MIT Project on Market Transitions for Low Carbon Transportation

Report 2

September 2010

Summary of Policy Insights from Alternative Fuel Vehicle Transition Analysis

Jeroen Struben
jjrs@mit.edu

MIT Sloan School of Management,
Cambridge MA 02142

DRAFT – not for distribution

Introduction

The purpose of our research program is to obtain an in-depth understanding of the major challenges in transitioning away from a fossil fuel and carbon based private transportation system, and to identify high strategies for success. Current transportation does not scale: if the projected world population of 9 Bilion people would live the way Americans do today, world oil production would increase 5 fold to 440 million barrels per day, and CO_2 emissions would increase with a factor 2.5 (MIT Transportation Initiative 2009). With increasingly volatile oil prices, unprecedented US dependence on imported petroleum, and growing environmental concerns, the creation of economically sustainable markets for alternative fuel vehicles (AFVs) is vital to the success of automakers and fuel and energy suppliers, and to the health of the US, and global economies. However, most efforts to transition away from a transportation system dominated by the gasoline fueled internal combustion engine have failed or had very limited success (Struben 2006). Diffusion of AFVs is complex, being both enabled and constrained by powerful positive feedback arising from various scale and scope economies and experience curves throughout the automotive and fuel supply chain, and from consumer behavior and word of mouth. Outcomes are strongly conditioned by decisions from diverse players including energy companies, governments, automotive OEMs, and their suppliers, utilities, and consumers. Further, while such a transition will play out over decades, mobilization of resources over the next decade has long run consequences, for firms, industry, and society.

Transitions towards alternative transportation are highly sensitive to policy support and require long term commitment. This document provides a summary of some of the key insights that have result from MIT project on Market Transitions for Low Carbon Transportation, started in September 2006. The work focuses on understanding important factor in the dynamics of AFV market transitions as well as on identifying major sweet- and weak-spots in and robustness of policies cutting across automotive, energy, utilities, and government players. The dynamics of AFV transitions is dynamically complex. Our framework, centered on dynamic analysis, enabled through simulation models, is particularly well suited to learn about the working, to explain fundamental constraints, and for the identification of high leverage policies to influence the AFV. The quantification of simulation results should not be interpreted as quantitative findings, and examples are not to be interpreted as forecasts for outcomes. While the models have been, where relevant, carefully calibrated, the insights provided should be seen, as qualitative statements that help deepen our understanding of the dynamics of AFV market transitions and that help generate further questions, or spur complementary research. At the moment of writing, additional policy analysis is in progress. Subsequent findings will be included in an updated version.

This report combines and summarizes findings that are analyzed and described in greater detail in underlying research documents and presentations. In this report we have categorized and numbered this subset of findings so that they can be used and printed for discussion as “stand alone” discussion topics. However, clearly, findings are strongly related to each other and their insights are most powerful when discussed jointly. The focus in this report is on the practical insights, their explanations, and policy implications. We do not focus here on the specific underlying assumptions. However, we conclude with a bibliography containing all project-related documents, comprising theses, peer-reviewed articles, working papers, news reports, and presentations, including videos that report in more detail on these findings and their underlying argumentation and assumptions. Most documents are available through open online access. In this report, for some of the insight discussions, we refer for further reading to the underlying research documents. Among that, we point to three workshop presentations that directly provide additional (graphical) descriptions several of these findings. Where relevant, these Power Point documents will be referred to as 2007_1, 2007_2, and 2009 slides respectively, with indication of page numbers. We refer to these accompanying presentations as “see also 2007_1 Slides pp 1-2”. We will also refer to some of this documentation, under the heading “further reading”.

This work is performed under MIT’s Project on Market Transitions for Low Carbon Transportation, at the Sloan School of Management, co-lead by Prof. Jeroen Struben (McGill University, Research Affiliate at MIT) and Prof. John Sterman (MIT). This work has benefitted from significant input by many others, including former and present MIT team members (alphabetically, Katherine Dykes, David Keith, Jessica Laviolette, Derek Supple, Qi Zhang). Moreover, this work is fundamentally cross-displinary and intends to bring actors from across industries and governments. In line with this, much of the thinking has been developed through workshops with industry and government players at the table, critiquing the analysis, challenging the scope and the assumptions and developing alternative questions. These actors, both sponsors and not sponsors, have provided a fundamental input throughout this project and remain doing so. We thank involvement and information from Ford Motor Company (David Chock, Yimin Liu, Mike Tamor, Margaret Whalen, Sandy Winkler), Shell Company (Dave Austgen, Nikunj Gupta, Henk Mooiweer, Jooske van der Graaf, Monisola Olaweraju), General Motors (Britta Gross), and the National Renewable Energy Labs (Cory Welch). We are thankful to participants to the MIT-FORD-Shell workshops (http://web.mit.edu/jjrs/www/3rdMITFordShellWorkshop.htm).

This Research is sponsored by Shell Hydrogen, Ford Motor Company, National Renewable Energy Laboratories, and the MIT Sloan Project on Industry and Organization Studies. We are grateful to all the funders of this project. Without their support this work could not have been performed. However, all statements are of the MIT authors. The authors claim no conflict of interest. No proprietary information/data have been used in the analysis.

A. Table of contents

B. Research goal

Understanding challenges to overcome thresholds for a self-sustaining AFV market

Diffusion dynamics of alternative fuel vehicles (AFVs) cannot be effectively described by the S-shaped curve that is typically used to describe diffusion of innovations. Instead their diffusion exhibits multiple equilibria. In the past many alternative fuel vehicle introductions have failed, including those propelled by natural gas, synfuels, diesels, and electric vehicles in various countries. Natural Gas Vehicles in Italy (stagnated at a penetration below 5%), Argentina (15% and growing), and New Zealand (Growth and Collapse), electric vehicles in the 19th and early 20th century and in the 60s all exhibited this behavior. Similarly, around the 19th century, many had put their faith in electric or steam vehicles. But the internal combustion engine won. These results cannot be explained by arguments of inherently inferior technology. Instead, underlying is that AFV diffusion dynamics is both enabled and constrained by powerful positive feedback arising from scale and scope economies, R&D, learning by doing, driver experience, word of mouth, AV competition, and complementary resources such as fueling infrastructure. The system is characterized by adoption thresholds, or tipping points. Our analysis show successful scenarios for radical and disruptive alternative such as Plug-in Hybrid Electric Vehicles (PHEVs), and Hydrogen Fuel Vehicles (HFCVs) are possible, but simulations using conventional policies either fail or generate generally negative NPV for at least some of the important players. The successful runs are those that include commitment from partners across all areas of the system. These policies may change as the system evolves and have a longer duration – on the order of two decades - than policy and strategy makers usually allow for.

Diffusion dynamics of AFVs are particularly complex, because the system in which this plays out harbors the 5 main factors that contribute to dynamic complexity in general. First their dynamics are conditioned by a set of feedback mechanisms (fueling-infrastructure and demand, technology improvement and vehicle sales, consumer acceptance and exposure to those vehicles) or "chicken and egg" problems. Further, there are many different types of stakeholders, that each their own perceptions, goals and way of operating. That is, the outcomes depend on the portfolio of commitments. Third, the interdependencies between factors in this system are highly non-linear. (e.g. the first few fuel stations yield very little drivers, but increasingly new fuel stations act to enrich the coverage for more drivers). We will discuss the particularities of each of these mechanisms in detail below. Similar dynamics can be seen between Apple and Microsoft: even though Apple is inherently inferior, the Microsoft operating system remains far dominant. User experience, familiarity, software complementarities, technology learning all play an important role in this. Research elsewhere has shown that the importance, working and strength of such reinforcing feedbacks, as well as the role of time delays are systemically underestimated by key decision makers. Such misunderstanding can lead to policy resistance: policies intended to stimulate adoption, may in fact harm the initiative. This is both shown by empirical analysis of the automotive industry (too fast growth of some vehicle or infrastructure suggested the alternative was ready to takeoff, however, this fast growth undermined building important experience). Below we discuss such examples of policy resistance in detail.

The analysis of factors that condition the existence, location and strength of thresholds makes use from tools from the system dynamics method and are especially well suited to analyze such dynamically complex problems. System dynamics is an approach for studying how socio-economic systems change over time. In studying the dynamic behavior of such systems, its focus is on feedback relations and delays embedded in the system structure.[1] Apart from constituting a representation of the dominant mechanism underlying observed behavior, the identified structure may also be used as a test ground for studying particular changes in the system and thus for exploring conditions under which thresholds for adoption and high leverage policies to influence this. Another fundamental component of this approach is that the internal causal structure of a system determines its dynamic tendencies. Hence explanations for the observed behavior is the system structure itself, not single decisions or external disturbances. This assumption is a key issue in determining the decisions regarding the system boundary in SD modeling approach; any component or relationship hypothesized to influence the observed behavior shall be considered as a part of the system.

To assess strategies for success in such a dynamic environment, this research project has lead to development of an integrated dynamic model that simulates the co-evolution of the technologies and market for AFVs and infrastructure. It allows for careful analysis of structure, for exploration of scenarios, and for testing of strategies. We use the method of system dynamics to develop such a model and analysis. Underlying this integrated model is a set of explicit behavioral dynamics models, using simulation to illustrate how diffusion proceeds under a variety of scenarios. We developed explicitly spatial, dynamic models uniquely suited for learning about and strategic decision making on AV transition dynamics. The models capture the coevolution of the car parc, improvements in technology, and changes in consumer attitudes and driving behavior. We draw our insights from a distribution of generic and calibrated models. Some models are spatially disaggregated to trace critical complementary interactions with fueling infrastructure. For those, the state of California served as our laboratory for experimentation. Hence, we have calibrated the models to California with respect to relevant parameters such as demographics, vehicle ownership, fuel stations, and travel behavior. The analyses highlight how, even with significant policies, any successful diffusion path is "fragile" for a long duration - small setbacks, or well-intended interventions may have large negative consequences. Further the strength of the various mechanisms that condition vehicle diffusion are influenced by the local context. Factors that contribute to the shaping of trajectories include geographic settings, cultural and historical contexts, competing platforms, an various institutions. There is thus strong leverage to selecting appropriate pilot regions. This will be discussed more in detail below.

[1] System Dynamics appeared in the literature by the work of Forrester in the 1960s. System dynamics is known as a modeling technique relying on differential equations. Broader, system dynamics is an approach for studying complex dynamic behavior of systems, which benefits from quantitative simulation models. In that sense SD does not just cover the issue of how to model a given system, but also how and where to look for underlying mechanisms of dynamic complexity.

C. Insights related to the general transition dynamics

Intentionally left blank so that each insight can be printed separately

1 Alternative Fuel Vehicle Diffusion: Slow and Fragile

Diffusion of AFVs is slow and fragile. Figure 1 shows vehicle diffusion patterns for a small selection of vehicle types and markets countries, as well as DOE's slow and fat scenarios for HFVCV diffusion. For each, the year count (horizontal axis) starts upon introduction. Notice: this Figure shows a small and biased selection of (sometimes temporally) successful vehicle introductions. The graph is necessarily biased, because many of the failures do not show up. Left shows the (equivalent) share of the total vehicle sales; right shows the installed base as share of the total vehicle market.

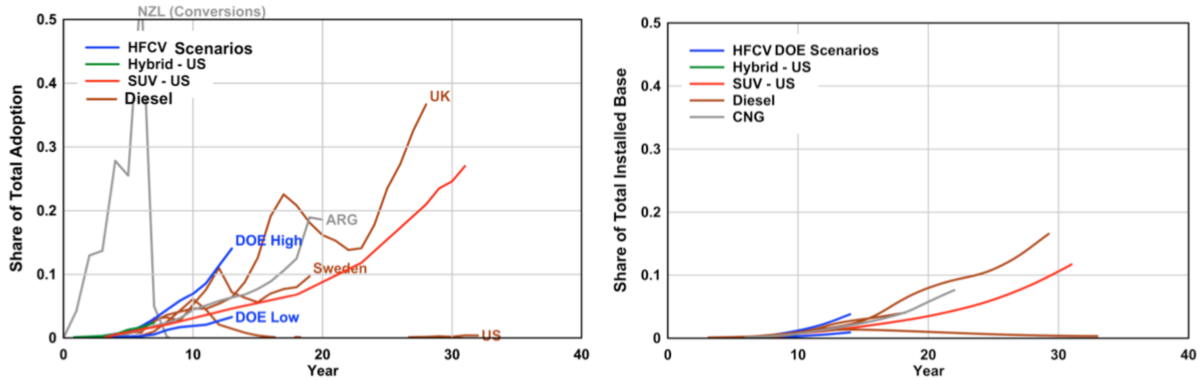


Figure 1. Diffusion patterns for various vehicle types and markets. Left: share of total vehicle adoption. Right: share of total vehicle installed base

Explanation

An example of a failed (though initially rapid) introduction is that of CNG in New Zealand. In 1979, in response to the high oil prices the government wanted to stimulate NGVs and targeted a large share of the market for 1990. This was possible due to discovery of natural gas fields in the end of the 1960s. Conversions (rather than new vehicles, hence the rapid early take-off) were high in first few years, due to much commitment and collaboration by industry and governments, leading to subsidies, education programs and fueling infrastructure in urban areas. However, 10 years later when incentives packages where taken out to let the market work, the program totally collapsed. Hence, 10 year intense support was not sufficient to build a self-sustaining market. Across and within fuel types a wide array of diffusion patterns. For CNG we see some success, low momentum, some fizzle/sizzle, as NZL, and much limited penetration.

