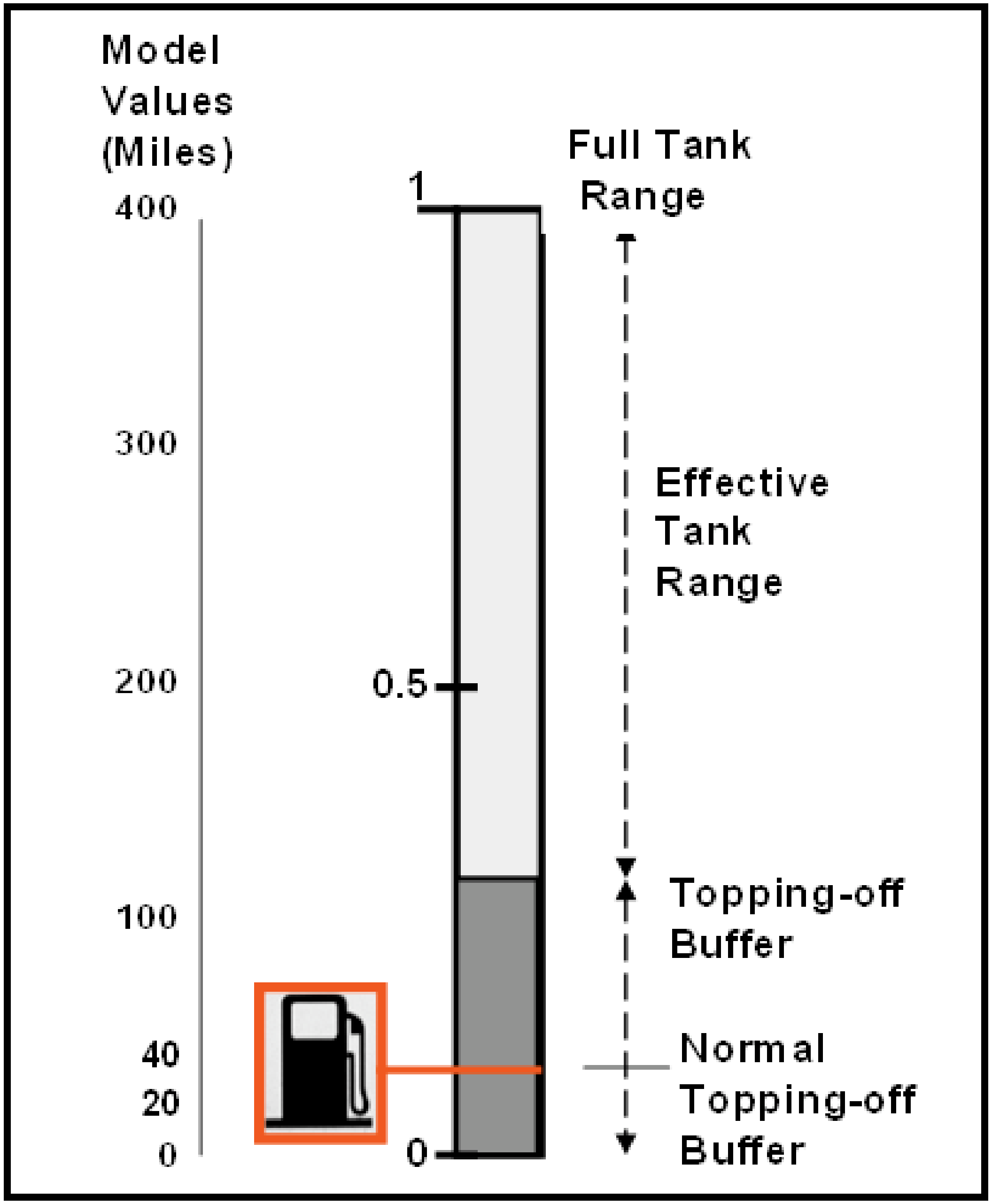


Some adoption in urban areas, but poor rural, exurb fuel availability leads to market collapse





Topping Off

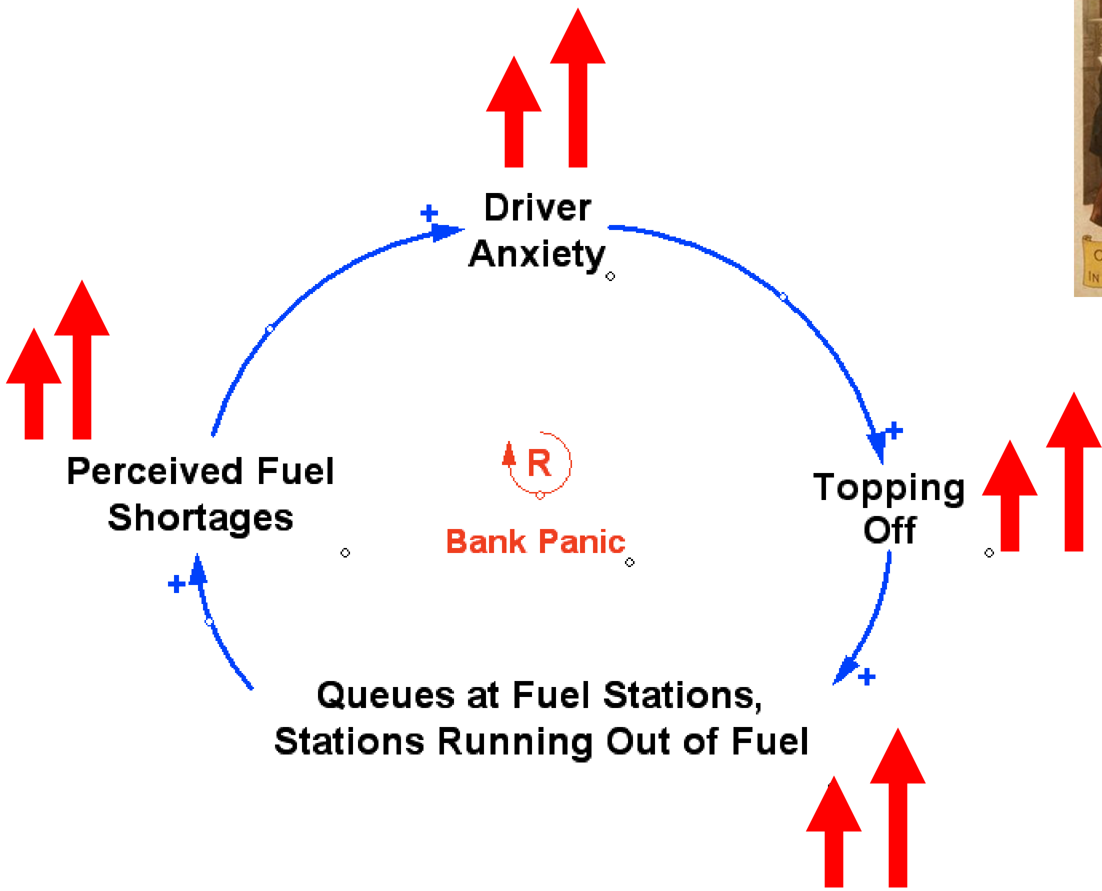


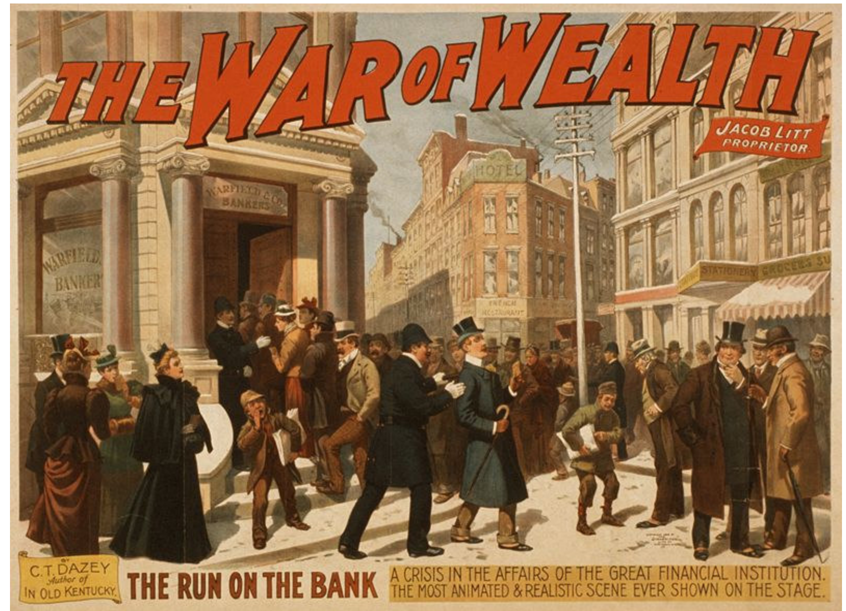
We examine the following behavioral assumptions for driver refueling behavior:

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**

What is the impact on AFV diffusion?

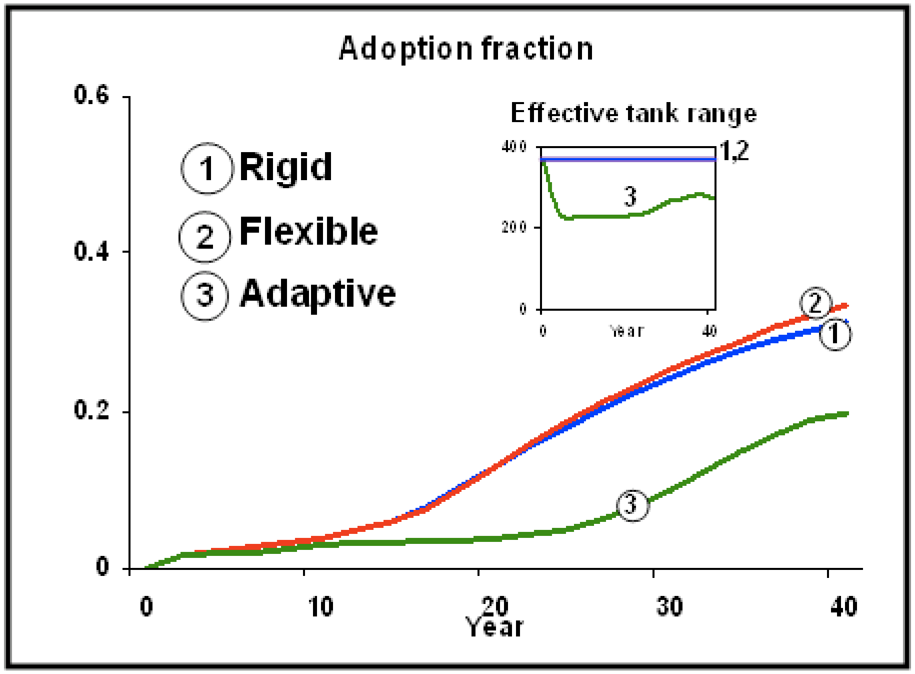
AFV Driver "Topping off" Creates Self-Reinforcing Fuel Shortages

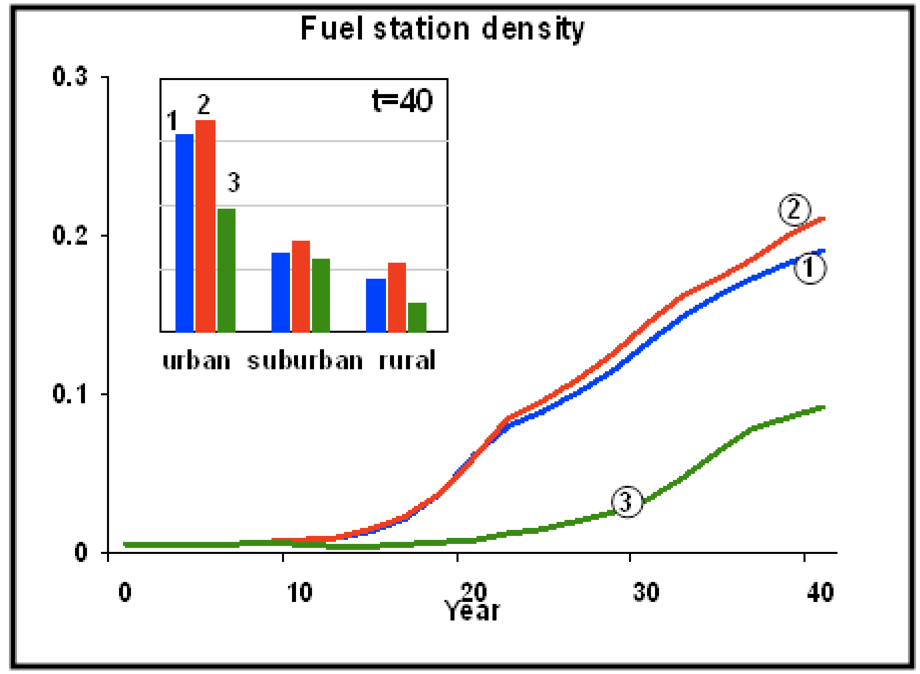




Gas line during 1979 crisis

Topping Off



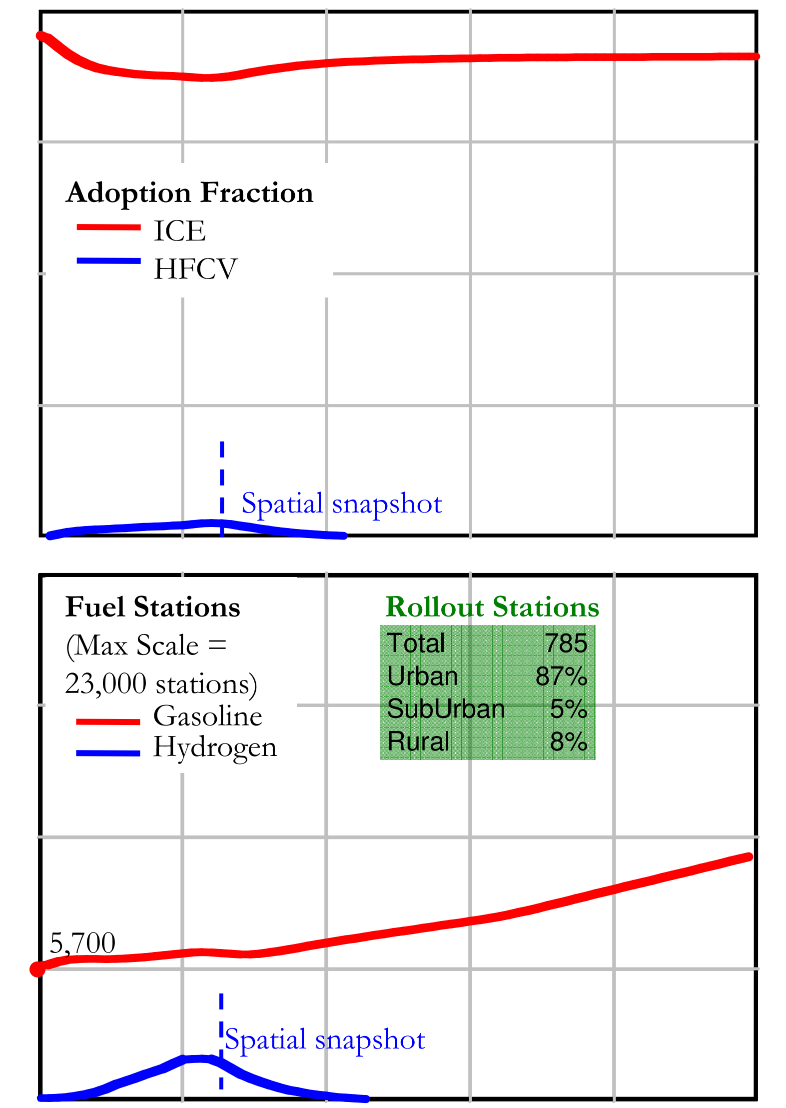


- **Topping off is individually rational when fuel availability is uncertain.**
- **But topping off lowers effective vehicle range,**
  - Increasing trips to and congestion at fuel stations
  - Increasing chances of "bank run" dynamics (gas lines and panic as in USA 1979, UK/France 2000)

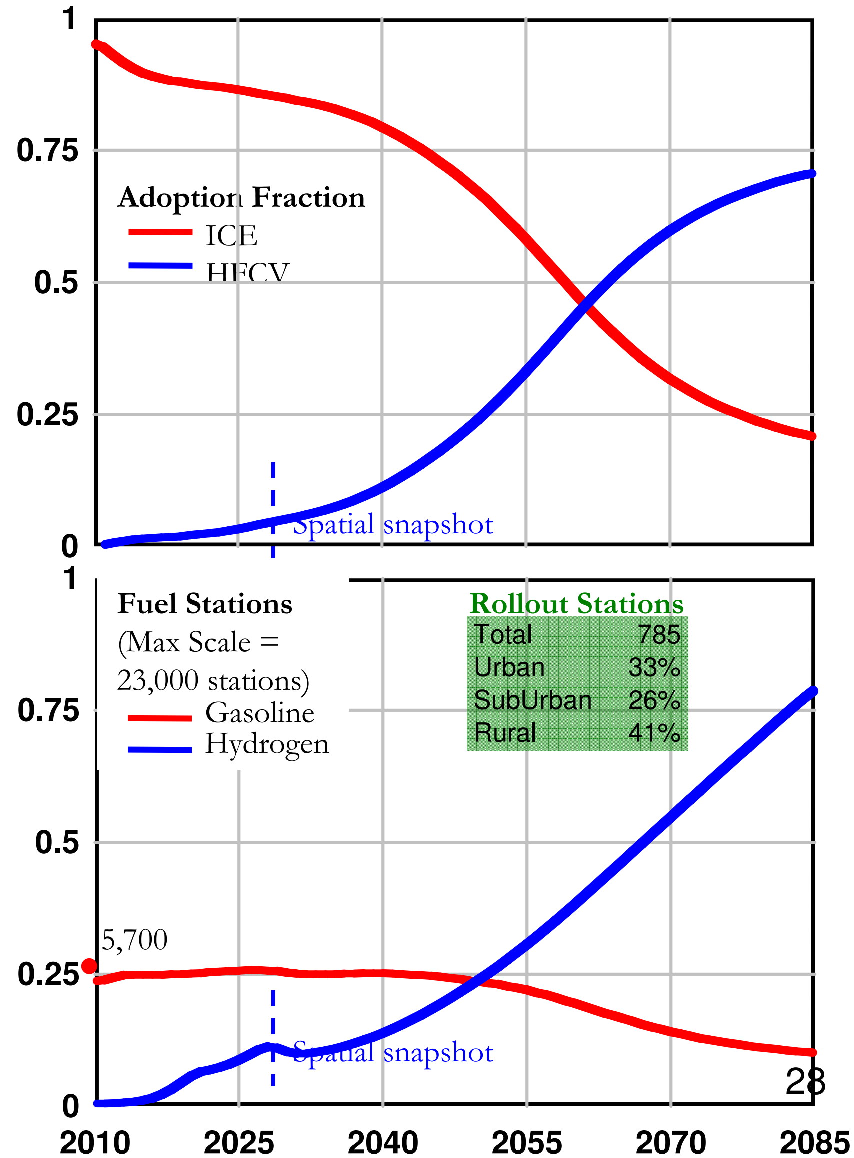
◊ **Result: Lower AFV attractiveness and adoption**

