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The Diffusion of Complex Market Technologies:
Multifaceted Dynamics for Alternative Fuel Vehicles

By

Jeroen J.R. Struben
Massachusetts Institute of Technology
Cambridge, MA 02142
jjrs@mit.edu

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The Diffusion of Complex Market Technologies: Exploring Multifaceted Dynamics for Alternative Fuel Vehicles

Jeroen Struben

jjrs@mit.edu

MIT Sloan School of Management, Cambridge MA 02142

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Abstract

This paper develops initial steps towards a framework for understanding factors that condition success and failure of complex market technologies. Dynamics of such technologies are conditioned by coevolutionary processes including the development of the installed base, consumer behavior, technologies, complementarities and interlinked supply chains. This paper analyzes diffusion patterns, including failures and successes, of alternative transportation fuel (ATF) and vehicle introductions, natural gas in New Zealand and Argentina, and ethanol in Brazil. I analyze the diffusion patterns of retrospective AFV introductions, failures and successes, through a behavioral dynamic simulation model. I characterize technology diffusion as a process of market formation which requires overcoming a period of fragility. During such a period at least one of the mechanisms conditioning its diffusion works against further spreading. Aggressive, simple strategies to overcome thresholds tend to fail. However, high potential strategies involve policy portfolios that are synchronized across multiple types of decision makers, sustained, and dynamic. Further, the efforts and their duration required to overcome this stage are strongly influenced by institutional and historical contexts. More broadly, the findings provide the groundwork for a framework to analyze diffusion of complex technologies and markets. Such a framework involves capturing the fundamental mechanisms cutting across inter-organizational fields but that also includes the important system-physiological aspects. Within this framework the traditional S-shaped diffusion curve can be seen as a special case with ex-ante usefulness constrained to situation with low market complexity and favorable institutional conditions. We discuss implications for policy and strategy.

Introduction

How do technologies enter the marketplace, gain traction, and sustain themselves? Whether the perspective is sociological (Ryan and Gross 1943; Rogers 1962) or economic (Griliches 1957; Gort and Klepper 1982), the S-shaped diffusion pattern is considered a stylized fact (Jovanovic and Lach

1989). Documented examples that follow this pattern are numerous and include: consumer end products such as microwaves motor cars, laser printers walkmans (Bass et al. 1994; Nakicenovic 1986; Christensen 2000), process technologies (Karshenas and Stoneman 1993), enabling products such as turbojet engines and minimills (Mowery and Rosenberg 1981; Tushman and Anderson 1986) and ideas and forms of social organization (Strang and Soule 1998). A large body of diffusion models exists that without exception explains this particular curve (Griliches 1957; Bass 1969; Stoneman 1986; Mahajan et al. 1990; Mahajan et al. 2000; Geroski 2000).

This paper tries to understand a body of data that produces patterns that deviate from this S-shape: introductions of alternative transportation fuels (ATFs) and vehicles (AFVs) in transportation. In the near future wide range of vehicle technologies – biodiesel, fuel cells, ethanol, compressed natural gas, and advanced petroleum – will compete for dominance. However, historical attempts to introduce them in the marketplace have at best yielded mixed success. Their modes of behavior across cases are multiple, even when vehicle technologies are identical. For example, compressed natural gas vehicles have experienced reasonable success in Argentina, sizzled and then fizzled in Canada and New Zealand, stagnated at low penetration in Italy, and failed to take off in many other countries. Similar variation can be observed with other alternative fuel vehicles (Cowan and Hultan 1996; Sperling and Cannon 2004). Actors seeking to stimulate AFV diffusion often recognize barriers that result from various forms of scale economies. Hence, their introduction often accompanies aggressive incentives to boost demand and technology, after which the market can take over.

Consider Brazil's attempt to substitute away from petroleum imports, through the internal production and use of ethanol. With currently 40% of its consumption in transportation deriving from ethanol, Brazil's transformation is considered proof that alternative fuels are technologically

and economically viable: *“Henry Ford predicted that “ethyl alcohol is the fuel of the future”. With Petroleum at \$65 a barrel, President Bush has now embraced that view, too. But Brazil is already there.”* (Rother, 2006).

Further, the successful case serves as a role model whose results can be replicated in other nations, as framed by U.S. Senator Maria Cartwell in May 2007: *“If Brazil can do it, we can do it here in the United States”*. In order too achieve this, the fundamental condition for success is seen boosting R&D in the main technology. Once seeded with initial R&D, this will improve with scale and learning. As U.S. President George W. Bush states in his 2006 US state of the union address, *“We’ll also fund additional research in cutting-edge methods of producing ethanol, not just from corn, but from wood chips and stalks, or switch grass. Our goal is to make this new kind of ethanol practical and competitive within six years”*.

However, the historic AFV introductions have failed, in spite of, or perhaps because the premise of seeding and take-off. Underlying this is First, AFVs and ATFs are only one factor within a much larger system. Trajectories are shaped through interactions between consumers, industries (including oil, automobile and agriculture), and other players (including local, regional, and national governments). Within this broad context, the dynamics of AFV introduction and diffusion are conditioned by a broad array of positive and negative feedbacks. For AFVs those feedbacks include word of mouth, social exposure, marketing, scale and scope economies, learning from experience, R&D, innovation spillovers, complementary assets, such as fuel and service infrastructure, and interactions with fuel and other supply chains. Within this system, multiple decision makers act in their own interests and perceptions. The potential pace at which such a system can change is constrained by factors within the physical realm, such as the obsolescence rate of existing capital, to the behavioral realm, the evolution of perceptions. Moreover, the dynamics can be differently conditioned across cases, because of variation in institutional and historical contexts. Hence, stylized generalizations from case to case risk of being deceiving (Sperling 1988).