Moreover, observe that adoption is very slow, even for the successful cases. This is true, even absence any infrastructure or technology challenges. Take SUVs (see the Figure): reaching 10% market share took 20 years and reaching 25% market share took about 30 years. Note that for this particular example no infrastructure issues (SUVs) or only minor ones (diesel), and that the costs of the vehicles were already competitive with conventional (due to near total spillover of the drive technology). Most of the inertia relates to the build up from consumer acceptance. Development of the installed base takes much longer to develop, due too the slow turnover. Typically, new vehicle purchases per person occur only every ten years; new fueling infrastructure stations need to permits, side selections; consumers need multiple exposures to become confident about the efficacy and safety of a new vehicle technology; such inertia means the network effects are strongly out of their equilibrium, imposing further challenges to players' commitment to the development of a technology.

See also: 2007_2 Slides p5 and 2009 Slides pp 13-15

2 Processes that condition the formation of a self-sustaining AFV markets

To assess strategies for success in such a dynamic environment, this research project has lead to development of an integrated dynamic model that simulates the co-evolution of the technologies and market for hydrogen fuel cell vehicles and H_2 infrastructure. It allows for careful analysis of structure, for exploration of scenarios, and for testing of strategies. Underlying this integrated model is a set of explicit behavioral dynamics models, using simulation to illustrate how diffusion proceeds under a variety of scenarios. We developed explicitly spatial, dynamic models uniquely suited for learning about and strategic decision making on AFV transition dynamics. In this section we highlight the core feedbacks in this system and discuss some implications for the long-run dynamics. Detailed insights are discussed in the subsequent sections.

The AFV diffusion process is mediated though mechanisms that span multiple coevolving markets, including among others fuel production and development, fuel dispensing and retailing, automotive production and the automotive after-sales market. A useful starting perspective is that automotive producers are seen to provide a platform, the vehicle, with particular performance over various dimensions of merits, but relying on a fuel that requires an infrastructure that differs from the dominant (i.e. gasoline)). In this environment, chicken-egg feedback exists between fuel retailing and fuel demand (thick feedback, R1): drivers will not find AFVs attractive without ready access to fuel, but energy producers and retailers will not invest in infrastructure without the prospect of a large market (Figure 1).

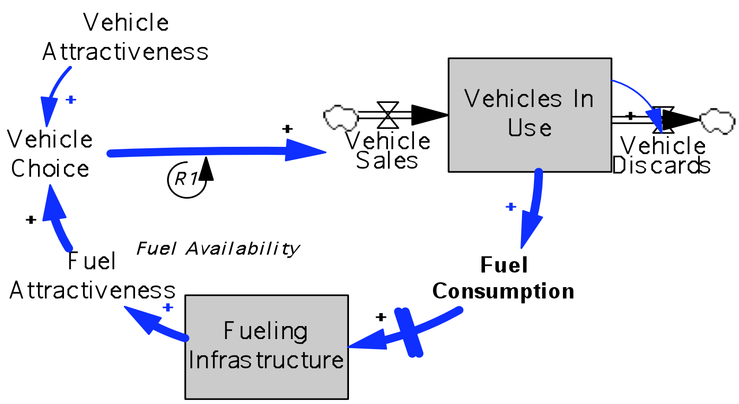


Figure 1 Chicken and egg dynamics between vehicle adoption and fueling infrastructure

This chicken-egg problem is well recognized as an "increasing returns to scale externality" and typical strategies to overcome the thresholds is to seed the infrastructure (estimates in the literature range from 5 to 15%, especially in the urban areas, to speed up demand).

However, experience with the study of complex systems and the study of AFV transition challenges show that we need a more complete characterization, or otherwise our policies/strategies are doomed to fail. First, other economies of scale effects exist. Those other feedback mechanisms interact with this infrastructure chicken-egg problem. The important mechanisms of this bigger picture are presented in Figure 2. The automotive industry exhibits itself strong internal economies of scale and scope: as automotive manufacturers invest in R&D, production improvements and portfolio occur with increased production and reinvestment of revenues (R2). Further, consumers' choice among platforms depends on their consideration of a new platform. Consumers consider a particular option only when sufficiently familiar with it, which depends to great extend on social exposure to the vehicles, which increases with the vehicles on the road (R3).

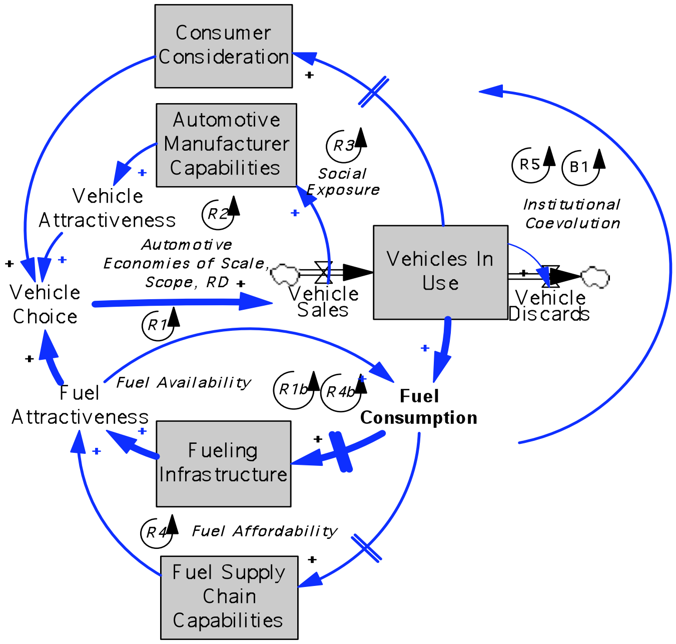


Figure 2 Principal processes conditioning AFV transitions

Further, technologies influence each other, harboring potential for complementary knowledge spillovers within a platform – but also to and from others. A second factor that makes the dynamics more complex is that the particular scale economies are highly non linear, generally working against adoption in the early stages. For example, as fuel providers determine where to locate and offer fuel, and whether to expand the refueling capacity, consumers also determine their transportation mode choice for their trips and when and where to refuel. Early infrastructure in central populated areas does little to boost long-distance driving. But only once demand is scaled up, retailers may find it lucrative to locate at more remote locations that are important, also for urban drivers, introducing another important feedback (R1b). That is, demand responses to early fueling infrastructure are highly convex. These last interdependencies in particular suggest a spatial representation of this process is crucial.

More behavioral details are necessary to represent the chicken-egg problem appropriately for our purpose: Retail stations themselves can be seen as intermediaries allowing drivers to perform fuel consumption transactions with fuel providers and other wholesalers. The fuel market is subject to additional positive feedbacks through interactions with other industries (R4). For example, in the case of biofuels, such interactions involve the growth of production and distribution experience. Other complementary, AF and AFV specific markets involve services, parts and their maintenance. AFVs involves the establishment of such interconnected multi-market platforms, with several distinct independent types of decision makers. Third, the institutional and contextual relationships are important, such as the existence of complementarities with particular growth markets related to alternative fuels and their vehicles, or the role of governments in stimulating particular technologies or fuels (R5): Just as petroleum replaced coal for home heating, during the vehicle transition, AFVs may co-evolve with stationary fuel cells; governments may choose to subsidize fuels, support a particular technology, or platform, or stimulate a broad portfolio; or, for historical reasons, particular fuels may be favored.

Implications

The risk of AFV failure depends much on the AFV specific strength of the various feedbacks. Our simulations suggest robust paths to widespread, self-sustaining PHEV diffusion exist. In contrast, for example, HFCVs, while viable, creating self-sustaining HFCV markets is much harder. PHEVs have advantages relative to HFCVs since self-sustaining diffusion much easier to achieve a fueling infrastructure has already (partially) been deployed (This infrastructure can transition to carbon-neutral via biofuels). Further, OEM technology and production capabilities have developed much further. Finally, consumer acceptance of PHEVs is much easier to build as the platform, from a user perspective is much less exotic than HFCVs.

Nevertheless, PHEV diffusion will be slow, consistent with history of other automotive technologies. Significant investment still required to pass tipping point, focused on marketing, consumer acceptance, cost reduction and reliability improvement through learning, R&D, scale. There are significant non-trivial risks of technical (e.g. battery reliability), economic (cost), and social (willingness to consider). Clearly, vehicles that just require consumer acceptance, such as advanced ICE and conventional HEVs can break through much easier.

See also: 2009 slides pp 16-19 (broad model boundary), and pp 38-41

3 Character of the Policy Insights

We identify insights from the detailed analysis in the document below in relation to each mechanism, as well as to the overall system. We separate insights into the fundamental behavior behind the processes and those that involve policies. However, some important high-level insights become apparent: Dynamics of AFV transitions are inherently complex. Policies that may work under particular conditions, or for particular technologies, may not work for others. As a corollary, extrapolation and forecasting in such systems is very dangerous. Both points are magnified by the fact that parameters (technical, behavioral, policy and environment) are inherently uncertain. This is in particular the case of the HFCV transition problem under study, with its long time over which the important dynamics play out. While it is very important to build the analysis on appropriate data and parameter assumptions, effective policies do not derive from a forecast based analysis. Research should be focused on understanding how mechanisms condition outcomes, rather than on the outcome itself. This understanding should lead to exploration of robust policies; or, policies that work under a variety of conditions. Conclusions have the character of why these policies work, much more so than the particular quantitative estimation.

Other implications of this multi-mechanism and multi-decision maker system are that large-scale adoption may take longer than expected. This is the case because several constraints work together "multiplicatively". For example, in absence of any affordable vehicle, improving the fueling infrastructure does not yield to significant adoption. Another argument for studying the mechanisms jointly is that there are potentially strong synergies between. Further, policy leverages change over time. In the earliest stages some policies may work, others don't. For example, one can imagine that improving vehicle action radius is critical for large-scale adoption, but this takes time and effort, and requires early attention. However, once action radius has reached acceptable levels, more incremental improvements will do and other constraints require more attention. Thus, we seek for a dynamic portfolio of robust policies.

The analysis also reveals areas where more accurate data or estimates are valuable. It is simply impractical to achieve "perfect data" on all relevant components of this system. Luckily we can perform sensitivity analysis as part of our robustness test. Based on such analysis, we can identify particular parameters that require more data research. Identifying those critical parameters gives information on prioritization of resources and is part of the objective of this study. However, identification of sensitive uncertain areas is not limited to parameters. We also test for structural and behavioral sensitivity. For example, we performed analyses under varying assumptions about how consumers assess their relative fuel expenditure fuels when comparing across platforms. Consider two extreme cases, the first assuming that consumers only look at the monthly fuel expenditure (the rational behavior), and another that assumes consumers compare of the fuel price. The latter disfavors a more fuel-efficient vehicle with an expensive fuel; reality lies somewhere in between these two extreme behaviors. We found that high leverage policies may differ between the two extreme cases. For better identification we can suggest to do more field analysis in this area. Moreover, policies may include information provision that influences where people look at.

Finding effective policies cannot come from shear optimization of the system. The inherent degrees of freedom are too many for this. The approach taken here is different: one by one we have analyzed the mechanisms carefully, to understand what kind of constraints of adoption they generate, each time including the other mechanisms in reduced form. With the understanding generated by these analyzes we integrated the models (this is were the Shell project started) and explored the integrated dynamics in depth. This was followed by policy analysis. Modeling however is iterative and policy insights also reveal where more analysis is beneficial.

4 Waiting for the oldies to retire

Insight

Even highly attractive vehicles require a long duration before reaching significant fractions of the installed base. The average useful life of vehicles is on the order of 10-20 years, which is much larger that of many products that frequently serve as an example (e.g. typical consumer electronics). This problem is reinforced because, while market shares of an alternative vehicle technology may be very high, slow turnover results in slow build up of the installed based, constraining potential contributions to social exposure (contrast this with, e.g. IPods).

