Managing the Transition toward Self-Sustaining Alternative Fuel Vehicle Markets: Policy Analysis Using a Dynamic Model*

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Abstract

Designing public policy and industry strategy to bolster the transition to alternative fuel vehicles (AFVs) is a formidable challenge as demonstrated by historical failed attempts. The transition occurs within a complex system with many distributed actors, long time delays, several feedback relationships, and multiple tipping points. A broad-boundary, behavioral, dynamic model with explicit spatial structure was previously developed to represent the most important AFV transition barriers. In this work, the integrated model is parameterized for various vehicle platforms. Structural and parametric sensitivity analyses are used to build understanding of system behavior and to identify policy leverage points. The qualitative impacts of policies are tested individually and then in combinations to find synergies. Under plausible assumptions and strong policies, successful AFV diffusion can occur but requires several decades. Findings indicate that some commonly suggested policies provide little leverage and are quite costly. The analysis demonstrates the importance of designing policy cognizant of the system structure underlying its dynamic behavior. To reach a self-sustaining market, coordinated portfolios of policy instruments must simultaneously foster the development of consumer familiarity, well-distributed fueling infrastructure, and vehicle manufacturer knowledge at similar rates and over long enough duration to surpass thresholds in these complementary assets.

Keywords: alternative fuel vehicles, diffusion, policy analysis, system dynamics

Introduction

This investigation addresses the challenge of designing policy to most effectively stimulate the transition to less greenhouse gas and petroleum intensive transportation fuels and vehicle drivetrains. Specifically, it illuminates the role of several causal feedbacks governing such transitions and suggests policy cognizant of the system structure behind its dynamic behavior.

Motivation

The future development of transportation energy systems is arguably the most difficult challenge society must confront in the quest for sustainable development. The steam engine, internal combustion engine, and turbo-jet have enabled a level of mobility unimaginable in prior human history. Mobility is vital to economic health and political stability. It enables global trade and provides access to employment, goods and services, health care, education, and recreation. Not surprisingly, motorization and personal travel growth rates continue to reach record highs worldwide (IEA 2006). The current global stock of 800 million light duty vehicles in use in the world today is projected to reach 2 billion by 2050 (WBCSD 2004).

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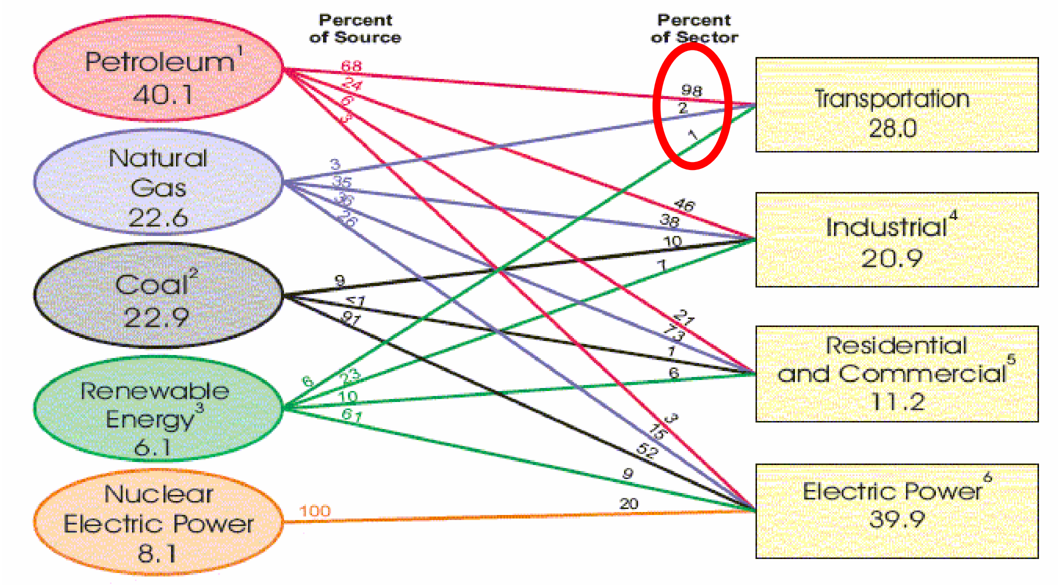
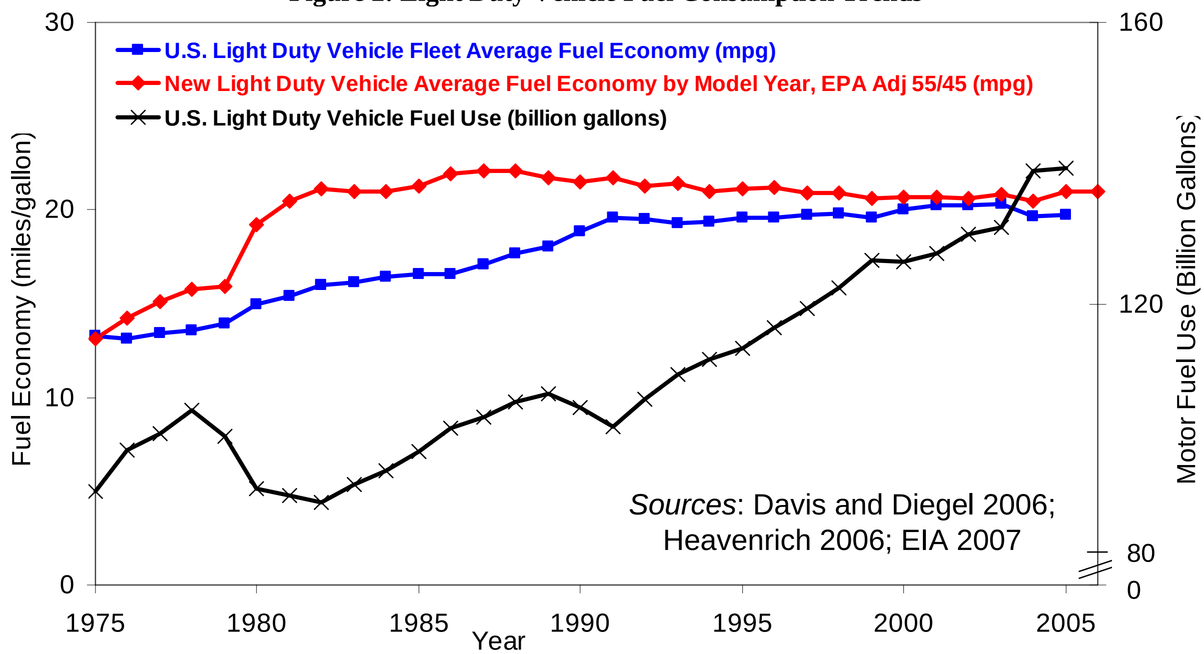
Figure 1: U.S. Primary Energy Consumption in Quadrillion Btu by Source and Sector, 2005 (EIA 2006)



Not unlike the rest of the world, the United States' system of transportation today is all but entirely dependent on petroleum as a primary energy source (Figure 1). Although versatile and cheap petroleum-based fuels have been a great enabler of today's unprecedented levels of mobility and quality of life, society's oil dependence is destabilizing economies, geopolitical relationships, and the global climate.

Yet while energy efficiency and renewable energy are making modest strides in the electric and heating sectors, the transportation sector continues to explode while fuel economy remains stagnant (Figure 2).

Figure 2: Light Duty Vehicle Fuel Consumption Trends



Reducing fossil-fuel dependence and environmental impact of transportation systems is a colossal challenge with no simple technological solution. Substitution of renewable transport fuels must be complemented in a comprehensive and integrated fashion by several other strategies to reduce the oil intensity of the economy including: urban and regional planning to reduce necessary vehicle miles, increasing passenger and parcel vehicle occupancy, improving driving and vehicle maintenance behavior, and shifting to more fuel efficient vehicle designs.

This analysis focuses on the alternative fuel substitution component of such an integrated strategy. It supports prior work suggesting that the diffusion of alternative fuels and advanced vehicles capable of using such fuels is a *complex system transition* governed by the interplay of many distributed agents and several feedbacks (Metcalf 2001; Cahill 2002; Sperling and Cannon 2004; Janssen 2005; Struben 2006; Struben and Sterman 2006; Welch 2006).

Audience

The paper is intended for a broad audience of folks working to support the introduction of hydrogen, biofuels, electricity, and/or other transport fuels with less fossil fuel-intensive pathways from primary energy source to delivered vehicle mile, or from "well-to-wheel." Business strategy and development managers within firms that are placing bets on alternative fuels and/or vehicle drivetrains are in great need of guidance. Just as important, the insights should engage agency program managers, policy analysts, and legislative aides to assist them in making public policies and programs to support new fuels more effective.

Research Question

In general system dynamics practice, one's research hypothesis takes the form of an evolving model intended to represent the most important system structure of the problem of interest at the most appropriate level of aggregation or detail. Although this work helped to test and to extend such a model, the research focus is primarily to build intuition and infer policy guidance from a very large, substantially developed model. The central research question is: what new and unintuitive policy insights for supporting transitions to less carbon intensive fuels can be gained from a dynamic and behavioral simulation model that would not be learned from the more common optimization models and static, end-state analytical approaches?"

Background

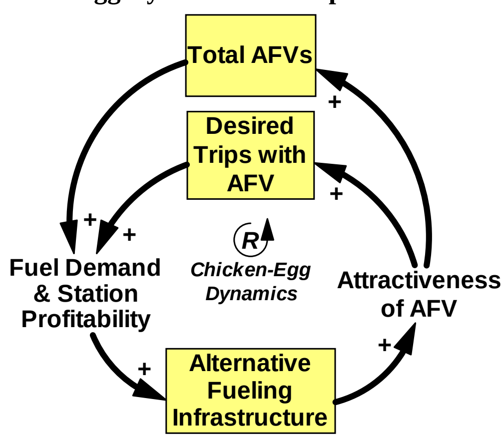
System Dynamics Approach: Modeling Feedback

System dynamics is a field of study of the structure and behavior of socio-technical systems to guide effective decision making, learning, and policy in a world of growing dynamic complexity (Sterman 2000). Grounded in the theory of nonlinear dynamics and feedback control, the method was pioneered at MIT in the 1950s by Jay Forrester (1961). The essential conceptual tools of the field include feedback-rich causal diagrams to elicit mental models and computer simulation models to quantify the interrelationships of physical and behavioral processes, information feedback and time delays. Systems are conceptualized as physical and information state variables (stocks) that are accumulated, depleted, and/or updated by corresponding rate variables (flows); all interact through closed chains of cause and effect (feedback loops). Formally, system dynamics models are sets of simultaneous, nonlinear differential equations solved through numerical integration. Generally simulations are implemented with graphical user interface tools useful for visualizing system feedback structure to assist in building an understanding of the patterns of behavior observed in simulation results.

The modeling process is a disciplined experimental approach to gain confidence in the hypothesis articulated by the model--that the model structure is indeed responsible for empirically observed patterns of behavior (Oliva 2003). The process of model creation and testing builds a richer understanding of the problem of interest using computer simulation to compensate for deficiencies in human intuition. Robust models can then be used to guide policy testing, what-if scenario analysis, decision optimization, and to anticipate unintended consequences of policies that could develop in the long run.

As an introductory example of the feedback concept, consider the most commonly cited barrier to the introduction of alternative fuel vehicles (AFVs): the so called "chicken-and-egg" dilemma (Winebrake and Farrell 1997; Wells 2001; Farrell, Keith et al. 2003; Romm 2004; Struben 2005). There is an obvious interdependence between vehicles and complementary assets such as refueling infrastructure. One can't grow without the other. Consumers will neither purchase nor choose to make the majority of their trips with alternative fuel vehicles without access to fueling stations. At the same time, energy companies and convenience store retailers won't invest in fuel production and distribution infrastructure without reasonable certainty of market demand. Thus, there is a positive or reinforcing feedback at play in the system (Figure 3).

Figure 3: Chicken-Egg Dynamics - Example of Reinforcing Feedback

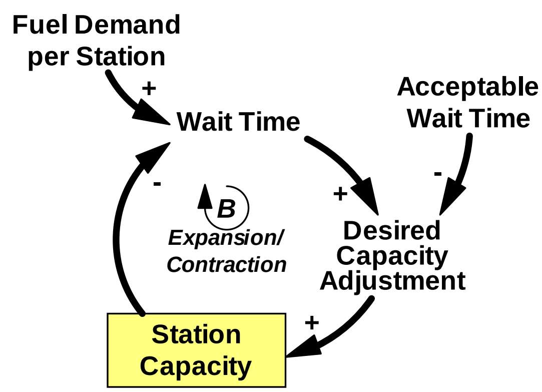


The behavior of a simple reinforcing feedback loop like that in Figure 3 is exponential growth and amplification (Sterman 2000). As the number of one type of AFV increases, there is growing demand for its fuel, more investment in new fueling stations, and consequently, that vehicle platform is more attractive to new buyers. While this complementary infrastructure feedback is often recognized as a growth driver to seed by those designing AFV supportive policies, the role of such reinforcing feedback in destabilizing the system and leading to collapse is overlooked.

What is once a virtuous cycle of growth may also become a vicious cycle of collapse**.** Just as growth in vehicle adoption leads to growth in station availability, a drop in station availability due to other feedbacks in the system leads to decay in vehicle adoption when this reinforcing feedback dominates. Reinforcing feedback can be a source of both explosive growth or of collapse in systems. Historical policy attempts to support alternative vehicle penetration in New Zealand and California are good examples of the potential for this type of collapse (Harris 2000; Flynn 2002; Paine 2006). This chicken-egg fueling infrastructure feedback loop described above is just one example of several reinforcing feedbacks at play. Some of the feedbacks are subtle or "below the waterline." As a result, the chicken-egg dynamics for AFVs are more nuanced than the simple one-loop market formation process often portrayed by policy analysts.

In addition, systems are also governed by balancing (negative) feedbacks that act to bring the state of the system in line with a goal or desired state (Sterman 2000). To provide another example from the AFV story, consider one feedback governing the size of fuel stations depicted in Figure 4. As station utilization rises and lines begin to form, station owners will invest to expand the number of fueling positions to the extent physically feasible in order to reduce waiting times, increase throughput, and earn more profits. Such expansion occurs with a delay and eventually reduces the difference between the actual wait time and acceptable wait time for drivers, bringing the system into equilibrium (or balance) with a desired goal. There are, of course, several other balancing loops at play in the system to bring waiting times to desired levels, but those will be described later.

Figure 4: Fuel Station Size Adjustment – Example of Balancing Feedback



The understanding of causal feedbacks and which are dominant provides a very useful conceptual framework for understanding dynamically complex problems. Nonlinearities in model relationships allow shifting dominance of feedback loops. Traditional engineering and economic models often make assumptions of linearity and equilibrium to ease mathematical characterization, implementation, and understanding. But the world is fundamentally nonlinear, and disequilibrium is the rule rather than the exception (Sterman 2000). It is then not surprising that the system dynamics approach is becoming more popular to address complex problems.

Survey of AFV Policy Analysis

There is no shortage of analysis of the alternative policy measures available to reduce motor fuel consumption and its associated externality costs via alternative fuel substitution, more fuel efficient vehicles, and/or less driving. A lot of valuable analyses have been performed on consumer vehicle technology choice preferences, vehicle and fueling infrastructure costs, and requisite fueling station coverage for a fully penetrated market. Little analysis has focused on the endogenous transition dynamics governing the transformation to new transportation systems.

Modeling Physical Vehicle Stock

The best AFV policy analyses recognize the inherent time delays in vehicle stock replacement as a constraint for rapidly reducing motor fuel consumption (Leiby and Rubin 2000; Bassène 2001; Leiby and Rubin 2001; Greene and Schafer 2003; Bandivadekar 2004). While the need may appear obvious, policy analysis scenarios are not always generated under constraints of an explicit stock turnover model. This is important, especially considering the average vehicle lifetime has been increasing. In applying Greenspan and Cohen's (1996) motor vehicle scrappage model to updated historical vehicle registration data, Davis and Diegel (2006) estimate the median passenger car lifetime is now 16.9 years.