The relevance of the view offered here stretches well beyond automotive transportation technologies. Diffusion paths of individual technologies are often much more complex (Homer 1983; Homer 1987; Henderson 1995) and the empirical literature increasingly identifies cases of diffusion challenges for new technologies across a wide range of complex environments, such as medical applications (Gelijns et al. 2001), renewable energy (Kemp 2001; Garud and Karnoe 2001), or automotive industry (Geels 2005). While S-shaped diffusion is a useful description for what ex-post emerges as the dominant technology (Abernathy and Utterback 1978; Klepper 1996; Jovanovic and Lach 1989), it does not provide, ex-ante, an explanatory framework for technology transitions, including competition between multiple technologies, and the variation in the diffusion path for individual technologies, including failure of potentially successful technologies. Without an operational understanding of the variation in their diffusion patterns, theories that rest on the assumption that new technologies succeed may be harmful. While powerful as an ex-post explanation, the S-shape assumption introduces a selection bias that hinders an understanding the process of technology diffusion.^{1 2}

Though an operational understanding of why technologies succeed or fail in the marketplace is absent, the literature offers various threads on what such a framework must contain. By the nature of the problem and the history of academic specialization these threads come from various fields. Epidemic technology diffusion models describe how cumulative adoption of new products follow the logistic growth curve, through a process that is driven by exponential sequential acceptance and saturation (Griliches 1957; Bass 1969). This approach emerged out of the early observers of the diffusion of sociological phenomena (Tarde 1903; Veblen 1908; Ryan and Gross 1943; Rogers 1962;

¹ Strang and Soule (1998) are careful to separate out the type two errors, observing that practices may rise and fall for all kinds of reasons not related to the cause process via communication and influence. However, they assume S-shape patterns as well.

² Rightfully Griliches (1982) responds to a critique on the model that more parameters do not serve the model right. This is justified, within the scope of processes with a similar outcome. However, when the behavior changes, different mechanisms need to be understood and different models are required.

Katz et al. 1963) and epidemic models biology (Pearl 1924; Lotka 1925). Marketing diffusion models describe the consumers to become aware of new technologies informational cascades (Bass 1969). Archetypical examples include color TVs and microwaves (Bass, Krishnan, et al. 1994). Extensions include concepts as replacement purchases (Olson and Choi 1985), successive generations and product substitution (Norton and Bass 1987), consumer uncertainty about value and product price (Kalish 1985), and learning (Bass 1980); see also Stoneman (1983), Mahajan et al. (1990) and Geroski (2000). Economists have a long research tradition in the diffusion of technology. Contemporary economic studies that explain differences in origins, slopes and ceilings of technology adoption patterns are based on the principle that uncertainty of development of a new technology reduces with its adoption, in combination with gradients in returns for potential adopters (Griliches 1957; Mansfield 1968; Reinganum 1981, 1983). Some combine marketing and economic perspective (Stoneman 1992) and explain how a radically different technology to develop in a niche, grow and sustain, resulting in the same S-shaped pattern (Christensen 1997).

Several authors explain variation on the basic symmetric S-shaped adoption patterns by focusing on heterogeneous demand thresholds (McFadden 1986; Adner and Levinthal 2001), characterizing observations of bimodal diffusion curves with “early and main markets” (Mahajan and Muller 1998), as “chasms” to be crossed (Moore 1991),³ or as “saddle demand” (Goldenberg et al. 2002; Tellis 2002*?*)). Economic and sociological traditions have studied the process by which customs and habits become taken for granted, that is technology being shaped by social actors, while shaping social values (Veblen 1918; Berger and Luckman 1966). Building on this, sociological perspectives on new technology adoption emphasize the distributed character of actors or their “seamless web”

³ Crossing the chasm only referred to information technologies, but the metaphor has been invoked to explain deviating diffusion patterns of many technologies, public policy of energy technologies, cork screws etc...

(Pinch and Bijker 1984) and dominant configuration can be socially shaped (Granovetter 1985; McGuire and Granovetter 1993; Hargrave and Van De Ven 2006). Studies of industry dynamics have long recognized the reciprocal character of technological systems and markets: infrastructure, distribution, production, regulatory and other institutions need to develop and co-evolve along with the technology (Rosenberg 1972). The working of individual mechanisms have been explored in much greater depth, including been learning by doing (White 1936; Arrow 1962; Argote and Epple 1990), by research (Constant 1980) and by using (Rosenberg 1982), spillovers (Jovanovic and Macdonald 1994), network externalities (Katz and Shapiro 1985; 1986; Choi 1997), potentially cutting across multiple markets (Rochet and Tirole 2003; Parker and Van Alstyne 2005). The increasing returns literature highlights the existence of tipping points in such contexts (Arthur 1989).

Taken together these strands suggest that new technologies may succeed and fail. But the process through which this takes place is underdeveloped. Scholars have begun to recognize that path dependence theories are too deterministic (Hargrave and Van De Ven 2006). This paper takes the view that to understand drivers of success research must avoid the successful technology selection bias of the S-shape literature and seek to understand the mechanisms of diffusion and account for the variety of observed patterns. Technology transitions require the formation of a self-sustaining market through alignment of consumers' interests, producers' capabilities, infrastructure development, and regulations. In particular technologies fate is fragile until all the dominant mechanisms work in the favor of the technology, which is decoupled from the desire of all actors to succeed. A process based view requires an appreciation for the dynamics resulting from not only the intrinsic economic characteristics of the products, but also the physiological aspects of the systems – such as the spatial and vintage distribution of a relevant capital and infrastructure; a multiplicity of actors, having varying interests and relying on imperfect and information that is under influence, and the institutional contexts. Such systems exhibit many powerful feedbacks and their diffusion

trajectories are strongly path dependent (David 1985; Arthur 1989; Sterman 2000) and require careful dynamic analysis of their non-intuitive behavior (Forrester 1975; Sterman 2000).

To initiate a step towards such a theory, we investigate the market formation challenges of alternative fuel vehicles (AFVs). AFVs face challenges to overcome a deficit of fueling infrastructure, consumer acceptance and technology improvement, while competing with each other and an established ICE/gasoline ensemble that is deeply embedded in interorganizational fields and institutions. We illustrate the transition challenges for alternative fuel vehicles, at hand of failed and successful attempts of natural gas vehicle (NGV) introductions. In what follows we start by discussing how we use retrospective studies to inform and explore a dynamic model of AFV diffusion. We next introduce the contexts of the three cases. The subsequent section describes a behavioral dynamic simulation model developed to analyze AFV diffusion. The model is developed at hand of the data available from these cases, other data and the literature. The model emphasizes the broad scope and a long time horizon, as well as multiple vehicle competition. Further, decisions by key actors – consumers, automotive manufacturers, and fueling infrastructure providers – are explicitly represented. We next discuss the generic underlying mechanisms that condition the dynamics. The analysis reveals not only adoption thresholds, but also substantially longer times required for AFV markets to become self-sustaining than decision makers expect and allow for with introduction programs. Having a fundamental intuition, I discuss the empirical cases. Implications are significant: successful diffusion of such technologies requires strategies and policies that are based upon an understanding of the collective dynamics, coordination, commitment and flexible policies. We close with a discussion on the implication for diffusion theory.