Implication

Irrespective of policies, it swill take long before alternative vehicles on the road form a significant share and can make an impact. For example, imagine a vehicle that produces 50% carbon emissions on a per mile basis compared to the incumbent vehicles. In case this alternative achieves instantly an ongoing 40% market share, it would require about 24 years to reduce the conventional to a 30% installed base share.[2] Finding ways that speed up the sales rate early in the diffusion is essential. However, beyond this we learned that the impact of more rapid replacements on the dynamics is much more critical because the power of the feedback mechanisms that drive technology learning, consumer acceptance, fueling infrastructure development depend on these replacement rates. For example, because of the long run it takes to generate fuel demand, it remains longer unattractive for fuel providers to provide fuel, for service facilities to develop. With a lack of fuel stations opening, few drivers that replace their conventional (Internal Combustion Engine) vehicle will switch to a HFCV. In contrast, consider a hypothetical market in which vehicles are replaced each year: in this case fuel providers will find it much less risky to boost investment in fuel stations. Similarly, with rapid vehicle replacement, HFCVs become quickly diluted with the vehicles in use, increasing exposures and consumers willingness to consider those. Simulations show that if the average vehicle life is reduced, the threshold for tipping significantly lowered and sometimes even disappears with basic policies. For this reason, high leverage policies may be uncovered in the working and influencing used car market dynamics.

Note

Diffusion dynamics depend importantly on the industry characteristics. The replacement rate of vehicles differs enormously, with wide implications: the "fruit flies" are products such as iPods, PDA's etc…On the other extreme, the “whales” are today's power plants last 20-40 years. In the first category, markets can be tested with rapid consumer exposure, feedback; experience accumulates fast. Thus for these technologies products change and adjust rapidly. In the last category, with the much slower feedback, it takes a long time before technology can be updated and improved. Vehicles are in between those two categories, but closer to the latter category.

---

[2] This test is just for illustration of the concept - in real life the market share of even attractive vehicles grows of course much slower.

5 The danger of extrapolation and benchmarking

Insight

Extrapolation from successful cases (benchmarking) is a frequent practice in industry. Such activities are important to find out, within the pool of current practices how things are currently being done best. However, relying on this is very dangerous in the case of complex market systems such as those for AFVs. This danger is illustrated with Brazil's transition to ethanol in transportation. With currently 40% of transportation fuel consumption deriving from ethanol, Brazil's is often cited as a successful example for transitions to alternative fuels and flex-fuel ethanol vehicles constituting over 60% of the market share. Various politicians, media, futurists and influential figures call for a replication in the US. However, examination of Brazil's success teaches us this. The current affordable ethanol price follows from 30 years of high volume production, initiated in the late 1970s. The initial ethanol vehicles emerged under extraordinary set of centrally coordinated and enforced policies (PROALCOOL program) that guaranteed fuel availability in every village above 1500 people, fuel supply from the main distributor (Petrobras), vehicle model availability, and large-scale consumer education programs. Even with those policies the ethanol vehicles failed 15 years after the program had started, with sales dropping to zero. Simulations make clear how the contemporary flex-fuel vehicles arise necessarily out of the ashes of an earlier failed experiment. For example, most of the vehicle and fuel production experience that allow for high performing and cheap ethanol vehicles and fuel at this point, derive from ethanol vehicle programs. A large share of the current ethanol demand still derives from those vehicles. This also has allowed fuel stations to remain in business – ready to serve the current flex-fuel vehicles that came on the market in 2001. Finally, while it is well possible that Brazil is underway to a reach a self-sustaining alternative fuel market, this is far from a given - the stress on the natural resources are being felt already.

Implication

While learning from earlier AFV introductions are of critical importance. However, simple extrapolations based on recent successes elsewhere, or their unsystematic comparisons fail to bring out the important conditions and particularities under which an introduction takes place and how these influence how the mechanisms that condition AFV diffusion play out. Careful studies illustrate the strong path-dependency of evolution of alternative fuel vehicle systems. Similarly, extrapolations across technologies, using hybrids as a reference diffusion rates for hydrogen fuel cell vehicles are ill founded.

Further reading

Struben (2009)

D. Insights related to consumer acceptance

Intentionally left blank

6 Generating consumer acceptance

Insight

Positive feedbacks conditioning driver familiarity with and consideration of HFCVs and other AFVs generate multiple equilibria dynamics (a tipping point). Even highly attractive vehicles require long periods, on the order of decades, to reach significant fractions of the installed base.

Explanation

While many consumers will be aware of the existence of Hydrogen Fuel Cell Vehicles (HFCVs), simple awareness of the new vehicle and its features is not enough for potential buyers. Consumers need to learn about the availability and relevance of this new technology. Automobile purchase decisions are not the result of "cold" economic calculation. Cars are an important symbol in society and a source of personal identity, status, and emotional resonance. Efficacy and safety of designs and their features are shaped by historic events, experience, and social interactions. New technologies need to become accepted as a viable alternative, yet in the early stages it is unclear what a new technology may bring. Many technologies, in particular automobiles, are complex and are evaluated along many dimensions of merit. Besides price, new platforms need to establish themselves on attributes such as safety, performance, reliability, and comfort. Thus, awareness of a new technology is not sufficient. Buyers need to hear about it from other people—owners and non-owners—until they are sufficiently comfortable with it to make the leap. For illustration: diesels, failing in the US, took 20 years to get to a 20% new vehicle registration plateau and another 20 years to achieve 50% of the market shares. SUVs, a highly successful vehicle class, took about 25 years (from 1976 to 2002) to achieve a 25% sales share.

The process of co-evolution of consumers' willingness to consider HFCV, and AFVs and their installed base growth in general is illustrated in the conceptual diagram on the left hand side of Figure 1.

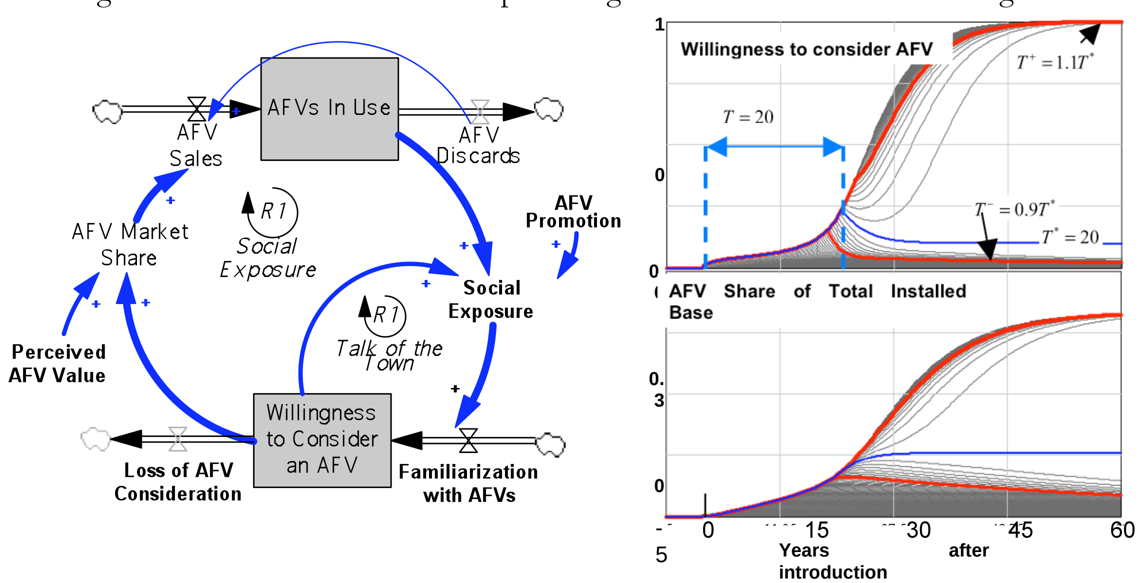


Figure 1 A tipping point from social exposure dynamics

As the AFV installed base grows, more non-users will be exposed to them, and more will be willing to consider it when replacing their own vehicles. As the market share increases, the AFVs on the road start to rise. Then with a growing ownership more AFV users become diffusers of the knowledge about the vehicles, further boosting their exposure to non-users and allowing. However, this mechanism may work in the opposite direction as well. Marketing and promotion campaigns and consumer education are instruments that boost social exposure in the early stages. Such instruments also need to battle against the degeneration of consumers' consideration, in a market with technologies that fiercely compete for attention. When exposure is infrequent, consideration decays rapidly: without marketing or an installed base, the electric vehicle, much discussed in the 1990's, has virtually disappeared from consideration. Once exposure is sufficiently intense, a technology is woven into the fabric of our lives, emotional attachments, and culture and there is no decay of consideration: "automobile" implicitly not only connotes "internal combustion", but also "hydrogen fuel cell vehicle".

Our analysis shows that these mechanisms that condition consumer acceptance and adoption exhibit a tipping point. This is illustrated with the simulation results shown on the right hand side of Figure 1. For analytical convenience, to illustrate the working of these mechanisms we introduce a generic AFV, equally attractive as the established gasoline/internal combustion engine vehicles (ICE).[3] The figure shows AFV installed base, and the willingness to consider AFVs among ICE drivers with an aggressive AFV marketing and promotion campaign. The grey lines represent different simulations for which only the duration of the marketing program varies (between 0 and 50 years). We see that simulations result in either successful diffusion or failure. The successes and failures are separated by a tipping point. The failures are those with a marketing campaign below a critical value. The thick blue line shows market evolution at the critical marketing duration separating the high- and low-diffusion equilibria. The thick red lines show the trajectories for program durations varied by ±10% relative to the critical points. Notice further, that in the case of equally attractive AFV and ICE—in terms of cost, range, and so on—adoption of the AFV still moves slowly. Because people buy new cars infrequently, it will take a long time for the installed base to grow. However, this also means it will be a long time before an individual consumer knows many people who have direct or even indirect experience with a given AFV, which further slows down the diffusion. This is quite different than a market for i-pods! Instead of the scenarios shown here, holding the marketing duration fixed, but varying the parameter that represents the strength of the marketing and promotion campaign would yield similar results.

The bottom line: Significant and endured consumer exposure and education programs are necessary to overcome these thresholds. Vehicles need to become considered appealing based on their particular strengths, which includes their exotic handling. However, even when vehicles have been adopted at increasing rates for 1 or two decades, the existence of a self-sustaining market is not guaranteed. This is particularly true in a largely saturated market in which each potential adopter has a mature option in hand.

Policy suggestions

The strong dependence of diffusion potential on the lifetime of vehicles suggests that policies aimed at removing old ICE vehicles from the installed base may have high leverage.[4] Such policies might be implemented through feebate programs or subsidies offered to vehicle owners who not only buy an AFV but have their ICE vehicle shredded rather than sold into the used car market.

Marketing and consumer education boosts can be very effective instruments and are critical for diffusion and must be timed well. Endogenous improvement in vehicle attributes from learning, R&D, scale economies, etc., and the interdependent development of a requisite fueling infrastructure add important

[3] That means, we assume price, handling, fuel availability, action radius safety, reliability etc. are all at par with ICE.

[4] Indeed, subsidies and marketing programs aimed at selling AFVs may lengthen effective vehicle life: As consumers trade in their ICE vehicles for AFVs, used car prices will drop. Lower used car prices will both undercut AFV sales and make it economic to keep old, inefficient ICE vehicles on the road longer.

additional positive feedbacks that can further hinder the diffusion of alternative vehicles. Such mechanisms interact strongly with these social exposure feedbacks. The existence of the multiple feedbacks suggest however that the efforts dedicated to early consumer education, will only work with availability of competitive vehicles and a supporting infrastructure.

More subtly, policies can be geared towards increasing experience with and exposure to AFVs through non-drivers.[5] Opportunities are large as during much of the early stages of the AFV transition, virtually everybody is a non-drivers. For example, experience and word of mouth by non-drivers can increase by targeting dedicated public transportation and taxi fleets for early transition. Other programs include dedicate leasing programs, for shorter periods, through which consumers can "experiment" with AFVs, without bearing the risks of purchasing an unfamiliar technology. Such early experience by non-owners can be extremely powerful to boost familiarity among non-owners, and to help overcome the tipping point. However, it is critical that the vehicles that are dedicated for these uses are up for the specific tasks and intensive use: if they are not word of mouth will be about underperforming AFV and act to reduce the willingness to consider.

Further reading

Struben and Sterman (2008)

[5] This mechanism played a role during the early transition towards the automobile in the 19th century. Early automobiles were feared due to their speed and perceived risks of explosion, but were also exciting novelties, attracting attention among those who had not yet purchased a car. These nondrivers, who were far more numerous than drivers, would then tell others about what they had seen, rapidly spreading awareness about each type of vehicle. Along with newspaper accounts and new journals dedicated to autos, word of mouth among nondrivers stimulated awareness of ICE faster than ICE vehicles could spread throughout the country.