As demonstrated later, effects of the new vehicle technologies become visible only after 10 to 20 years at best due to the slow rates of fleet turnover. Substantial delays also exist in product development and turnover of the fueling infrastructure capital stock. Clearly representation of these physical delays stocks is important in trying to assess realistic speeds of market penetration that might be achieved through policy.

Static Analysis vs. Dynamic Transition Analysis

In the study of alternative fuels such as hydrogen, electricity, and biofuels, a majority of the research has focused on the optimal requirements for and the implications of "end-game" scenarios in which the alternative fuel has substantially penetrated the market. This category includes detailed analysis to estimate the costs and benefits of new fuels once diffused (Thomas, Kuhn et al. 1998; Mintz, Molburg et al. 2000; Simbeck and Chang 2002; US DOE 2003; Ogden 2004; US DOE 2004).

Because fueling infrastructure is such a massive capital stock, other work has focused on how it can be developed cost effectively initially in addition to the long term. Notable research includes optimization of fuel production pathways (Thomas, Kuhn et al. 1998; Mintz, Molburg et al. 2000), architecting the lowest-cost delivery mode for geographic and market characteristics (Yang and Ogden 2006), and estimating the number and spatial distribution of fueling stations to sustain large public vehicle fleets (Melaina 2003; Melendez and Milbrandt 2005).

The greatest efforts in this space have focused on estimating the well-to-wheel environmental impact under future scenarios of substantial alternative fuel penetration (Wang and Huang 1999; Weiss, Heywood et al. 2000; Heywood, Weiss et al. 2003; Demirdoven and Deutch 2004; Farrell, Plevin et al. 2006). This type of end-state focused work is critically important to inform whether a certain alternative fuel dominated market is even a goal worth realizing.

However, as much, if not more, consideration must be given to the transitional dynamics concerning if and how such end states can be reached and how quickly. In fact, the authoritative National Research Council assessment of the needs for a hydrogen economy suggested that the Department of Energy focus on transition strategies rather than markedly different ultimate visions (National Research Council 2004). Others emphasize that, because transition barriers matter a lot for the technology's ultimate market success, static equilibrium analysis of the prospects for new vehicle technologies is misleading (Leiby and Rubin 2003). This argument suggests that dynamic models with broad boundaries including the endogenous growth of the AFV fleet and its complementary assets would now be in high demand and thus be plentiful and diverse. However, this is not the case. The universe of this important class of model for vehicle and fuel technology transitions has been slow to develop (Welch 2006).

Alternative fuel vehicle penetration has been represented within several bottom-up, dynamic MARKAL (MARKet ALlocation) models integrated with Climate-Economy models for the purposes of climate policy analysis (Schafer and Jacoby 2006). Such models solve dynamically in discrete time, period by period, for the least cost portfolio of transport technologies that are available in the model to meet the exogenous transport demand from the computable general equilibrium (CGE) economic model. In using linear optimization to specify technology shares and diffusion patterns to satisfy energy and mobility demands over time, these models make very strong perfect rationality assumptions. Thus they provide a weak treatment of time delays and transition barriers, undermining the cost benefit analysis for which they're intended. In addition, MARKAL models assume exogenous scenarios for technological learning and infrastructure rather than modeling such complementary assets as an endogenous function of vehicle penetration in prior periods.

The most well-known transition model that incorporates dynamic elements such as learning and scale economies in modeling the adoption rates of alternative fuels and vehicles is the Transitional Alternative Fuels and Vehicles (TAFV) model (Greene 2001) and its hydrogen-fuel specific successor HyTRANS (Greene, Leiby et al. 2004). Representation of the dynamics included in the TAFV model has proven very useful for policy analysis to assess the cost and time scales need for such a transition (Leiby and Rubin 2001; Leiby and Rubin 2003). However the TAFV and HyTRANS models do not include the endogenous behavioral entrance and exit of fuel stations in response to market demand. Rather, simulations are run using various infrastructure development scenarios with *optimized* spatial distribution as exogenous inputs to the model. Until Struben (2005), there was no model that *endogenously* modeled the *behavioral* evolution of both supply and demand of vehicles and fuel at the same time.

<u>Coordinated Policy Portfolio Analysis</u>

Policy options to increase the substitution of low carbon alternatives for conventional motor fuels such as renewable fuel standards, alternative fuel tax exemptions, vehicle purchase tax credits, or gasoline taxes are normally assessed individually. (Bandivadekar 2004) reveals that reinforcing combinations of policies that balance cost and responsibility amongst stakeholders will more effectively clear political and institutional hurdles. Not only does such an integrated approach aid the development of political support, but it also aims to harness synergies between policy instruments that make impact greater than the sum of individual policy impacts (Agras and Chapman 1999; Schipper, Marie-Lilliu et al. 2000; Rafaj 2005). This insight calls for more impact evaluation of coordinated sets of policy instruments or *policy portfolios*.

In response to the commonly conceived chicken-egg conundrum, policymakers (Arthur 1989; Energy Policy Act (EPACT) 1992; U.S. Congress 1992) have proposed to harness this feedback to create "momentum" by independently seeding one or the other, particularly via government and private vehicle fleets. More sophisticated approaches advocate for coordinating incentives to closely match the growth rates of both the vehicle stock and fuel stations in order to artificially maintain a stable and economically viable vehicle to fuel station ratio of 1000-2000 vehicles per station (General Accounting Office (GAO) 2000; Kolodziej 2002; Zhao and Melaina 2006).

Overview of Struben AVMT Model

To gain understanding of these transition challenges, several system dynamics models have been developed (Struben 2006; Struben and Sterman 2006). These models, each focused on a critical part of the transition challenge, have recently been joined together into one large integrated model titled the Alternative Vehicle Market Transition (AVMT) model (Struben 2007). There are three important attributes of this integrated model that make it unique for addressing the AFV transition challenge: spatial disaggregation, explicit behavioral decision-making, and, most importantly, dynamic system structure.

Spatial

The model is unique in representing how supply and demand evolve endogenously in space, representing important spatial heterogeneities and behavioral implications. The simplified "chicken-and-egg" reinforcing feedback presented earlier, as widely conceived, leaves out important characteristics of the relationship, calling for a more detailed understanding of spatial interactions. For example, the aggregate number of stations in the region of interest alone does not fully characterize fuel availability. The spatial distribution of stations is important to driver's trip choices (Struben 2005). Notably, establishing the geographic distribution to maximize early station profitability (e.g. urban clusters) may not be the distribution that best enables the emergence of sustainable, fully-penetrated fuel market in the long term (Struben 2005).

Behavioral

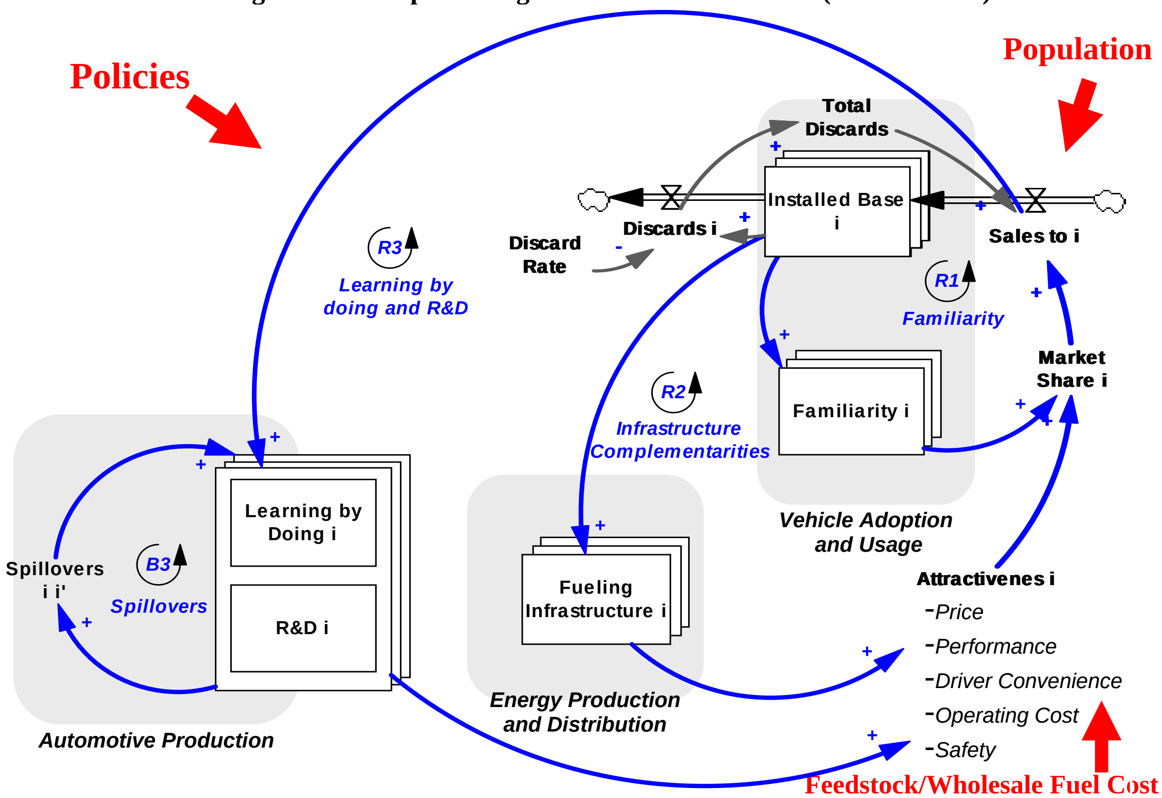
This model treats decision-making of the various stakeholders explicitly. The psychology, economics, and org behavior literature provide strong evidence that humans have cognitive limits and decision making is not perfectly rational. Rather than optimizing with perfectly comprehensive information, people use simple decision rules in the face of uncertainty and situations of even modest dynamic complexity (Sterman 2000). For example, while many current hydrogen market penetration models assume competitive equilibrium in hydrogen prices and retail margins, the AVMT model captures the decision-making process by fuel retailers to set markups in the face of pressures to increase utilization and gain market share as well as pressures to reduce crowding and earn sufficient profit to stay in business. To their credit, the more commonly used optimization models usually include extensive monte carlo sensitivity analysis for various parameters. Yet the attempt to represent how decisions are actually made by agents in the system can yield insights that would be missed by assuming perfect rationality.

Dynamic

A system's dynamic behavior arises from its structure of stocks, flows, feedback loops and the nonlinear interaction of these basic structures (Sterman 2000). The AVMT model captures the physical evolution of the installed vehicle base, automaker production capacity, relevant vehicle attributes, as well as refueling outlet infrastructure location, size, and age. It also endogenously represents the evolution of awareness, perceptions, and knowledge of various agents such as vehicle buyers, fuel station operators, or automotive companies. Adjustment of the physical assets and decision-maker perceptions introduce crucial time delays into the system such as the average vehicle life, the average fuel station life, station capacity adjustment delays, and the time for fuel retailers to adjust market expectations, amongst many more.

These adjustments to physical stocks and information states operate as part of a system of several interacting feedbacks that condition the level of difficulty for AFVs to penetrate the market. A high level overview of the model boundary and primary feedbacks is depicted in Figure 5.

Figure 5: Conceptual Diagram of the AVMT Model (Struben 2006)

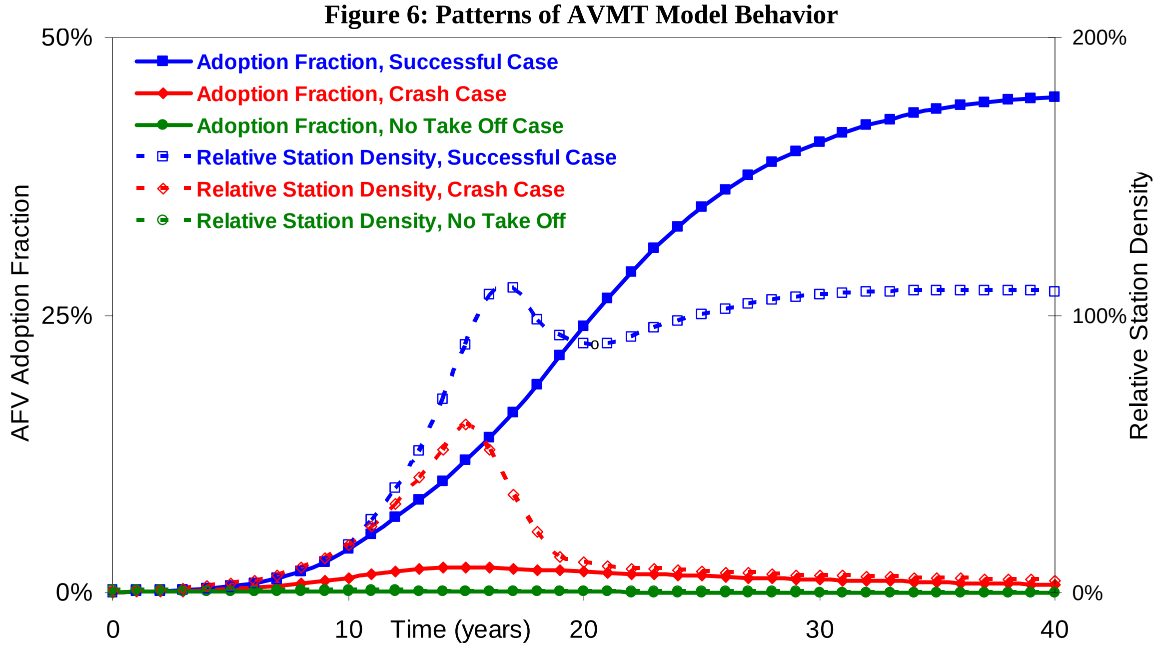


Policy may intervene at many points in this system to seed and strengthen the rates of the three major reinforcing feedback groups in order to sustain the installed base beyond various tipping points to form a self-sustaining market. Also outside the boundary of this model are feedstock or wholesale fuel availability and cost, population growth, and vehicle ownership patterns.

All of the reinforcing and balancing feedback loops and the time delays embedded within them together make the light duty vehicle market prone to tipping points and lock-in effects and make successful support of a transition towards alternative fuels a formidable challenge. The respective challenges presented by the various feedbacks must be well understood to inform both public policy and business strategy in this arena.

The fundamental behavior of the model can be summarized as very slow s-shaped (logistic) growth vulnerable to collapse or to stagnation at a low penetration equilibrium in which limited clustered adoption occurs only in urban areas where density can sustain a niche market. As a generic and illustrative example of the modes of behavior the model generates, consider a hypothetical alternative fuel vehicle entrant technology called ENT that is equivalent in all aspects to the incumbent internal combustion vehicles (ICE) except that it cannot run on gasoline. Rather ENT vehicles run on another fuel, OTH, equivalent in all costs and characteristics to gasoline. The three diffusion patterns are presented for the ENT/OTH platform in Figure 6, each conditioned by different policy settings.

Figure 6: Patterns of AVMT Model Behavior



Despite ENT's technological equivalence to the incumbent technology, the market for ENT vehicles does not take off without policy support. Infrastructure and consumer familiarity are not sufficiently developed to sustain growth without sufficient policy. An important implication is that alternative fuel vehicles (and policies to support them) may fail even if the technology is mature and its cost is competitive. Transition barriers created by feedbacks within the system must be overcome with policy for an AFV to achieve its true market potential.