Methods, data and concepts

This paper develops an understanding into the diffusion dynamics of AFVs drawing upon empirical cases in conjuncture with the development of a formal simulation model. The collection of data comprises quantitative time-series, retrospective literature, reports and surveys, combining over 30 sources. We discuss past introductions of AFVs in three different countries: natural gas vehicles in New Zealand and Argentina and ethanol vehicles in Brazil. The cases exhibit different degrees of success for AFV introductions. Successful cases generate an abundance of tractable data and provide one particular explanation in the outcome. However, a dynamic process based framework should rely upon accounts with a variation of contexts, initial conditions, and outcomes. In combination with other data and literature these cases support together the development of the underlying critical relationships, a set of common fundamental mechanisms that together may yield the variation in behavior, and of the operant parameter ranges. However, it is difficult to build intuition around the complex dynamics generated by the joining of these mechanisms; simulation models built allow analyzing such dynamics that derive from an explicit and internally consistent structure (Eisenhardt 2007, Sterman 2000). The simulation model developed here follows standard principles of behavioral decision making, consumer choice theory and economics. This model elaborates on and integrates earlier work that identified and studied some key mechanisms of AFV diffusion (Struben 2006; Struben and Sterman 2007); here we discuss the main relationships only; details of the formal equations are available in the electronic companion.⁴

We inspect first the fundamental behavior patterns by analyzing the diffusion dynamics of a generic, hypothetical AFV, avoiding distractions from specifics of the historical and institutional contexts.

⁴ For the draft versions, the appendix will be with the author.

Building on this understanding we turn to the historic analysis. The variety that these cases bring illustrates how the institutional contexts may favor or disfavor transitioning. We focus in particular on ethanol in Brazil. We use counterfactual analysis to understand the importance of historical contexts in how the mechanisms play out. The development of the purposefully stylized model at hand of the cases, and the analysis of the model behavior and of the cases together serve to develop conditions for successful AFV market formation. However, the insights stretch well beyond the ATF and AFV context, but relate to complex market technologies in general.

We facilitate generalization of the insights by characterizing the state of a technological diffusion, not in terms of the level or rate of adoption, but in relation to the extent to which the market can sustain itself. In line with this, drawing upon insights from complex systems theory and systems biology (e.g. Krakauer and Plotkin 2002, Csete and Doyle 2002, Doyle and Carlson 2002), we care to highlight to what extent an existing state is sensitive to disruption. Of particular relevance here are understanding to what extent early growth rates are sensitive to changes, conditioned by the mechanisms, the historical and institutional contexts, and the active policies. We define four states of technology diffusion: i) an inert state in which not one single additional policy can stimulate (further) diffusion. Most, and certainly more than one, mechanism work against its diffusion; ii) a fragile state in which elimination, or significant reduction of at least one policy results in collapse (and the inert state). In this state at least some mechanisms work against its diffusion; iii) robust growth, in which few of the policies if active, are needed to stimulate further diffusion; iv) saturation, in which few of the policies if active, are needed to maintain the state, but no direct policies can significantly improve the diffusion. Through evolution, policy changes, external shocks, including the entrance of new technologies, the state of a technology may change. Technologies typically must undergo all states, but to what extent depends on the market complexity and

institutional factors. For example, a simple technology such as walkman effectively starts in the fragile state, but when sufficient marketing policies have been maintained for a period, we quickly see robust growth. In contrast, technologies with increased market complexity spend a long time in the fragile state.

Four attempts to achieve self-sustaining Alternative Fuel Vehicle markets

Attempts to achieve large scale fuel substitution in transportation are not new. Non liquid fossil fuels have been competing with petroleum for vehicle propulsion since the early conception days of the vehicle. Besides electric and (often coal based) steam, biofuels, especially alcohol based fuels were in contest to propel internal combustion engines. In particular the agricultural sector was an important driver. However, with taxes and competition between industries, fuels such as ethanol disappeared from the picture (Armstrong 2002; Lovins et al. 2004). Efforts to introduce alternative fuels (AFs) in transportation have never seized since. Natural gas has been introduced in the marketplace in many countries, industries and governments, with a variety of results. NGVs in Canada and Bangladesh experienced the same fate as those in New Zealand while their diffusion has stagnated in Italy for years around a few percent.⁵

While specific parameters are different in each particular case, the same coevolutionary mechanisms are at play in such transitions – irrespective of outcome. Such mechanisms involve development of vehicle attributes portfolios, fuel production, distribution and dispensing infrastructure and consumer confidence about the fuel and the vehicle technologies, as well as supporting institutions, evolving in a highly reciprocal fashion. Further, the system includes many self-interested parties and long adjustment times involved in the informational and physical components of the system.

⁵ Brazil has similar aggregate adoption as Argentina, but in Sao Paolo, having 38% of the total vehicle installed base, has seen a surprising low penetration of NGVs, on the order of 1-2%.

To help develop a model for analyzing the dynamic implications of such interactions, we focus on three cases of alternative fuel introductions in the transportation sector, in New Zealand, Argentina and Brazil. Table 1 summarizes the initial situation. For the purpose of readability, we leave detailed reference out of the paper; a chronological description of the cases and all references are provided in the electronic companion.⁶ Governments' initiatives to introduce AFs and AFVs were in all three cases motivated by a desire to reduce the country's dependence on foreign oil. Brazil sought introduction of ethanol vehicles in the 1976, while New Zealand and Argentina aspired to introduce natural gas vehicles (NGVs). In each case the AFVs offered different value and costs to a driver than traditional internal combustion engines that run on petrol (ICE). Their key selling point was the much lower fuel price. Further, these cars could be sold as environmentally friendly and as a national interest fuel.⁷ On the other hand the gaseous bi-fuel vehicles have a much lower volume based energy density which reduced the luggage storage capacity and the action radius of the vehicle. With cost of the AFVs being slightly higher, they were promoted to private and fleet owners especially as an economic choice. Confronted with the many challenges – the buildup of consumer interest, the requisite infrastructure and cheap high performance vehicle offerings, governments and various industry partners undertook efforts with intention to guarantee a successful transition. The AFV introductions were accompanied with combinations of financial and non-financial incentives that affected consumers, automotive producers, retailers and fuel producers. Dynamics however, show a variety of patterns (Figure 1). We will now explore the dynamics as we develop and analyze a formal model that captures the mechanisms and allows representing the different contexts.