7 Exploiting mechanisms for consumer exposure: the role of non-drivers

Insight

Our research shows the importance of consumers being sufficiently exposed to the AFVs so that they may take them into consideration. What processes are most powerful for consumers learning about and acceptance of those "exotic" vehicles? Our study finds that one unexpected important channel is the influencing of non-drivers. This mechanism involves non-drivers sharing their knowledge about such exotic vehicles and in this way "educating each other". This process is particularly important and effective because of this. First, the slow replacement rate – the pool of drivers that will contribute to traditional exposure will remain small for a long time. Second, the products are complex and potential drivers require multiple exposures from different perspectives in order to increase their confidence. While not sufficient to generate sufficient exposure for acceptance in absence of vehicle availability, this mechanism can be of particular importance early on when vehicles start to enter the market, but are still in very limited numbers seen on the road. For example we performed simulations in which we introduced an AFV that is equivalently attractive to incumbents, but to which people are unfamiliar (imagine gaseous fuel, different handling, size, shapes etc…). We compared results from a simulation in which the role of non-users was activated with those in which this was switched-off. We assumed that the effectiveness of conveying a message by fully familiar non-user to be much weaker (25%) compared to users. In those simulations where the role of non-user word-of-mouth was activated, allowed marketing programs that required up to half the strength compared to the simulations that did not include the non-users. The point: because of the slow replacement, potentially interested non-users remain in large numbers for a long time. They are important carriers of information about AFVs.

Implication

The process is quite different than direct marketing. The appeal of the product needs to be tangible. In the 19th century many social groups organized around the different platforms (electrics, steamers), as well as vehicles in general informed the public about the vehicles. Races where held that acted to stimulate such discussion. Art and movie industries make use of such 2nd hand information channels. Programs that are directed to experiencing, rather than using include short term leasing programs, virtual experiences, are potential ideas that contribute to this indirect information. The finding does not attempt to propose a marketing program for HFCVs. Rather this finding illustrates the importance of exploring policies that make are based on the structural characteristics of this AFV system.

E. Insights related to OEMS and vehicle development

Intentionally left blank

8 Vehicle technology evolution: the threshold for a mature AFV market

Insight

Technology learning significantly strengthens the tipping characteristics of the overall transition. Their workings introduce a threshold for large scale adoption. Vehicles improve in attractiveness and decrease in cost with experimentation in production and R&D that is reinvested from sales. However, growth of production and sales require attractive vehicles. Thus, in the early stages AFVs can get caught in a low improvement / low sales volumes basin. This basin is strengthened by the existence of other chicken-egg problems and the long duration between vehicle replacements.

The significant challenges involved with endogenous technology evolution become particularly clear when considering the moderate fuel economy and the limited tank capacity of a first generation AFV. Together these two factors determine the potential action radius of the vehicle. A limited action radius puts several constraints on consumers' likelihood of their adoption: the number of refills per month are much larger than for conventional vehicles. Moreover, each refill require much more effort, as fueling infrastructure is limited and search time for fuel large. These combined constraints imply that the net experience gain is not sufficient for demand and production volumes to grow fast enough, to meet requirements of return of investments.

Implication

Finding the proper early markets is critical. Such markets include consumer groups that feel less constraints by the weaknesses (such as action radius), but provide experience/testing ground that enable rapid improvement of those weakness. Further, these early markets should bring forward the future potential of these vehicles to the mass market. An important perspective that this study brings in: the choice of early fleets should be compatible with needs of a rapid scaling up of the fueling infrastructure and contribute to their (positive) exposure. Introducing AFVs (depending on the type) in taxi-fleets addresses some of all these requirements. However, the risk of their subsequent high utilization is that failures are likely, and that any failure will be highly visible.

Note

Research on innovations has shown that major innovations often start in a niche market. Entrant technologies, while immature and inferior to the dominant technology, have particular attributes in which they excel that allow them to start in a small niche market. In such a specialized market they get a chance to mature and develop the attributes that, as is gradually learned over time, are the most important to provide the value. Related to this, disruptive technologies are often introduced by players outside the market – startups or diversifying companies that perceive it financially more attractive to introduce them at small scale and through different networks. Such a process is certainly conceivable in the automobile industry. In fact, HFCVs already exist and are tested. However challenges to enter the market from the outside are particularly large in the automotive industry because of the barriers involved in developing small scale niche markets (such barriers include scale economies, legal challenges, standardization of technology and practices around refueling, consumer perceptions, competition from a deeply and widely embedded ICE platform etc..).

9 Technology coevolution and spillovers

Insight

Introduction of alternative technologies has two direct technological consequences for the conventional technology: First, sponsors of the conventional technology intensify R&D investments to protect sunk investments. It is much easier to develop small efficient conventional vehicles than to make radical progress to alternatives. Second, the conventional technology can benefit, to some degree, from the alternative (and vice versa). Spillovers between technologies have an important impact on the adoption dynamics. This issue is particularly relevant when considering that multiple technologies compete contemporaneously. For example, the experience gained in plug-in hybrids may benefit the HFCVs as well and vice versa.

Implication

ICE vehicles will evolve in response to alternatives entering the market. For example, traditional vehicles have already benefited from transmission developments that were particularly important for hybrid vehicles. In our simulations we learned that superior technologies that were successful when introduced together with a hybrid competitor (with which they shared some relevant knowledge), would not succeed when introduced 10 years later. While early formation of standards will help early take-off, they may impede emergence of a large enough repertoire of technologies, critical to further improvements.[6] Other implications are that the timing of introduction is important. In the medium short run not one technology is likely to dominate.

Policy insights

Policy analysis should search for routes that make use of the complementarities between and within AFV paltforms. For example, electrification is one platform route, on which HEVs, PHEVs, EVs and (plug-in) HFCVs can compete.

See also: 2009 slides pp 33 and 53

[6] However, many technical developments and infrastructure investments may not be privately appropriable; late entrants may benefit from the investments and mistakes of pioneers.

10 AFV competition dynamics

Insight

Understanding multiple AFV competition is critical. The transition takes place in the context of many alternatives that compete intensely in an initially very unstable market. Moreover, This is for serveral reasons. First, a imagine a between internal combustion (ICE), Ethanol (E85), Biodiesel, Natural gas (NGVs), Hydrogen fuel cell vehicles (HFCVs), Electrics (EVs), Hybrids (HEVs), Plug-In Hybrids, PHEVS, etc). Multiple AFVs compete for a partially conserved demand. Thus, for all R&D reinvestment, production experience, social exposure, and fueling infrastructure will b suppressed. Policies that may seem sufficient to lead to diffusion. In contrast to the competitive effects, AFVs may complement each other. For example drivers of hybrids, may also be willing to consider plug-ins, or even electrics when these technologies make their way into the market place. Similarly, technology may be useful across technologies. This is discussed elsewhere. Similar dynamics will take place within each platform.

The discussion should not be interpreted as the suggestion that one technology should be selected in advance, or within each platform one standard. Such dynamics as described here are an inherent part of technology introductions. However, typically such factors are not explicitly included in the formal analyses and the tradeoffs depend on the complexity and other characteristics of the markets and technologies.

Implication

Detailed study is necessary (and in progress).

11 Rebound effects may suppress AFV diffusion: Example PHEV diffusion under a long-term upward oil-price shock.

Insight

Imagine the following thought experiment: what is the effect of an upward, long-term, shock in the oil price on the diffusion of PHEVs? At first sight, the higher oil price should make PHEVs more competitive to ICE, since the relative cost-of driving for PHEVs is lower than it would have been without the shock. As such, PHEVs are more attractive than without the higher oil price, leading to a higher market share. Higher market share propels the positive feedback of learning, making the vehicle more attractive. Hence, PHEV should clearly benefit from a higher oil price. The answer is, however, much more ambiguous.

Explanation

Following insight #9, the introduction of alternative technologies direct consequences for the conventional technology. Our simulations show that, while PHEV sales may grow (assuming they are on the market), conventional ICE (and HEV-ICE) may become more competitive because of a series of fast and slow but strong compensating feedbacks. First, consumers can instantaneously switch to smaller and more fuel efficient vehicles. Second, automakers adjust the balance of offered models in favour of smaller and more efficient vehicles, if the shock is expected to be long-term.

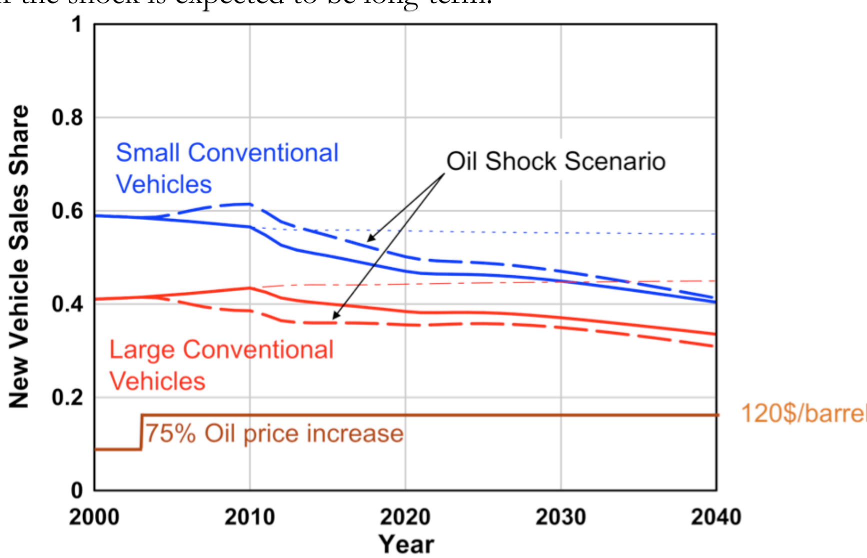


Figure 1 Simulated dynamics of evolution of small (cars) and large (small trucks) conventional vehicles without (line) and without (dotted) oil price increase. Not shown: increasing market share of PHEVs that were introduced in 2005.

Additionally, R&D for improving on these vehicles will rise (at the cost of that for PHEVs), which will lead to improvement and better fit with the new environmental situation of conventional vehicles. There are more feedbacks: consumers now become more accustomed to smaller vehicles. Further, they reduce replacement rates, lowering the overall and PHEV sales, whose progress is very much dependent on the early sales. Finally, the higher petroleum price has two other effects: it reduces petroleum demand counteracting the initial price pressures (through reduced VMT, stationary applications). At the same time electricity prices will go up as the cost of producing and distributing electricity, partially dependent on oil, will rise and as some of the stationary applications will substitute (over time) to electricity based systems as well.

Implication

AFVs are introduced in a much more competitive situation than may seem at first sight. The value proposition of AFVs should be compared with current ICE, but with what they could be. While electrification of transportation, for example, through PHEVS, is a viable trajectory (see discussions elsewhere), their introduction may lead to important rebound effects.

See also: 2009 slides pp 54-60

12 Rebound effects may suppress AFV diffusion: Example Used car sales

Insight

When AFVs enter the market, a glut of used ICE vehicles delays the AFV adoption.

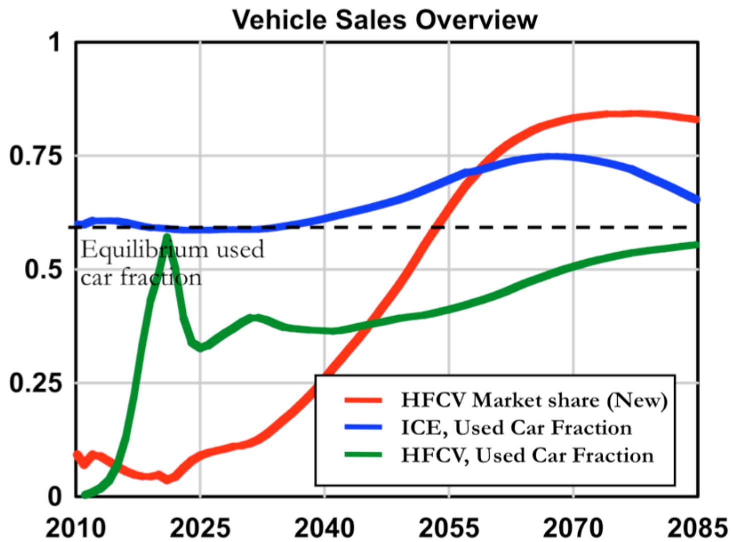


Figure 1 Base case simulation showing used car fraction for ICE (blue) and for AFV (green, here HFCV) under successful HFCV penetration (red).

Explanation

The surplus used conventional vehicles depress conventional used car prices, make the used car market compete with new vehicles, including AFVs, thus suppressing AFV adoption. Figure 1 shows this by the above normal ICE used car fraction starting in 2035. The early small peak in HFCV market share and in ICE used car fraction comes from fleet conversion, to HFCV, programs that were part of the simulated successful policy portfolio.

Policy Implications

These perverse used car dynamics also suggest policy opportunities: "Cash for Clunkers", when designed for it, can speed AFV market success, stimulate new car sales. Targeting the decommissioning (and shredding!) of old gas guzzlers is an effective way to improve the vehicle replacement rates into AFVs and to reduce greenhouse gas emissions.