As seen in the "crash case" plot, policy may temporarily excite the market, but if it is not strong enough for sufficient duration, the market may crash. The successful case is a scenario in which temporary policies are sufficient to bring the market to a self-sustaining level, reaching equilibrium near 45% adoption among households. Only 3% of households choose not to own a vehicle. The reason ICE finishes with a slightly larger market share than ENT even though the average density of OTH fuel stations reaches that of gasoline, the average OTH station size is still not yet as large as the average gasoline station in year 40.

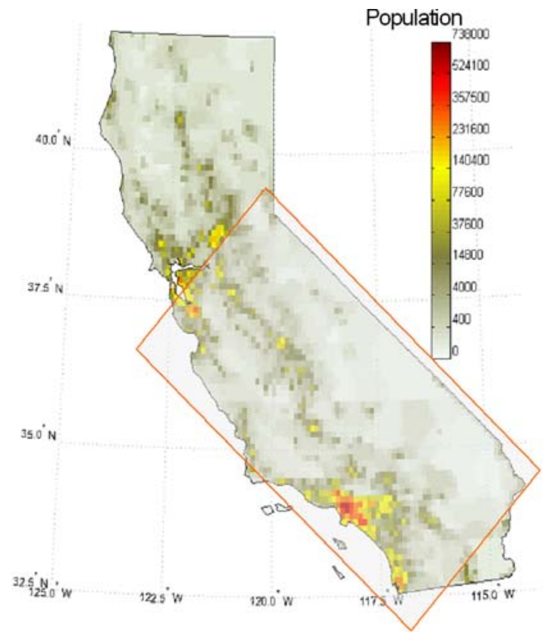
These dynamics will be discussed in greater detail in the following sections. This example is intended to give an introduction to the type of behavior the model generates.

Model Setup and Parameter Specification

Model settings, assumptions, and parameters were chosen for this analysis with three primary goals in mind: to build credibility in the AVMT model, to set parameters using the best available data from the literature and other detailed technical models, and to fix exogenous inputs for tractability of the model structure's endogenous behavior.

The nominal time horizon of the model is a 40 year period, such as 2010-2050. The continuous time model is simulated via numerical integration using a time step of one quarter of a year.

Illustrative Geographic Region



The model is applicable to any region of interest. As an illustrative laboratory for experimentation, simulations in this paper take place for a large Central/South subsection of California covering 89,000 square miles. To represent spatial asymmetries, this region is divided into 252 patches of equal size (~350 square miles). Perfect mixing is assumed in each patch so spatially relevant model variables (e.g. adoption fraction, station density, utility to drive) are calculated for each patch. The use of a specific region rather than a generic model not only makes the results more tangible but also provides a source of useful spatial data.

Driver trip generation in the model is based on a log-normal trip distribution frequency, with radially symmetric short trip frequency distributions and long trips weighted toward high population density region gravitational attractors (including those outside the region boundary). The average driver desires 12,000 vehicle miles per year.

The California region modeled has a fixed population of 28 million people and 13.5 million households. Simulations begin assuming a fully penetrated base of 13 million vehicles and 6,500 gasoline fueling stations distributed spatially according to US Census data.

For a more detailed explanation for the derivation of and the sources for specifying the technical parameters for the various fuels and vehicle drivetrain technologies, see (Supple 2007).

Hydrogen Base Run

The base run used for this paper consists of a simplified scenario in which hydrogen fuel cell vehicles (HFCV) are introduced as the lone entrant competing against a spark ignition internal combustion engine (ICE) vehicles, which begin at an adoption fraction of 96% of households. In this scenario, hydrogen vehicles are incompatible with existing gasoline fueling infrastructure (GAS) and must develop an infrastructure of fueling positions at which hydrogen is generated at the station forecourt via steam reformation of natural gas (H2FSMR).

Before presenting the dynamics for the base run, now is a good time to re-emphasize that the AVMT model should not be misinterpreted as point predictive. The base run simulation plots are *not* to be interpreted as the most likely "business as usual" future, although the tendency to do so is strong. Rather, the purpose of the base run is to provide a starting point for comparison with addition simulations (Ford 1999).

It should also be noted that the Base Run is very optimistic in many assumptions and already includes some policy interventions. The reason such an optimistic case is chosen is to allow more variation in results by varying parameter settings and applying policies.

Optimistic assumptions must be made explicit. First, there is only one entrant fuel/vehicle pair (HFCV/H2FSMR) competing against only one incumbent pair (ICE/GAS). In reality, more fuels and platforms compete in the marketplace including diesel, compressed natural gas, and flex fuel vehicles capable of running on gasoline blends with up to 85% ethanol (E85), amongst others. In addition, population and motorization are constant over time to simplify behavior. To seed the market, simulations begin with 0.1% of household adoption (13,000 vehicles) and a hydrogen station density at 1% of the typical gasoline station density (65 stations).

Technical and economic parameters are also optimistic in this base run. The HFCV production cost and manufacturer suggested retail price (MSRP) is only 25% higher than conventional ICE vehicles. HFCVs are assumed to have 2.5 times the ICE vehicle's fuel efficiency (52.5 vs. 21 miles/gge). The HFCV tank capacity is 8 kg, or 40% on an energy basis of the typical 20 gallon ICE fuel tank. Eight kilograms is the U.S. Department of Energy's FreedomCar technology target for 2010 (US DOE 2003). Such aggressive fuel efficiency and tank capacity assumptions combine to give HFCV the same maximum range as ICE. Even assuming 75% vehicle performance (e.g. less cargo space) compared with ICE, this range is very optimistic.

Based on DOE's H2A model for forecourt steam methane reformation (H2FSMR) fuel stations, the annualized fixed cost per fueling position is 50% higher than gasoline stations. The variable cost at stations is assumed to cost $2.10 per gge of hydrogen delivered. Assuming a 70% energy efficiency in producing and compressing the hydrogen (4.635 cubic meters of natural gas per kilogram of hydrogen produced), this translates to a commercial natural gas price to the fuel stations of about $9 per thousand cubic feet of natural gas, which is conservatively high.

Hydrogen fuel stations have optimistically low initial permitting and entrance delays, albeit they are greater than those for gas stations due to unfamiliarity and safety concerns with the new fuel technology. Again, these delays are dynamic in the model and increase as the market becomes crowded or as the rate of permit applications leads to long backlogs.
One of the only pessimistic settings for the initial base run is that learning feedback effects are switched off to first build understanding of other feedbacks and technical parameter sensitivities. Instead, initial attribute values are optimistic, as they are held constant for the forty year period.

Behavioral parameters for the value of service time, trip interdependency, and the sensitivity for topping off are also set conservatively so that these feedback concepts do not dominate dynamics. Because these feedbacks are not included in other models, they are set weak for now until more confidence is developed in their actual strength. Social exposure parameters are on the strong side compared to the marketing science literature estimates.

In terms of policy, the base run includes a strong fifteen year marketing promotion that reaches 4% of the non-adopter population per year, a ten year demonstration phase in which the retail markup on variable cost at the hydrogen fueling outlet is fixed at $3/kilogram, a two year station honeymoon in which none exit the market, and a full exemption for hydrogen on the

$0.50/gallon gasoline tax (which includes federal excise taxes, state and local sales taxes, and the underground storage tank fee).

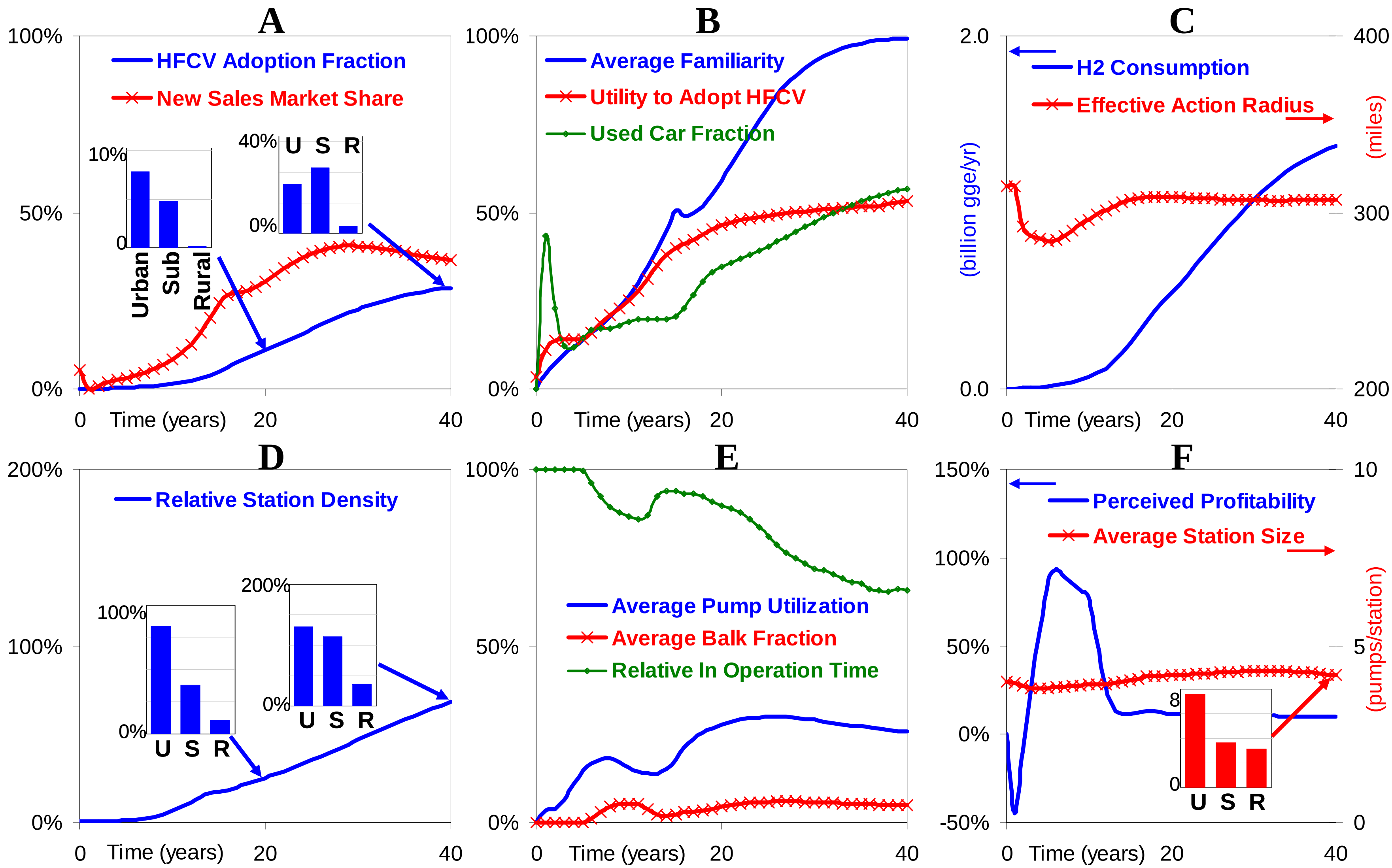
The key output variables are plotted for the forty year Base Run simulation in Figure 7. The Adoption Fraction, or fraction of households that own a hydrogen fuel cell vehicle, is plotted in frame A at the upper left. Despite all of the optimistic assumptions described, the adoption fraction grows quite slowly, reaching only 29% in year 40. Simulations of longer duration show this adoption fraction reaches equilibrium at 32% after about 70 years.

Plotted along with the adoption fraction is the HFCV market share amongst new vehicle sales. It is consistently higher, grows more quickly, and is markedly more volatile than the adoption fraction. The sales market share reflects the flow of new hydrogen vehicles entering the stock of vehicles on the road, which accumulates with news sales and decays with vehicle scrappage. Stock variables dampen volatility and give the system memory. The new sales market share has two small peaks over the first ten years. The fuel cell share of new vehicle sales is a function of both the familiarity amongst non-adopters with and relative utility of the HFCV. The first peak in new sales market share can be explained by examining the behavior of the "utility to adopt" variable, which is plotted in frame B.

Utility to adopt (or the attractiveness of purchasing) an AFV is a function of both vehicle attributes and the utility to drive that vehicle platform. It increases initially in the base run as fueling stations enter and coverage grows, yet it quickly saturates while station coverage continues to increase. This saturation is due to crowding at the stations as utilization increases (frame E). Drivers have to wait in lines for more than thirty minutes at some busy stations to refuel. As drivers see and hear about these queues, more choose to balk, that is to go elsewhere or not to make a trip at all due to inconvenient refueling in a patch. As a result of these pressures, the supply of refueling infrastructure works to catch up while growth is demand is suppressed until eventually utilization comes to balance at a reasonable level.

Hydrogen Base Run

Figure 7: HFCV/H2FSMR Base Run



The second local peak in the market share, occurring just after year 15, is the result of the consumer familiarity dynamics at play. Year 15 marks the end of the public marketing campaign, which had steadily increased familiarity over its duration as plotted in frame B of Figure 7. At the end of this aggressive marketing campaign familiarity dips slightly. Forgetting is slightly greater than new awareness generation because a limited fraction of households own and communicate about hydrogen vehicles. By this point however, fuel station coverage, utility to adopt, and the fleet of HFCVs have reached high enough levels to continue to grow familiarity via word of mouth and normal marketing funded by the manufacturers with a fraction of sales revenue. The tipping point threshold has been passed so that the installed base of vehicles and consumer familiarity continue to reinforce the growth of the other via positive feedback.

Upon first inspection, it is unclear why the HFCV share of new vehicle sales begins to drop over the final ten years even as familiarity, utility to adopt, and fuel station density continuing to increase. Yet this dip can be explained by the increasing share of hydrogen vehicles purchased from the used hydrogen vehicle market. By this point, the stock of used hydrogen vehicles for sale has increased substantially, which temporarily depresses the news sales growth rate.

The behavioral topping off phenomenon, described earlier, is reflected by the plot of “effective action radius” in frame C. The typical ICE driver chooses to refuel when at or below one quarter of the tank. The normal action radius is then 75% of the 420 mile maximum range, which is simply the tank capacity (8 gge) multiplied by the fuel economy (52.5 mi/gge). Yet, upon model initialization and endogenous calculation, the effective tank range drops for the HFCV because vehicle owners perceive very low station coverage and decided to refill sooner to maintain a larger safety buffer in the tank. As average station density increases beyond 15%-20% of the average gasoline station density due to perceived profitability of the industry (frame F), the effective action radius nearly fully recovers to its normal level by year 15.

Average station size, in red at the lower right, begins at four fueling positions per station and grows due to utilization and profitability. While the average size falls in the last five years, this is not because stations are contracting. Rather, large urban stations enter and saturate those markets first. Stations entering in later years are in rural areas and are typically smaller, bringing down the statewide average. Significant spatial heterogeneity is also large in the adoption fraction and fuel station densities as demonstrated by the snapshot bar graphs. Early adopters and stations are predominantly in urban areas where stations are most profitable. Rural areas lag.

Finally, the base run also reflects physical constraints in the volume of hydrogen that can be produced and stored at each fuel position, an important capacity constraint separate from a station’s vehicle throughput capacity. Plotted in frame E, average operating hours fall because high utilization urban stations run out of fuel. Such station closures or interruptions for hydrogen tanker deliveries lead to even higher utilization and lines when stations are open, yet profits remain low (especially with the more competitive markups on fuel after year 20). Consequently, new station entrance to bring utilization in line with desired levels is constrained. This balancing effect is a strong barrier for alternative fuels with low volumetric energy density and hence expensive fuel station inventory holding costs.

Policy Testing

The purpose of the AVMT model is to characterize global patterns of behavior and identify policy strategies for overcoming transition barriers, not for quantitative policy cost modeling, cost-benefit analysis, nor for forecasting of the most probable market futures. Such uses are premature due to uncertainty in technology attributes and in parameters conditioning consumer choice among AFVs. Extensive sensitivity testing has shown that diffusion speeds and thresholds in the AVMT model are quite sensitive to several uncertain parameters that are difficult to calibrate due to lack of empirical data (Supple 2007).