⁶ For the draft versions this will be with the author.

⁷ Government and CNG industry were firmly committed to the declared CNG program as the indigenous fuel delivered by pipeline is secure, is only half the price of petrol, and each conversion New Zealand substantial overseas funds.

Modeling Framework

Below I describe a framework that facilitates the exploration of transition dynamics - failures and successes - from ICE to AFVs, or more generally from incumbents to entrants. First, the AFV diffusion process is mediated through mechanisms that span multiple coevolving markets, including among others fuel production and development, fuel dispensing and retailing, automotive production, automotive after market. A useful starting point is the two-sided markets literature (Rochet and Tirole 2003) that studies the working of markets in which an intermediary platform serves to connect multiple types of users (such as document reader and writer users at the adobe platform). Such markets often involve several economies of scale, internal, but in particular across-market-sides and are prone to lock-in (Parker and Van Alstyne 2005). Typical strategies to overcome chicken and egg adoption thresholds of two-sided markets include below margin pricing on one side of the platform to boost demand, which generates demand (or supply) on the other side. In this case, automotive producers can be seen to provide a platform, the vehicle, in which exploiters of fueling infrastructure exchange a transaction with consumers (Figure 2, top). A cross-market network externality 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 (e.g. Farrell et al. 2003, NAE 2004).

However, AFV transition mechanisms require a more complete characterization (Figure 2, bottom). First, multiple economies of scale effects exist: 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 extent on social exposure to the vehicles, which increases with the vehicles on the road (R2). Similarly, 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 (R3). Further, technologies influence each other, harboring potential for complementary knowledge spillovers within a platform – but also to and from others. Second, 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.

A second important driver of AFVs dynamics is the existence of multiple markets that co-evolve: 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 involve 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, HFCVs 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.

A final important characterization of AFV transitions is the pace at which it may evolve. 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.

Central to an understanding of AFV diffusion dynamics are the identification of multiple interacting markets and of the principal feedbacks mechanisms, their non-linear relationships and the time delays involved, and the characterization of the institutional settings. Together they suggest that overcoming lock-in is significantly harder than in standard cases of two-sided markets. To explore the diffusion dynamics, we now provide an exposition of the simulation model corresponding with the structure in Figure 2. We focus on the main structural relationships and how they were influenced across the three cases. We begin discussing the consumer adoption structure (vehicle sales, in use and replacement). We then proceed by discussing the factors influencing choice, from top (consumer consideration, R3) to bottom (fuel production capabilities, R4). The electronic companion describes the model in full detail.⁸

Consumer adoption structure

We begin with the evolution of the installed base and consumer choice among vehicle platforms. The total number of vehicles for each platform $j=\{1,\dots, n\}$, V_j accumulates new vehicle sales, s_j less discards, d_j . In addition, alternative fuel vehicles may increase through conversion from one c_j^- into

⁸ For the draft version this is with the author.

another platform, c_j^+ , such as was the case with the bi-fuel CNG/gasoline vehicles in New Zealand and the first two decades in Argentina:

$$\frac{dV_j}{dt} = s_j - d_j + c_j^+ - c_j^- \quad (1)$$

Sales consist of initial and replacement purchases. Initial purchases dominated sales near the beginning of the auto industry, and do so today in emerging economies such as China, but in developed economies replacements dominate.⁹ For simplicity we assume an exogenous fractional growth rate for the total installed base. Thus:

$$s_j = \sum_i \sigma_{ij} (d_i + gV_i) \quad (2)$$

where σ_{ij} is the share of drivers of platform i replacing their vehicle with platform j , and g is the fractional growth of the installed base. The term $\sigma_{ij}gV_i$ ensures that the total installed base will grow at rate g and assumes, reasonably, that people buying their first car or adding another car to their household are familiar with platform i in proportion to each platform's share of the total installed base. The share switching from i to j depends on the relative perceived affinity, a_{ij}^p , $\sigma_{ij} = a_{ij}^p / \sum_j a_{ij}^p$. Perceived affinity is a population level effect of utility on consumer choice and is, in standard multinomial logit choice models, an exponential function of the utility of platform j as judged by the driver of vehicle i . Because driver experience with and perceptions about the characteristics of each platform may differ, the expected utility of, for example, the same fuel cell vehicle may differ among those currently driving an ICE, hybrid, or fuel cell vehicle, even if these individuals have identical preferences – hence the two indices. Vehicles are discarded on average after τ^d years:

$$d_i = V_i / \tau^d \quad (3)$$

Total conversions to platform j c_j^+ , are the sum of conversions from all other platforms c_{ij} . For example, in Argentina and New Zealand, both gasoline and diesel vehicles could be converted into

⁹ The full model also allows for testing the role of a used vehicle market, left out of scope here.

NGVs. Conversions c_{ij} adjust to their indicated level over conversion time τ^c . The conversion time is a function of the frequency at which drivers desire to rep their vehicles, but could also depend on capacity constraints by the shops who convert those. A characteristic of the automotive market is an average vehicle life that is large compared to, say consumer electronics. For a typical vehicle life of 10 to 15 years, if a new platform has a 50% market share from the outset, it takes 10 year to achieve 25% installed base share. While used vehicle markets may (temporarily) reduce the effective replacement time, vehicle conversions (such as in New Zealand and Argentina) allow for a much faster turnover of the installed base.

This concludes the basic vehicle replacement structure, we will now discuss how the turnover of the installed base is influenced through the market share.