See also: 2007_1 slide 32

F. Insights related to fuels, fuel retailing and fueling infrastructure rollout

Intentionally left blank

13 Unpacking the chicken-egg dynamics between fueling infrastructure and fuel demand

Insight

While it is common knowledge that the co-evolutionary dynamics between vehicle demand and fueling infrastructure involve a "chicken-egg" dynamics. Their intraction is much more complex than this analogy suggest. Our analysis is based on a simulation model in which consumers respond in a spatially explicit structure to the availability of fuel. This conditions consumer adoption-, drive-, refueling,- and topping-off behavior. Likewise, consumer demand as generated has implications for the also endogenous entrance of fuel retailers. Stations are constrained to supply to their maximum capacity, however, at much lower utilization consumers have to line up too long, which lowers their attractiveness and likelihood of driving. The co-evolutionary dynamics between vehicle demand and fueling infrastructure are more complex than the stereotypical "chicken-egg" dynamics. The system tends towards a bi-stable equilibrium of low demand with urban clusters, because of the distributed character of the fuel supply and demand by vehicle adopters, and the disparity between fuel demand volumes and service requirements in remote areas.

Explanation

For technologies such as HFCVs, fuel and other infrastructure must be built up together with the installed base. Often stereotyped as "chicken-egg" dynamics, these co-evolutionary dynamics are more complex. The local scale of interactions is paramount: Fuel availability differs for each driver, based on their location and driving patterns relative to the location of fuel stations. For fuel providers, considering opening a station, the location of fueling infrastructure is of great importance. Station entry and exit are determined by the expected profitability of each location, which, in turn, depends on the demand for fuel at that location and the density of competition from nearby stations. Households within each region choose AFVs according the perceived utility of each platform depends on the effort required to find fuel.[7] Driver behavior also responds to the fuel availability. For example, the number and length of trips increases as fuel availability rises. Figure 1 shows a simulation calibrated for California.

To highlight the impact of spatial vehicle-fuel infrastructure interactions, the simulation assumes all drivers are willing to consider the AFV. Further, we set the performance of the hypothetical AFV equal to that of ICE. [8] The initial ICE installed base and infrastructure distribution are set to current California values (roughly 16 million vehicles and 8000 gas stations, concentrated in urban areas). The simulation begins with an AFV installed base of 25,000 vehicles and about 200 fueling stations (approximate values for CNG in California in 2002, including private fleets and stations). We assume, optimistically, that all AFV fuel stations are accessible to the public. To encourage the development of AFV fueling infrastructure, fuel stations are heavily subsidized for the first 10 years. Figure 1 shows the AFV installed base and alternative fuel stations. Despite performance equal to ICE, universal consideration of AFVs and large subsidies to fuel station owners, overall diffusion is slow, and after 40 years has largely saturated. Fuel stations grow roughly with the installed base, though many are forced to exit when subsidies expire in year 10 (entry slows and exits rise before the end of the subsidies as forward-looking entrepreneurs anticipate the

[7] Refueling effort is a function of (i) the risk of running out, which depends on vehicle range and the location of fuel stations relative to the driver's desired trip distribution, and (ii) expected refueling time, which includes the time spent driving out of the way to reach a fuel station and crowding at fuel stations.

[8] These assumptions are highly optimistic—actual AFVs offer low performance relative to ICE and are not universally included in drivers' consideration set—but isolate the dynamics caused by the interactions among the installed base and fueling infrastructure in an important region with considerable heterogeneity in human and vehicle population density.

expiration of the subsidies). Though not shown, miles driven per year for the typical AFV are also far less than for ICE vehicles.

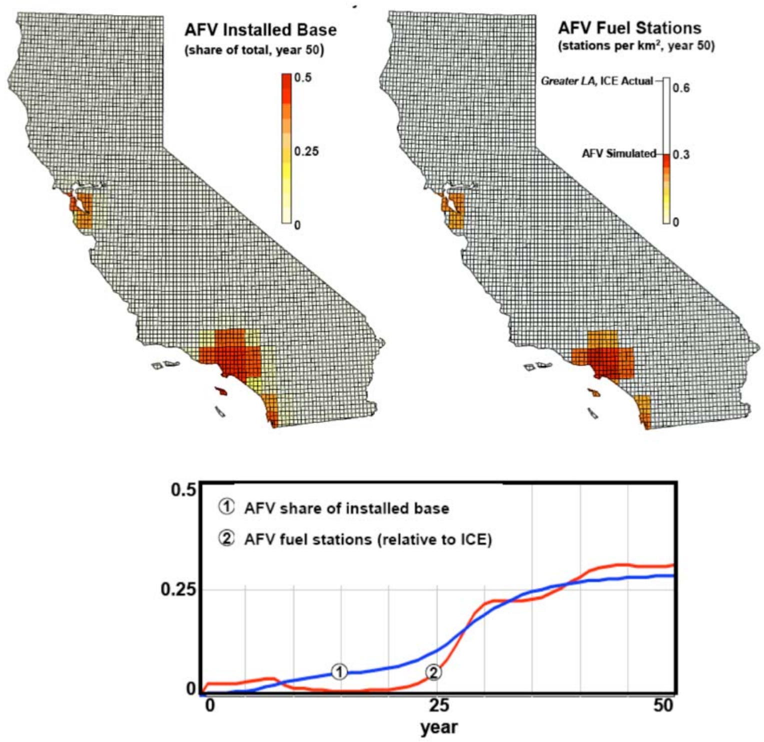


Figure 1 Clustering behavior of vehicle and fuel demand, and fuel availability

The spatial distribution after 50 years shows essentially all AFVs and fueling stations are concentrated in the major urban centers. Limited AFV adoption is a stable equilibrium in the cities, because high population density means fuel stations can profitably serve the alternative installed base, and the resulting availability of fuel induces enough people to drive the alternative vehicle, sustaining the fuel providers. The area with the highest fuel station concentration, roughly covering the greater Los Angeles area, has a station density about half that of gasoline stations. However, though a few alternative fuel stations locate in rural areas when subsidies are available, they are sparse in rural areas, so rural residents and city dwellers needing to travel through these regions find AFVs unattractive. Further, urban AFV adopters, facing low fuel availability outside the cities, use their AFVs in town, but curtail long trips, using their ICE vehicles instead. Consequently, demand for alternative fuel in rural areas never develops, preventing a profitable market for fuel infrastructure from emerging, which, in turn, suppresses AFV adoption and use outside the cities. While the fundamental insights derive from the model analysis, empirical cases are abound: Natural Gas Vehicles in Italy (stagnated at a penetration below 5%), Argentina (15% and growing), and New Zealand (Growth and Collapse), all exhibited this behavior. seems counterintuitive.

The Bottom Line: The spatial dynamics of the AFV and fuel markets significantly alter the conditions for sustained adoption. The system tends towards a bi-stable equilibrium of low demand with urban clusters, because of the dispersed character of the fuel supply and demand by vehicle adopters, and the disparity between fuel demand volumes and service requirements in remote areas. While islands of limited diffusion might be sustained in the cities, broad adoption of AFVs can easily founder even if their performance equals that of ICE. Further, the time it takes to replace vehicles and to grow fuel stations (find a location, select site, obtain permits, and build them) significantly influence the long term dynamics.

Policy suggestions

Policies designed to achieve self-sustaining AFV adoption must overcome the urban-rural asymmetry in adoption (together with other challenges, discussed elsewhere). Many programs to introduce AFVs have failed, arguably due to limited understanding of these dynamics.

During and after the rollout phase, policies need to be in place to keep stations sufficiently long in business. Typical timeframes before the market can become self-sustaining are on the order of two decades. In particular a significant fraction of stations need to be located in the non-metro regions, even when the early focus is on metro consumers.

Automakers and fueling infrastructure providers need to coordinate on a plan for "cascaded diffusion". Besides the distribution of fuel stations, the action radius of the vehicle is an important factor that determines the refueling effort. The tendency for fueling infrastructure and vehicle adoption to cluster in metropolitan areas has implications for AFV diffusion beyond the infrastructure/adoption interactions. For example, while not considered in the simulation shown, low diffusion limits knowledge accumulation from production and R&D reinvestments that can improve AFV performance. Further, absent any coordination, auto OEMs would likely respond to the demand for AFVs in cities by offering small, efficient, inexpensive models adapted for commuting but ill suited for touring. Such vehicles would be even less attractive for long trips and use in rural areas, and would likely restrict adoption to affluent households who can afford an AFV for commuting and an ICE vehicle for weekend excursions. The target market and vehicle characteristics that fit that market will impact the spatial distribution of the fuel stations. Coordination can be directed to overcome such clustering tendencies.

See also: Slides 2009 23-24

Further reading

Struben, J. (2006). Chapter 2.

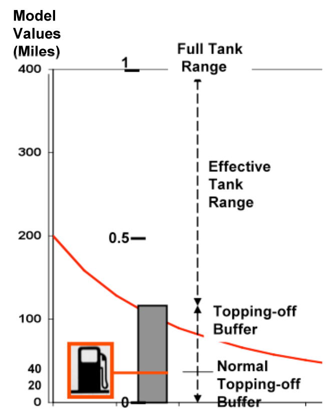
14 The unanticipated side effects of topping-off behavior

Insight

Consumers' responses to fuel availability include adjustment of their topping-off level of their fuel tank, to mitigate risks of getting out of fuel. While intended to increase drive convenience, the long-run effect may reduce diffusion speed. Such behavior of increasing refueling flexibility seems sensible for an individual driver who faces supply uncertainty. However, besides reducing the effective action radius, at the aggregate this increases crowding at stations. Further, demand is reduced in especially those areas where supply is sparse and uncertain, which induces local fuel station exits and provides incentives to increase the topping off buffer.

Explanation

Driver behavior responds to fuel availability (see also insight 12). For example, the number and length of trips increases as fuel availability rises. Besides the distribution of fuel stations, the action radius of the vehicle is an important factor that determines the refueling effort. Effective vehicle range is also endogenous: drivers facing low and uncertain fuel availability, say because fuel stations are sparse or crowded, will seek to refuel before their tanks near empty. Such topping-off behavior provides more flexibility, but reduces effective vehicle range, requiring more frequent refueling stops and increasing congestion at fuel stations. Imagine a large refueling effort in the remote areas. This has the effect to reduce the attractiveness of driving an AFV, reducing both AFV purchases and their use for longer trips, creating additional positive feedbacks that can hinder AFV diffusion.



Defining an endogenous topping of buffer

This is illustrated in Figure 1 which shows a simulation calibrated for California. To highlight the impact of this behavioral vehicle-fuel infrastructure interaction, the simulation assumes all drivers are willing to consider the AFV. Further, we set the performance of the hypothetical AFV equal to that of ICE.

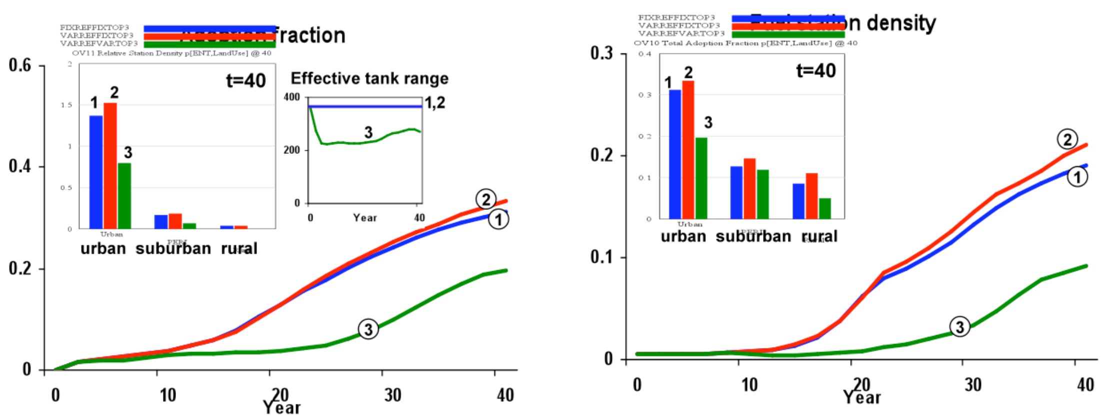


Figure 1 AFV adoption for three different assumptions on consumer topping-off behavior

Figure 1 shows three simulations: for (1) consumers are assumed to always top-off at a fixed level (in this case when the tank is 20% full). In scenario (2) we assumed that drivers refill on average at this 20% target level. The increased flexibility compared to the first case improves the overall dynamics slightly. In scenario (3) we let consumers adjust their target topping-off level as well. Facing limited fuel in the early stages, consumers have a tendency to top off earlier –when they see a station, and one that is not overly crowded. Surprisingly, diffusion is suppressed. Side effects of this behavior is that if many people practice this, it increases the wait times, and gives the perception of a fuel shortage even when there isn't one. Further, demand turns to the regions where supply is more guaranteed – urban areas - which results in less volume, and more fuel station exits in remote areas. This at the outset reasonable behavior thus enacts a self-fulfilling prophecy regarding drivers' uncertainty about fuel availability. This induces consumers to refill even earlier. The inset shows the effective topping-off range and the distribution of stations in different rations. The net result: potential buyers see the technology as even less attractive, and adoption becomes significantly slower. Such behavior has been observed in introductions of AFVs, such as compressed natural gas in New Zealand.