Despite these uncertainties, policy testing in complement with sensitivity analysis and extreme condition testing can provide useful qualitative guidance. The model is a useful tool for understanding the relative directional impacts of public and private policies. The goal is to explore and identify which types of policies have significant leverage and under what context. Assessing the robustness of policies under varying model parameters also guides subsequent efforts to elaborate the model and gather needed data.

For the purposes of this analysis, policy is defined broadly as "a plan or course of action, as of a government, a political party, or a business, intended to influence and determine decision, actions, and other matters" (American Heritage 2004). Thus, policy testing includes regulatory requirements, government incentives, private firm strategies, or a combination thereof.

Individual Policy Testing

Policy testing begins by comparing the sensitivity of various public policies and industry strategies applied individually. An extensive list of policies have been tested and a plethora more have not yet been explored. To generally categorize the purposes of policies in support of low greenhouse gas emitting fuels, they either require or provide economic incentives for one or more of the following:

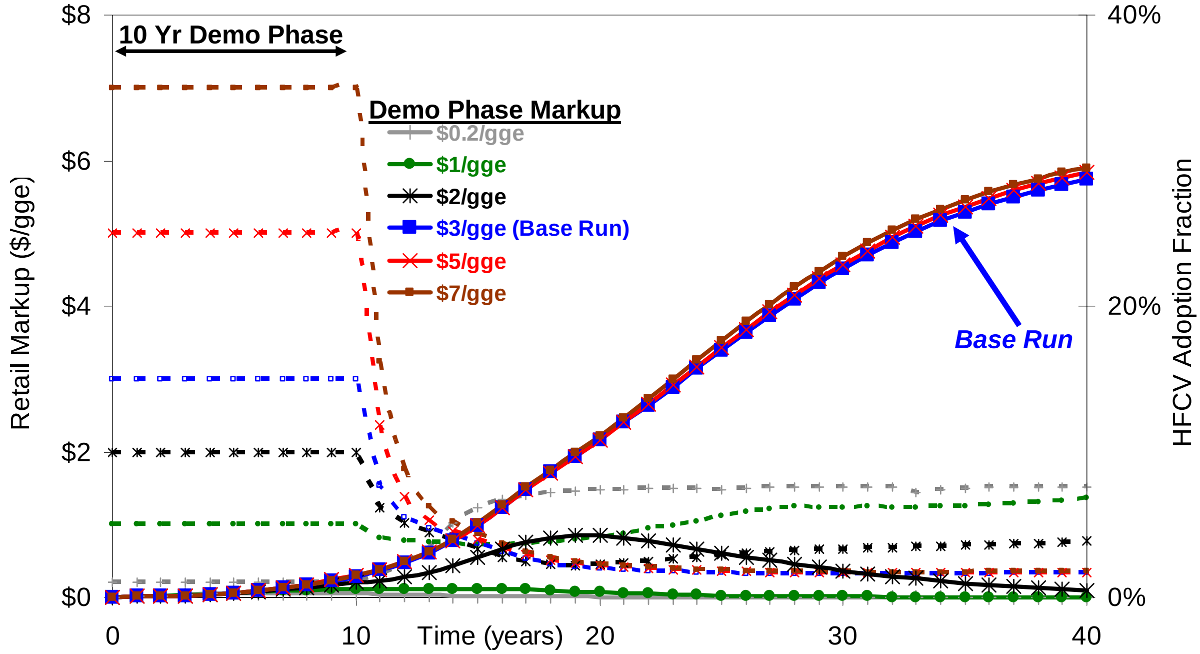
- alternative fuel vehicle purchase,
- alternative fuel use,
- alternative fuel vehicle production to the market,
- production and distribution of alternative fuel,
- more frequent vehicle replacement, and/or
- improved awareness and acceptance of the AFV as a viable option.

The most interesting findings from extensive scanning of individual policy tests are highlighted here. Other policy test results can be found in Appendix B.

Managing Retail Fuel Outlet Markup

The model draws most fuel station cost parameters from the Department of Energy's H2A forecourt station model (James, Lasher et al. 2006), which assumes a retail markup of $5/kg hydrogen or $5/gasoline gallon equivalent (gge) for stations to maximize profits. Yet this markup is an important policy choice for fuel providers.

Figure 8: Policy Test - 10 Year Demonstration Phase Retail Markup



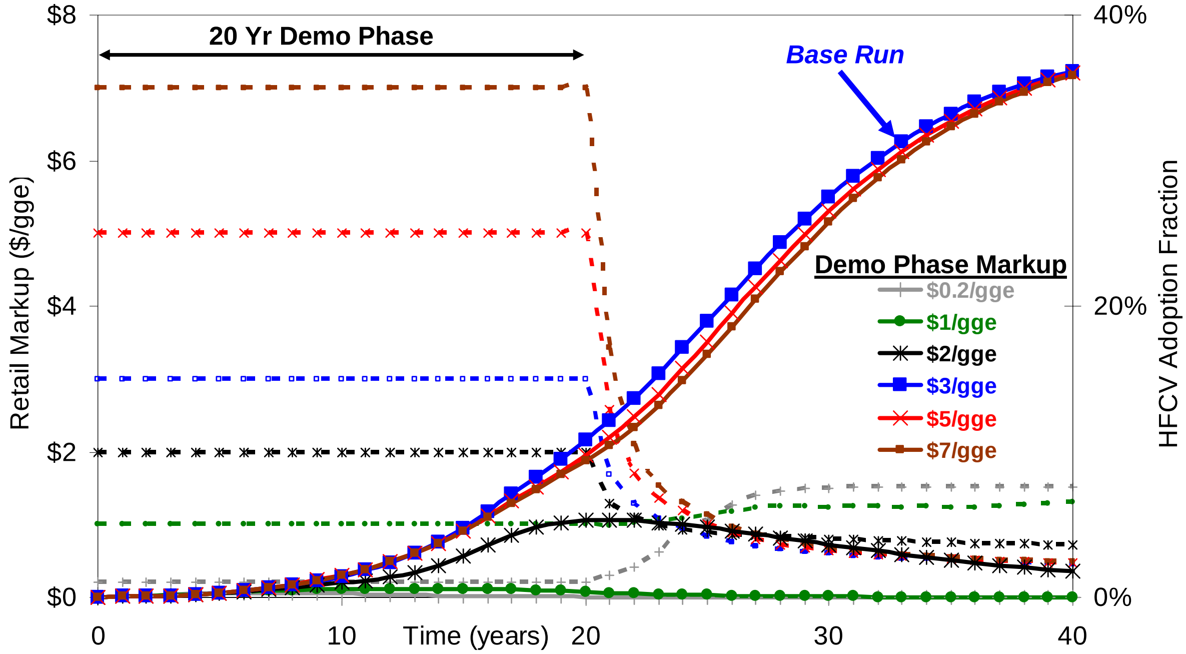
One policy, which could represent either industry coordination or govern minimum markup regulations, sets the retail markup at a fixed level for the first ten years during what might be called a "demonstration phase." After the demonstration phase, a transition to a deregulated commercial phase brings local markups to levels set based on competitive pressures.

In the test depicted in Figure 8 retail markups are plotted by the dashed lines and the starting level ranges from 20¢ to $7 per gge. If the mark-up starts too low, such as at current gasoline retailing levels, the system crashes; not enough stations enter to sustain AFV fleet growth. As this initial markup increases to $1-2, take off occurs faster and faster. However the market does not pass the self-sustaining tipping point until the initial markup goes above $3/gge (the base run setting). Because fueling infrastructure is such a dominant bottleneck, the markup for this short demonstration phase should be quite high to induce station entrance.

Yet when the duration of the demonstration phase is lengthened to twenty years (Figure 9), the potential downside to increasing the markup level becomes clearer. In moving above $3/gge, penetration is suppressed because of reductions in new vehicle purchase and fuel demand due to the high cost of hydrogen fuel. Thus, there is a sweet spot markup that is best for long term growth. In the twenty-year example, the best results are achieved with a $3/gge retail markup.

The implication of this policy test is certainly not a quantitative markup prescription of $3/kg over a twenty-year demonstration period. Rather, the key point is that retailing must be well managed by early entrants. Fuel retailing is a very competitive and low-margin business. If the hydrogen market becomes too competitive too early, sustained market growth will be impeded. The emergence of intellectual property rights for fuel production and dispensing technology is not modeled here, but it, along with permitting and construction delays, may constrain competitor entry enough to provide some early price-setting power by retailers. The qualitative insight is that there is leverage in ensuring high station profits early in the transition.

Figure 9: Policy Test - 20 Year Demonstration Phase Retail Markup



An ideal policy would be dynamic and adaptive, gradually ramping down the retail markup as the government observes large infrastructure development and growing profitability. For more testing of markup regime paths, see Appendix B.

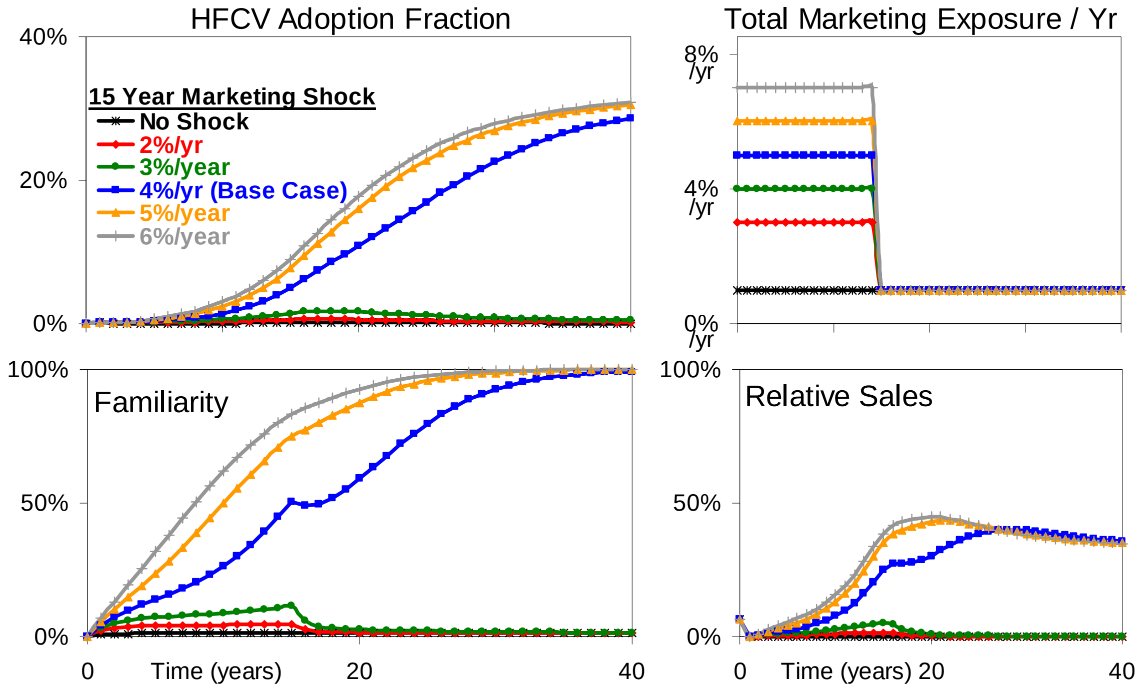
Marketing and Public Education

Policy can be and often is used to create awareness and acceptance of new technologies, behaviors, or business strategies. The structural sensitivity analysis demonstrated that reaching a threshold of self-sustaining consumer familiarity may be a more significant barrier than is commonly understood by policymakers. As discussed earlier, a driver's willingness to consider HFCV as a serious option is primarily increased through growth in the installed base of hydrogen vehicles on the road, but marketing is also an important early driver or trigger.

By explicitly representing these social exposure dynamics in the model, one can also more formally test marketing and public education policies. Such "soft policies" are only briefly mentioned in most policy analysis because their cost effectiveness is to hard quantify on a case by case basis. While the representation of familiarity development is subject to uncertain parameters, the model provides a framework for testing the impact of proximate indicators achieved by marketing policies. For example, the base run includes a fifteen year marketing shock of 4%/year effectiveness on top of the vehicle manufacturer's normal marketing efforts (with assumed 1%/year effectiveness). The direct effect of this shock is an additional 4% of the non-adopter population considering HFCVs when car shopping each year. The shock's larger effect is indirect and nonlinear, seeding word of mouth between non-drivers about hydrogen.

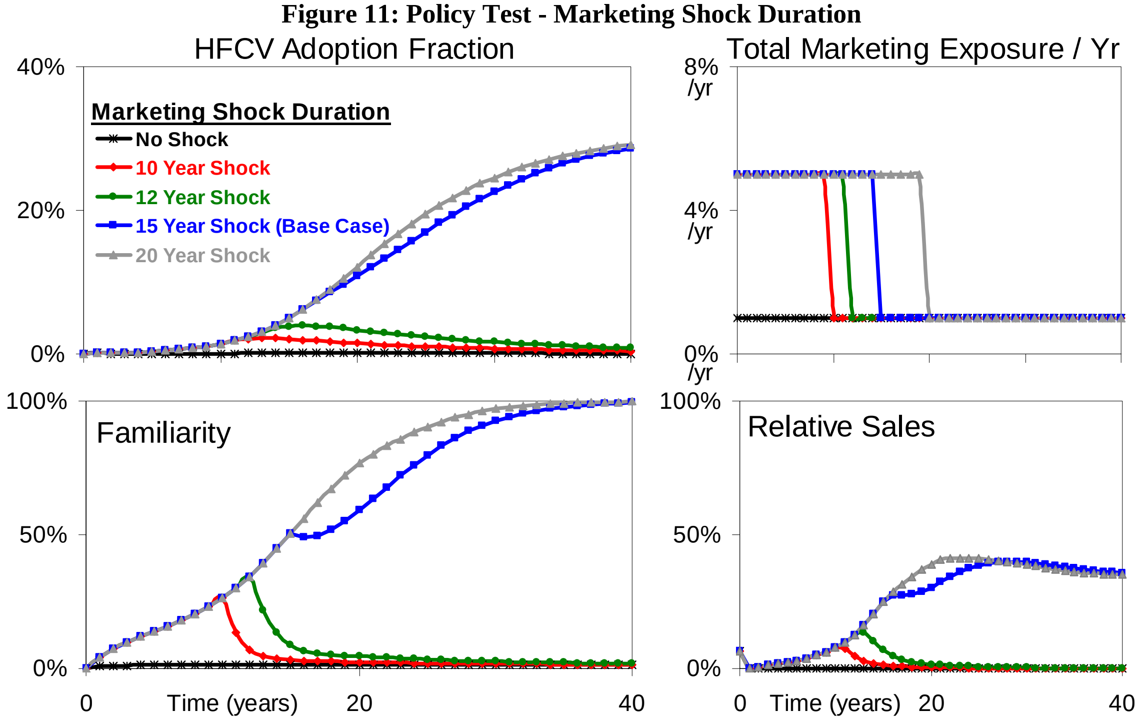
The effectiveness of the fifteen year marketing shock is varied from 0-6% per year in Figure 10. Shocks of these strengths are ambitious and very expensive but within the realm of possibility. Total marketing exposure is dominated by the shocks as normal marketing exposure is only 1%/year. Notably, a 1% increase in the effectiveness reduces the time to 15% fleet penetration by almost 10 years. Broad marketing and education are thus valuable policies.