Successful Policy: Subsidize fuel stations in rural areas

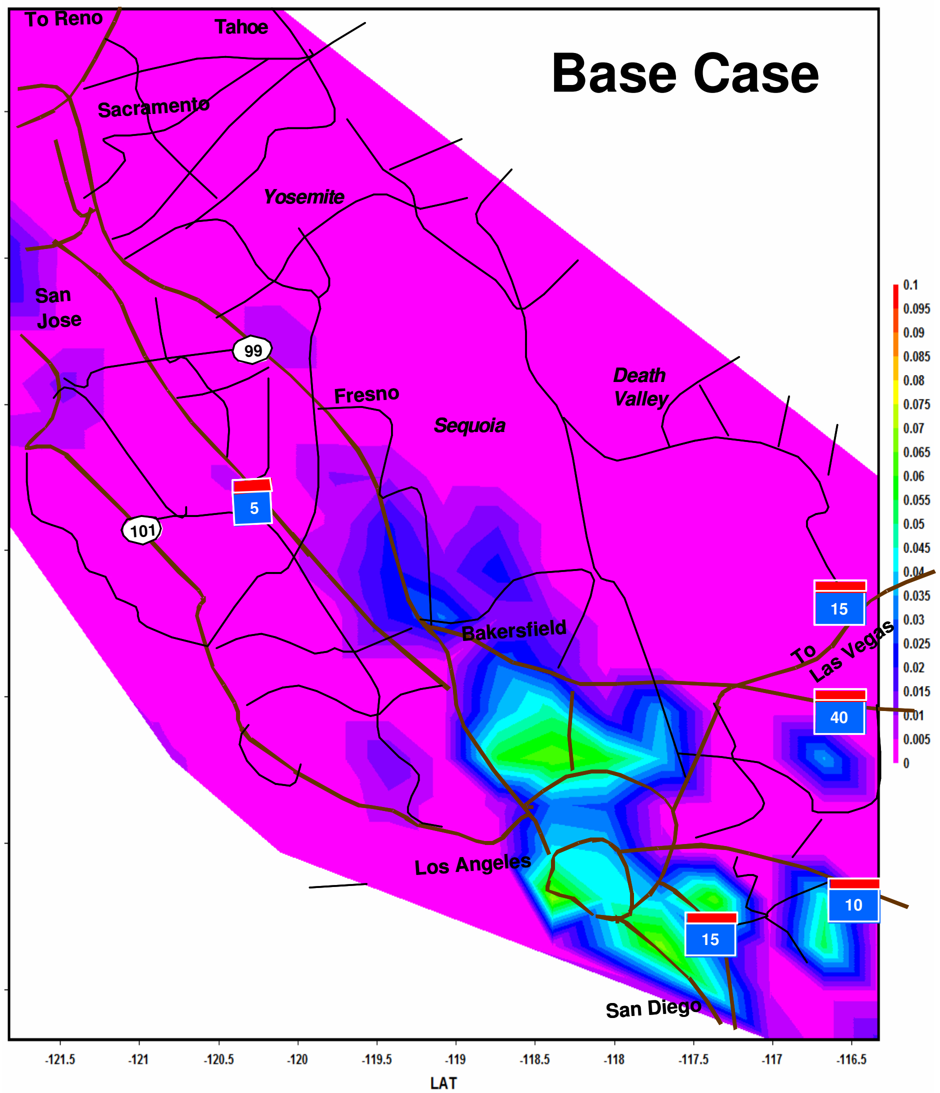
Base Case

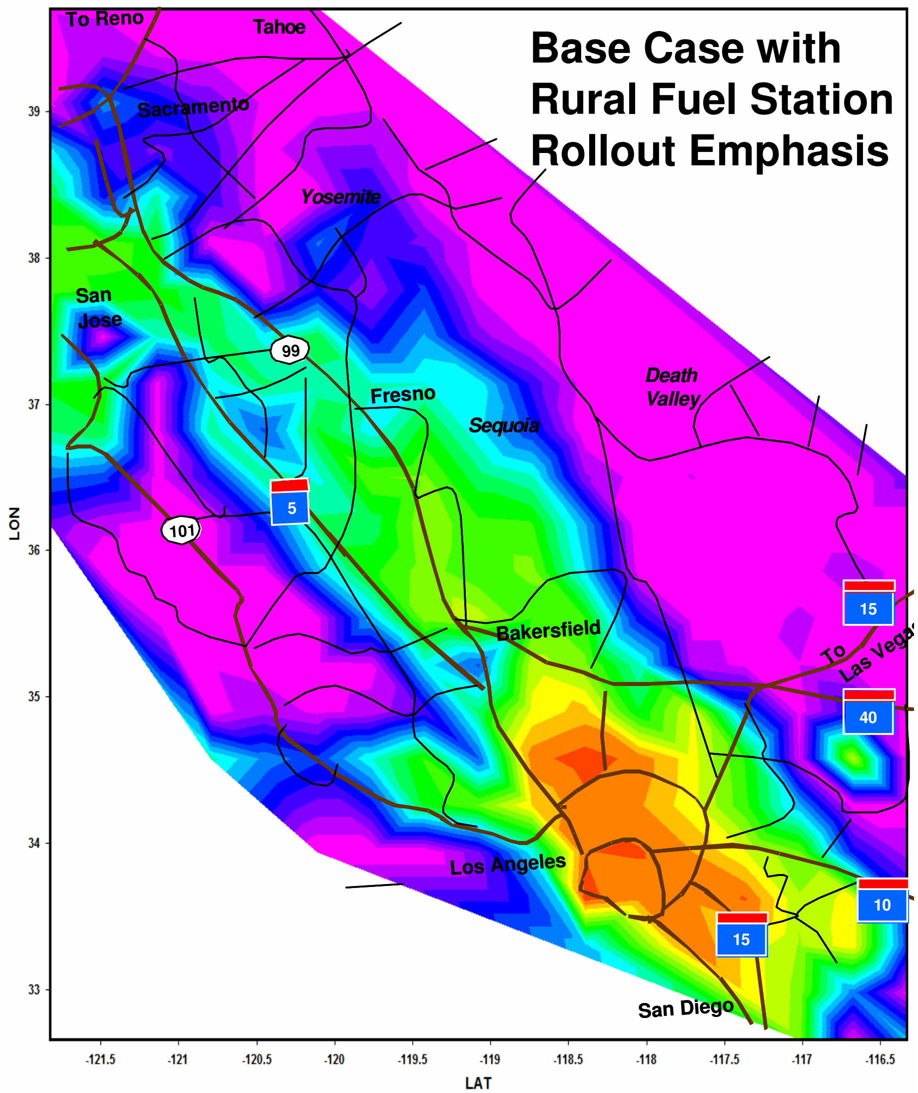


Fuel Station Rollout, Rural Emphasis

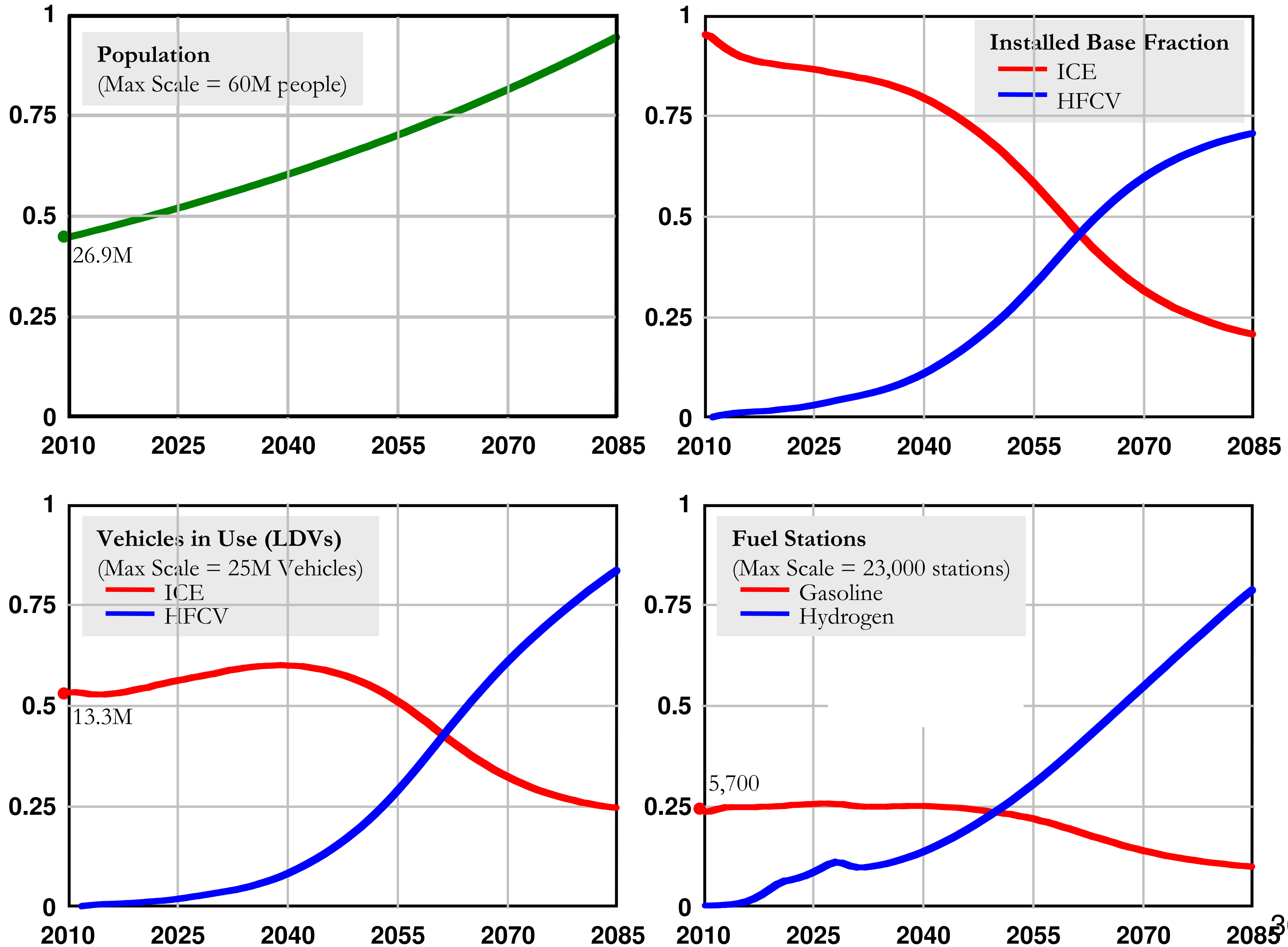


AFV Adoption Fraction in 2030

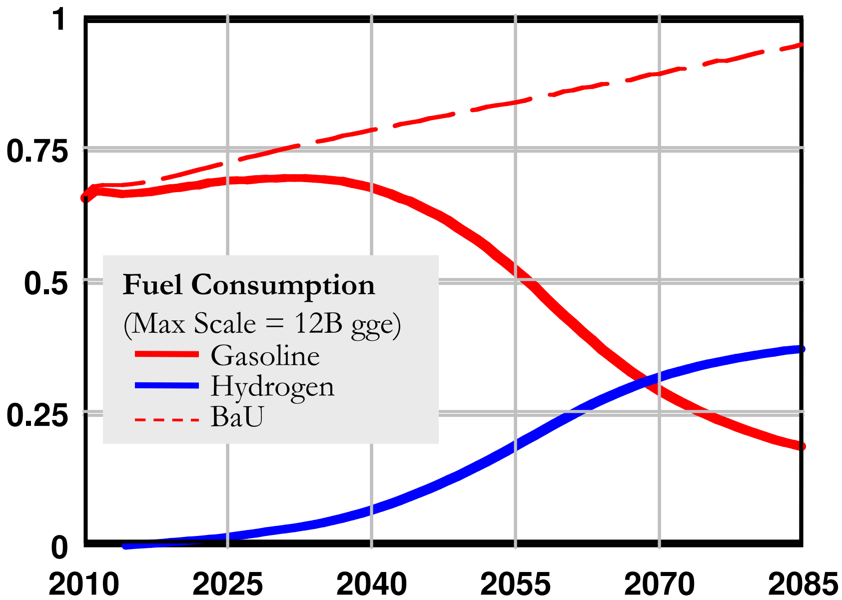


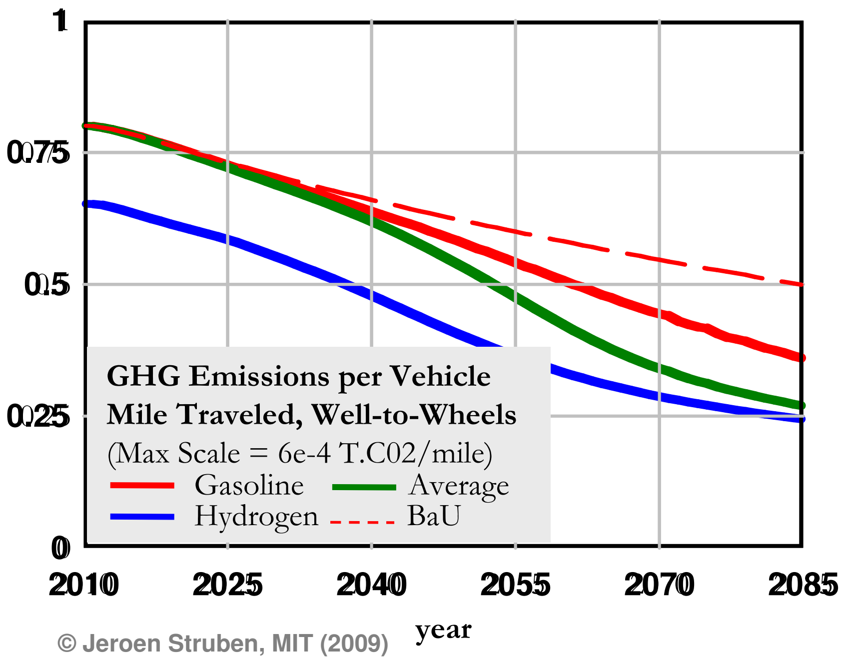


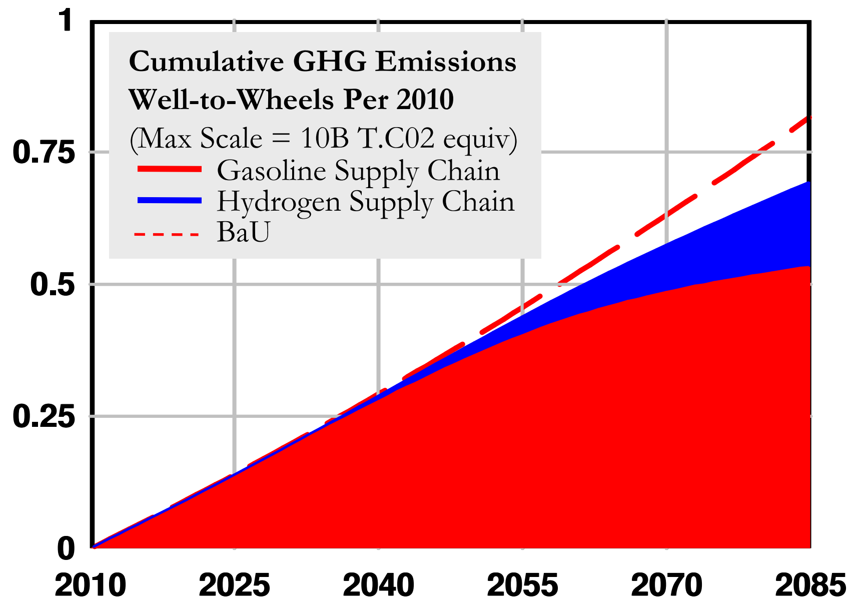
Successful Diffusion: Overview



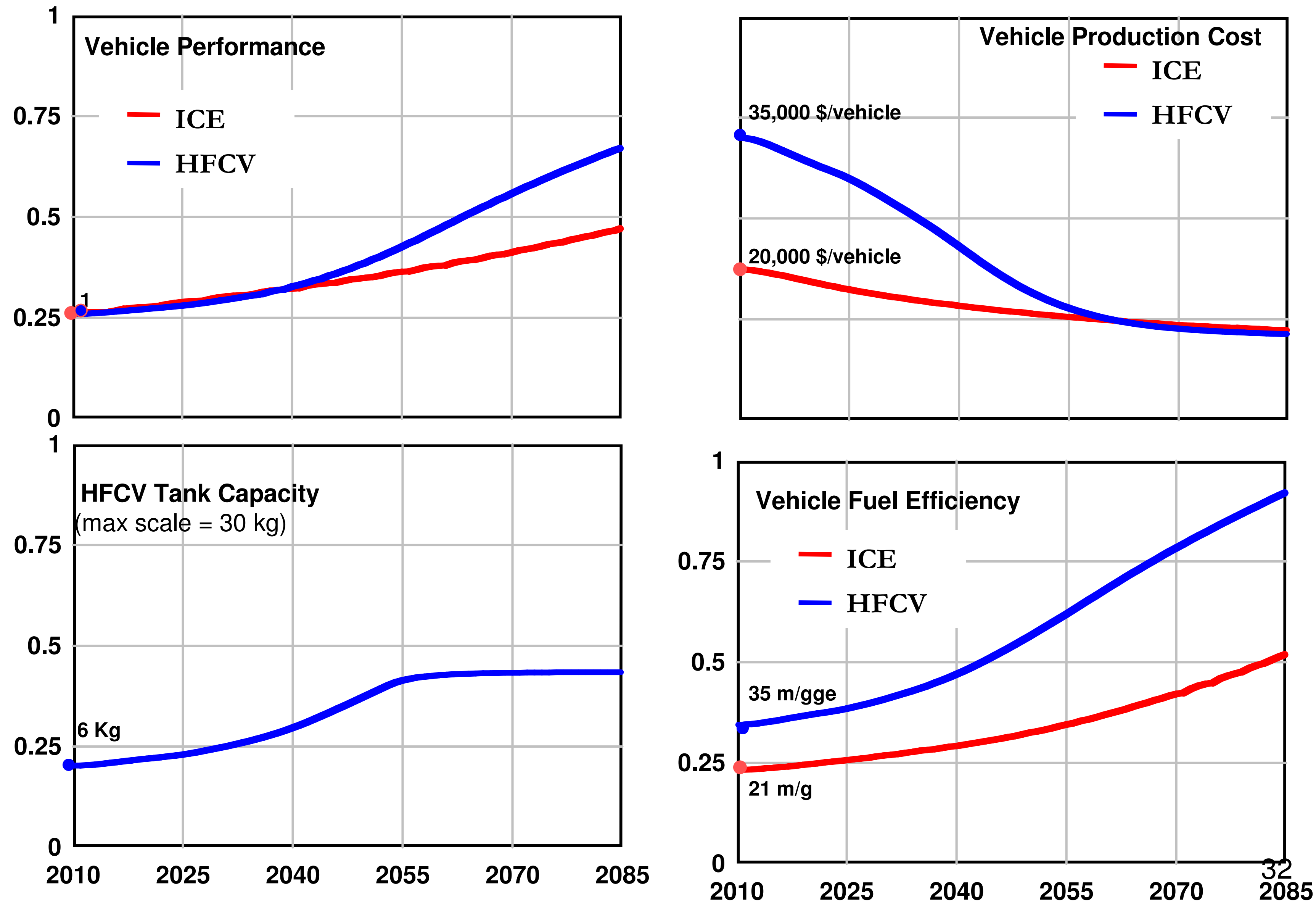
Fuel Consumption and Emissions



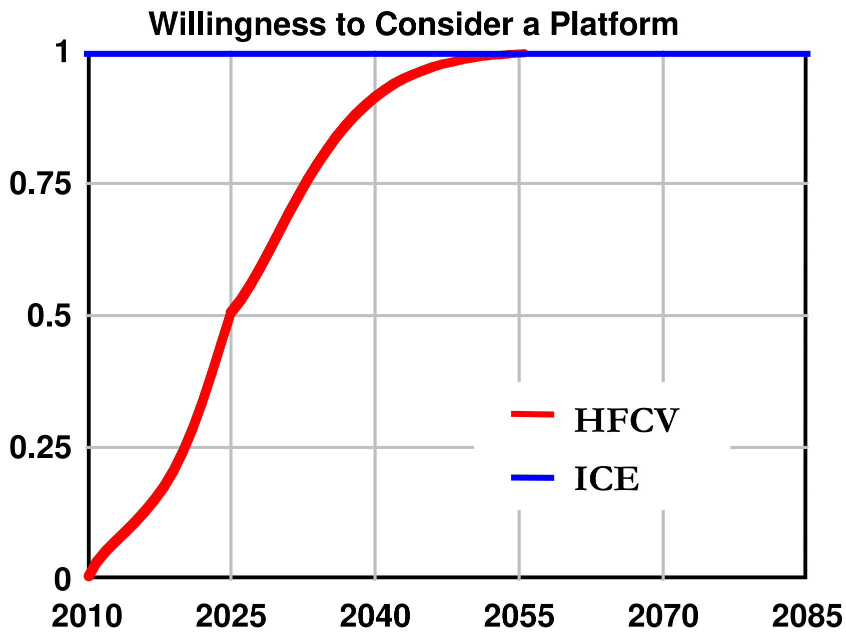


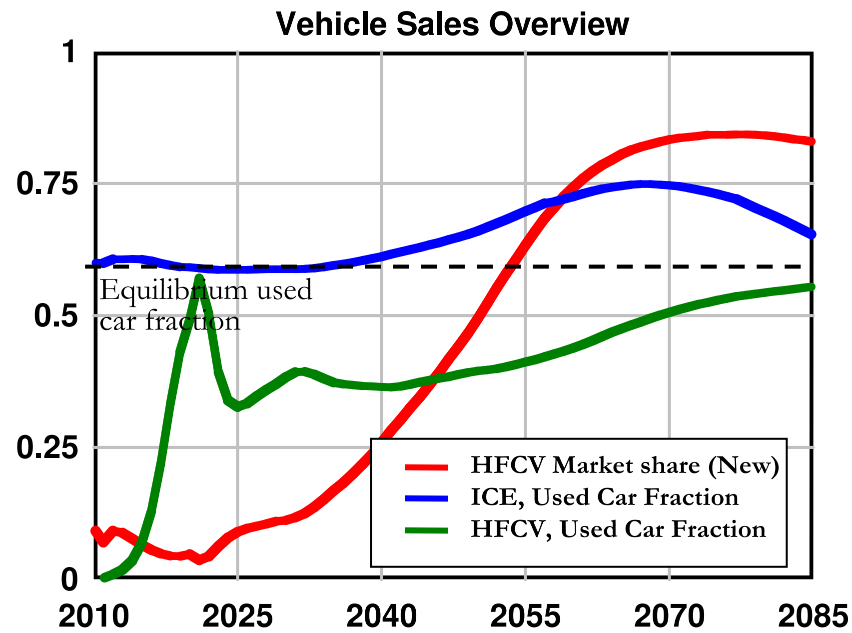


New Vehicle attributes



Consumer consideration and vehicle sales

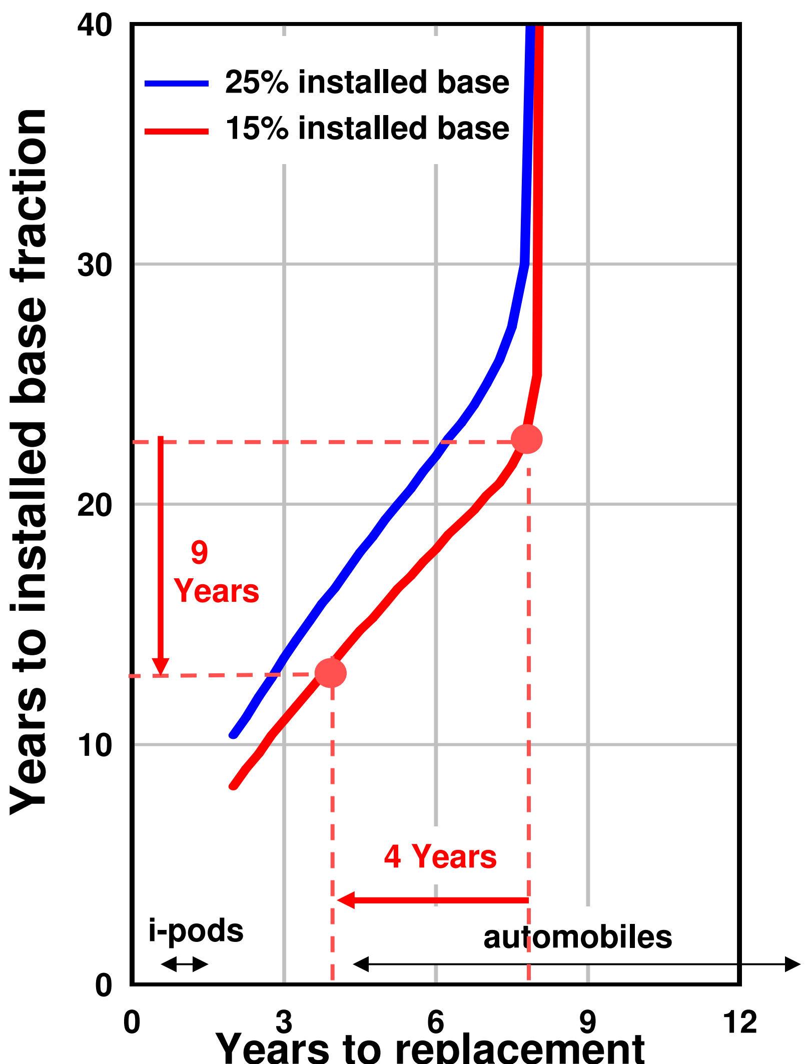




- Assumes aggressive, sustained marketing effort, demonstration fleet program to build awareness, increase consumer consideration of AFVs
- Surplus used conventional vehicles depress used car prices, delay AFV adoption