Bottom line: Consumers responses to fuel availability are not limited to adoption and adjustment of what trips to make. More subtle behaviors include consumers' adjustment of their topping-off level of their fuel tank, to mitigate risks of getting out of fuel. Because of externalities of such at the outset rational behaviors, aggregate diffusion is strongly affected in the long run. In order to understand the implications of policies and strategies, it is critical to include such behaviors in a dynamic analysis.

Implications/policy suggestions

Such perverse dynamics are particularly common in systems that include multiple decision makers and long time between action and result. Those behavioral feedbacks have significant impact on the take-off. Our approach includes these.

See also: Slides 2007_1 p21 and Slides 2009: p24-28

Further reading

Struben (2006) Chapter 2

15 Stimulate vehicle usage, not only rapid adoption

Insight

Subsidizing fuel stations in low demand rural areas improves adoption and demand in dense urban areas for a wide range of drivers. The threshold for overcoming the infrastructure-vehicle adoption chicken-and-egg problem is much reduced when coverage is assured in the "rural" areas, for long enough duration.

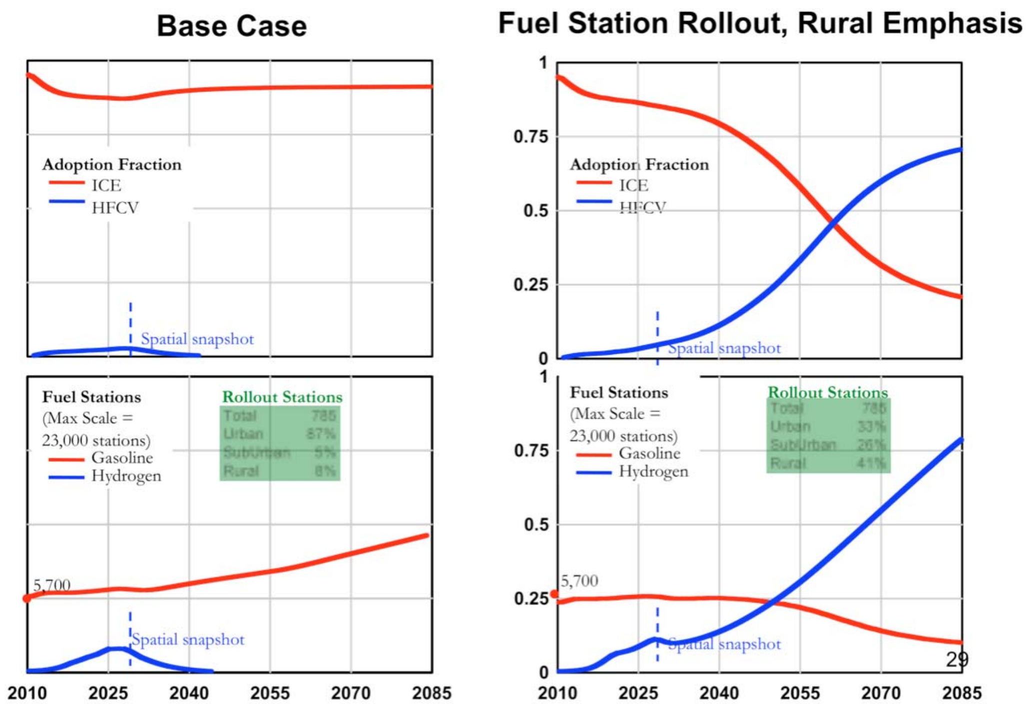


Figure 1 AFV adoption over time under infrastructure rollout with urban (left) and rural (right) emphasis. Simulation for HFCVs

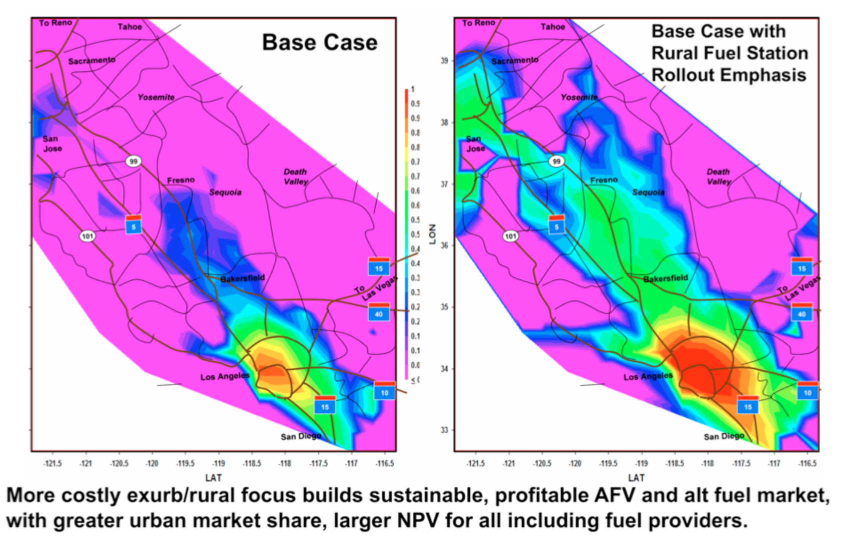


Figure 2 Fuel Availability, 2030 spatial distribution snapshot, for the simulation run above, for base case, with urban infrastructure rollout emphasis (left), and rural emphasis (right).

Explanation

These policy-related insights are a direct corollary insights # 13 and # 14. The interactions between fuel demand and fueling infrastructure tend to move the system towards a low demand equilibrium with urban adoption clusters; though most of the population lives in urban areas, when infrastructure is focused on urban rollout, adoption is suppressed because driving to remote destinations is not appealing for the urban dwellers. Urban dwellers are very sensitive to fuel availability in more remote areas. Hence, the adoption of AFVs in urban areas is much lower than it would be in the presence of rural stations. Further, rollouts that allow a disproportional high number of stations in rural/suburban areas (compared to current gasoline stations), address vicious cycles that limit drive behavior in the early stages and can have a long run positive effect on crossing major tipping points for adoption. Even though, for the rural bias policy, fewer stations are rolled out in urban areas, after 20 years adoption is higher in those areas, and is fuel consumption (as well as in other regions). Because the rural bias policy involves larger cumulative vehicle production and sales in year 20, the vehicle fuel efficiency is superior to the gasoline proportional scenario. Thus, all else equal less fuel consumption in that case. The larger consumption (and stations) derives in particular from the effectiveness to mitigate effect from vicious cycles related to fuel demand and supply interactions.

Policy Insights

These findings provide a basic understanding critical for policy design. In chicken-and-egg adoption situations a natural tendency for policy-makers is to focus on the low-hanging fruit to scale up adoption as quickly as possible. This makes sense in many cases. In line with this, most advice on AFV fueling infrastructure rollout strategies follows such a traditional "seeding" strategy (typically focused on minimizing the average distance/travel time between a population's home and the nearest fuel station). However, due too the demand-supply asymmetry and the behavioral feedback interactions discussed above, that are sensitive to coverage where one drives rather than where one lives, such policies are not the most effective in this case. Instead, it is key to focus on coverage of trips for key demand groups. Therefore, distribution of rollout stations should not be coupled to "where people live", but where people care to drive. Consideration needs to be given the non-metro areas. Fueling service need to be guaranteed in some form. These areas may need longer commitments to keeping them in operation; guaranteed fuel margins to retailers; roaming fuel stations may increase effective fuel availability.

More broadly, the asymmetry between consumers' need for fuel availability and the volume of demand point to the perverse chicken-egg dynamics involved with vehicle adoption. Risks to consumers need to be reduced. This can be achieved for example through leasing or car sharing services. To stimulate overall growth we need to sponsor the most sensitive side of the market. Subsidizing one part of a market to stimulate that overall growth is more common in two-sided markets. For example, adobe makes the read software available for free, while charging those who write. Here we want to stimulate the rural market to grow the overall market. Thus, such subsidies benefit also the urban market development and all actors.

See also: 2007_1 Slides pp 29-30 and 2009 slides pp 29-31

16 Failing of fuel efficient vehicles

Insight

The introduction of very fuel-efficient vehicles, while beneficial in the long run, has a negative effect on take-off, due to reduced volumes and incentives for fueling infrastructure – especially in rural areas. The net effect of introduction of more fuel-efficient vehicles is not necessarily positive.

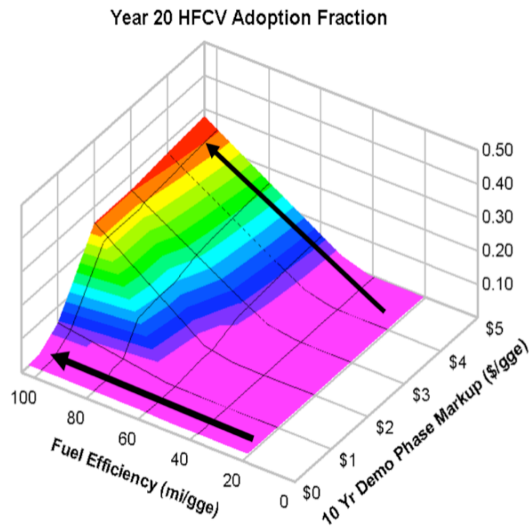


Figure 1. Year 20 HFCV adoption as a function of vehicle fuel efficiency and fuel station retail markup.

Explanation

Higher AFV efficiency limits demand for alternative fuel, especially in rural areas. Fewer alternative fuel stations will be developed or survive there, limiting appeal of AFVs and further depressing demand for the alt. fuel (low arrow). The AFV market collapses, unless very high markups guaranteed for alt fuel retailers (top arrow).

Implication

Significant guaranteed fuel margins for retailers will provide the critical incentives to overcome such challenges. Subsidizing one part of a market, and especially one that is subject to limited upfront investment (than for example OEMS) seems counterintuitive. However to stimulate overall growth we need to sponsor the most price sensitive side of the market. Such policies are more common in two-sided market platforms. For example, adobe makes the read software available for free, while charging those who write. Here we want to stimulate the fuel stations, seemingly at the cost of consumers or tax payer. However, stimulating the infrastructure side yields very large and fast market response and allows growing the overall market. Thus, such subsidies benefit also the automotive OEMS and consumers.

See also: Slides 2007_1 page 22

G. Insights related to policy

Intentionally left blank

17 Mandates can help, or hurt, AFV takeoff: Example Biofuels

Insight

Mandates have goal to increase adoption of a practice, technology, or inputs, where the market does not take initiative. While mandates can be effective, an effective design and implementation of its policies is difficult and can actually lead to side-effects that in the long-term can lead, on the net, to a reduced adoption of the practice, technology, or input. Our simulations that focused on Biofuels mandates help illustrate this point. We find that the current Biofuels mandate, absent other policies, while leading to increased uptake of ethanol (through blending), the usage of ethanol as flex fuel is suppressed. Since the long-term potential must lie in the flex-fuel, rather than blending, the long-term potential of Biofuels in transportation is threatened.

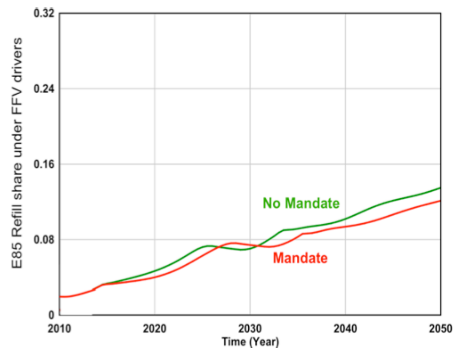


Figure 1. E85 Prevalence for Flex Fuels with and without Mandate.

Explanation

Central to the underlying dynamics is the pressure on and rise of the corn-input price, resulting from the mandate. This I turn reduces demand for ethanol as share in flex fuel, which suppresses also motivation to produce (Figure 2) and rollout of ethanol infrastructure. All effects depend largely on the timing of breakthrough of higher generation Biofuels.