Figure 10: Policy Test - Marketing Shock Effectiveness



In addition, such marketing policies must be of long enough duration to grow the HFCV fleet beyond the threshold at which it is large enough to sustain familiarity. Even at an effectiveness of 4%/year, ten and twelve year policies fail to push the system over the tipping point (Figure 11). *The takeaway is that familiarity is quickly lost if campaigns are ended after early success.*

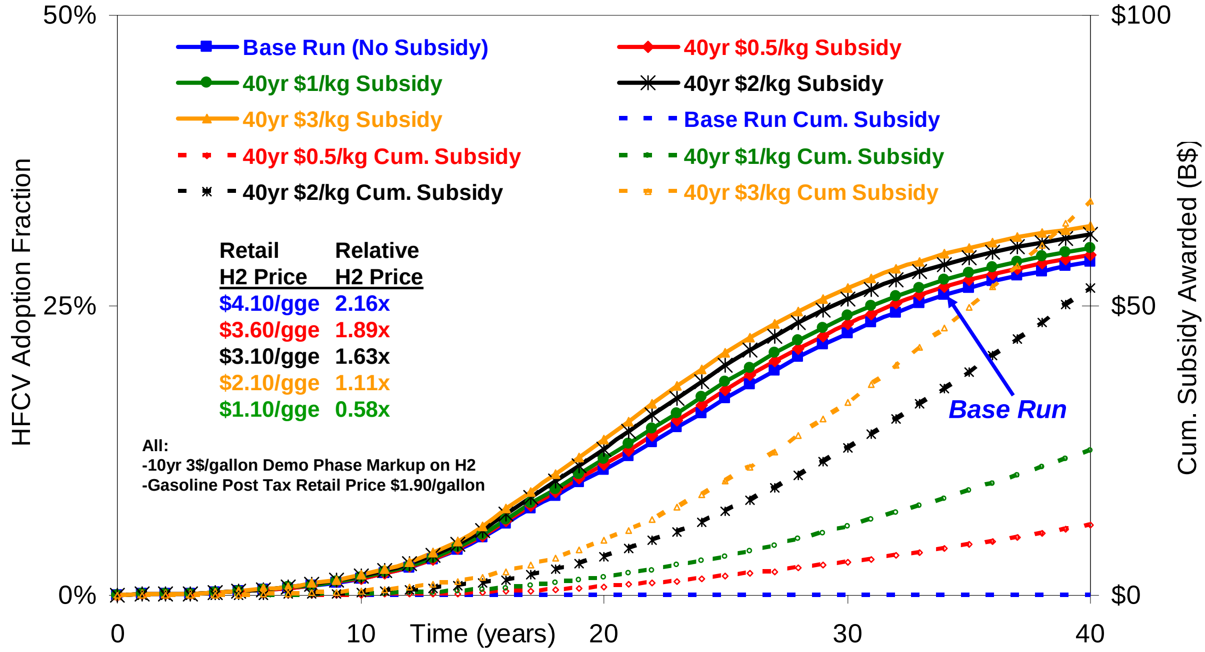
Figure 11: Policy Test - Marketing Shock Duration



Hydrogen Fuel Subsidies and Gasoline Taxes

Moving on to the more commonly suggested Pigouvian policy instruments intended to internalize externality costs (Pigou 1952) and align private economic incentives with the social interest, the comparison of fuel subsidies and gasoline taxes is a useful starting point. For one thing, these are probably the two most popular policies suggested to support alternative fuels. Habit rules and fuel subsidies (tax exemptions or tax credits) have been used to support ethanol as a fuel additive and substitute in the United States since the Energy Tax Act of 1978.

Figure 12: Policy Test - Hydrogen Fuel Subsidies

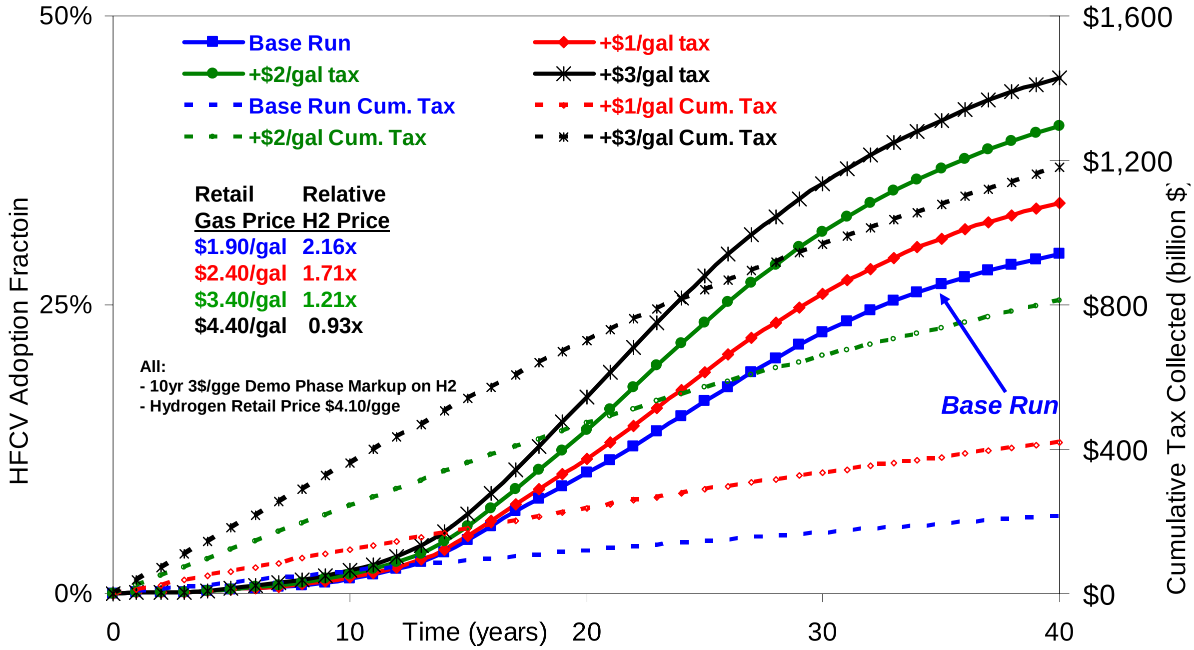


In the hydrogen scenarios depicted in Figure 12, fuel subsidies amounting to billions of dollars over the forty year time period do not appear to have a significant impact on top of the policies already included in the base case. An understanding as to why is developed by comparing hydrogen fuel subsidies with increased gasoline taxes depicted in Figure 13.

The results are consistent with intuition. In moving from the base case to scenarios improving the relative price of hydrogen to similar ratios, the gasoline tax has more leverage. The reason for this lies in the widely variant fuel efficiencies assumed for the two competing vehicle technologies. Recall that the average hydrogen fuel vehicle is assumed to be 2.5 times more fuel efficient than the average ICE vehicle. The HFCV's high fuel efficiency effectively dilutes the fuel subsidy whereas the added gasoline tax severely increases the cost of travel.

In short, it is the fuel cost per vehicle mile, not per unit of energy delivered at the pump, that determines the relative utility of driving an AFV in the model. Giving a fuel subsidy to a more fuel efficient entrant is a weaker incentive than imposing a tax on the fuel for the less efficient vehicle to establish the same relative price differential. This rationale may be fairly obvious but reinforces the idea the policy must be cognizant of what drives system behavior. It also raises an interesting behavioral question of consumer psychology.

Figure 13: Policy Test - Gasoline Taxes



Will drivers indeed make fuel price comparisons on the rational basis of cost per vehicle mile rather than the cost per gallon? This question is up for debate and may be very important for AFV platforms like hydrogen fuel cell vehicles that are lauded more for their radically increased fuel efficiency than for their ability to make use of rapidly renewable primary energy sources.

Because fuel economy will always vary by vehicle type and size, fuel retailers will not be able to advertise alternative fuel prices on a per vehicle mile basis for the typical value. Rather the cues accessible to consumer choice will be the price per unit weight, volume, or energy content. The implication is that it may then be a shrewd marketing strategy to sell hydrogen on a per weight basis in order to avoid the perceived cost per gallon equivalent comparison with gasoline.

Regarding the attractiveness of using gasoline taxes to speed diffusion, political challenges are just as important a consideration as their relatively strong effectiveness in accelerating diffusion. Despite the power of market prices to signal reductions in fuel consumption as evidenced by demand response following the oil price shocks of the 1970s, more significant gasoline taxes comparable to those in other developed countries has been unpopular and overwhelmingly cast as “politically infeasible” in the United States.

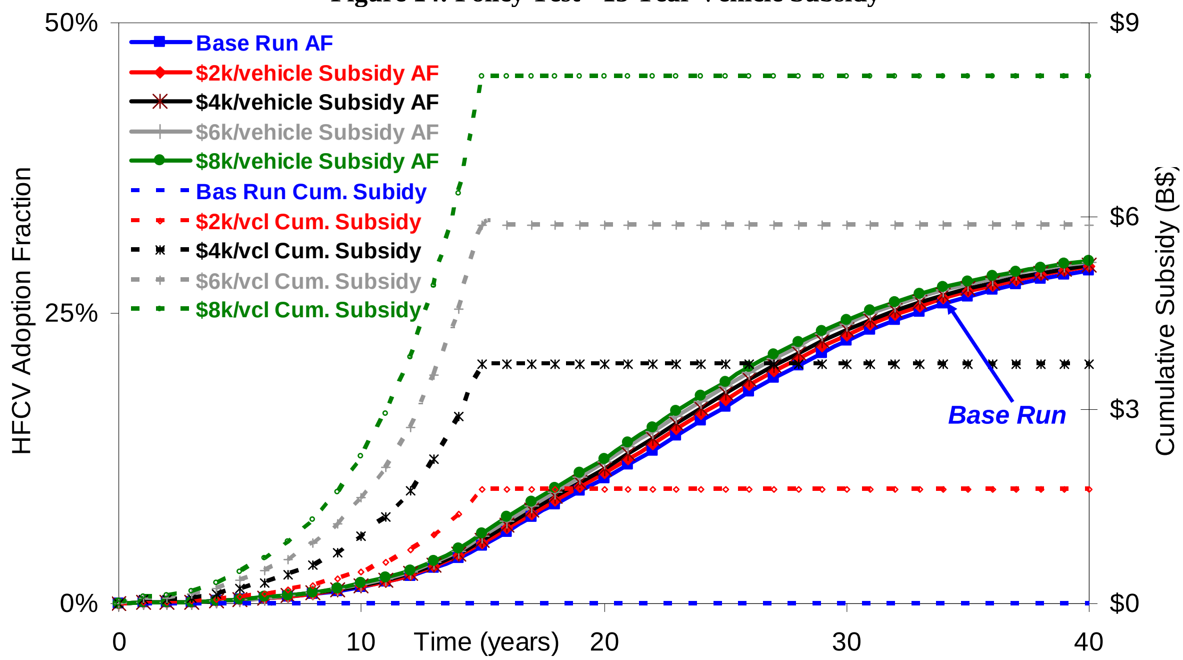
Arguments of economic cost and regressivity of this type of tax stem largely from the observed small *short-term price inelasticity of demand* for motor fuels. On the order of days and months, the imposition of such taxes is likely to have very little effect on demand, and therefore is perceived as quite a burden on the economy. From a dynamic viewpoint, this apparent inelasticity may partially conflate actual price elasticity of fuel demand with the long physical time delays within the system to adjust to one’s new desired level of demand. There are long delays in replacing one’s vehicle with a more efficient model, finding new transport modes, changing travel patterns, or moving to more location efficient communities. In any case, any added fuel tax would require strong complementary fiscal policies to be politically feasible.

Vehicle Subsidies

Another popular policy instrument requested to bolster AFV sales are vehicle purchase tax credits or rebates. In Figure 14, one-time subsidies between zero and eight-thousand dollars are tested over a fifteen year period. Total cumulative subsidies are even greater than those over the first fifteen years in the fuel subsidies test, yet the policy's impact is quite small.

At least early in the transition, vehicle subsidies do not appear to have much leverage. As a useful point of reference, hybrid electric vehicles are currently eligible for a federal income tax credit of up to $3,400 depending on the manufacturer's cumulative sales volume. Yet even a subsidy at double that value, which more than makes up for the assumed incremental price of hydrogen vehicles, does not have a strong impact on the pattern and speed of vehicle diffusion.

Figure 14: Policy Test - 15 Year Vehicle Subsidy



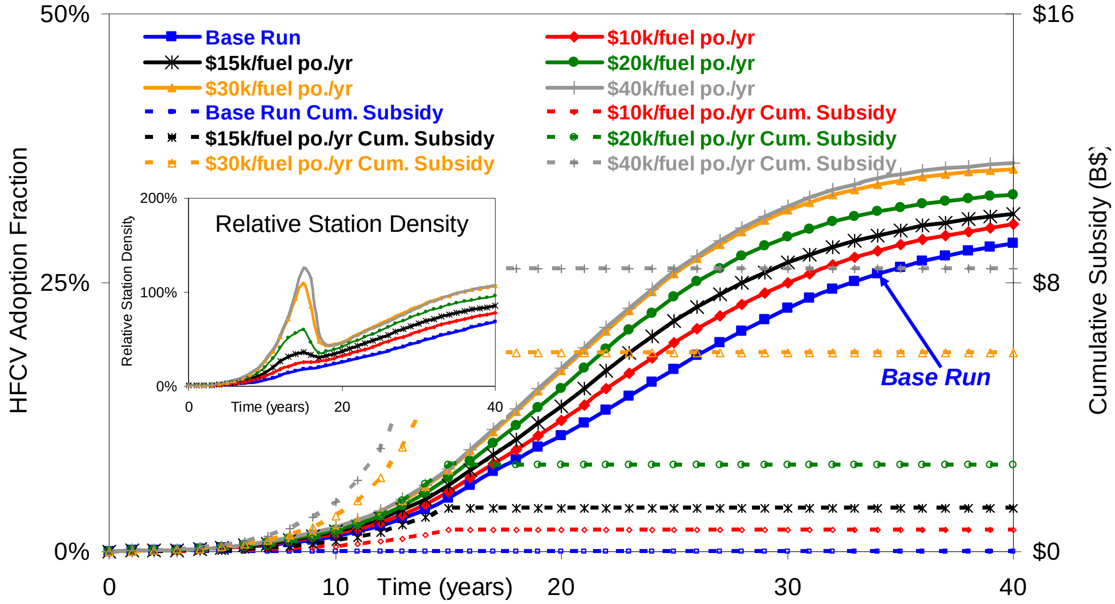
The small qualitative effect of this policy is initially surprising to most audiences. The explanation lies in the highly non-linear relationship of one's utility to drive the HFVC with increases in fuel station coverage. Without co-aligned incentives to directly support hydrogen infrastructure, subsidies for vehicles are ineffective. The problem with vehicle subsidies alone is that they directly bolster vehicle adoption but only indirectly provide incentives for alternative fuel use. Because utility to drive in the model remains unchanged, the vehicle purchase subsidies do help to bolster the depressed number of trips made with HFCV. *Simply put, subsidizing vehicle purchase does not ensure vehicle use.*

As a side note, this insight is particularly telling for the case of bi-fuel (or flex-fuel) vehicles. For example, while the Corporate Average Fuel Economy (CAFE) standard dual-fuel credit is intended as a fuel substitution incentive, very few flex fuel vehicles actually use high concentration ethanol fuel blends at all. The effective E85 use is certainly not enough to give credit for 50% gasoline displacement (Leiby and Rubin 2001). For this reason, the National Research Council recommended eliminating the dual fuel credits (National Research Council 2002).