- "Cash for Clunkers" can speed AFV market success, stimulate new car sales

Experiment 2: Waiting for the oldies to retire: vehicle life strongly affects AFV adoption

AFV diffusion vs. average vehicle life

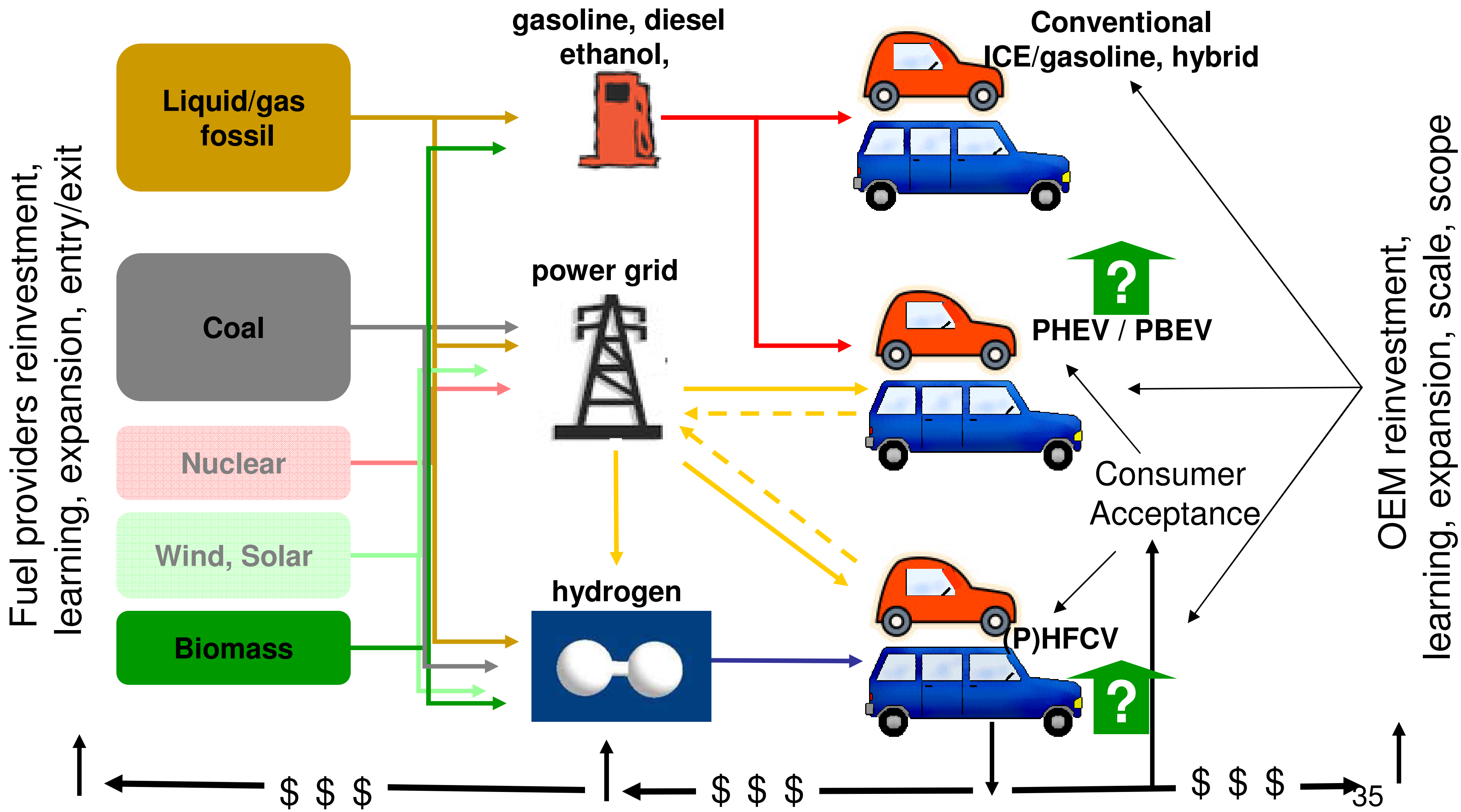


- **Market penetration increases rapidly with a reduction in the replacement time** (dynamics result from social exposure effects, infrastructure, technology learning effects ignored)

- **Policies that reduce the effective replacement rate of vehicles have a large impact on moving us over the tipping point: "Cash for Clunkers"**

- **IMPORTANT: "Clunkers" must not only be deregistered but shredded, with materials recycled. Cannot be sold into used markets in the US or other countries.**

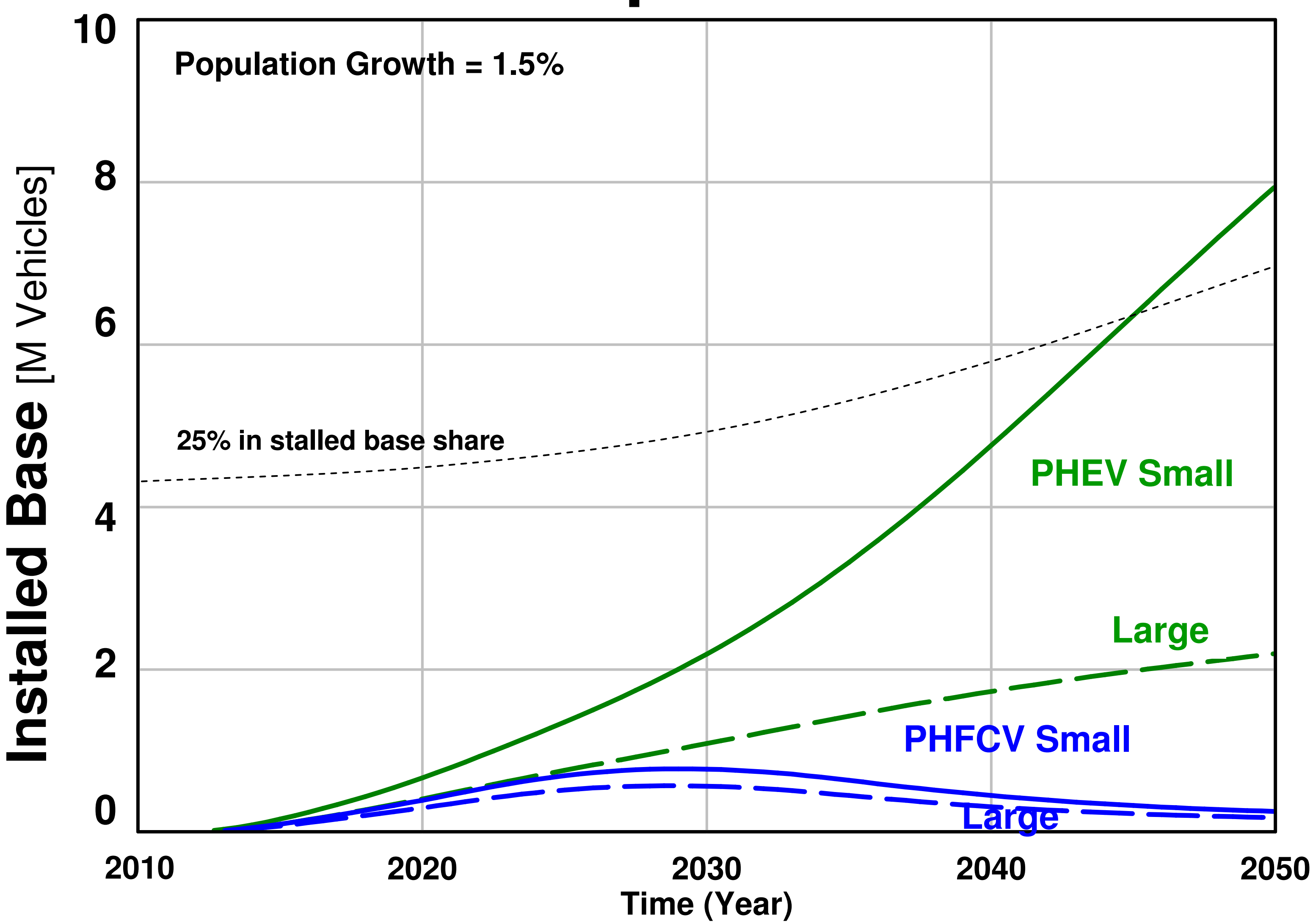
Experiment 3: Multiplatform Competition



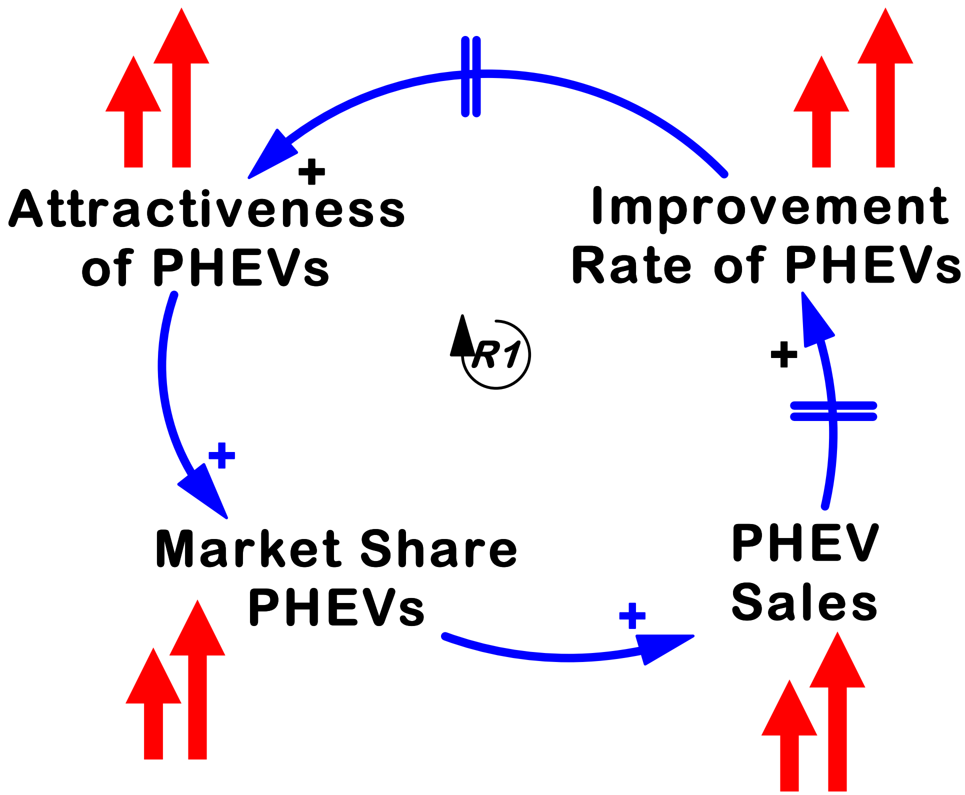
Exploring PHEV and PHFCV Introduction: Basic Assumptions and Data