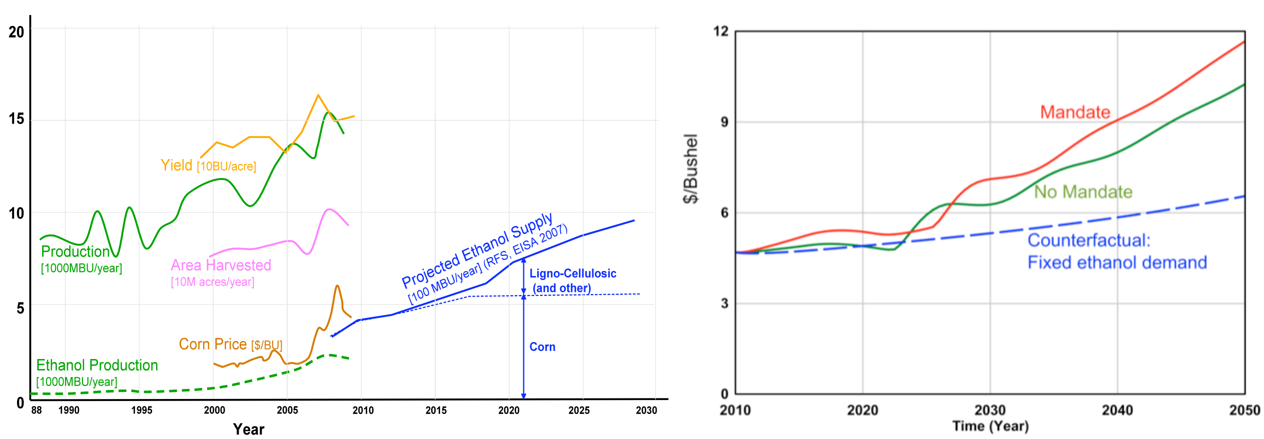


Figure 2. Left: historical evolution of production of corn (prices, yield, acres harvested) and ethanol (as well as projected supply through the mandate). All variables normalized to indicated value. Right: simulated price of corn, under three scenarios (mandate, no mandate, and under fixed ethanol demand). Source for

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

Policy Implications

The argument is not that mandates are good or bad. However, the analysis shows that mandates are implemented in a complex policy and market environment. Policymakers need to consider the side-effects. In the case of Biofuels, once can deal with such side-effects, by providing significant guaranteed fuel margins for retailers will provide the critical incentives to overcome such challenges. Of course, the side-effects are larger, as food consumption are also affected.

More broadly, one needs to carefully study the role of mandates and standards in market transition management. Moderate fuel and fuel efficiency mandates and standards may hurt AFVs as it is easier for both supply and demand to improve the conventional technologies.

See also: 2009 Slides pp 42-50

18 Carbon Prices are critical lever, but need to be strong

Insight

Carbon prices strongly affect the competitive landscape of conventional and the various AFVs. Importantly, Carbon prices affect AFVs differently. Carbon prices help conversion to smaller flexible alternatives, such as small conventional vehicles and smaller, but not larger, PHEVs.

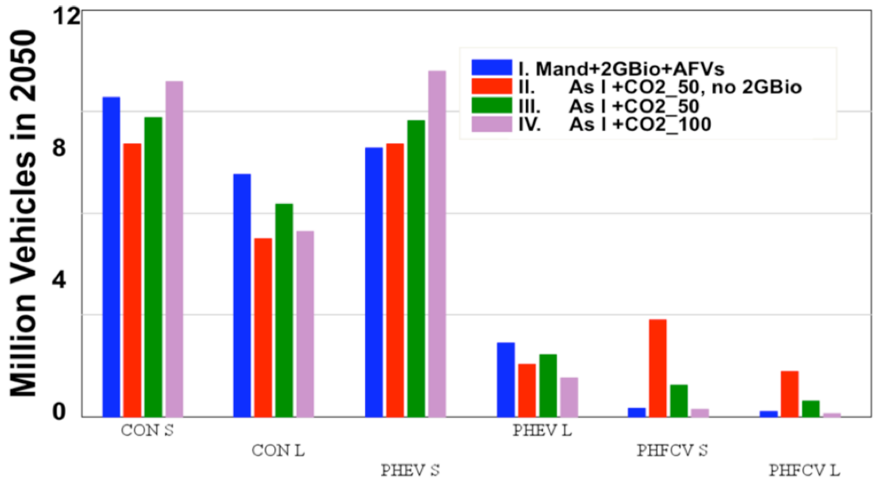


Figure 1 Vehicle Installed base in 2050, for different carbon policy and Biofuels scenarios, with competing conventional (CON), PHEV, and PHFCV, both small (S) and large (L), vehicles.

Implications

Under moderate to large Carbon prices, absent an early fuel alternatives (2G Biofuels), more radical alternatives such as (P)HFCVs become viable. However, when alternative fuels are available, the more mature flexible alternatives, such as PHEV, lock-out the exotic technologies. Policy-makers (governments, fuel providers and automakers) should use carbon prices with other tools (see esp. insight #17 to shape the evolution of the market transition, which includes multiple alternatives and fuels.

See also: 2009 Slides pp 61-64

19 Fuel taxes and tax revenues need to have a central position in the policy discussions

Insight

A successful transition demands large upfront investments. However, investments are dwarfed by the scale of fuel taxes. The fear of avoided tax income by federal and state governments may hamper policy support absent a strategy that considers budget neutrality (Figure 1 left).

Explanation and implication

Budget neutral policies are economically feasible (even through politically challenging). Tax increases that result in a budget neutral are very modes (Figure 1, right, blue line).

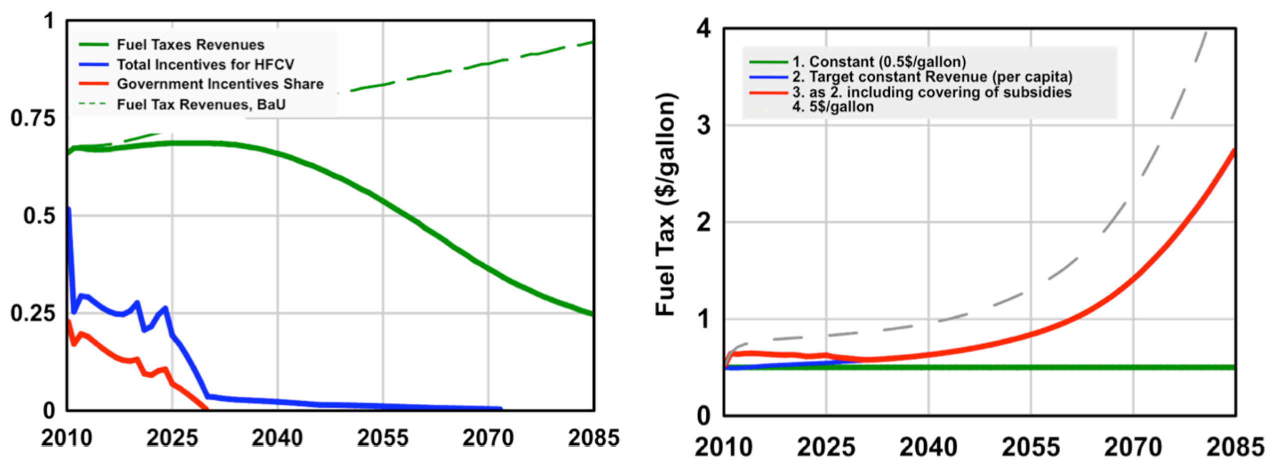


Figure 1. Tax revenues over time. Left, California gasoline tax revenues from gasoline during a transition, as well as incentives provided for the alternative (HFCV). The normalized value of 1 equals 6$B/year, which is 6% of the 2006 budget of the state. The right graph shows (green) the fuel tax applied for the scenario on the left, as well as a tax-income neutral (blue) scenario and full subsidy neutral (red) for the state of California.

More broadly, the policy debate needs to be casted in the wider and longer-term implications of AFV market transitions. For example, significant benefits may derive from limiting climate change impact, avoided oil imports, local job increase.

H. Insights related to strategy for success

Intentionally left blank

20 Exploration of high leverage policies for successful AFV diffusion require an integrated analysis

The mechanisms that condition AFV diffusion (such as those including social exposure to and adoption of vehicles, fueling infrastructure development and fuel demand or vehicle technology and model evolution and vehicle adoption) strongly reinforce each other. This is illustrated by our analysis that compared simulation runs in which the base policies that addressed the barriers imposed by each mechanism where switched on and off. Such base policies included a marketing program, fleet rollout, infrastructure rollout. We translated the effort of each policy in a cost (NPV). Optimistically we assumed the cost of each policy to be linear with the influence (thus doubling the marketing cost also yielded twice the effect). This favored having individual policies. However, the research found that for large regions of testing, in particular those that involved low to moderate policy efforts, switching more policies on involved much least cost. The underlying reason is that the various factors that condition adoption are highly complementary: similar to the idea that someone who prefers to drinks tea with milk, would not consume a drink in absence of either tea or milk, a typical consumer would not adopt.

Implication

A critical understanding of the potential value of policies can only come after analyses that focus on individual mechanisms. However, the existence of such complementarities across mechanisms implies that by ignoring some mechanisms in the transition analysis, one not only produces base runs that are too optimistic, but one also denies her/himself finding of potential high leverage policies. For similar reasons the multi-AFV competition needs to be included in at least some of the policy analyses. Note further that the non-linearity of the factors that influence the dynamics implies that the effectiveness of policies saturates at different levels. Combining those points, this means that effectiveness of a policy depends on the complete portfolio of policies (and system conditions).

Note

The extent to which the diffusion of AFVs is constrained by the mechanisms depends very much on the characteristics of the platform. Current hybrid electric vehicles are much less constraints by the powerful feedbacks, as there is more experience with their vehicle technology, and consumer acceptance may grow faster as they are less exotic than HFCVs. Finally, they rely upon a fuel that is already widely available.

21 The right policy at the right time

Policies need to be aligned with one another. For example, building consumer acceptance through costly marketing programs is important early on. However, those efforts will be wasted in absence of a vehicle that can be introduced, and used, shortly. Vehicle platforms compete for attention. Attention declines without continued exposure – vehicles on the road or costly marketing programs. Consumer attention needs to build at the right time. Similarly, incentives that stimulate the purchase of AFVs, through financial instruments will have limited impact in absence of incentives that stimulate the driving of them. For example, vehicle taxes that lower the price below what drivers expect to pay for a vehicle (with ICE as reference) require parallel policies that sufficiently stimulate the expansion of the fueling infrastructure.

Implication

Policies need to be considered within a portfolio that changes as the conditions change. Coordination among players is critical.

See also: 2007_2 slides p14

22 Effective stimulation of adoption requires coordination and commitment

Insight

Overcoming the multiple thresholds for self-sustaining AFV markets require long commitment by and coordination among multiple parties across industries. With this study we find that overcoming barriers to successful diffusion, a transition to AFV markets requires coordination between energy companies, governments, automotive OEMs and their suppliers. The mobilization of resources and commitments in the early stages will have long-term implications for the success of the transition as well as for individual firms.

Explanations

Figure 1 illustrates the issue, by comparing a (successful) base-case simulation of an AFV launch (here HFCV) with alternative policy scenarios under which each time one policy is reduced (by 50%). Left shows the policy intensity, committed to for 10 years, across a portfolio for the various scenarios in a radar diagram, comprising from top, clockwise: AFV fleet rollout, AFV R&D, alternative fuel station rollout, alternative fuel station markups, gasoline fuel tax, marketing/education programs, and vehicle subsidies (Slides 2007_2 pp14-27 for additional details and analysis). The blue line shows the base case - involving considerable commitment on all policy dimensions. The radar-diagram on the right shows the impact of the policies for the respective scenarios. The blue line is again the base case. Impact is measured, most importantly for the adoption rate, i.e. share of vehicles in use being HFCV, after 30 years - in 2040 (from 0 in the center to 100% on the outside). The base case gives 10% of vehicles in use being HFCV. Other measured impact includes the NPV and near term returns for OEMS, fuel retailers, and government.

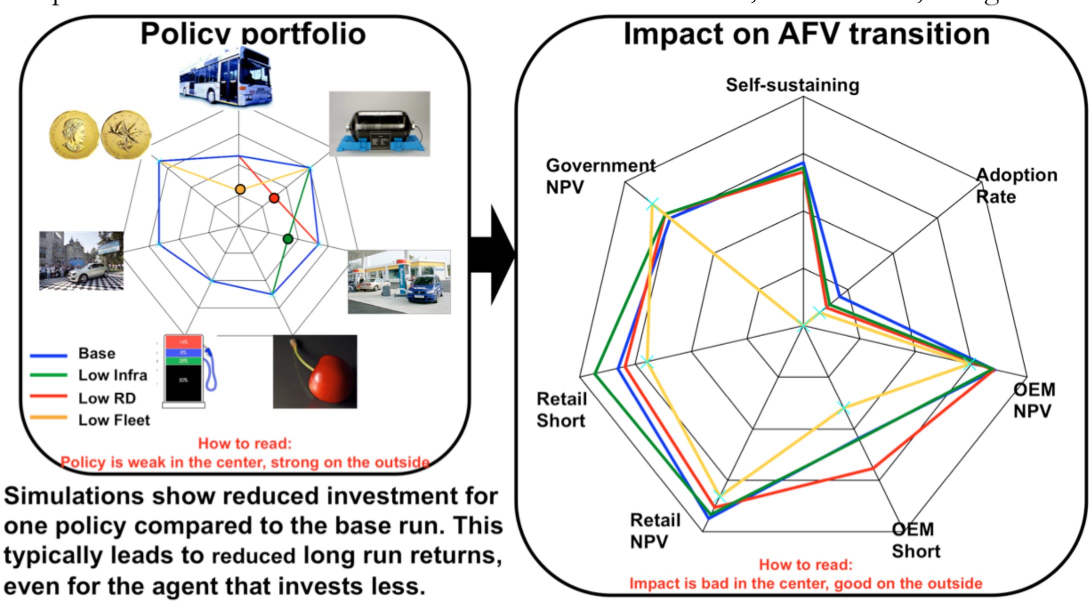


Figure 1. Radar diagram comparing policy portfolios with their impact for AFV introductions (simulated for HFCV). A successful base case (blue), with strong policy commitment for 10 years across is compared with cases in which individual policies are reduced by 50%.