Fuel Station Operating Subsidies

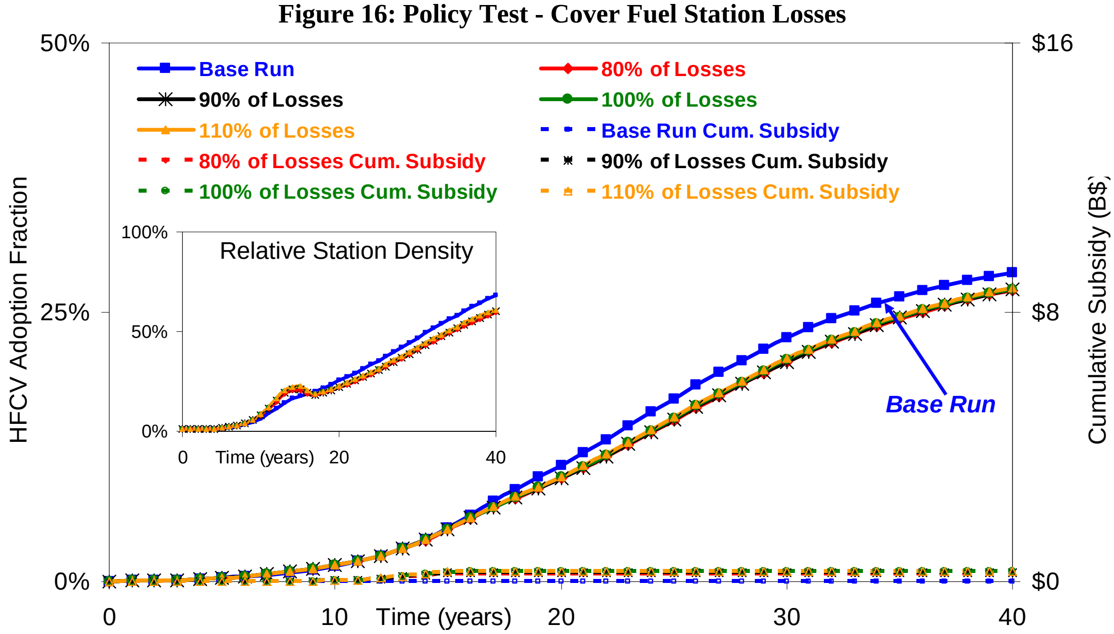
Compared to vehicle subsidies, operating subsidies to retail fueling outlets during the first fifteen years make more of a difference (Figure 15), reinforcing the importance of propelling infrastructure development as quickly as possible in early stages of the transition. To reiterate the explanation, station subsidies have more leverage because the fueling station coverage is a bottleneck affecting so many strong feedbacks governing one's utility to drive AFVs. These station incentives are even more important when the AFV platform is highly fuel efficient.

Figure 15: Policy Testing - Fuel Station Operating Subsidies



Another type of operating subsidy is to cover all station losses until a profitable fuel market develops. Such a mechanism would not be possible as public policy but would be a viable strategy for energy companies with other revenue streams to subsidize hydrogen retailing.

Figure 16: Policy Test - Cover Fuel Station Losses

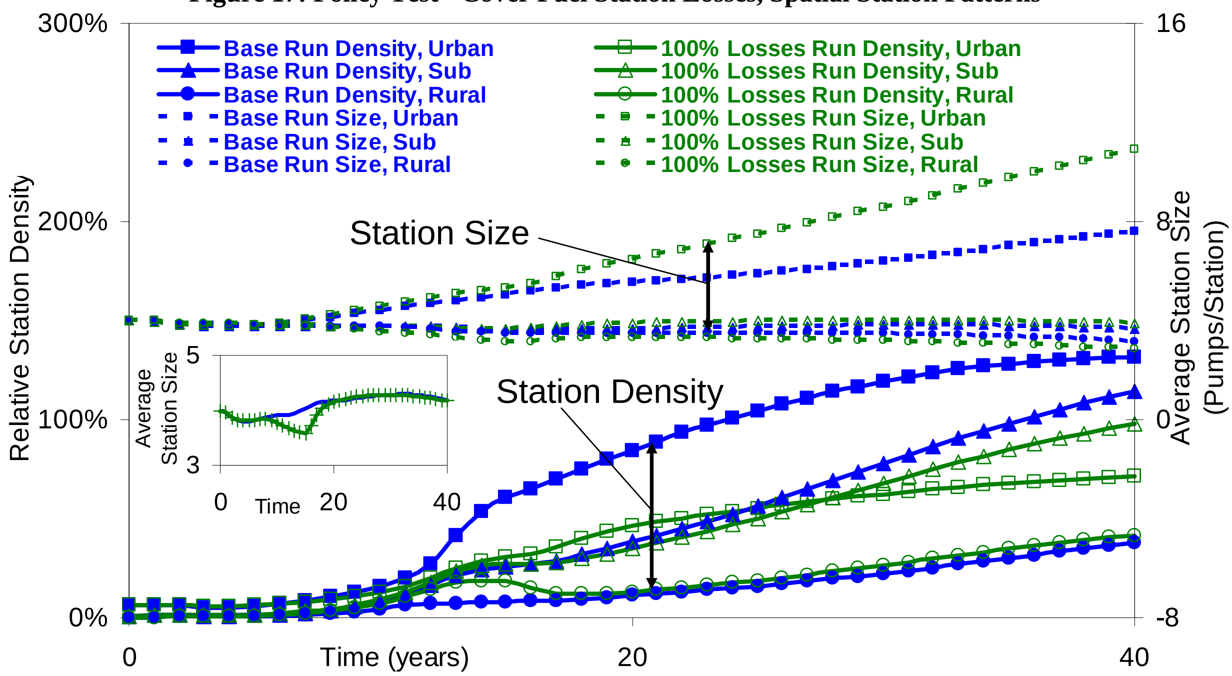


One might guess that this strategy would have similar effectiveness to the previous test. Similarly, it would theoretically be more efficient in that profitable stations wouldn't be "unnecessarily" subsidized beyond what is needed to stay in business. However, this policy may distort the spatial distribution of stations and lead to perverse outcomes like that shown in Figure 16 where the policy actually slows adoption.

The rationale for the policy's ultimate suppression of station density and vehicle adoption, in comparison to the base run, is that this subsidy mechanism shifts marginal investment from the most profitable patches to stations that would not otherwise be profitable. Plots of relative station density and size are spatially disaggregated in Figure 17 for the base run and the case above in which stations receive subsidies equal to one hundred percent of their losses.

As seen below, the effect of making station financial performance more uniform is increased rural station density, slightly lower suburban station density, and greatly reduced urban station density. By not subsidizing the already profitable urban market stations, the rate of early urban station entrance is less than optimal. The ultimate effect of the policy is busier pumps, longer waiting times, and eventually bigger stations in urban areas. To avoid such intended suppression effects, policy must be quite nuanced in overcoming the spatial non-uniformity challenge. Even though station subsidies are necessary for take-off, the use of markets and profit signals to guide infrastructure investments should not be thrown out with the bathwater.

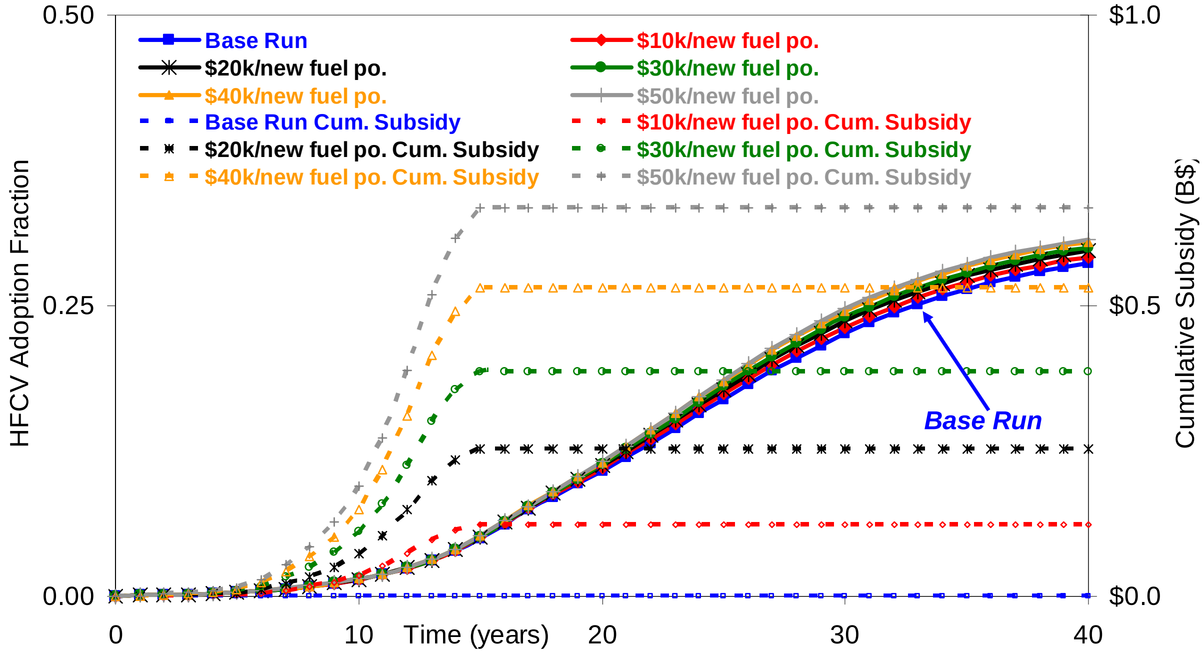
Figure 17: Policy Test - Cover Fuel Station Losses, Spatial Station Patterns



<u>Fuel Station Capital "Buy-Down" Grants</u>

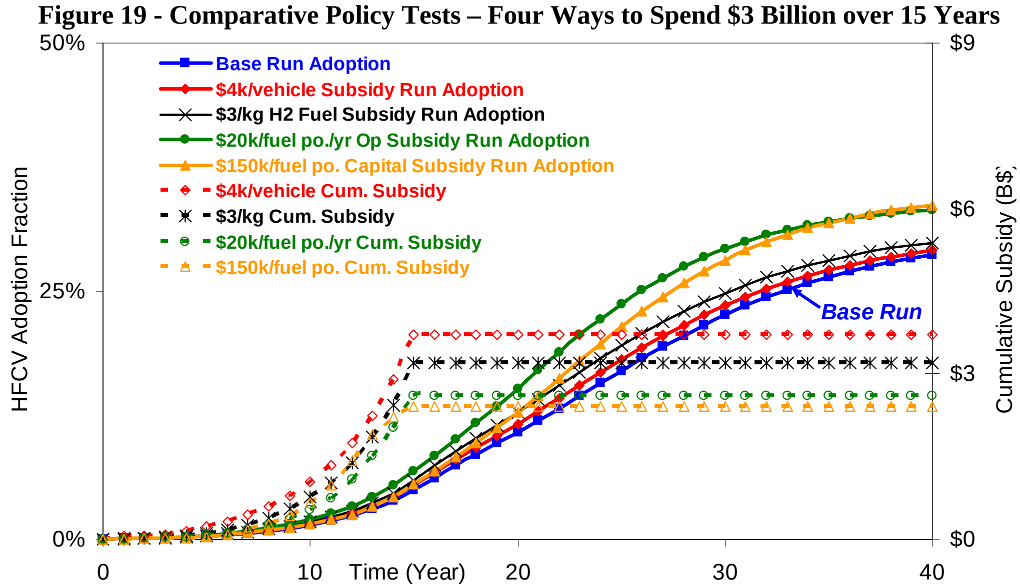
Another incentive mechanism to grow station infrastructure is to use subsidies to buy down the high capital cost of hydrogen production, compression, and dispensing systems. Under the policy presented in Figure 18, new or recently expanded stations during the first fifteen years receive a grant upon completion of construction varying between $25,000 and $100,000 to defray the initial capital cost of about $250,000 per fueling position. There are benefits to front loading the subsidy in this way, even on a net present value basis. Not only does the grant reduce capital depreciation charges for the fuel stations, it also uses the public dollars to leverage additional savings in reducing debt service costs to further decrease annualized fixed costs.

Figure 18: Policy Test - Fuel Station Capital Subsidies



As these later policy tests illustrate, it appears to be more effective to offer stations direct incentives than to subsidize vehicle buyers to compensate for lack of infrastructure. This comparison is made directly in Figure 19, with station operating subsidies having the greatest leverage under the base run conditions. Using the chosen policy parameters listed in the plot legend, these policies require similar levels of cumulative public investment over a fifteen year period (~$3 billion), yet they have quite different impacts in improving upon base run diffusion.

Figure 19 - Comparative Policy Tests – Four Ways to Spend $3 Billion over 15 Years



This order of effectiveness amongst individual policies is also observed when applied to a failure reference case in which a lower demonstration phase markup is set (see Appendix C). Early in the transition, it is most important to build familiarity with the marketing shock and to grow infrastructure with station incentives. Yet once sufficient station coverage is reasonable, the vehicle subsidies may gain slightly more leverage in overcoming attribute shortfalls such as a greater vehicle production cost and retail price to buyers.

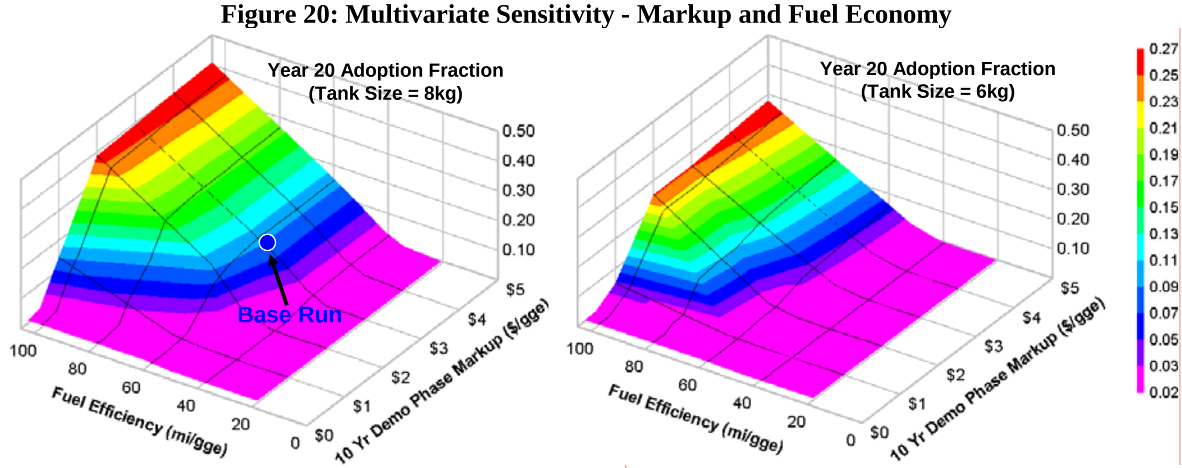
The key to designing effective portfolios of policies lies in designing them to adapt to which bottleneck is dominant at a particular moment in time. In other words, to the extent policy can be dynamic, it should respond to observed conditions by accelerating whichever reinforcing feedback is not keeping pace with the rest. In most cases, the lagging complementary asset is likely to be fueling infrastructure, particularly in rural areas.

Multivariate Policy and Parameter Sensitivity

Policy testing becomes more interesting and robust as sensitivity analysis across the space of technical, cost, and behavioral parameters is implemented at the same time. In the face of inherent uncertainties, policy analysis must seek to find policies that have robust leverage under a variety of scenarios.

In Figure 20, the HFCV adoption fraction in year 20 is plotted for fifty model runs with varying demonstration phase markup policies and with varying average fuel efficiency assumptions for the fuel cell vehicle. As you would expect, high fuel economy cases generally achieve greater diffusion but only if markup is sufficient to build station coverage.

Figure 20: Multivariate Sensitivity - Markup and Fuel Economy



When the markup is low, market penetration remains low no matter what the fuel efficiency, further reinforcing the importance of retailer decision-making. In the univariate markup sensitivity plot back in Figure 9, it was observed that when markups are too high ($5-$7/gge) penetration occurs more slowly than at the sweet spot. Another insight from this plot is that high fuel efficiencies allow even the very high markup cases to succeed. In fact as average HFCV fuel efficiency is as high as 80 miles/gge, it is best to raise markups to more than $4/kg in order to sustain revenues as drivers need less fuel. The position of this slope across this parameter space depends greatly on other assumptions. As tank capacity is decreased, this slope shifts to the left as shown for the 6kg tank HFCV in Figure 20.