- **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
- **Calibration from established data sources; fuel supply chain and (public) PHEV data from Ford and Shell Hydrogen**
  - For illustrative purposes: electricity predominantly derived from fossil inputs (coal, natural gas)

Installed Base Dynamics for Multiplatform Competition



Conditions favor successful PHEV diffusion



PHEVs use existing fuel infrastructure

Sustained diffusion through self-reinforcing learning, scale effects

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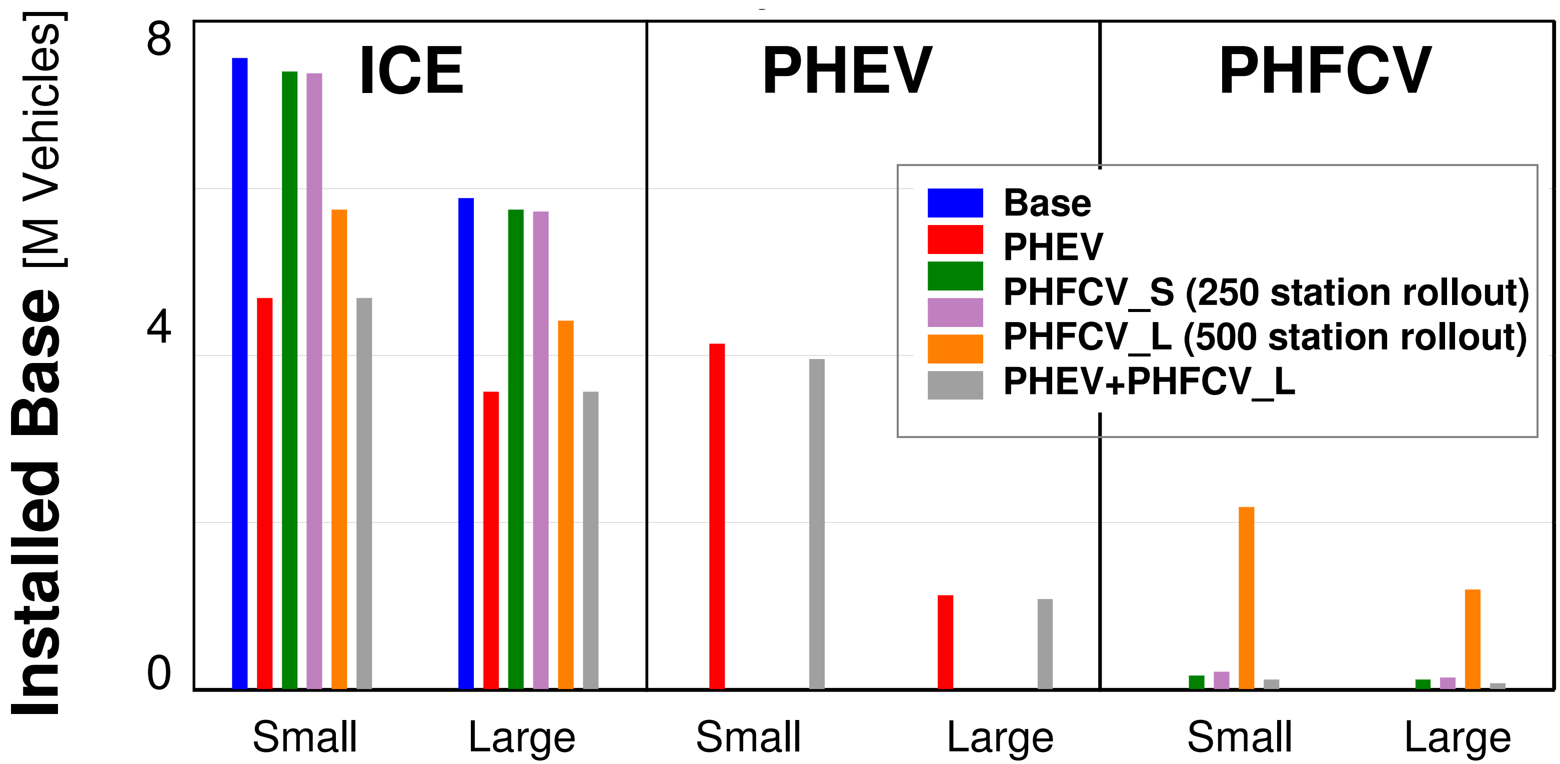
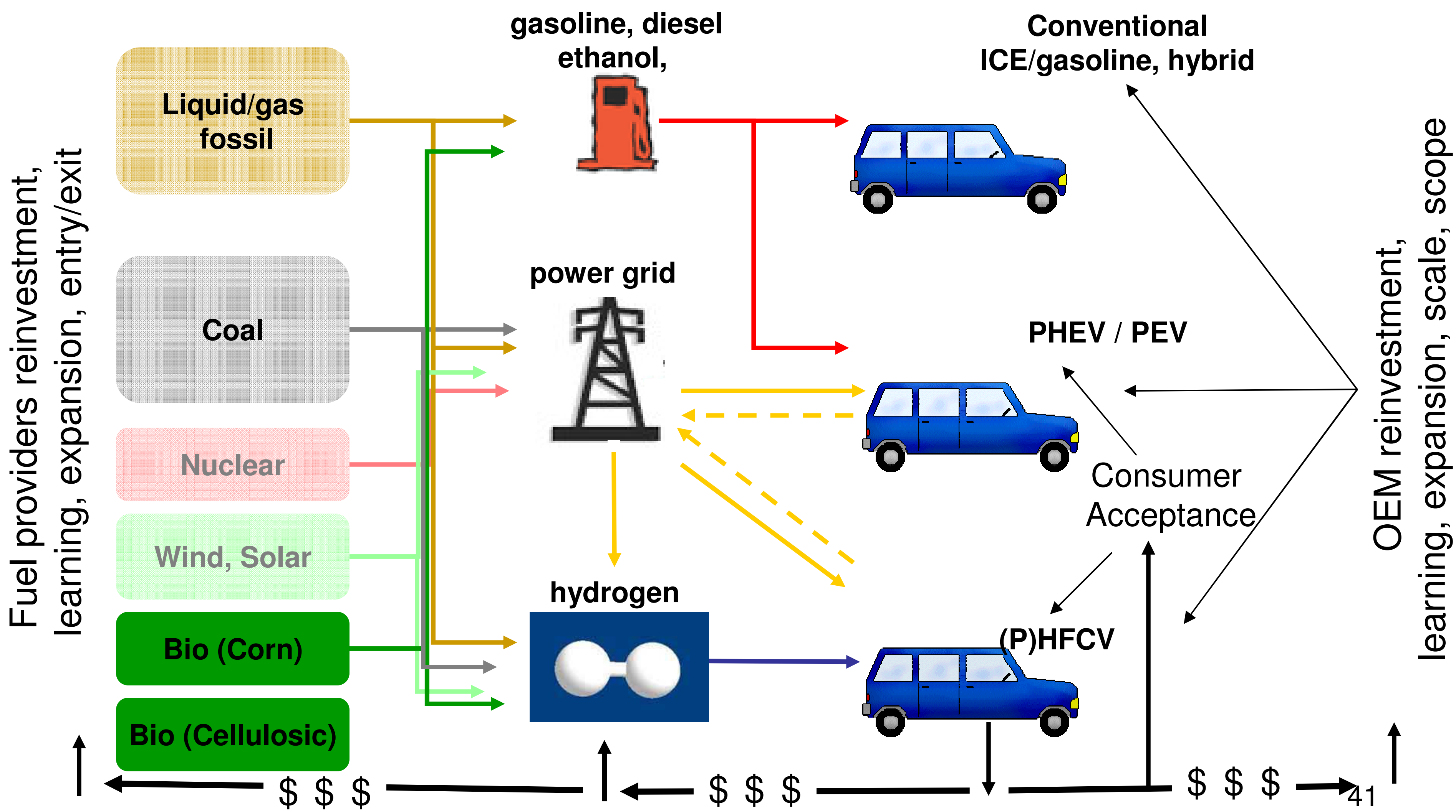
Platform Installed Base Distribution in 2050 for Different Competition Scenarios



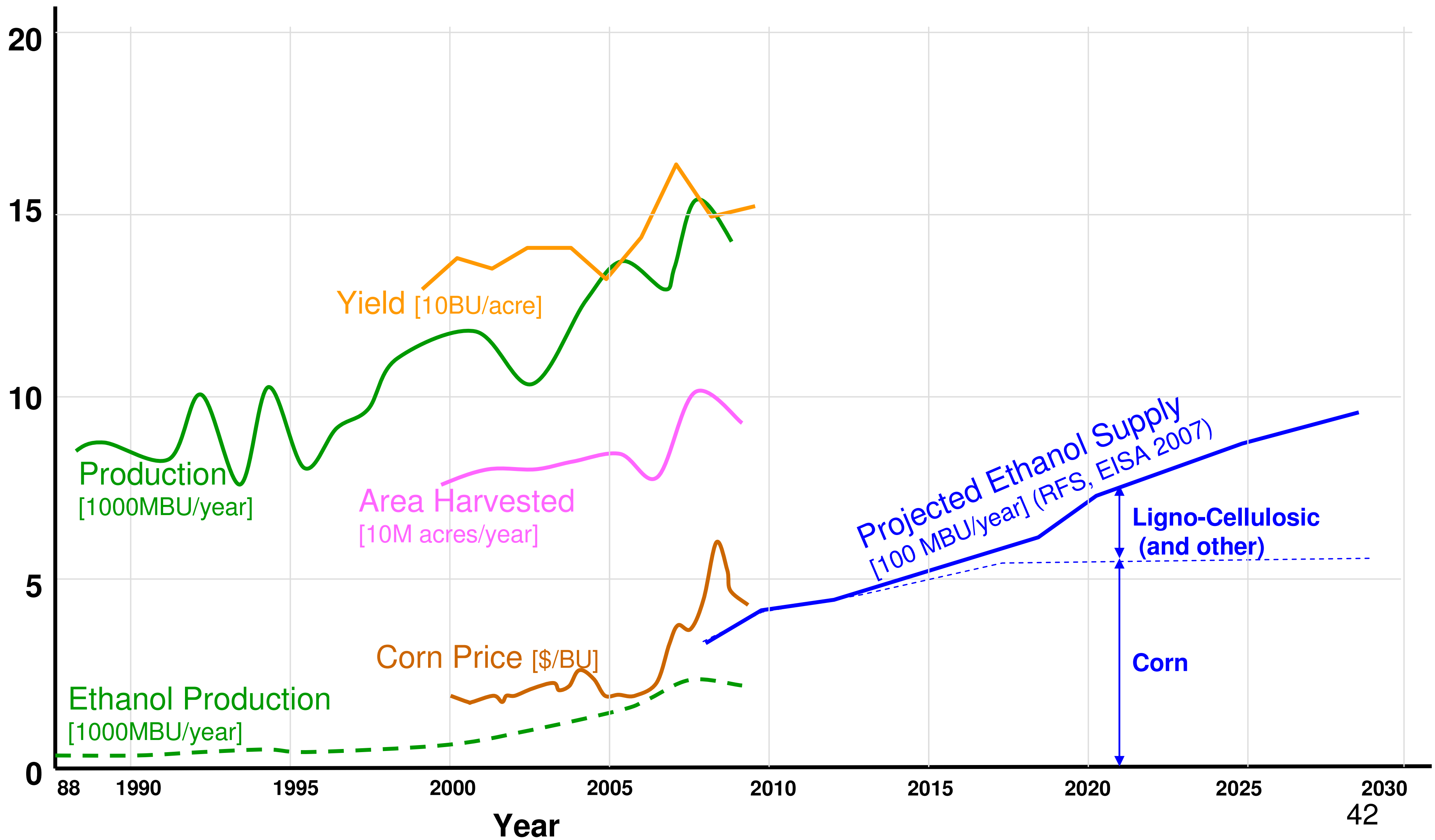
PHEV versus (P)HFCV Diffusion: Preliminary Insights

- **Simulations suggest a viable path to widespread, self-sustaining PHEV diffusion**
  - PHEV has advantages relative to e.g. HFVC:
    - Fueling infrastructure already deployed; can transition to carbon-neutral via biofuels
    - Self-sustaining diffusion much easier to achieve
  - Nevertheless, diffusion is slow, consistent with history of other automotive technologies
  - Significant investment still required to pass tipping point
    - Marketing; consumer acceptance
    - Cost reduction and reliability improvement through learning, R&D, scale
  - Nontrivial risks:
    - Technical (e.g. battery reliability)
    - Economic (cost)
    - Social (willingness to consider)

Experiment 4: Biofuel Pathways



US Corn Production and the Renewable Fuel Standard Projection 1988-2030



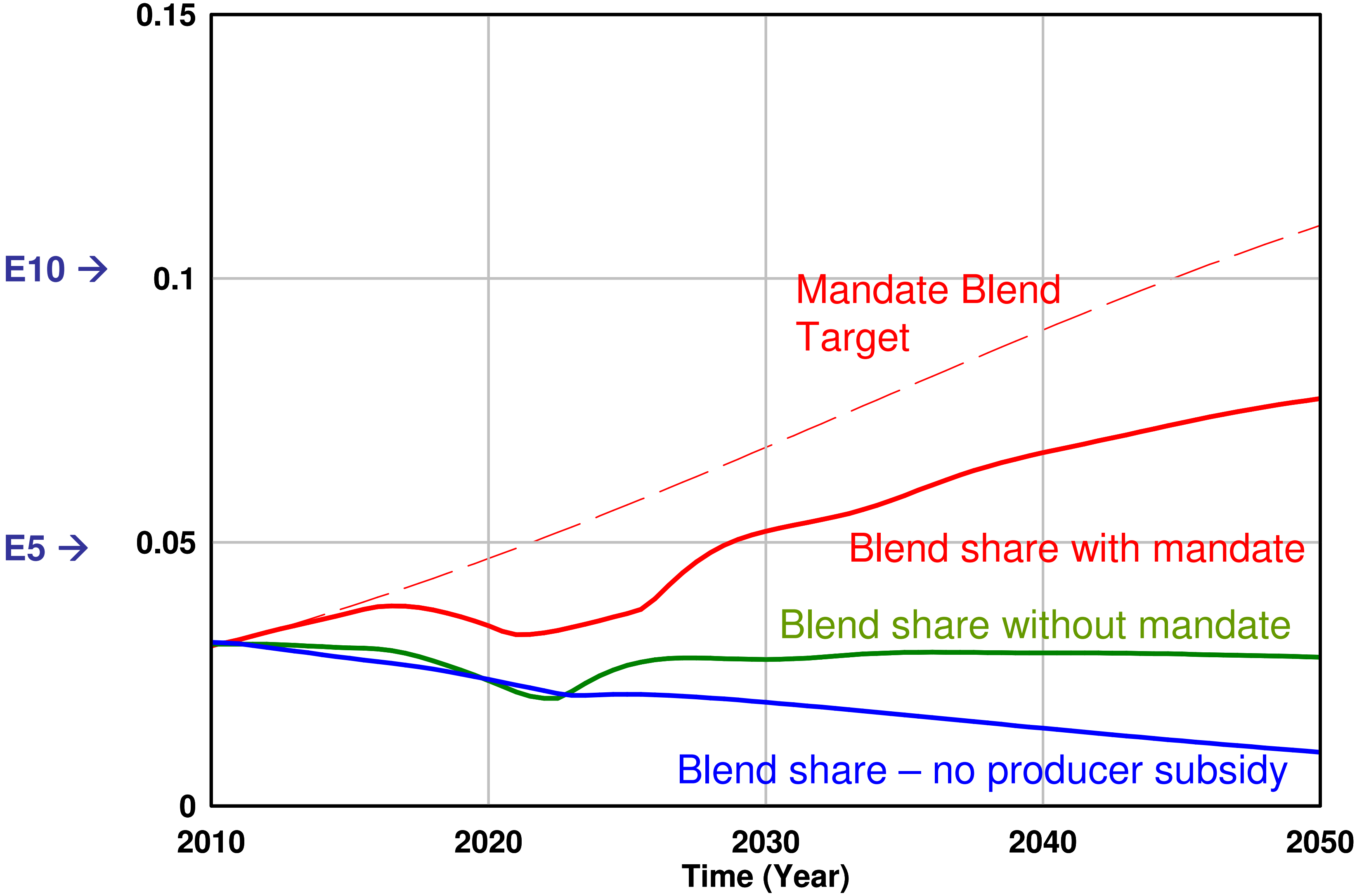
Source: USDA (ERS; 09-09 based on ProExporter Projections); Tradex; Renewable Fuels Association, EISA 2007

Biofuels Experiment, Main Assumptions

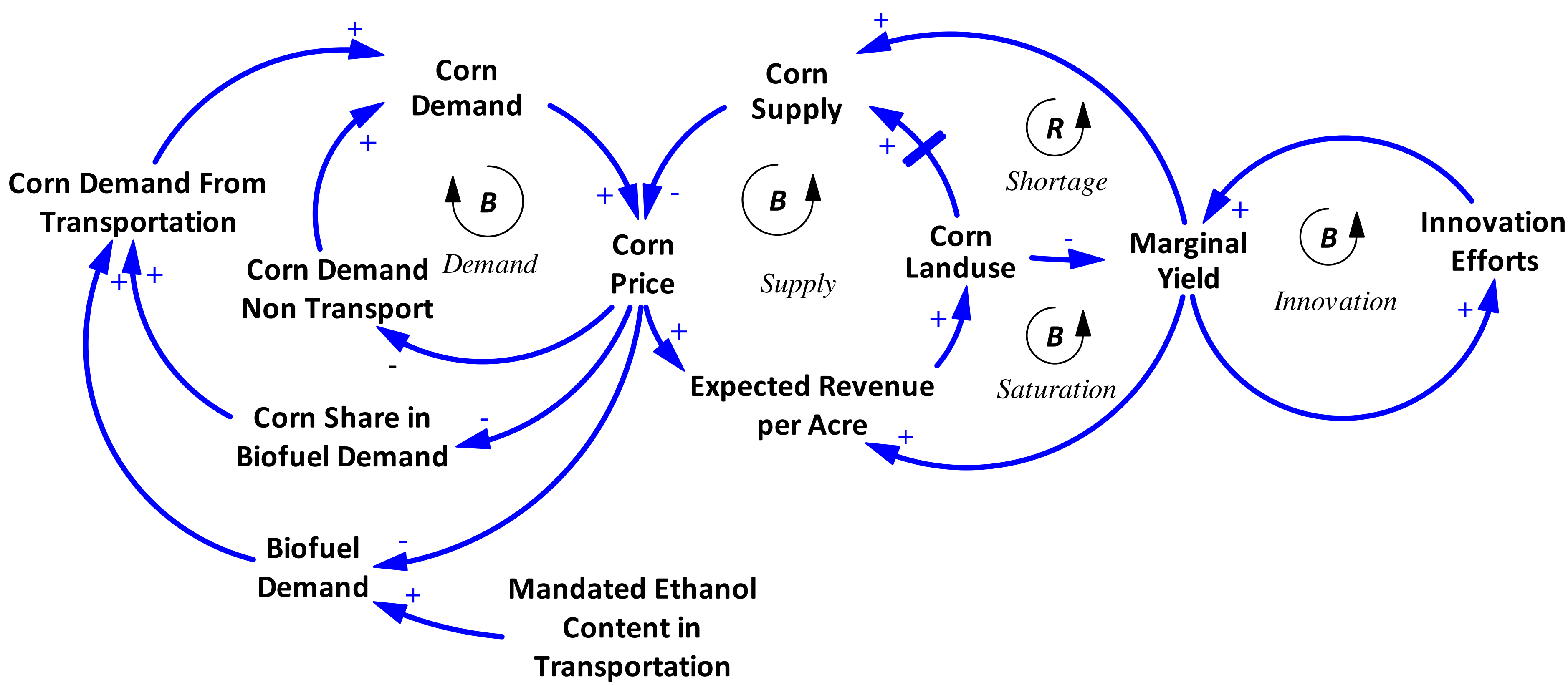
- **Crop yield grows with 1% per year**
- **Fleet grows, new conventionals are 100% FFV**
  - As well as full awareness by their drivers etc..
- **Market conditions**
  - Mandate is pursued by indicated blending level that changes over time. Producers understand demand as indicated by mandate.
  - Ethanol production for blending and E85 is market driven, but producers receive 50c/gallon subsidy
  - Corn price start in equilibrium at 4.5 $/Bushel
  - Initialized and calibration to US corn land use, yield, price and production data
- **Demographics:**
  - Population growth 1.5%
  - CA to US extrapolation to examine fuel demand impact
- **Timing of 2G Biofuels depends on scenario**
  - One scenario (2G 2015) involves highly optimistic successful availability for commercialization as of 2015 (after which 2G market performance depends on endogenous scaling up and improvements by learning)

Experiment is for qualitative interpretation only!