The actual market share of a vehicle is conditioned by consumer choice. Consumers' choice among platforms depends first on their consideration set, and, within that set, on the relative attractiveness of each (Hauser et al. 1993). Consumers consider a particular option only when sufficiently familiar with it. Their willingness to consider W_{ij} increases through direct exposure to the different platforms, marketing, media attention and word-of-mouth (Bass 1969, ***). The actual share of those considering a platform that actually decides to purchase it depends on the expected utility of that platform as judged by the driver of vehicle, u_{ij} . The attractiveness of each platform in the consideration set is a function of attributes including price, operating cost, performance, driving range, fuel and service and maintenance availability, and ecological impact. We capture the important determinants for the population level consumer affinity for a vehicle:

$$a_{ij} = W_{ij} f(u_{ij}^d); f' > 0 \quad (4)$$

We use standard multinomial logit choice frameworks (Theil 1969; McFadden 1978; McFadden 2001; Ben-Akiva and Lerman 1985) to model the effect of individual consumer choice among

platforms in the consideration set, implying an exponential form for $f(u)$ (see appendix). The consumer utility in Equation (4) is determined by a set of attributes x_{jq} , which we limit to vehicle performance (aggregating vehicle handling, acceleration, speed, trunk space etc...), vehicle price, action radius, fuel cost, and drive convenience. Further, the population level utility is influenced by the number of models available. In general, the utility sums over the perceived state of each attribute: $u_j = \sum_q \beta_q \left[x_{jq} / x_q^* \right]$, where β_q is the sensitivity of utility to performance and x_q^* is the value a driver is accustomed to. The attributes as defined here are determined by conditions that are influenced by dynamics in the automotive industry (for example through improvement of the fuel efficiency of a platform), the fuel supply & distribution (for example fuel price), the fuel availability, which each are affected by institutional factors. The utility for conversion is established in similar fashion, but includes a cost of conversion, rather than a new vehicle price.

Different types of vehicles offer different potential performance across the set of attributes: having a larger tank volume, valuable trunk capacity was compromised (as well as the action radius), but with a cleaner burning of natural gas, the engines durability, and emissions were much improved. Most importantly, the NGVs could be marketed as an economic choice as their fuel cost was significantly lower. Further, subsidies and taxes are often imposed to offset some (early) shortcomings. For example, the dual fuel NGVs in New Zealand could be converted, initially, for around \$NZL 1100 – the same for Argentina. With subsidies from the government these costs were reduced to 50% of that. Typical payback time would be 1-2 year. We now discuss how consumer WtC evolves and how utility is influenced by decisions elsewhere and at the same time influence those other elements.

Consumers willingness to consider

The process by which the diffusion of a technology is conditioned by consumer awareness is well studied (Rogers 1962; Bass 1969, see Struben and Sterman (2008) for a detailed discussion). These underlying social processes are a critical driver of vehicle adoption dynamics. Beyond that, automobile purchase decisions are strongly shaped by cultural norms, personal experience, and social interactions. While drivers may be generally aware that a platform exists, they must be sufficiently familiar with that platform for it to enter their consideration set (Hauser et al. 1993). For example, when New Zealand was nearly a decade into the program, CNG was still considered a second rate fuel by the majority of the population. Further, with the limited familiarity, many unrelated incidents (e.g. at liquid petroleum plants) were associated with CNG safety issues.

We capture the important social processes that condition AFV diffusion, including the generation of consumer consideration through feedback from driving experience, word of mouth, and marketing (R3, social exposure in Figure 1). We describe here the main structure layed out by Struben (2006) and Struben and Sterman (2008). To explicitly capture the formation of a driver's consideration set we introduce the concept of willingness to consider (WtC) of platform j by drivers of vehicle of i W_{ij} . Willingness to consider a platform captures the cognitive and emotional processes through which drivers gain enough information about, understanding of, and emotional attachment to a platform for it to enter their consideration set. For the aggregate population average WtC varies over the interval $[0, 1]$. Everyone considers ICE, so $W_{i,ICE} = 1$, while $W_{ij} = 0$ for those completely unfamiliar with platform j ; such individuals do not even consider such a vehicle: $W_{ij} = 0$ implies $\sigma_{ij} = 0$. WtC builds up over time through social exposure, but is also subject to forgetting. It takes effort and attention to remain up to date with new vehicle models and features. Hence WtC for a platform erodes unless refreshed through marketing or social exposure:

$$\frac{dW_{ij}}{dt} = \eta_{ij}(1 - W_{ij}) - \phi_{ij}W_{ij} \quad (5)$$

where η_{ij} is the impact of total social exposure on the increase in WtC, and ϕ_j is the average fractional loss of the WtC platform j among drivers of platform i .

Total exposure to a platform arises from three components: (i) marketing, (ii) word-of-mouth contacts with drivers of that platform, and (iii) word of mouth about the platform among those not driving it, yielding:

$$\eta_{ij} = \alpha_j + c_{ij}W_{ij}(V_j/N) + \sum_{k \neq j} c_{ijk}W_{kj}(V_k/N) \quad (6)$$

Here α_j is the effectiveness of marketing and promotion for platform j . Marketing efforts for Brazil's ethanol vehicles were very effective (explain the PROALCOOL program). The second term captures word of mouth about platform j —social exposure acquired by seeing them on the road, riding in them, talking to their owners. Such direct exposure depends on the fraction of the installed base consisting of platform j , V_j/N , and the frequency and effectiveness of contacts between drivers of platforms i and j , c_{ij} . For example, the many ethanol vehicles in the 1990's provide rich information for drivers of those and flex-fuel vehicles. The third term captures word of mouth about platform j arising from those driving a different platform, $k \neq j$, for example, an ICE driver learning about bi-fuel vehicles from drivers of a diesel vehicle.

The loss of consideration is nonlinear: When exposure is infrequent, WtC decays rapidly: without marketing or an installed base, the electric vehicle, much discussed in the 1990's, has virtually disappeared from consideration. But once exposure is sufficiently intense, a technology is woven into the fabric of our lives, emotional attachments, and culture: “automobile” implicitly connotes “internal combustion”— WtC for ICE = 1 and there is no decay of consideration. Thus, the fractional decay of WtC is $\phi_{ij} = \phi_0 f(\eta_{ij})$; $f' \leq 0$, WtC decays fastest (up to the maximum rate ϕ_0) when total exposure to a platform, η_{ij} , is small. Further, the vehicle conversions of NGVs in New

Zealand and Argentina, allowed the vehicle installed base much faster, significantly helping the buildup of familiarity.