Policy Testing with Integrated Learning Feedbacks

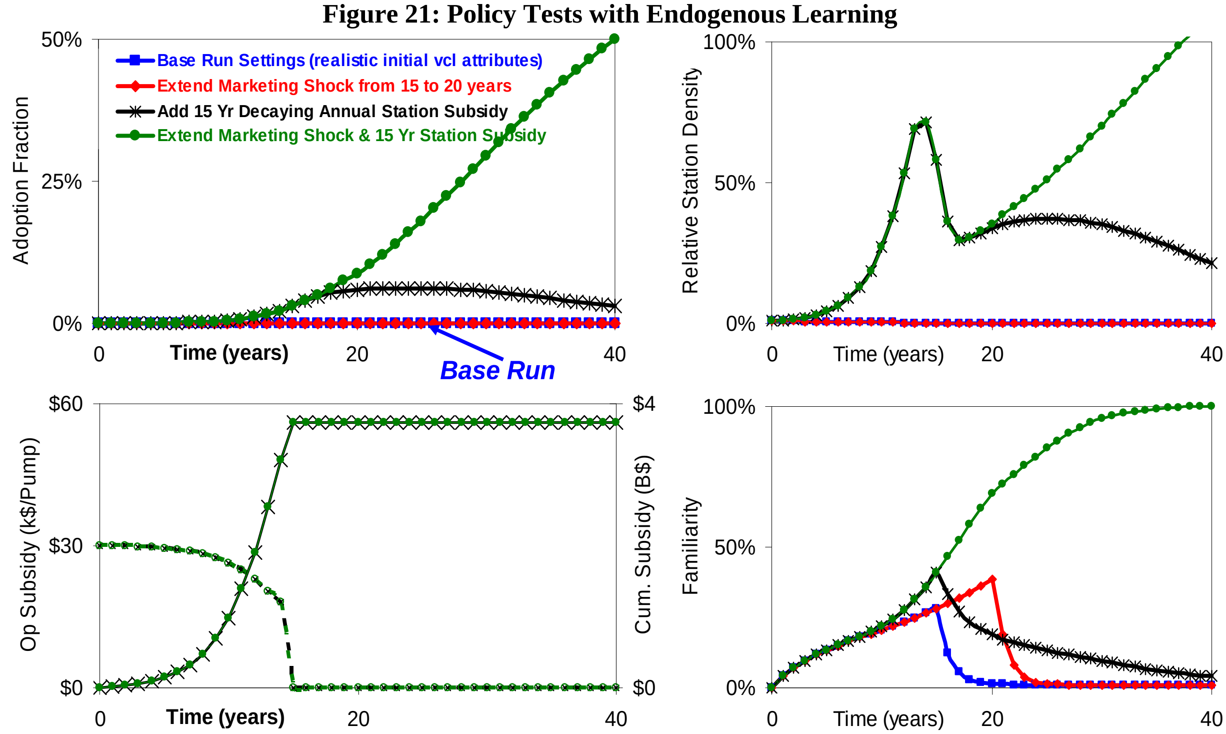
When the endogenous learning feedbacks are switched on and more realistic initial parameter values are selected for the hydrogen fuel cell vehicle, the transition challenge appears even more daunting and tipping dynamics become even more pronounced.

While learning feedbacks, once strong, help the hydrogen fuel cell vehicle to reach a higher ultimate adoption fraction, the development of original equipment manufacturer (OEM) knowledge represents another threshold or metaphorical hill to be climbed to achieve self-sustaining markets. Learning curve and scale economy reinforcing feedbacks only become strong once familiarity, infrastructure and adoption surpass limited levels.

In Figure 21, the base run settings remain the same except that initial parameter values are less optimistic but learning feedbacks are in effect. In this case, even with the ten year $3/gge fixed markup and the fifteen year marketing shock, there is no takeoff.

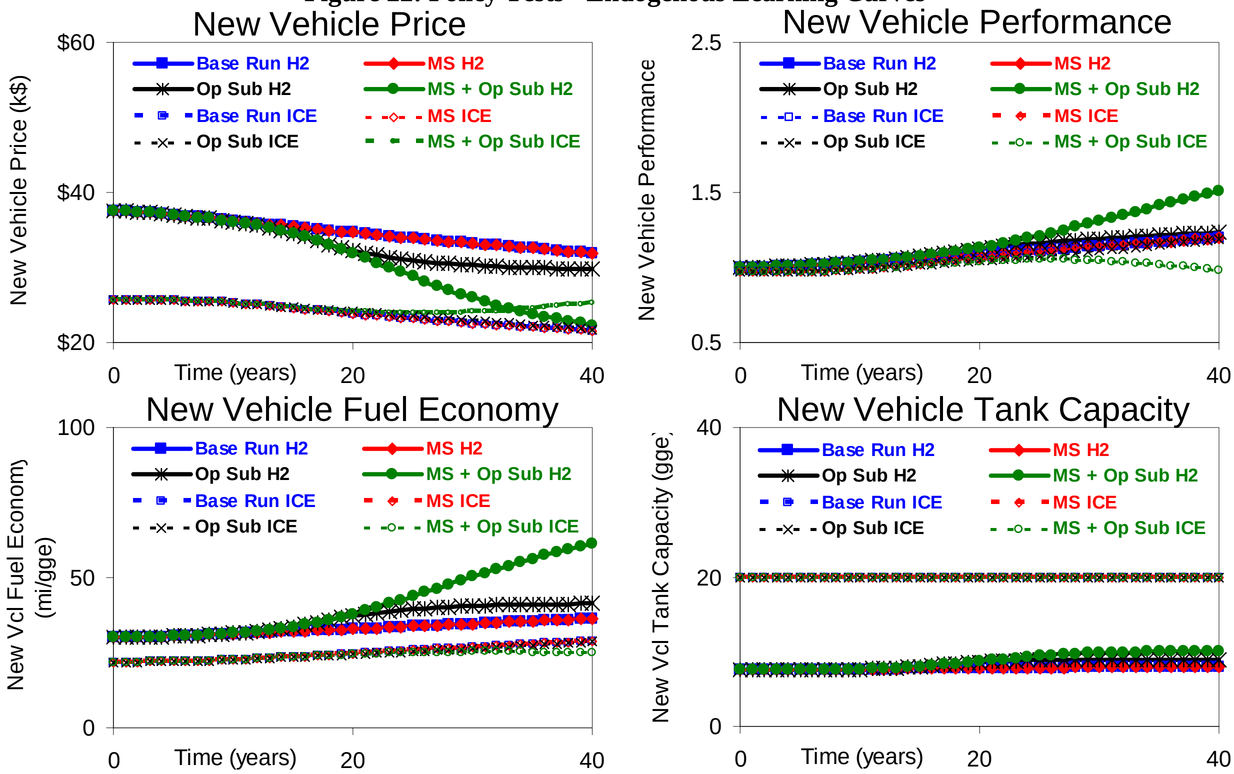
Multiple policies were tested to further bolster early growth from the base run failure case. Consistent with earlier results, vehicle adoption subsidies alone had no strong effect. Two additional policies changes were necessary to achieve successful take-off. First the marketing shock was extended by five years to twenty total years in duration. Second, all hydrogen fuel stations are given an annual operating subsidy per fueling position that begins at $30,000 and decays over the fifteen year subsidy period as the cumulative subsidy approaches eight billion dollars. Notably, applying either of these policy changes alone is insufficient to surpass the requisite thresholds. Yet application of both policy changes results in markedly successful diffusion compared to the other cases plotted below.

Figure 21: Policy Tests with Endogenous Learning



As expected, once the market surpasses the tipping points, further diffusion occurs more and more quickly due to endogenous learning effects. In fact the adoption fraction is still continuing to climb rapidly at year 40. The improvement curves for the respective HFCV and ICE vehicle parameters for these four policy test runs are plotted in Figure 22.

Figure 22: Policy Tests - Endogenous Learning Curves

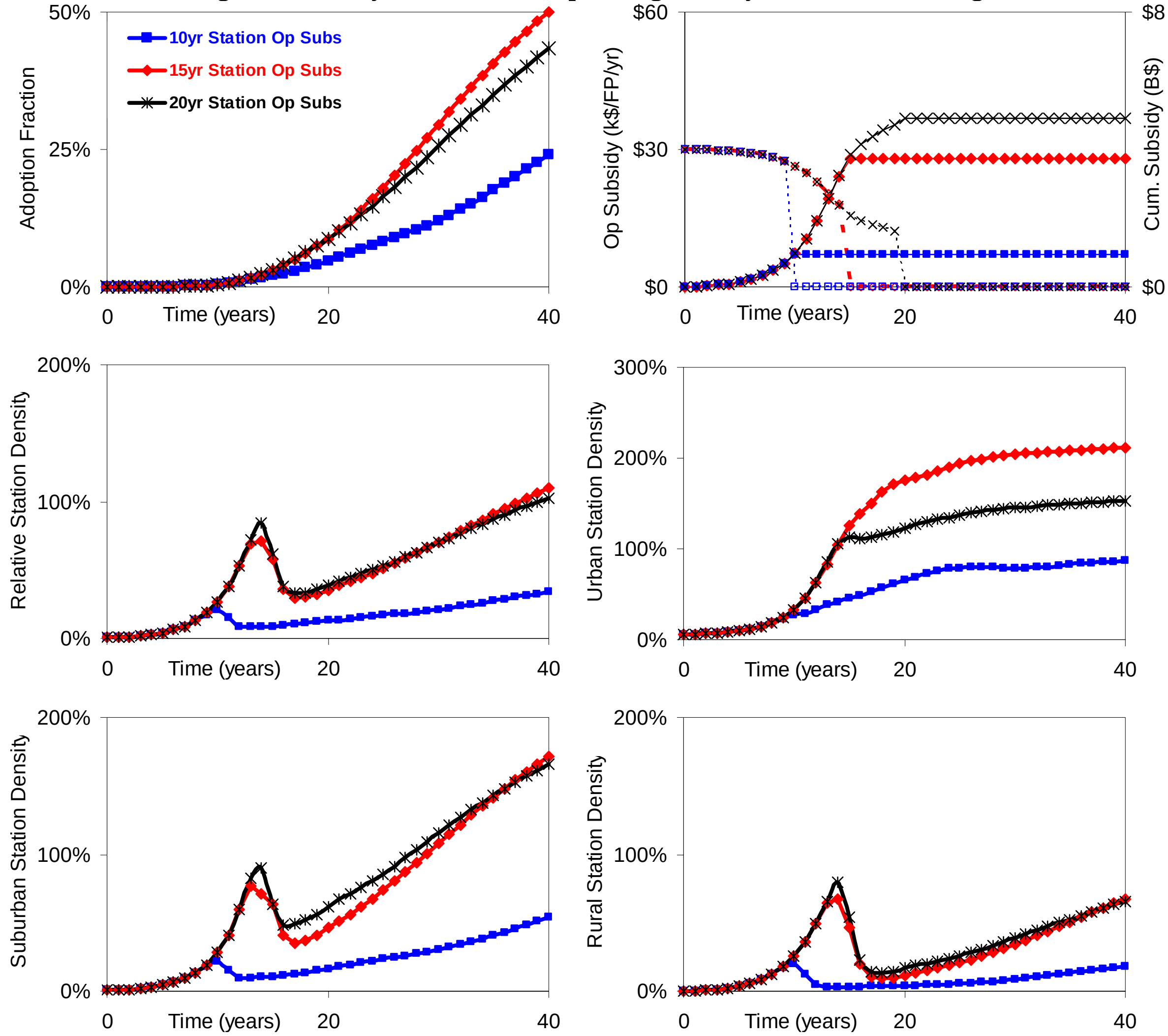


One reason the transition challenge becomes harder with endogenous learning feedbacks is because the ICE incumbent vehicle improves too. As observed in Figure 22, ICE's performance and fuel economy continue to climb while vehicle production costs fall. Of course, because cumulative fuel cell vehicle production is growing at a greater exponential rate from a small base, its rate of learning and attribute improvement is greater. Hence, as long as the market is sustained by policy for long enough duration, the learning feedbacks will eventually become stronger and improve the ultimate level of adoption of the hydrogen vehicle.

Although the station operating subsidy is the most effective policy found to complement the demonstration phase markup and marketing shock to achieve successful take-off, further policy testing again demonstrates the need for great care in applying this type of instrument. As illustrated in Figure 23, diffusion is actually limited by increasing the duration of the annual subsidy per fueling position from fifteen to twenty years. There is a strong sweet spot in policy duration. The system requires more than ten years to properly accelerate station development, yet if the subsidy is left in place too long, it distorts the spatial distribution of fueling stations from the optimum that emerges under competition without such supports.

As one would expect the longer subsidy policy results in more total stations. However, it also results in significantly less urban stations and slightly more rural and suburban stations. This difference in geographic distribution reduces utility to drive and ultimately HFCV adoption. This example mirrors the negative impacts seen earlier when testing the strategy of subsidizing station losses over the first fifteen years.

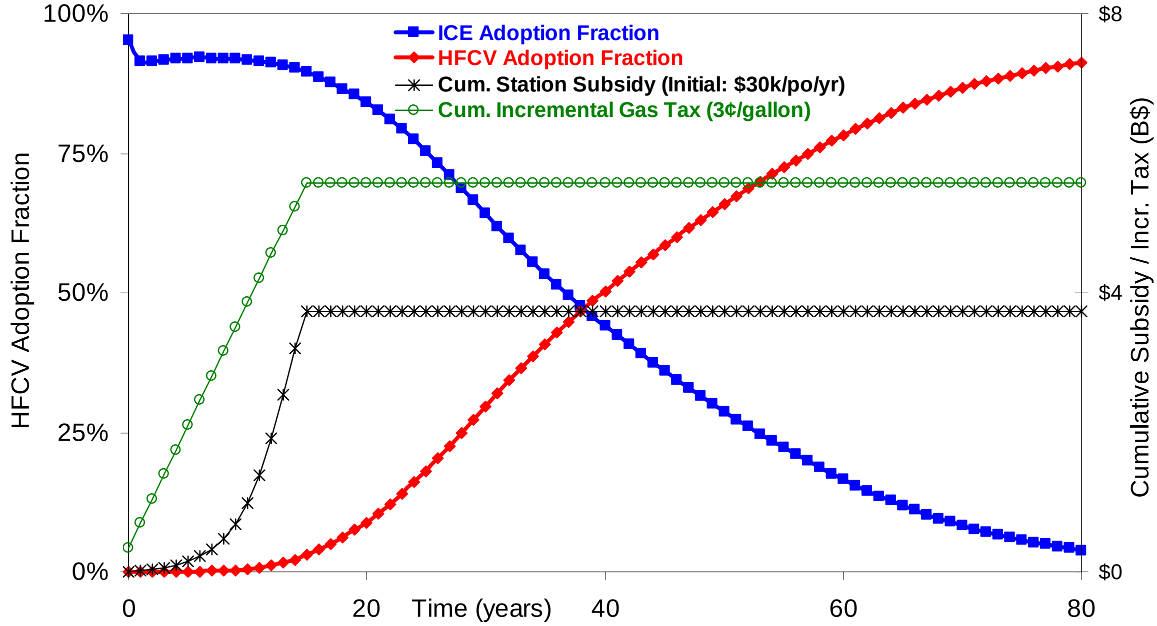
Figure 23: Policy Test - Station Operating Subsidy Duration, Learning On



So, while the chicken-egg dilemma in achieving rural station density is an important challenge to overcome, it appears that policies intended to do so may overcompensate and actually constrain market penetration rates. The need to overcome market and behavioral failures does not preclude the goal of harnessing competitive markets for the optimal emergence of infrastructure.