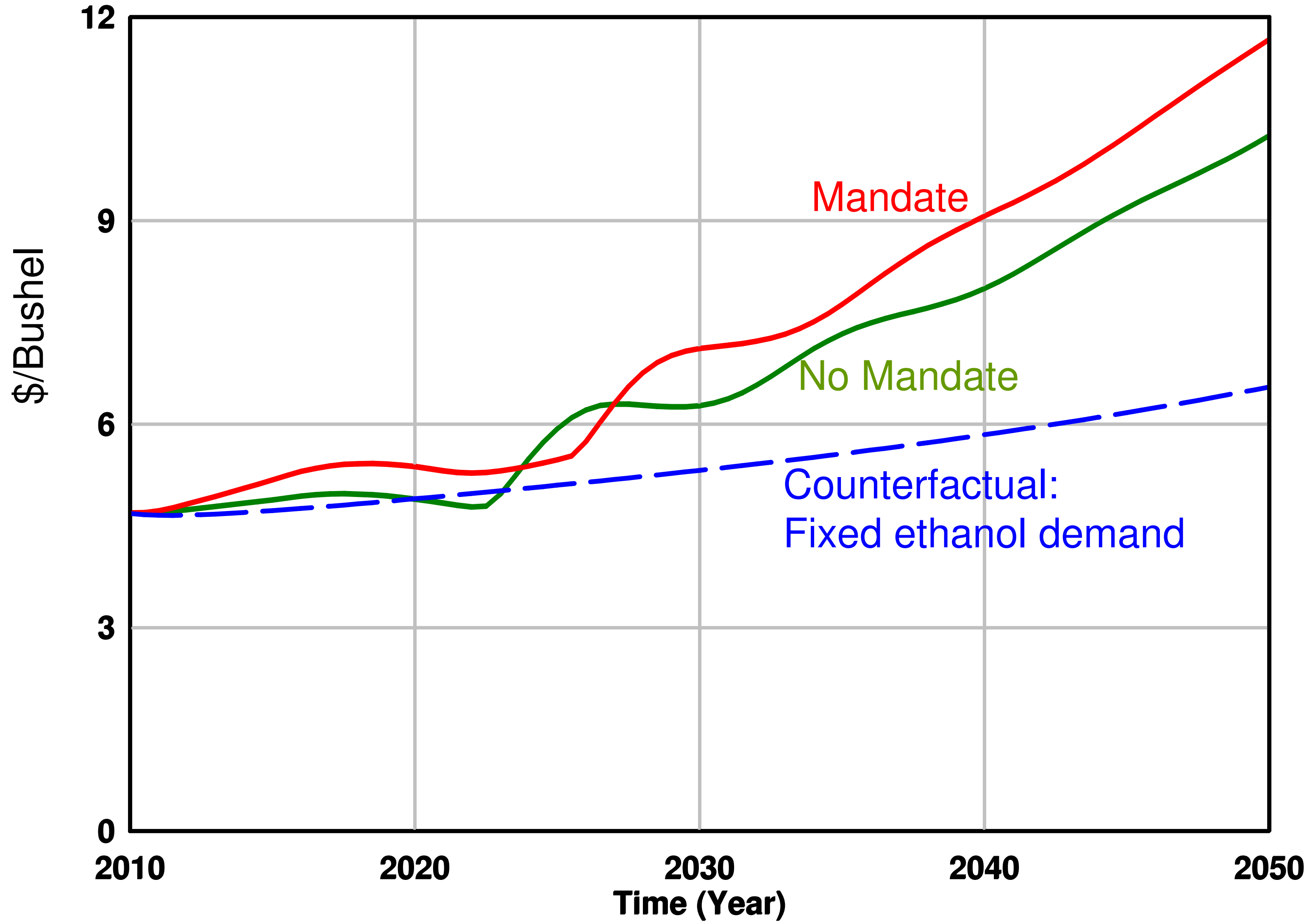
Ethanol (Energy) share in gasoline blend



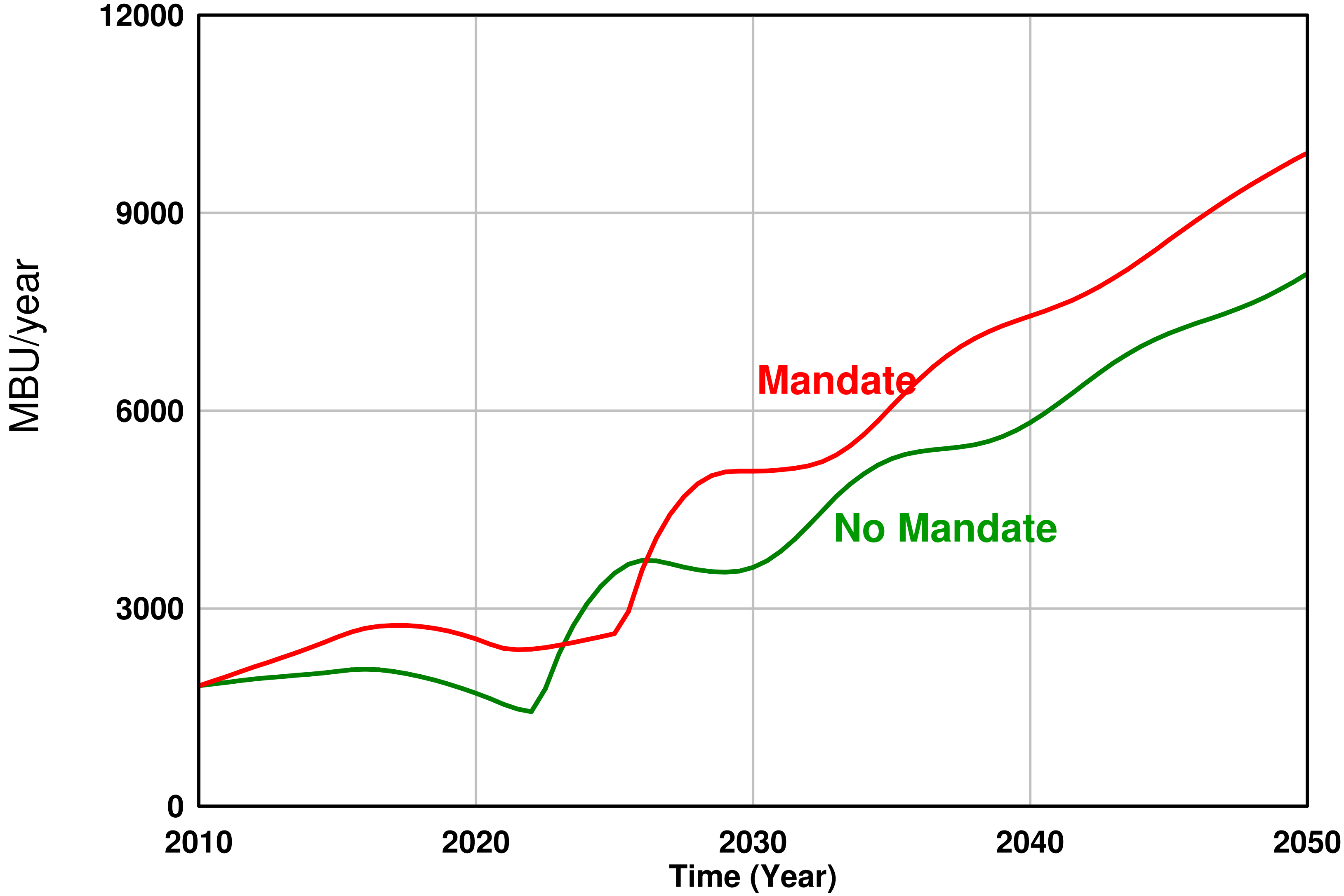
Principle feedbacks of corn price dynamics