These channels of awareness generation create positive feedbacks that can boost familiarity and adoption of AFVs. On the other hand, even for an equivalent technology, marketing programs for the AFV need to be maintained for considerable time before self-sustaining. Critical is the long life of vehicles which means that the share of AFVs in the installed base will increase only slowly even if AFVs capture a large share of new vehicle sales.

Indeed governments in the three countries attempted stimulate adoption through large marketing programs, as well as by increasing the installed base early on by mandated fleets. Anticipating consumer acceptance challenges, the government in New Zealand the government had set up a coordination team that was among others, responsible for marketing program. This was considered a critical component of the program, and its effect was reported every year. In a country with little experience with gaseous fuels, the flyers and television adds were not sufficient to overcome the perception of natural gas as a second rate fuel. In contrast, Brazil's PROALCOOL program involved a central massive, unequivocal and coordinated campaign to stimulate the use of alcohol in transportation (first only intended to be blend with gasoline). The stimulus was mixed with a nationalistic message to stimulate the local agriculture, producers of ethanol, which felt well in a troubling economy. Further, consumers had a long history with alcohol in transportation was. Argentina's situation is somewhat in between the situations in Brazil and New Zealand: the vehicles were new, but households were at least familiar with the gas as a fuel for the home.

Automotive producers: learning, economies of scale and scope

Scale and scope economies, learning effects, and related interactions with the technology, manufacturing, and fueling supply chains promise to significantly lower costs and improve performance for OEMS. Whether efficacy and cost gaps are closed or inverted depends, besides the relative potential performance, on the realization of actual sales and production volumes that allow OEMS to experiment and reinvest in R&D together constituting the set of automotive increasing to scale economies (R2 in Figure 1). However, sales and market shares depend in turn on how efficacious such vehicles are, but also on other factors – such as the availability of fuel (see Eq. (4) and below). HFCVs and hybrids, plug-ins and hybrids all will have to build with limited early experience; the share of the production that depends on non-automotive knowledge differs. At that time vehicles were used to driving their gasoline with 10% (anhydrous) ethanol in their engines which required adjustments solely to the carburetor. The jump to pure ethanol vehicles was big though, requiring changes to for example the entire the fuel system, the tank, the engine and the rubber rings and performance of early ethanol vehicles was inferior compared to the standard (Rothman et al. 1984); on the technology was not new and the vehicles were little more expensive than their gasoline counterparts. Similarly, in New Zealand and Argentina the conversions offered significant performance problems early on.

Attributes that are influenced by the OEMS include vehicle cost, tank capacity, fuel economy and conversion cost. We use one generic structure to capture how each vehicle attribute x_{jq} improves. For readability we omit indices in the rest of this section as we trace improvements for attribute x (the appendix provides detail for each technology). Conform conventional experiences, technology improves with the accumulation of relevant knowledge K at a diminishing rate. We proxy the knowledge that results from reinvestment R&D and learning by doing experience (Zangwill***;

Epple and Argote 1990) by the accumulation of production (aggregated by platform over all regions). Hence:¹⁰

$$x = x^0 f(K/K^0); f' \geq 0; f'' \leq 0 \quad (7)$$

This structure helps us organizing some similarities and differences across the countries. There is no reason to believe that the learning curve is different across countries – technologies are quite similar – typical learning curves for such technologies are 30%. On the other hand with the much larger market volume, the scale of the Argentinean market allows for reaching its normal technology level fast at much lower market shares than New Zealand.

Beyond these direct learning, experiences with related technologies allow improving the technology at a faster rate. In Argentina the production of natural gas vehicles and services could benefit from a mature natural gas industry on areas as maintenance, storage/leakage, dispensing and standardization all benefited knowledge spillovers. For example in Brazil the (anhydrous) ethanol content in gasoline, or “gasohol”, was gradually increased over the year. Vehicles needed to be adjusted for that - with the increasing experience of ethanol vehicles this knowledge could spillover to the production for the normal vehicles and such adjustments were easier. By 2000 when flex-fuel vehicle development started, the gasoline vehicles in Brazil had already made the transition from being able to operate on 10% to 25% ethanol content (gasohol). The flex fuel vehicles in Brazil could rely upon extensive knowledge from this, as well as from the earlier boom and bust of pure ethanol production vehicle conversions and the gasohol vehicles. The technological breakthrough for flex-fuels implied that only moderate adjustments were necessary to the vehicle: the key enabling technology was only a computer chip that registers the current fuel content. In contrast, in New Zealand very little related experience in converting vehicles existed. Similarly, other emerging

¹⁰ A more detailed model with actual reinvestments modeled based on expected ROI is discussed in Struben (2006). For the purpose of the argument here this, more traditional proxy suffices.

platforms, such as plug-in hybrids, HFCVs, electrics, will require completely different powertrain systems and electric systems. In sum, effective production of knowledge K becomes easier when the knowledge base for related technologies, K^e is larger:

$$K^* = f(K^i, K^e); f(\cdot), f'_{K_i}(\cdot), f'_{K_j}(\cdot), f''_{K_i K_j}(\cdot) \geq 0; \quad (8)$$

Depending on the relevance of knowledge across platforms, the level of complementarity and the current state of knowledge, the cross knowledge derivative $f''_{K_i K_j}$ will be a larger. Knowledge is of course not instantaneously available – it takes time to absorb and transfer this. Analysis illustrates how the existence of learning and spillover dynamics greatly increases path dependence.¹¹

Internal scale economies are important in the automotive industry, where larger production volumes guarantee lower cost of vehicles:

$$x_{jc} = x_0 f(s_j); f' \leq 0; f'' \geq 0 \quad (9)$$

In addition, economies of scope exist, as vehicle portfolios expand with increasing sales. Vehicle portfolios play an important role in the AFV transition dynamics. The representation of portfolio introduces another asymmetry that played a significant role in various contexts. First, while not all types of vehicles are suited equally for conversion, the fraction of the market that is available is larger compared to early vehicles. Further, different types of vehicles are better suited for particular