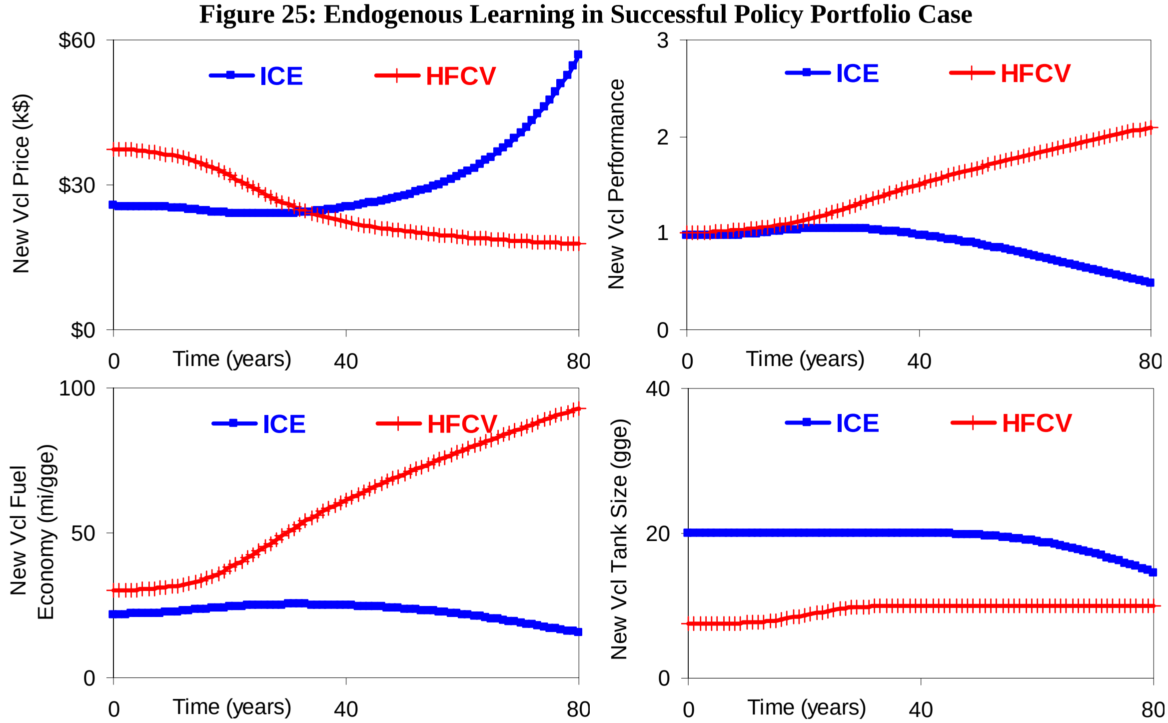
With so many uncertainties, how are policy designers to choose the appropriate duration to avoid such unintended consequences? Unfortunately the AVMT model does not provide perfect forecasts to do so. However, it does provide an understanding of system structure that would enable an adaptive policy approach in which, for example, policymakers knew such subsidies could be phased out after reaching average rural relative station densities greater than 50%. The effects of endogenous learning are particularly powerful in influencing dynamics after some threshold of successful take-off has been reached. Once these reinforcing feedbacks are enabled, they strongly improve the ultimate equilibrium level of AFV penetration.

Figure 24: 80 Year Simulation, Successful Policy Portfolio with Learning



In fact, if the successful policy portfolio from the previous example is simulated for eighty years, HFCVs grow to fully penetrate the market (Figure 24) rather than equilibrating at around 45% of market share as seen in the prior success cases without the learning feedback effects. Once tipping points are surpassed, learning feedbacks bring HFCVs great advantage (Figure 25).

Figure 25: Endogenous Learning in Successful Policy Portfolio Case

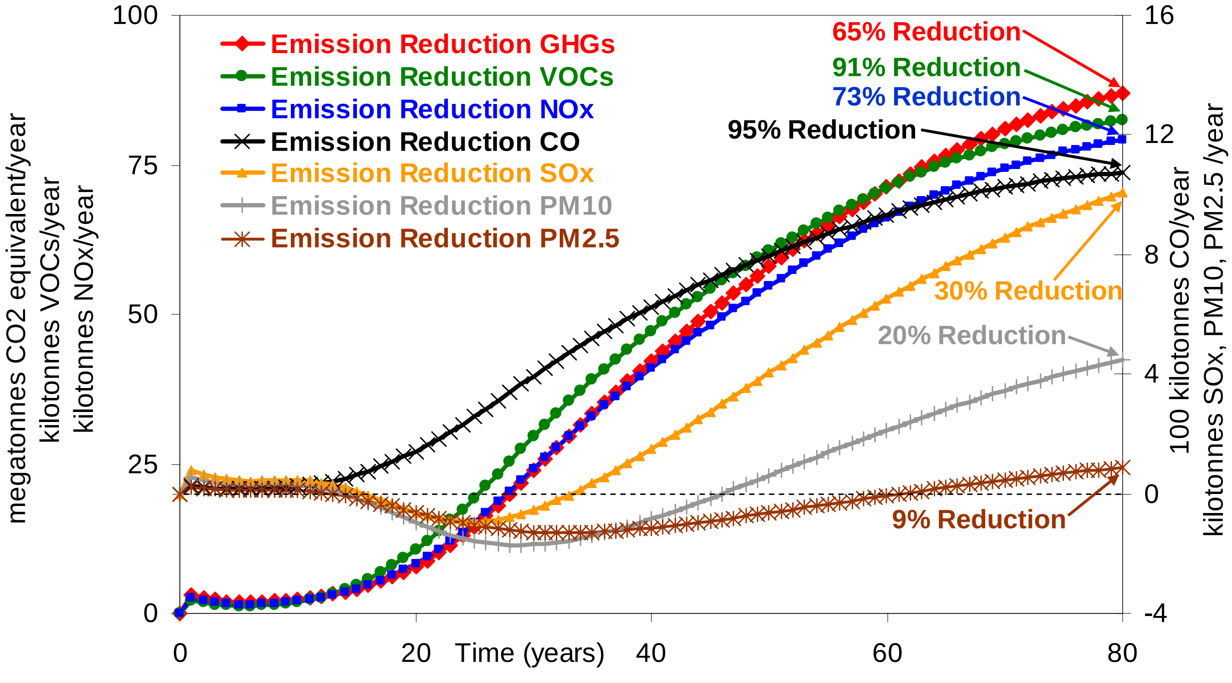


In addition, Figure 24 illustrates that endogenous OEM knowledge can also be lost with drastic decreases in vehicle sales. As the ICE is edged out of the new sales market, its technical attributes actually worsen. Thus, one can see how reinforcing learning feedbacks give great advantage to the market leader or to a new technology growing quickly from a small base of cumulative production.

Furthermore, this policy portfolio example illustrates that an additional gasoline tax of only 3¢/gallon over the first fifteen years is more than enough to fund the necessary fuel station operating subsidies that are necessary on top of the base run policies to achieve take-off when learning effects are modeled endogenously. The strong marketing shock to building awareness and comfort with the new technology will also be very expensive. Yet, after subtracting funds for station subsidies, the multi-billion dollar surplus from this incremental tax revenue could also fund the marketing shock to make the entire policy portfolio revenue neutral.

This sort of revenue neutral program of moderate taxation and government subsidy would be well justified to create the simulated emission flow reductions plotted in Figure 26. Particularly dramatic are the savings achieved in carbon monoxide and nitrogen oxides emissions compared to reference levels. Thanks to the HFCV's radically increased fuel efficiency, the reduction in greenhouse gas emissions is also significant. Interestingly, although the policy actually results in worse sulfur oxide and particulate matter emissions initially due to the emissions during hydrogen production, eventually the fuel efficiency improvements achieved via learning lead to substantial reductions in the emission rates for these pollutants too. On the whole, even if hydrogen continued to be produced from natural gas as assumed in this run, the emissions from a fixed-level stock of light duty vehicles would be much improved.

Figure 26: 80 Year Simulation, Successful Policy Portfolio Avoided Emissions



Conclusions & Recommendations

General Conclusions

The AVMT model represents several important feedback relationships that govern the effectiveness of policies to displace conventional motor fuels with substitutes. In a simplified, one-entrant scenario, the hydrogen fuel cell vehicle can diffuse to a self-sustaining level but *requires strong policy support over decades*, confirming earlier conclusions (Struben and Sterman 2006) now with a broader integrated model that has been carefully parameterized for that vehicle technology and hydrogen fuel reformed from natural gas at the station forecourt.

The rate of market penetration is sensitive to policy, behavioral, and technology assumptions, but remains longer than commonly conceived in all cases. In cases of successful diffusion, equilibrium market shares depend primarily on the relative technical attributes (price, performance, range) across the competing vehicle platforms. However, the *likelihood of a successful transition is strongly dependent on the rate of growth in three critical complementary resources*: spatially balanced refueling infrastructure, consumer familiarity with the technology, and OEM knowledge for vehicle design and production. Nonlinearities in utility as these assets increase necessitate that each be grown beyond thresholds to reach financially sustainable fuel and vehicle markets. In other words, there are *multiple important tipping points*.

Developing statewide average station densities at 15-20% of gasoline station infrastructure is not sufficient alone for the market to become self-sustaining. Infrastructure coverage in infrequently visited rural areas plays a disproportionate influence on both vehicle purchase and trip destination choice. Integrated model results confirm that locally rational behavior of drivers and fuel providers reinforces the spatial asymmetry problem. Because urban fuel markets are most profitable early on, they attract the most station entrance. Drivers then make a habit of topping-off in and/or traveling to urban areas where perceived station density is high rather than risk running out of fuel in remote areas, further reinforcing the low profitability in rural locations (Struben 2006). Unless this urban-rural asymmetry chicken-egg problem is overcome, the system will come to an equilibrium consisting of only niche market adoption in urban clusters.

On top of these hurdles, competition between various AFV entrants is to the detriment of all, making the transition challenge even more staggering. A balance must be achieved between coordination and competition needed to avoid lock-in to other inferior technologies.

The presence of the used car market is another important feature of the AVMT model. While it has both reinforcing and balancing effects, the net effect of this structure is to speed AFV penetration as there is a larger shift in the share of ICE vehicles that are purchased used.

Sensitivity analysis repeatedly reinforced the importance of a wide multivariate search of the parameter space when testing policies to influence systems with nonlinear relationships. The important role of some parameters, such as a driver's sensitivity to station coverage in adjusting their fuel tank buffer, would be overlooked by univariate sensitivity analysis, no matter how precise the probability distribution for inputs. Such multi-dimensional search is also needed to observe nonlinear interaction effects between parameters like fuel economy and tank capacity.

Policy Recommendations

The broad lesson from this analysis is that policies to support technology transitions should be designed cognizant of the system structure driving dynamic behavior. Most importantly, coordinated portfolios of policy instruments must be used over long enough duration to surpass thresholds in complementary assets before markets will become self-sustaining. Simply assembling a politically feasible package of policies used in the past without attention to the system's dynamic structure is likely to be insufficient to surmount the key transition barriers within reasonable costs.

More specifically, this analysis provides examples of how policy leverage varies with an alternative vehicle's technological attributes and infrastructure needs. It is understandably intuitive for policymakers to try to apply policy instruments that worked to speed diffusion for one technology (e.g. tax credits for efficient household appliances) to others such as hydrogen fuel cell vehicles. Yet in cases where requisite complementary assets are highly non-linear in shaping the attractiveness of driving a vehicle, such purchase incentives have little impact and will go wasted if not combined with higher leverage incentives and coordination strategies to grow familiarity and infrastructure. Simply put, *subsidizing vehicle purchase does not ensure vehicle use* and a level of fuel demand to sustain infrastructure. This lesson is just one example of the type of insight that system modeling efforts produce.

Several tests illustrated the additional policy challenges for AFV platforms with lower driving range or radically higher fuel economy. A key insight gained from the behavioral model is that management of retail margins by early hydrogen station entrants is critical. Even supplemented by ancillary sales revenues, the competitive retail margins seen in gasoline retailing would not be enough to drive growth in capital intensive hydrogen fuel stations. The importance of this decision rule would be missed by economic optimization models that do not include this agent's behavioral decision-making. What is the potential for high markups during a demonstration phase? In addition to intellectual property and technology leadership, the time delays for station entrance (permitting, etc.) may be important in constraining the entrance of competitors so that early entrants will be able to maintain relatively high margins. Clearly, early competitive price wars will thwart the transition. This challenge also suggests a strategy of looking for complementary hydrogen applications such as stationary backup electric power provision.

The demonstration markup and fuel subsidy policies also raise the important question of how consumers perceive the cost of driving. With entrant AFVs that are more fuel efficient compared to the incumbent, all else equal, it is important to help drivers perceive cost on a per vehicle mile basis. Retail markups on variable cost to cover more capital intensive fuel production processes at the fuel outlet can then be higher while consumers would still perceive prices to be competitive with gasoline. This challenge becomes easier if such the higher markups are combined with a gasoline tax, which could also be temporary.

Despite the relative effectiveness of policies such as fuel station operation subsidies or gasoline taxes observed in the analysis, these policies face major political hurdles. If large oil companies dominate alternative fuel production and retailing, imagine the difficulty of convincing legislators to subsidize their alternative fuel operations. Indeed, political stakeholder considerations are just as important a policy portfolio design constraint as any transition barrier, particularly because of the need for stable policies over durations longer than several election cycles for this type of technology transition. For this reason alone, the effective transition-oriented policies may need to be complemented by direct incentives to households, such as the provision of tax credits on the total volume of alternative fuel purchased over the course of a year. Other fiscal policy measures to reduce the net regressive impact of gasoline taxes would also be a vital complement to that policy.

Regarding infrastructure policy incentives, coordination to achieve comparable growth rates in the vehicle fleet and fueling infrastructure is paramount. Choice of incentive instruments for fueling stations provides another example of the need to derive polices from an understanding of the feedback and behavioral processes at work. Analysis of the urban/rural asymmetry problem suggests that an effective transition requires a disproportionate share of public support for fueling outlets outside urban areas. Yet, a strategy of covering all fuel station operating losses may overcompensate for the rural station development challenge. It was observed that some station incentives distorted spatial distribution from the appropriate geographic balance resulting in too small an urban concentration. This finding, along with the political difficulties of awarding asymmetric subsidies to various cities and counties, suggests uniform capital grants or operating subsidies per fueling position are the most appropriate policy incentive for stations.

In addition to infrastructure incentives, the analysis emphasizes the criticality of *aggressive consumer marketing campaigns* over long periods for emerging technologies competing with durable goods with long lifetimes such as automobiles. Technological superiority alone will not necessarily lead to widespread diffusion without efforts to build awareness and willingness to consider the new technology. Such marketing campaigns will be more expensive than manufacturers and fuel retailers can afford using early sales revenues alone. Stable government support for such education is critical and should not be terminated early even the AFV appears to be having early success, because *familiarity can collapse fairly quickly.*

In summary, the three dominant reinforcing loops operating in AFV market bring growth potential but also instability into the system. The aspiration of policy engineers should be carefully coordinated policies to simultaneously develop consumer familiarity, fueling infrastructure, and OEM knowledge at similar rates in order to avoid overshoot and collapse. Even better, policy should dynamically adapt to observed conditions to identify and lessen the dominant transition constraints in effect. It cannot be emphasized enough that policy incentives must be stable over long duration to surpass multiple tipping points in the system. Policy and strategy makers should be warned from the outset that successful diffusion will take a long time.

Supporting the transition to a self-sustaining AFV market is a staggering challenge. Yet smart policy and bold leadership can result in successful market transformations, creating long lasting private and social benefits.

More generally, although policy analysis guided by system dynamics modeling may require more time up front to build an understanding of the feedback structures underlying a problem, it will serve entrepreneurs, policymakers, and their public quite well.

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