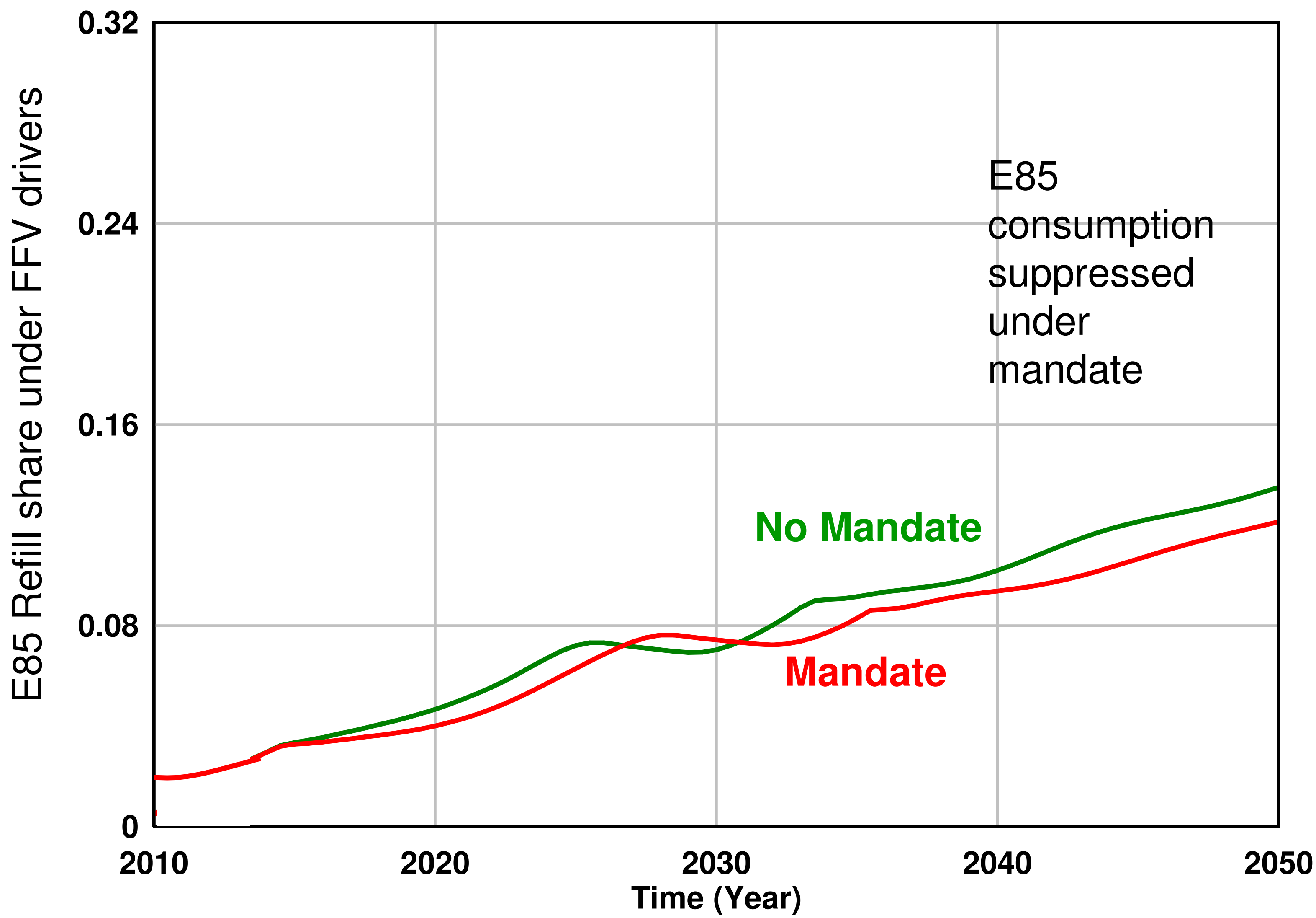
Corn Price under Mandate



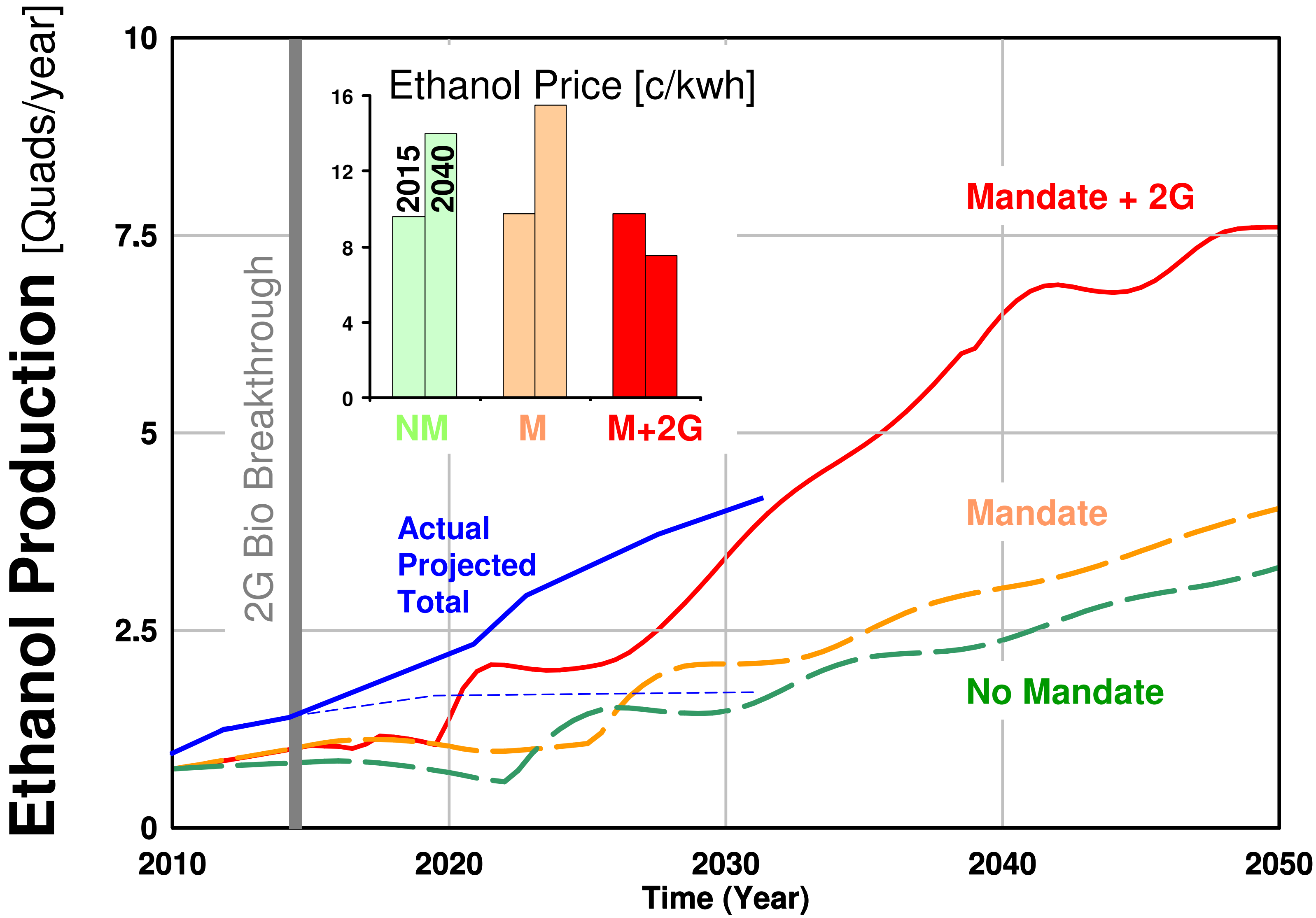
US Corn Demand for Transport Biofuel



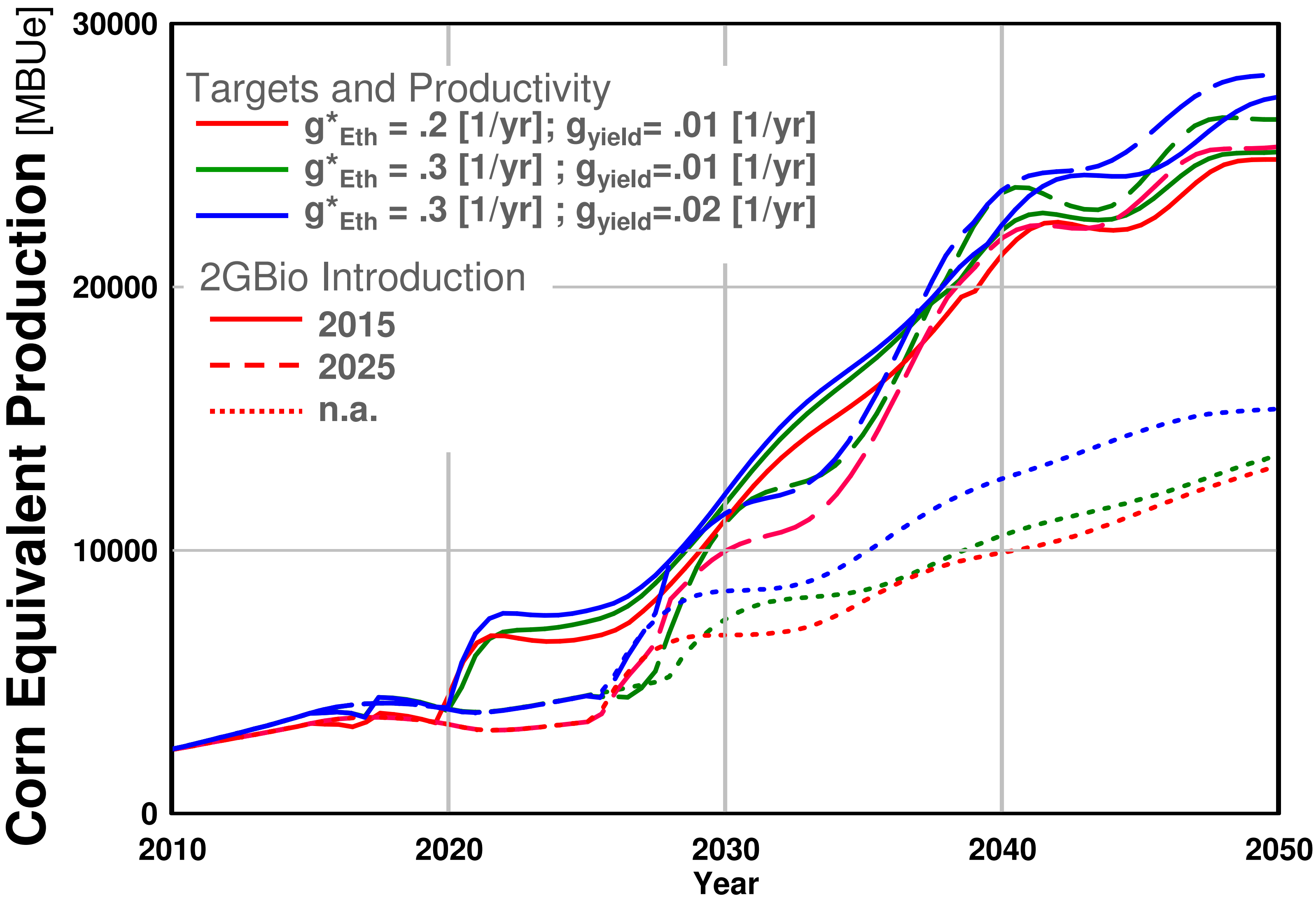
E85 Prevalence for Flex Fuels



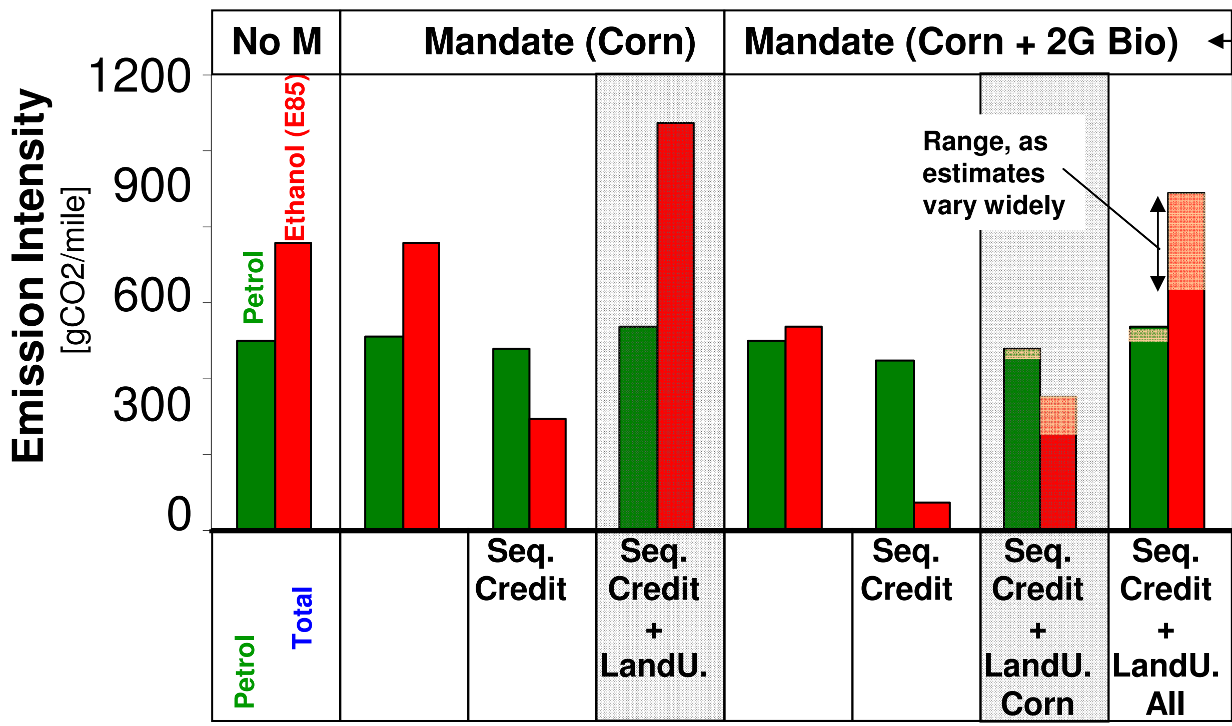
Total US Ethanol Production



Sensitivity Analysis: Biofuel Production



Example Scenario Impact on GHG Emissions (2050) (No Carbon Pricing)



Note: Corn / 2G bio mix in ethanol evolves over time, depending on market conditions

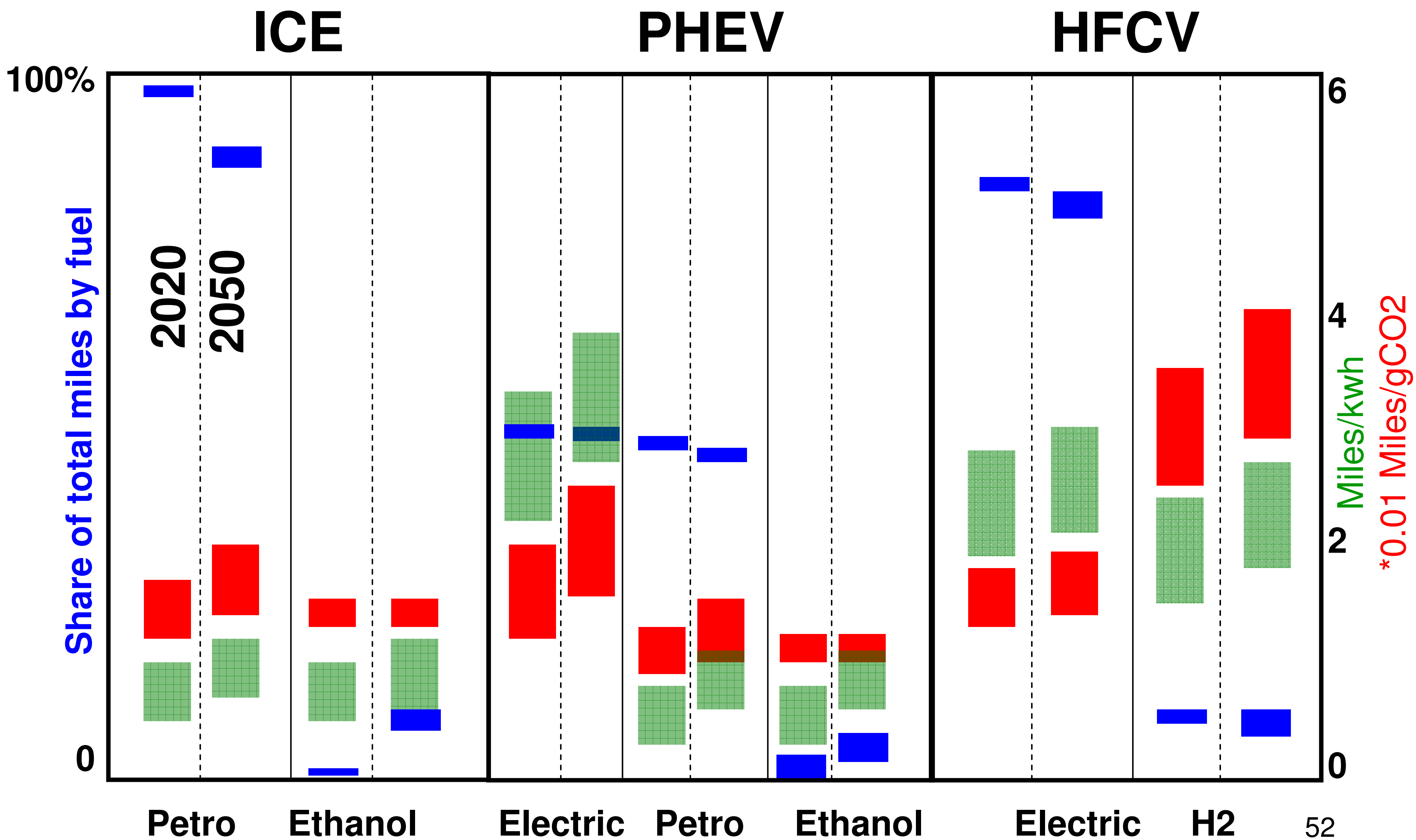
Current Main Sources:

- Tilman et al. 2006
- Searchinger et al. 2008
- Fargione et.al. 2008
- EPA 2009

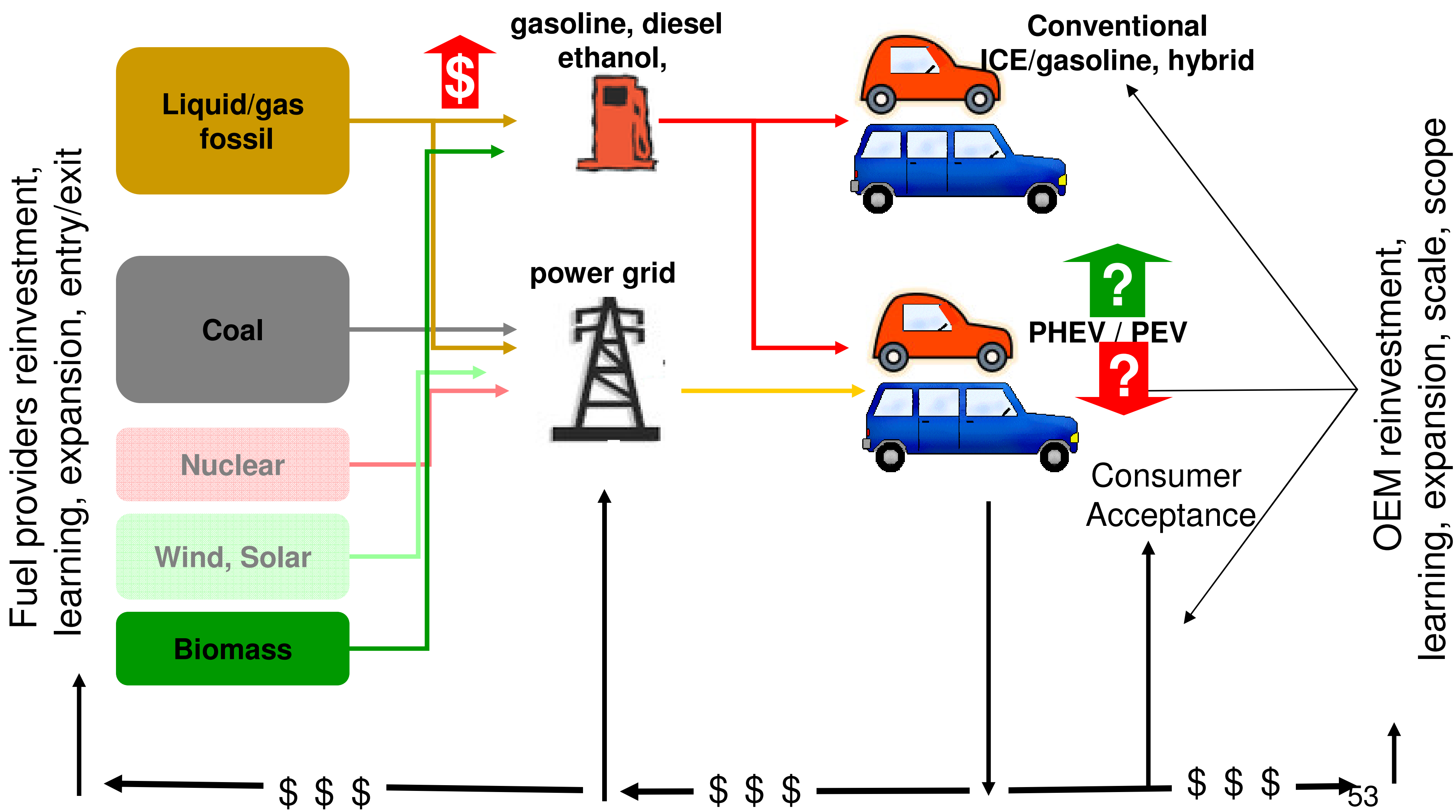
We perform scenario analysis, with different emission intensities throughout the fuel supply chain, using inputs from multiple expert studies. Note that 2G biofuel estimates in particular vary considerably