The base case is contrasted with three alternative scenarios of which one party is assumed to not cooperate, leading to reduced commitment along one policy dimension (infrastructure rollout, AFV R&D,

and fleet rollout). All scenarios show that relaxing just one of many policies by 50% results in severe reduction in adoption (about 50% for all). Moreover, the financial consequences are negative in nearly all cases, even for those players who invest more. Other thought experiments show similar results, including the importance of aligned goals.

In one exercise we compared the cost and impact of 10,000 simulated policies (slide 2007_2 pp20-21 summarized this). We compared simulations within and between 10 batches of fixed policy resource constraints (for each batch the total budget of was held constant, but we performed 1000 simulations varying the allocation of these funds across policy targets (R&D, fleet rollout, infrastructure rollout, marketing/education etc…). The pattern is clear: alignment across policies (that is, distributing a given budget across policies, rather than focusing on one or two) helps higher adoption within each batch. Comparing the different batches. Higher investment leads to more adoption, but obviously, there are diminishing returns to investment, at some point strong.

Implication

Policies are highly complementary: "extrapolation" from history and piece-by-piece optimization are failure prone. The findings highlight how, even with significant policies, any successful diffusion path is "fragile" for a long duration. Take-off may occur, but as soon as one policy is reduced, the joined trajectories might implode. Further, policies that enthusiastically, but unsystematically fuel early growth in the process of diffusion, but that do not build important conditions for long run success (e.g. experience) may contribute to its failure. Such failures have been documented for synfuels in the US, and natural gas in vehicles in Canada - but are much more spurious in other industries.

Policies need not only be designed in sync with others, but other partners need to be aware and have confidence that all remain committed. For example, automotive initiated policies that are geared towards boosting early adoption by a combination of programs (short and long term leasing, fleet programs, scrapping programs etc..) are only valuable when governments and fuel providers are aware and have confidence in this and so that, for example, fuel providers will commit to a fitting and aggressive rollout. Simulations have shown that limited commitment from one of several parties will lead to failure.

See also: 2007_2 Slides pp 14-27

Further reading

Struben (2009)

23 Avoid the competitive pressure from established platforms

Insight

Potential for self-sustaining adoption may be larger in other regions, such as China and India. Simulations of a small but growing vehicle market showed that the diffusion of AFVs was much faster than in a saturated market. This is because Installed base growth rates speed diffusion of alternative fuel vehicles, as the ICE fleet is more quickly diluted with AFVs, boosting social exposure; potential diffusion rates exhibit strongly diminishing returns as the growth in total ownership declines. Further, in those regions established infrastructures, regulations for the dominant technology (ICE gasoline or diesel) are less developed and therefore it is easier to make an inway for AFVs. For example, comparing a simulation on the California region, with the first having an incumbent with otherwise similar conditions yielded

24 Finding policies that yield consumer response

Insight

Subsidizing hydrogen fuel is much less effective in stimulating takeoff, compared to an equivalent gasoline tax. This is because the fuel cost that is reduced is much less. Simulations show however, that gasoline taxes generate a large fund and can be used to generate policy portfolios that are net revenue neutral when used to balance cost of other critical policies (such as marketing programs and markup guarantees for fuel station retailers).

Implication

To what extend this behavior is true, depends on whether consumers are more sensitive to fuel per mile or fuel prices. Simulations with consumers focusing only on the fuel prices, resulted in a worse base case that improved considerably with hydrogen fuel subsidies. However, subsidies needed to be very significant.

25 Get AFVs in by getting others out

Insight

Policies geared towards the effective vehicle life, such as scrapping programs and introducing them into existing (long-term) leasing programs may significantly impact the threshold. The average useful life of vehicles is on the order of 10-20 years, which is much larger that of typical consumer electronics. The long duration between purchase and scrapping (scrapping cycle) is an important contributor for the strength of many indirect and direct network effects that are active in the automotive industry. While AFV market shares may be very high, it still will take long before the vehicles on the road form a significant share. Thus, the slow scrapping cycle suppresses the rate at which consumer exposure to AFVs may grow and complementarities, such as fueling infrastructure, will therefore grow at a relative slow pace. However, the existence of the used car market complicates these dynamics. Our simulations give insight in illustrate multi-prong dynamics introduced by used vehicle markets: On the one hand, the replacement cycle of vehicles , the time between consumer vehicle purchases (new and used), is much shorter than the scrapping cycle. Because the used car market forms a significant share of the market (well above 50% in various important vehicle classes) AFVs may diffuse in the market faster than in the absence of a used car market. On the other hand, in response to a a fast growing market – more and more people offer their ICE vehicles on the market with a resulting oversupply of used incumbent vehicles when AFVs flood the market. This yields low used vehicle prices and with the large supply of ICE vehicles this acts to increase demand for (used) ICE vehicles which suppresses the positive effect of fast replacement on AFV diffusion.

Implication

Besides altering the diffusion dynamics, the used car market offers alternative policy leavers. Vehicle scrapping programs might offer high leverage for CO2 reductions, especially when offered in combination with AFV replacement incentives. Such programs provide incentives that are targeted to older and most pollutant vehicles - with increased subsidies for those that drive more (arbitragers may emerge that collect these vehicles). These programs have a large effect on AFV penetration rates as they act to increase demand for new vehicles and thus effectively lower the replacement rate and effective life of ICE gasoline vehicles, reducing the strength of the positive feedbacks that constrain AFV adoption. Such a program is particularly effective jointly with taxing pollution and Carbon emissions.

Following similar trains of thought, vehicle leasing and shared vehicle program are important policy levers. This lowers the risk for drivers and significantly.

26 When exploring policies and evaluating a policy - challenge the boundary of the system and its of response

Through various analyses we explored how the various mechanisms together condition the adoption dynamics of AFVs. Analysis does not stop there. As part of our analysis approach, we explore the potential implications of any analyzed dynamics, conditions under which they are valid and consequences of expanding the boundary. In doing so the importance of a broad perspective and coordination becomes even more apparent. For example, the tendency for fuel availability and demand to cluster in urban areas, is likely to increased share of small urban cars. While islands of limited diffusion might be sustained in the cities, broad adoption of AFVs can easily founder even if their performance equals that of ICE. Such dynamics have implications for AFV diffusion beyond the infrastructure/adoption interactions. For example, while not considered in the simulation shown, low diffusion limits knowledge accumulation that can improve AFV performance. Further, auto OEMs would likely respond to the demand for AFVs in cities by offering small, efficient, inexpensive models adapted for commuting but ill suited for touring. Such vehicles would be even less attractive for long trips and use in rural areas, and would likely restrict adoption to affluent households who can afford an AFV for commuting and an ICE vehicle for weekend excursions. Such dynamics are also suggestive to have occurred historically: compact cars where the dominant electric vehicles in the 1960s, which were called “city cars”. Further, during the transition from horses to vehicles, electric vehicles competed which had a relatively short range, relied on an infrastructure of charging stations that become more and more concentrated in urban areas. The vehicles competed increasingly – initially successfully - in the urban areas as delivery trucks, taxicabs and local pleasure rides.

Implication

Challenging the boundary means in terms of policy design implies asking:

1. What other "unanticipated" dynamics may occur, in the long run when we introduce a policy
2. What might be the responses of other players be to initiated policies.
3. Who are the relevant actors that may influence the condition the diffusion dynamics – constrain it, or that may offer high leverage policies. Bringing various insights listed together, throughout, the important role of less visible players and factors that influence the dynamics, including: leasing (companies), used car (auctioneers), car sharing (services), stationary fuel cell (producers), refueling at the home (services),

27 Identification of sensitive and uncertain areas

The research has identified critical areas that require empirical work, sensitivity analysis and/or model elaboration. These areas include those factors for which we found a) the behavior to be sensitive to and b) little prior research exists. They include driver sensitivity to fuel availability for trips (involving factors as risk of getting out of fuel, search time), and consumer sensitivity to marketing efforts.

Implication

Our research is focused on analysis, but for some of these factors we also have been doing research. Some of For example, results from the empirical diesel Europe study allows reducing the uncertainty around social exposure parameters

I. Project References

Supplementary Presentations

2007_1 Slides: 2007_AETT_MIT_Shell_Workshop_Session_1_Fin.pdf

2007_2 Slides: 2007_AETT_MIT_Shell_Workshop_Session_2_Fin.pdf

2009 Slides: 2009_AETT_MIT_Ford_Shell_Workshop_Fin.pdf

Peer reviewed Articles

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

Theses

Struben, J. (2006). "Essays on transition challenges for alternative propulsion vehicles and transportation systems." Ph.D. diss., Massachusetts Institute of Technology. http://hdl.handle.net/1721.1/37159

Zhang, Q. (2008). "Analysis and calibration of social factors in a consumer acceptance and adoption model for diffusion of diesel vehicle in Europe" S.M. Thesis Massachusetts Institute of Technology, Engineering Systems Division, Technology and Policy Program http://dspace.mit.edu/handle/1721.1/43162

Supple, D. (2007) "Managing the transition toward self-sustaining alternative fuel vehicle markets : policy analysis using a dynamic behavioral spatial mode." S.M. Thesis Massachusetts Institute of Technology, Engineering Systems Division, Technology and Policy Program http://dspace.mit.edu/handle/1721.1/40297

Selected Working papers (additional work is in progress)

Struben, Jeroen (March 2010). "Explaining Firm Success during Technological Uncertainty: The Coevolution of the Technological Field and Organizational Processes."

Struben, Jeroen (September 2009). "To Flounder or to Flourish: Exploring Fragility in Alternative Fuel Vehicle Market Formation." Industry Studies Conference Paper. Available at SSRN: http://ssrn.com/abstract=1135732

Reports

Struben, J. (2007). "Transition dynamics for alternative propulsion vehicle markets - model reference". Cambridge, MA. MIT Project on Market Transitions for Low Carbon Transportation. Report 1.

Struben, J. (2010). "Summary of Policy Insights from Alternative Fuel Vehicle Transition Analysis". Cambridge, MA. MIT Project on Market Transitions for Low Carbon Transportation. Report 2.

Workshops, Presentations, and Videos

Sterman J. (2008) "Why Bad Things Happen to Good Technologies" MIT World http://mitworld.mit.edu/video/553

MIT/Ford/Shell Research Workshop (2009) "Strategies for Market Transitions to Alternative Energy and Transportation Systems", Tuesday/Wednesday June 9-10, Dearborn, MI, http://web.mit.edu/jjrs/www/3rdMITFordShellWorkshop.htm

Struben, J. (2009) "Transition Strategies for Alternative Transportation Fuels and Vehicles" http://web.mit.edu/jjrs/www/AETTPresentations/StrubenAETT200906.pdf

Sterman J. (2010) "Sustainable Accessibility: A Grand Challenge for the World and for MIT" MIT World http://mitworld.mit.edu/video/750

Sterman, J.D. and J. Struben (2010) Transition strategies for alternative transportation fuels and vehicles – Research Summary (3 pages PowerPoint)

Press Coverage Sample

News Release (2007) Massachusetts Institute of Technology on our alternative fuel vehicle transition research (May 2007) http://web.mit.edu/newsoffice/2007/alt-fuel-0530.html

Stauffer, N. (2007) "Alternative-Fuel Vehicles: Enabling the Transition Energy and Environment" Newsletter, MIT Laboratory for Energy and Environment (LFEE), Cambridge, April 2007 p8-10 http://lfee.mit.edu/public/e&e_April_07.pdf

MIT Tech talk (June 2007, page 6) http://web.mit.edu/newsoffice/2007/techtalk51-29.pdf

Stauffer, N. (2007) "Alternative-fuel vehicles - Enabling the transition", MIT Energy Initiative http://web.mit.edu/mitei/research/spotlights/alternative-fuel.html