¹¹ As R&D and learning by doing lead to improvement for an individual platform this may also spill over to other platforms (e.g. Cohen and Levinthal 1989; Jovanovic and Macdonald 1994; Klepper 1996), which means that K^e is a vector, including factor contributions from various automotive platforms, that each change endogenously. Here we keep K^e fixed, but see Struben (2007) for an exploration of the endogenous spillover dynamics between heterogeneous knowledge of platforms.

alternative fuels. Café standards benefit the upward shift to larger models (Brazil), and when taxes were shifted from technology specific to “small vehicles” and “grams pollution/mile”. The technological breakthrough for flex-fuels implied that only moderate adjustments were necessary to the vehicle – just a computer chip that registers the current fuel content. - **report number models available** Offering multiple portfolio’s was not a challenge. However, HFCVs, electrics, and various forms of hybrids will allow their own build up of models, which takes on average a number of years. Thus, available models m_j adjust to the indicated level m_j^* which increases with sales:

$$m_j^* = f(s_j^r); f' \geq 0; f'' \leq 0 \quad (10)$$

The shape of the function, or the number of models depend on the complexity of the technology. Further, the improvement rate depends on actual investments. Such endogenous decision can yield additional dynamics, including***. Here we do not model the revenue stream and resource allocation for OEMs explicitly (though, see Struben 2006).

Consumer travel and refueling behavior

A major feedback that involves the co-evolutionary interdependence between AFV demand and the requisite refueling infrastructure (R1 and R1b, Fuel Availability in Figure 1). This “chicken-egg” problem is widely considered as one of the critical challenges to diffusion of many AFVs (e.g. Farrell et al. 2003, National Academy of Engineering 2004; Ogden 2004). While the chicken-egg analogy is useful, analysis of this feedback reveals however much more subtle dynamics than this simple analogy suggests. Interaction between drivers’ demand and fuel supply are dispersed in space: Utility to adopt and drive depends on the effort to find fuel, (which includes out of fuel risk and effort to go out of the way to get fuel) and servicing time (which includes waiting at the pump) which depends on technological attributes, but also changes endogenously over time as the infrastructure evolves with vehicle demand (Struben 2006). The responses to fuel availability include the effort involved in searching or getting to a station, the risk of running out of fuel, and the service time (as a function of supply and demand), and number of service points. The behavioral elements in the

model includes drivers’ decisions to adopt an AFV, their trip choices, and their decisions to go out of the way to find fuel, as well as their topping-off behavior in response to the uncertainty of finding fuel. In return, supply-side decisions include station entry and location decisions, exit, and capacity adjustment. The local scale, but long-distance correlation of interactions is paramount in this dynamic and behavioral setup.

Perceived drive convenience influences the adoption decision. This perception is informed by experiences by existing drivers of those vehicles. The drive experience also conditions utility to adopt: A Canadian survey on drivers of bi-fuel CNG/gasoline vehicles in Canada illustrates that commitment to a vehicle is not only a financial one, but also a personal one, finding that: ‘carrying a minimum (often a bare minimum) of gasoline in their tanks, purely for unforeseen (and highly undesirable) emergency situations, and are intent on using nothing but natural gas on their fuel...every time they are forced to resort to the gasoline switch, then, they are forced to admit a small defeat, and to the extent this happens they are unhappy with natural gas vehicles’ (Sperling 1988, p299). A driver’s utility to refuel is a function of fuel cost ε_{hi}^c , the effort to find fuel ε_{hi}^f (finding stations when needed, having to drive out of the way, and out of fuel risks) and the effort at the pump ε_{hi}^s (including wait and refill time):

$$u_{hi}^d = f(\varepsilon_{hi}^c, \varepsilon_{hi}^f, \varepsilon_{hi}^s); f'(\cdot) \leq 0 \quad (11)$$

Utility from fuel cost ε_{hi}^c depends on drivers on (moving) average of annual (monthly) fuel cost defined by the retail fuel price multiplied with the fuel efficiency and normal miles traveled.¹² Retail

¹² Arguably people way the fuel price per liter of gallon into their perception, this form of non-rational behavior would burden the perceived utility from energy dense, or efficiently used, but expensive fuels with the same cost per mile as other fuels. An example would be Hydrogen.

fuel price equal the whole sale cost, c_f plus markup and taxes t_f (which are negative when representing a subsidy), $p_f = (1 + m_f)c_f + t_f$.

To stimulate demand substitution, many policies include a tax or subsidy; Argentinean and Brazilian governments mandated the retail price of compressed natural gas and ethanol to be kept at a constant fraction of the gasoline price. A drivers fuel search effort depends on the concentration of fuel stations, the frequency of refueling, which is determined by a vehicles action radius and a drivers topping off behavior, and on the flexibility of refueling. Topping off reduces the effective action radius, but provides more freedom to refuel when needed, increasing the flexibility for refueling. A driver's refill effort is determined by the wait time at the pump, which depends on the throughput at the station and the time to fill up. For example, gaseous fuels are much less energy dense in volume, take much longer to refill.

Constrained and informed by fuel availability, fuel prices and their vehicles' characteristics, drivers improve their driving experience, affecting the factors of effort by adjusting their refueling and travel patterns, by choosing how much to drive with their vehicle, but also when, where and, in the case of bi- or flex-fuels, what to refuel. However, as drivers adjust their drive and fuel patterns, selecting stations of their likings, they influence utilization patterns of all stations. Imagine the early years of natural gas vehicles in Argentina. Initially natural gas stations existed only in the region with the largest and most dense population, Buenos Aires. The hypothetical situation of a disproportional large number of natural gas vehicle adopters would result in large utilization of these few stations; as utilization reaches critical levels, wait times would surge. However, demand adjusts as people will modify their trip routes to find the best alternatives, others decide to refill with gasoline or use another mode of transportation. Such demand adjustments are fast relative to the supply adjustments that include the number filling stations, throughput capacity and fuel prices. Thus, fuel

station utilization η_{if}^* depends on equilibrium demand for refills, r_{if}^* and fuel station capacity for refills k_{if}^s :

$$\eta_{if}^* = f\left(r_{if}^*/k_{if}^s\right) \quad (12)$$

Where the total demand for fuel refills multiplies the trip fulfillment fraction with the share of refills going to a region and the normal miles, divided by the tank capacity and fuel efficiency:

$$r_{if}^* = \varphi_{hif}^* \sigma_{hif}^* m_{hl} / \gamma_{hif}^f k_{hif}^t \quad (13)$$

A unique equilibrium demand that results from the adjustment behavior is found by solving for these equilibrium conditions: trip fulfillment and shares are a function of utility, which depends on the slow adjusting factors (such as fuel stations), and on the wait time, which determines equation 12 (see appendix). In one extreme case, when filling stations and refill capacity is abundant, search and wait times are low and the utilization in each area depends solely on fuel prices, but for high wait times demand gets redistributed, and trip fulfillment is reduced. Drivers in New Zealand and Argentina experienced wait times up until an hour in the early years.