Fuel Choice and Efficiency by Platform

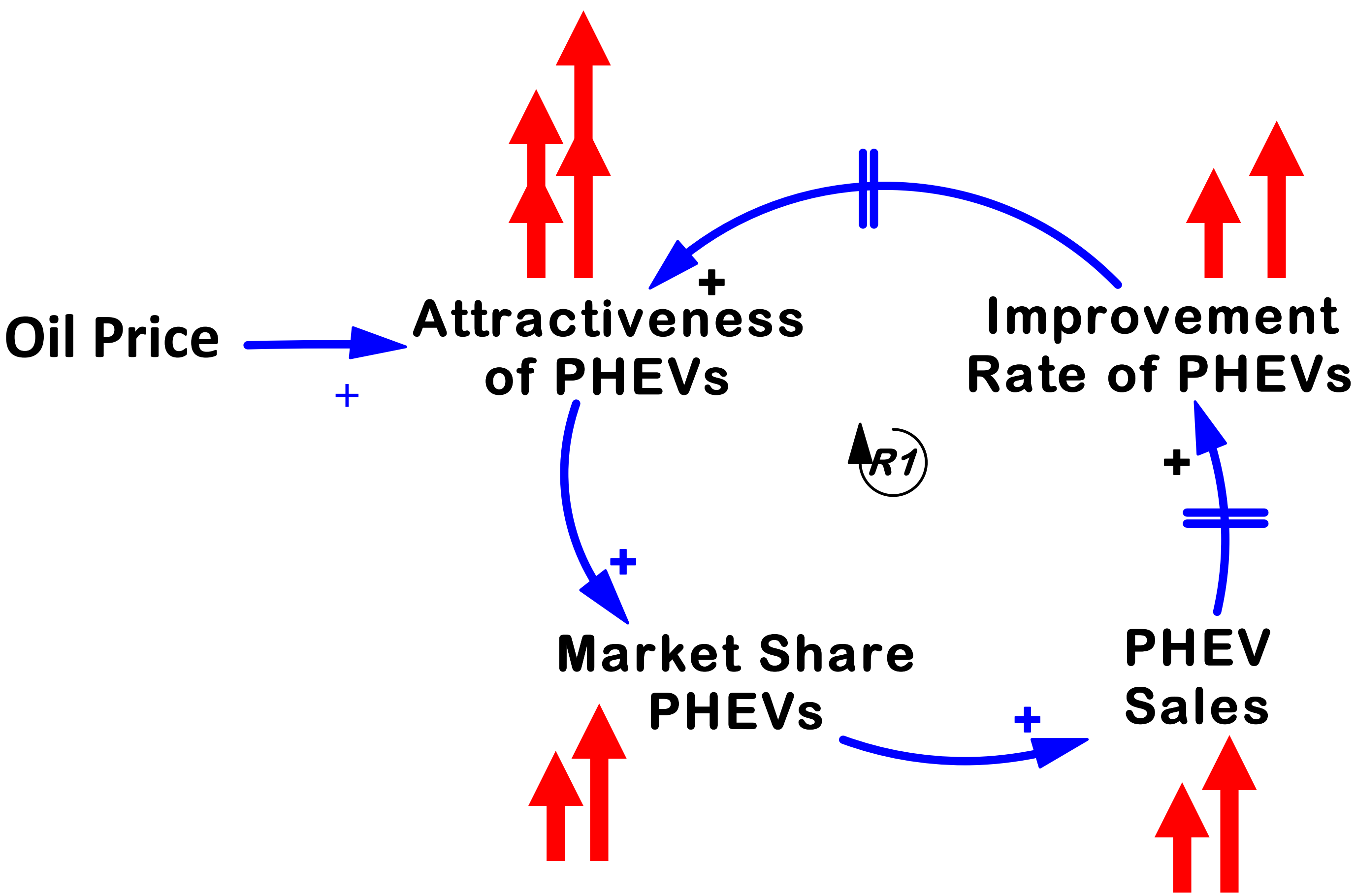
Scenario: Seq.Credit, LandU., No 2GBio



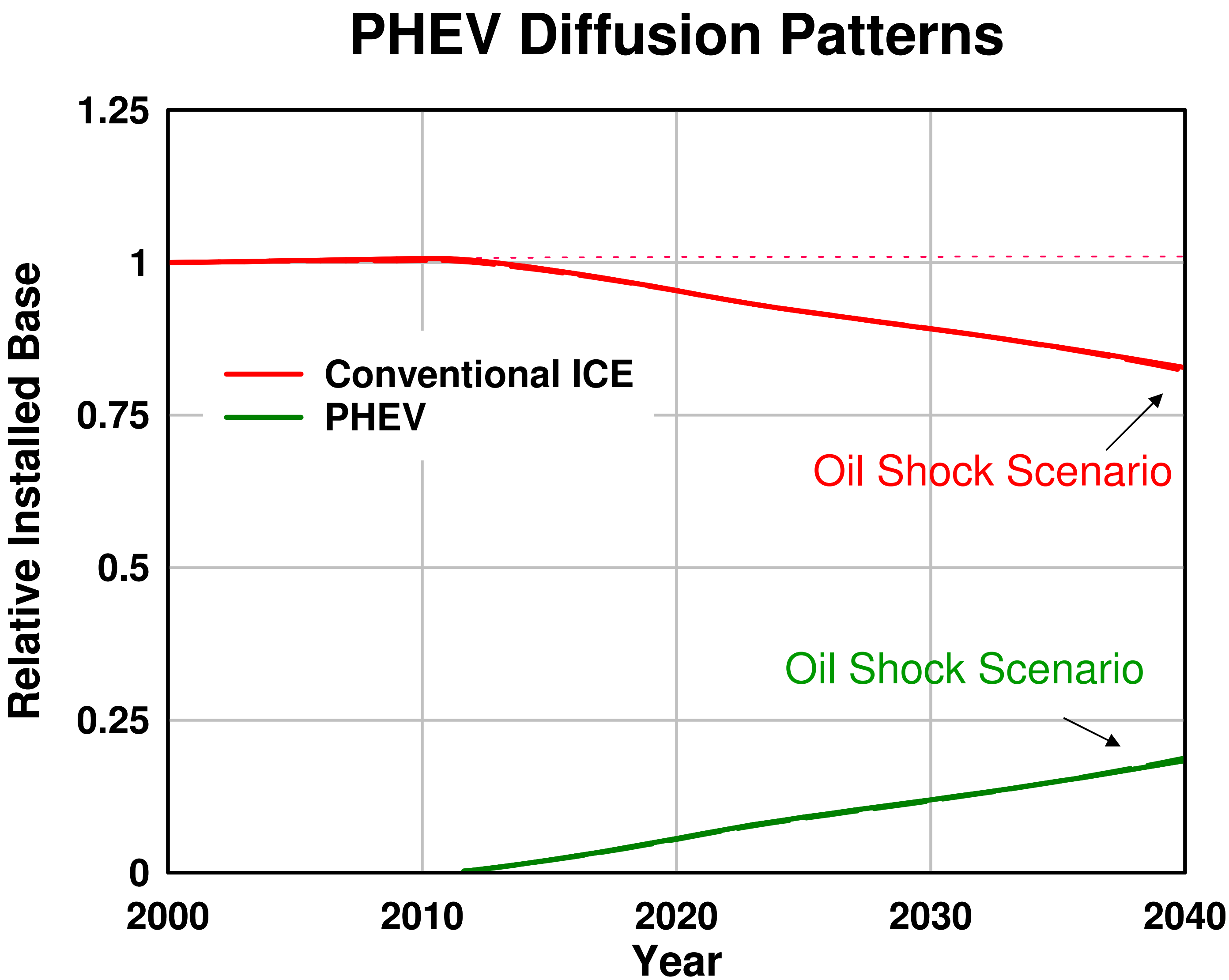
Experiment 5: The Effect of Oil Shocks on PHEV Diffusion



Hypothesis: Higher oil prices improve relative attractiveness of PHEVs

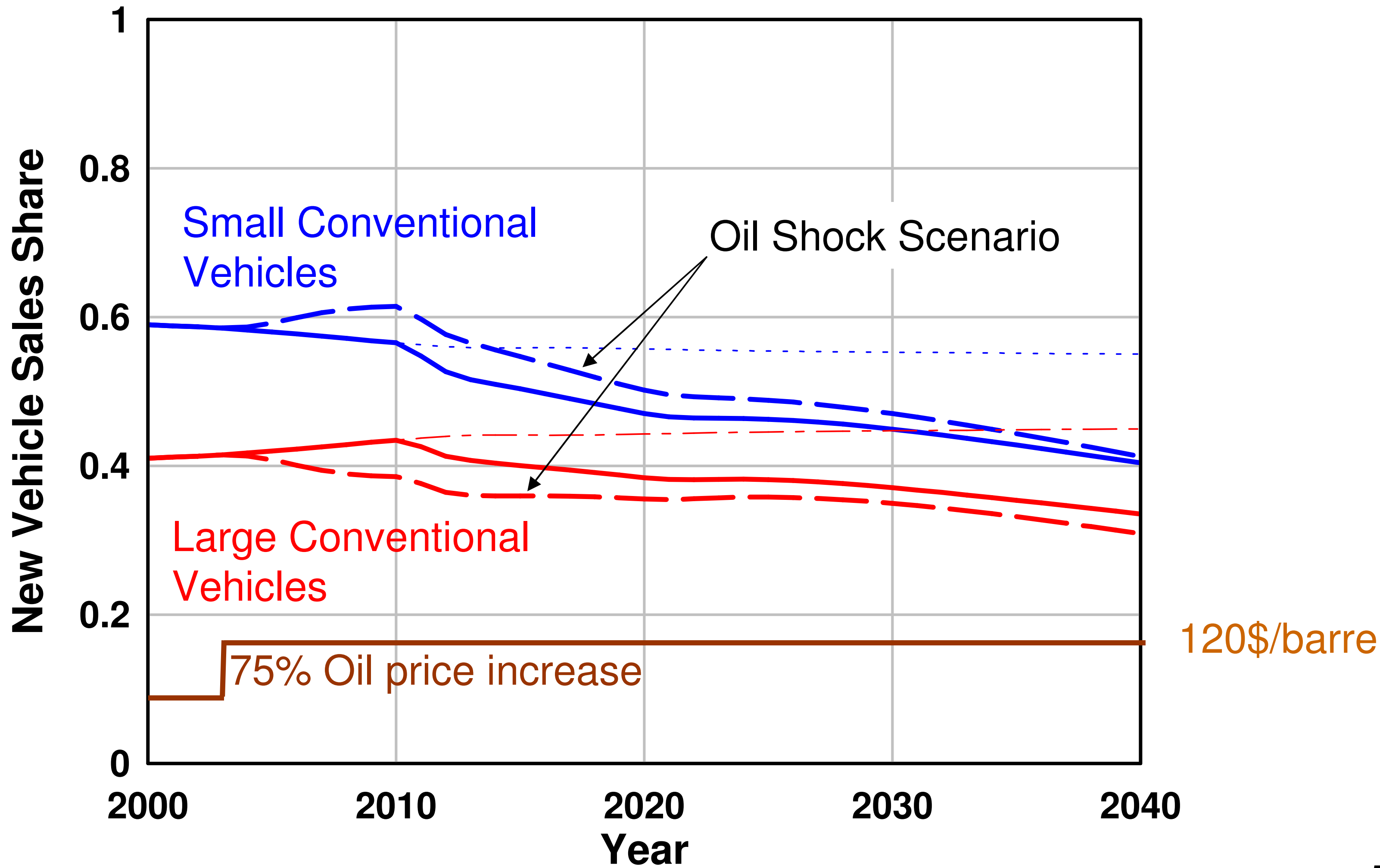


By strengthening self-reinforcing learning, and scale effects



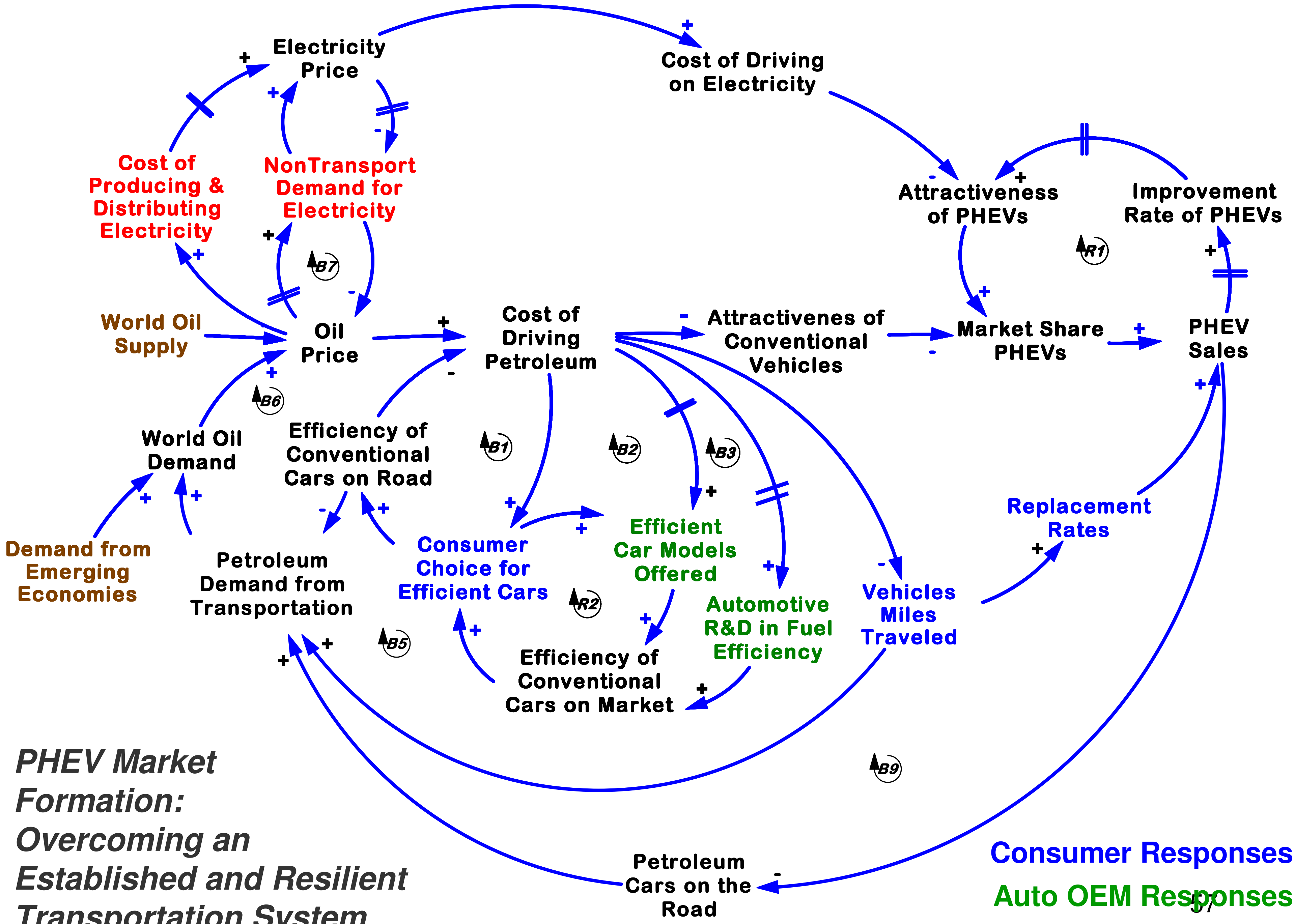
Actual Effect: Negligible!

Higher fuel prices lead consumers to choose smaller, more efficient vehicles



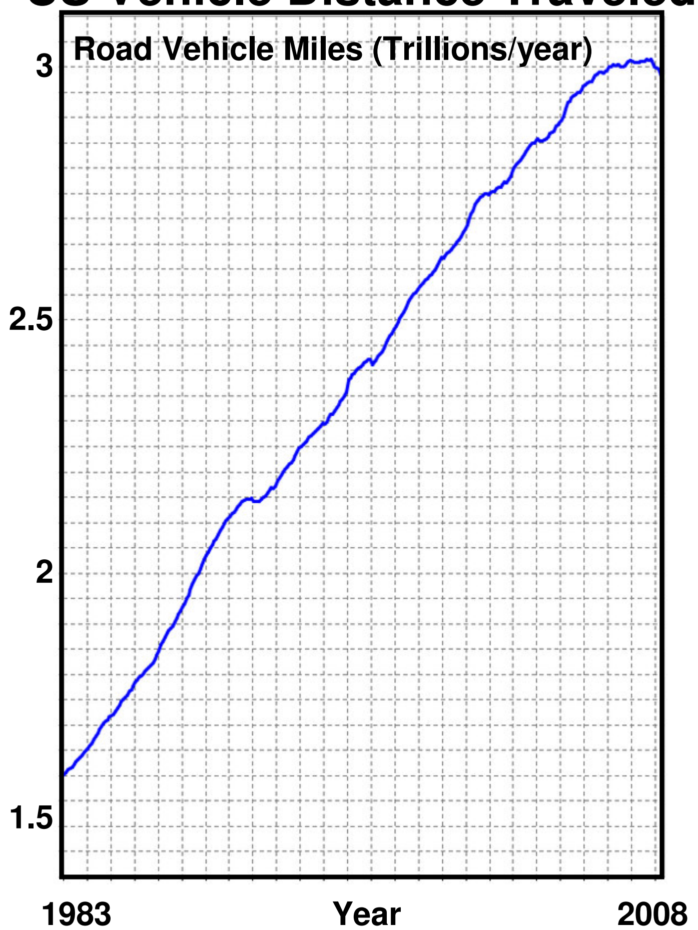
And there is more…

PHEV Market Formation: Overcoming an Established and Resilient Transportation System

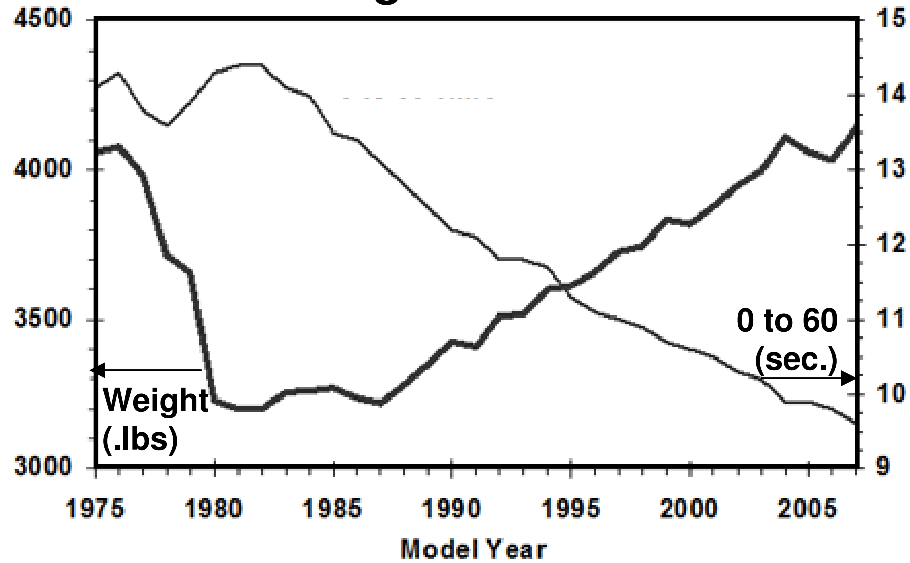


Behavioral Responses Have Been Observed

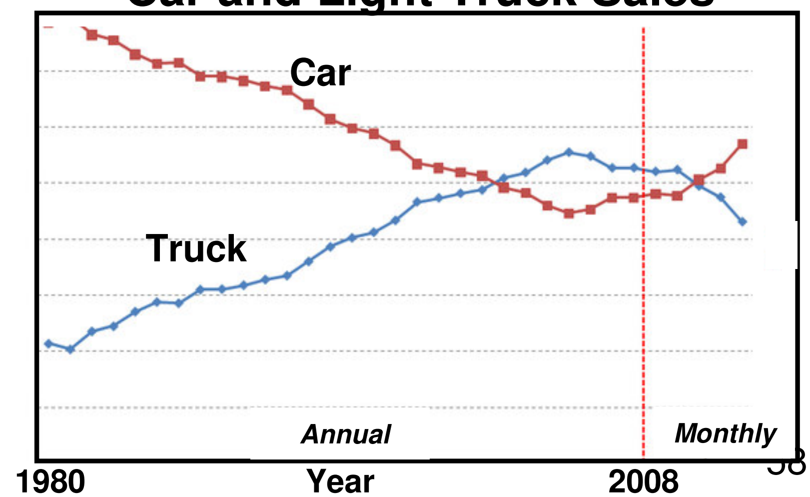
US Vehicle Distance Traveled



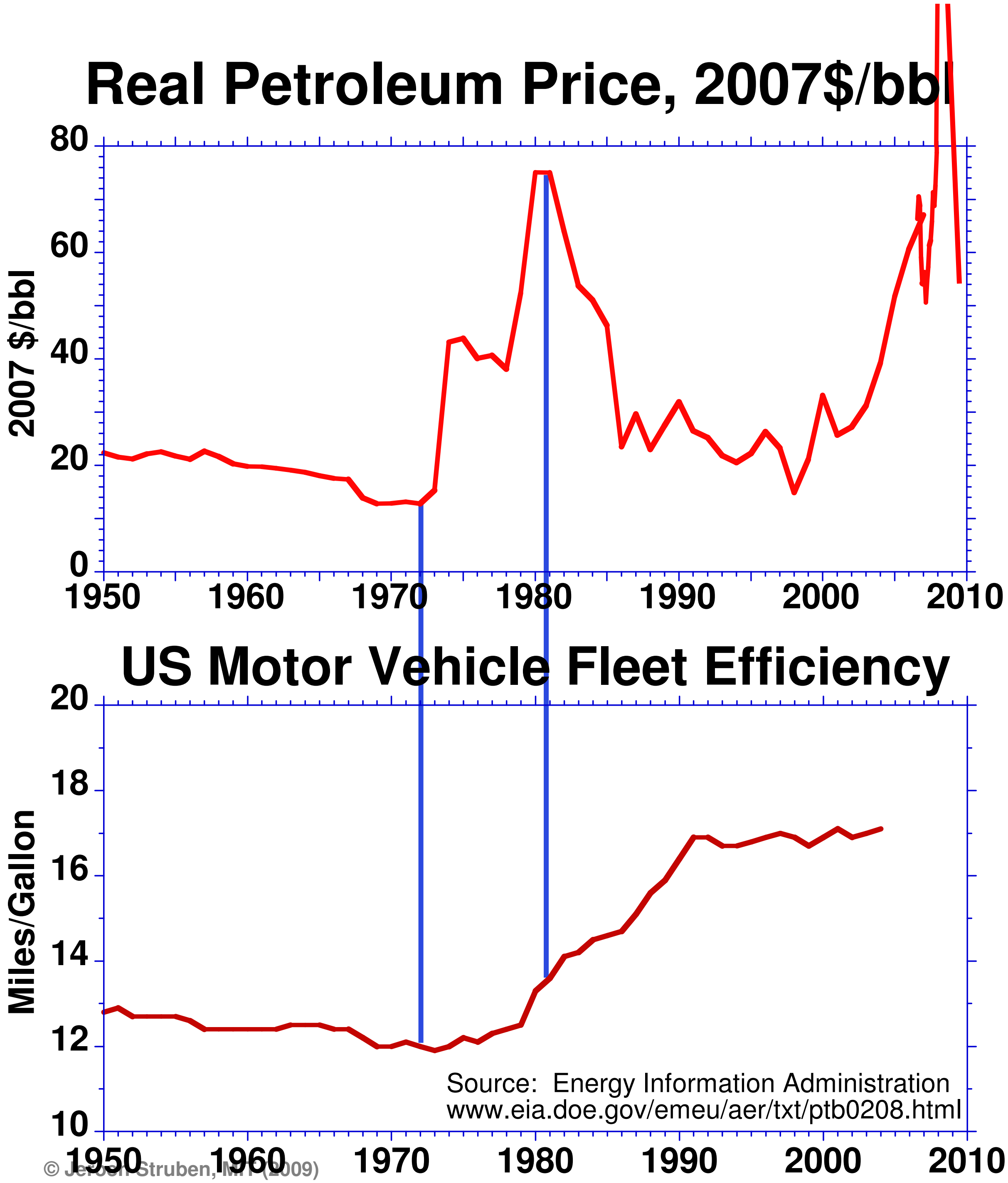
Vehicle Weight & Performance



Car and Light Truck Sales

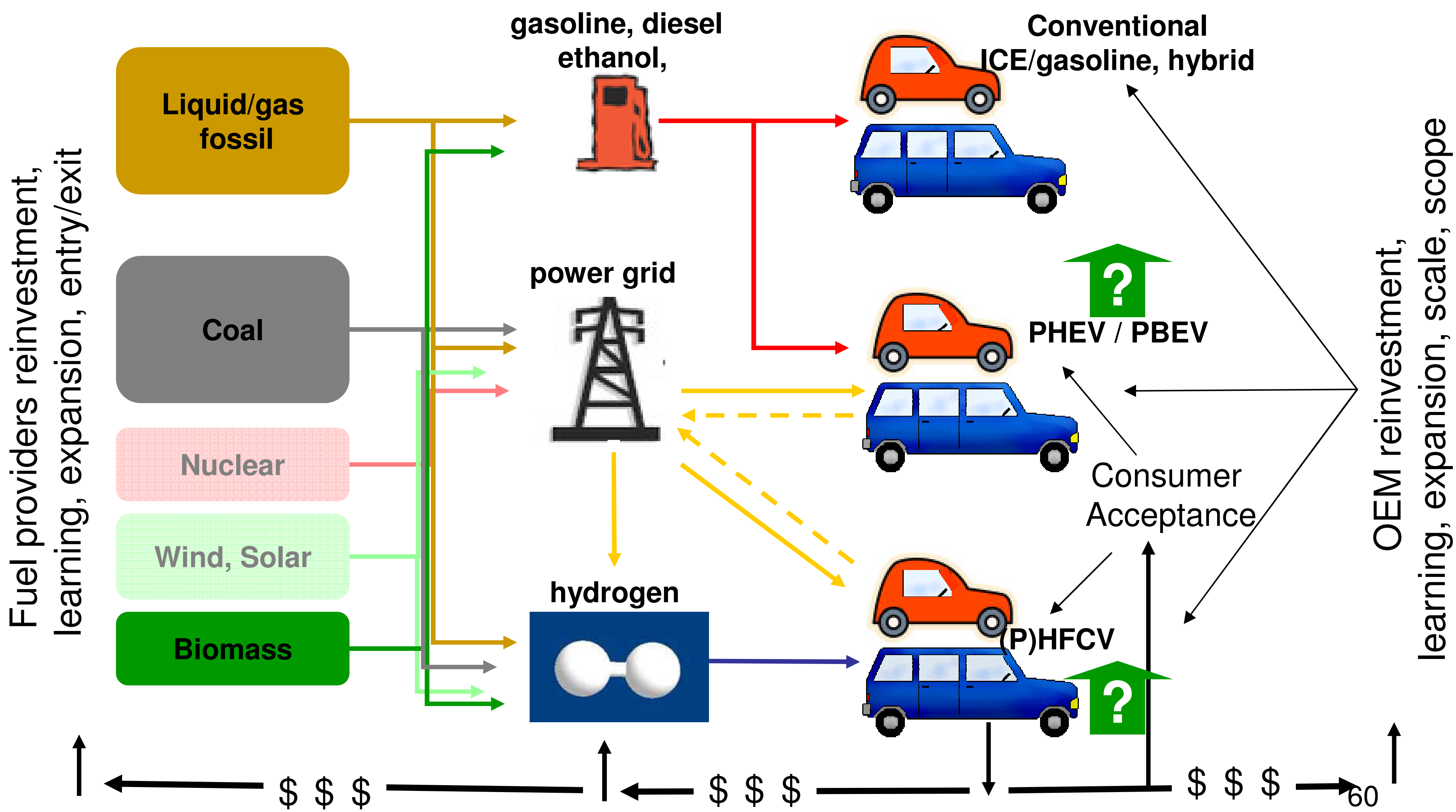


Data: US Census; http://www.greencarcongress.com/, accessed June 2008; Transportation Energy Data Book, Ed. 26-2007 Table 4.6, Autodata and Ward's

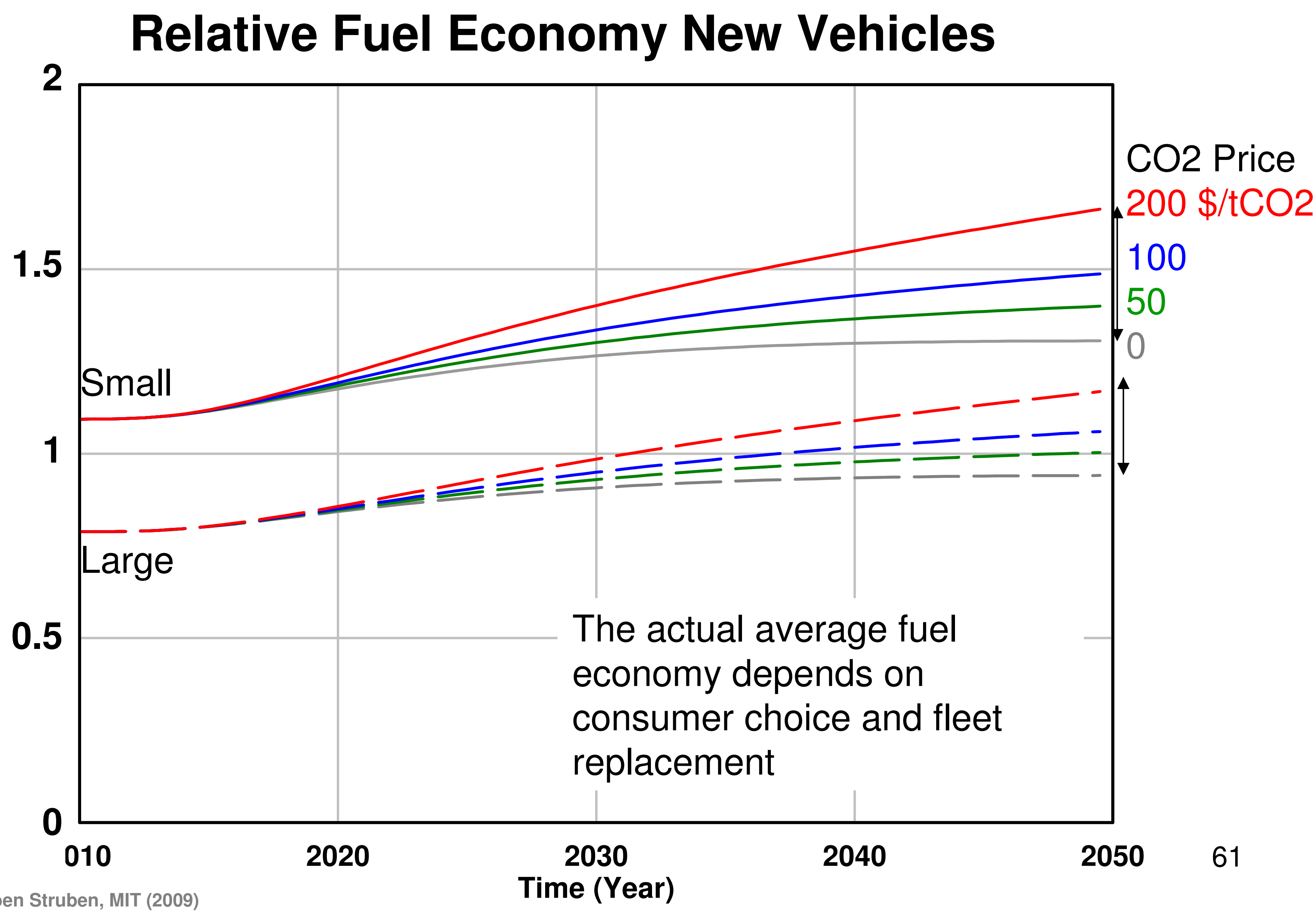


Vehicle average fleet efficiency responds to real prices with a very long delay. Prices jump in 1973, but efficiency remains nearly constant until 1980. Prices fall to about $20/bbl by 1986 and efficiency gains stall in 1992 as automakers use technical improvements to boost performance instead of mileage, and as consumers switch to larger vehicles and SUVs.

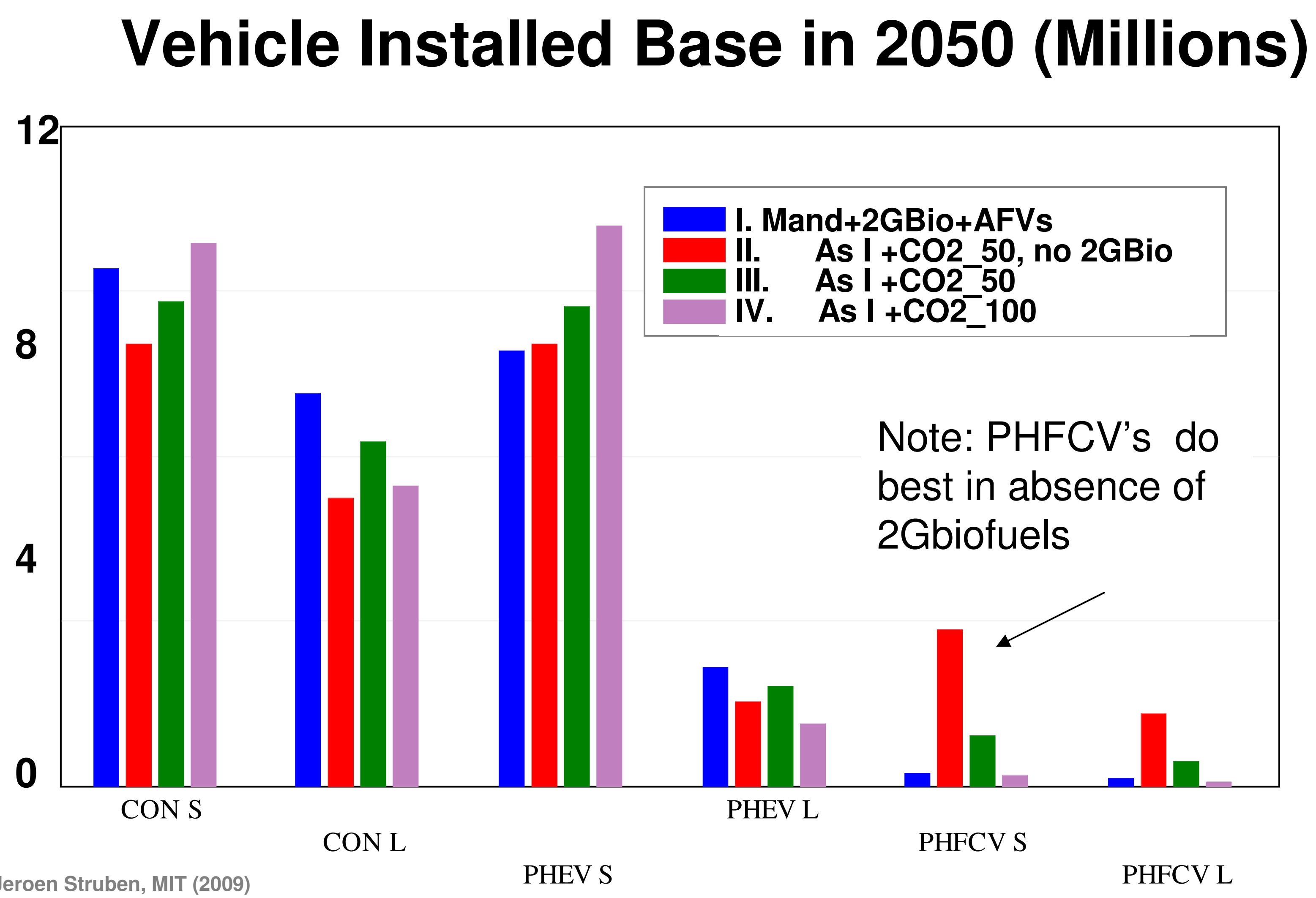
Experiment 6: Varying CO2 Prices



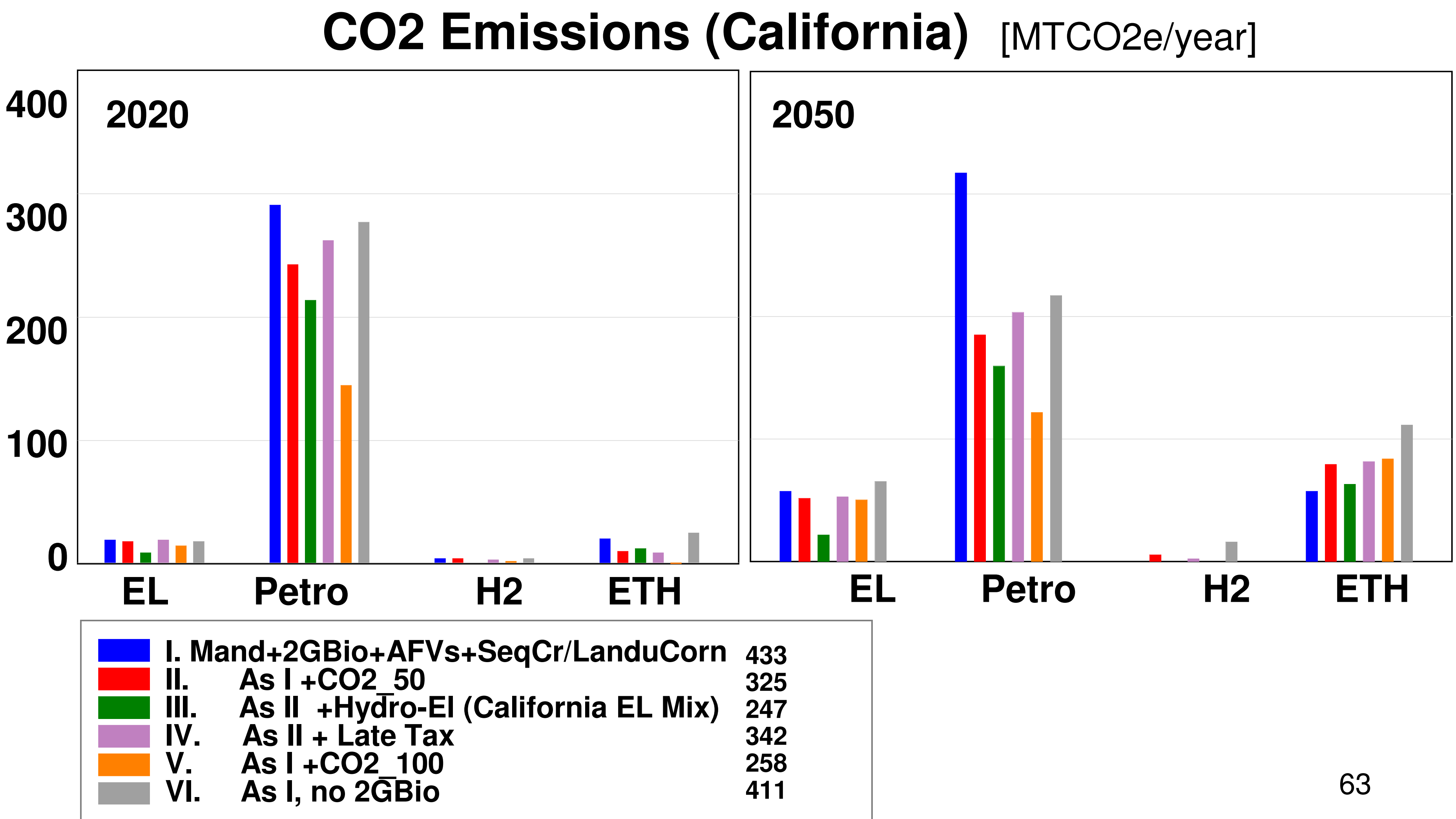
Automotive Responses to CO2 Price



$50/tCO2 carbon tax has moderate impact on platform installed base shares



CO2 Emissions from transportation under varying CO2 Scenarios



Other Analysis Performed, in Progress, and Planned

- **Extensive model testing**
- **Further PHEV analysis**
  - Base scenario using: CAFE, (CA) renewable fuel standards, Waxman-Markey, etc..
  - Sensitivity to technical, economic, behavioral uncertainties (e.g. CCS, biofuel commercialization timing)
  - 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)
  - H_2 from sustainable sources (e.g. Nocera process, biofuels)
  - Electricity peak and base load, battery supply chains, storage

- **C-Price and CCS Scenarios**
- **Interactions among all items above**
- **Other regions**

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…

Summary: Transition strategies for alternative transportation fuels and vehicles

- **Understanding AFV diffusion requires sensitivity to**
  - Technical, economic and socio-behavioral factors
  - Understanding counterintuitive dynamics
  - Worse-before better dynamics

- **Effective policy making and market success requires coordinated/shared understanding, long-term commitment**
  - Value and challenge of coordination among key stakeholders
    - Auto OEMs (entrants)
    - Fuel providers, electric utilities, power producers
    - Fed, state governments

- **The modeling process is designed to enable learning with, and coordinate across different market players**