Fuel retailer behavior

Such policies also impact profits for fuel station operators. Their profits equal to the throughput v_{if} times the wholesale fuel cost and their markup (plus a fixed term for ancillary sales), minus fixed cost (capital and capacity specific operating cost):

$$\pi_{if} = m_{if} c_{if}^w v_{if} - C_{if}^{sp} \quad (14)$$

The throughput multiplies the pump utilization η_{if} , the number of pumps n_{if}^n , the effective pump operation fraction during a refill o_{if} , the fraction of total time a station is in operation and the physical dispensing capacity of pumps k_{if}^p .

Fuel stations The fixed cost in Equation (14) are equal to the fixed cost when stations have the number of reference pumps n_{ref}^p :

$$C_{if}^{sp} = f\left(n_{if}^p/n_{ref}^p\right)C_{if}^s; \quad f(1) = 1; f'(\cdot) \geq 0; f'' \leq 0 \quad (15)$$

Further, fuel station attributes (normal fixed cost C_{if}^s and pump dispensing rate k_{if}^p) are subject to learning. In New Zealand many early problems existed: the effective dispensing rate was low due to leakages; ***; further, improvement was slow due to lack of initial experience, as well as lack of scale economies; while in Argentina, for the fueling infrastructure the knowledge was large. As learning allows for improvement of the dispensing rate, effective utilization is increased, wait times reduced. We use similar learning structure as for the vehicle attributes (see Equation (8)). Fuel station attribute knowledge improves with cumulative pump installations (aggregated by fuel over all regions).

Fuel stations enter at increasing rate when expected profits exceed required profits more. However, entrance time into the market place may take several years (permits, finding sites, construction). Shutting down a fuel station is costly, for example sites need to be cleaned up, but as profits remain low stations are closed at increasing rate. In similar fashion, stations tend to increase (reduce) the number of pumps per station n_{if}^n , when making profits (losses) and wait times are above (below) desired wait times.¹³ Obviously, for alternative fuels that enter the transportation sector market incentives are not likely to be sufficient for entrance to occur. Recognizing this, governments

¹³ Several other relevant constraints are involved here. Finding strategic sites is difficult. Especially for new, unfamiliar fuels obtaining permits is a challenge (such as gaseous fuels in a fuel based transportation system). Similarly expanding a fuel station is difficult, thus much must come from conversions of existing gasoline sites. Other challenges are dimensioning the stations, such that at high utilization, the inventories are sufficient. In a detailed model these constraints have been taken into account. Here an acknowledgement of such constraints suffices as a fortiori argument.

stepped in on this side in each case: in Argentina provided markups to fuel stations, while New Zealand offered **, and ***. Further, the CCC*** permits. Brazil mandated Petrobras, then a monopolist fuel distributor and retailer, to equip each city above 1500 persons with at least one fueling station, to purchase the ethanol and make it available to the consumer.

The cross-market network externality that describes the interdependency fuel demand and fueling infrastructure development is captured in equations (1) to (4) and (11) to (15), and produces on its own important dynamics, to great extent because of the spatial characteristics (Struben 2006; working paper). First, while a high demand equilibrium exists, the analysis of mono-fuel vehicles reveals that the system tends to be drawn to a bi-stable, low demand equilibrium with urban adoption clusters. New fueling stations crop up in urban areas, but few appear in the less-densely-populated areas, even with a decade-long subsidy. Because urban residents must pass through those rural areas to reach, say, Las Vegas or the Sierras, those that buy an AF vehicle will do that as their second car as their only car. Thus, adoption in urban areas is also hindered. Such clustering and stagnation behavior corresponds with empirical observations of AFVs that are introduced in the market. For example, in Italy, with a CNG penetration of 1% in 2005, 65% of the CNG vehicles and 50% of the CNG fuel stations are concentrated in 3 of the 20 regions (Emilio-Romagna, Veneto, and Marche), together accounting for about one-sixth of the population and area (Di Pascoli et al. 2001). Similar dynamics hold for bi-fuels: in Argentina, 55% of the adopters live in Buenos Aires and 85% in the biggest metropolises. Similarly, in the beginning of the 20th century, EVs remained clustered in urban areas, with virtual absence of recharging locations outside urban areas (Schiffer et al. 1994). Many attempts to introduce AFVs collapsed after government support, subsidies, or tax credits were abandoned, for example with bi-fuel CNG/gasoline in Canada and New Zealand (Flynn 2002). While islands of limited diffusion might be sustained in the cities, as can be seen in Argentina, broad adoption of AFVs can easily flounder even if their performance equals

that of ICE. The acknowledgement of different relative “tipping points” for rural and urban markets and their interdependency illustrates a behavior that is far more complex than the basic chicken-egg dynamics suggests, or than can be inferred from standard economic analysis of complementarities. Modeling the behavioral decision making and the spatial aspects dynamically is essential for revealing, and potentially overcoming, such patterns. Further, the interaction of fuel demand with some of the critical vehicle parameters, such as fuel efficiency and tank capacity is paramount. This suggests that early challenges are even larger when experience with the technologies is limited, as was discussed in the section discussing the influences of automotive factors.

Uncertainty about refueling elicits another consumer behavior—topping off. Worried about finding fuel, drivers may fill up their tank when it is only half empty. As this halves the effective range of the vehicle, a driver would trade this off with the number of trips to the fueling station. However, acting in this way in cohort with others people, wait times increase, giving the perception of a fuel shortage even when there isn’t one. Further, demand would turn to the regions where supply is more available – urban areas; this results in less volume, and more fuel station exits in remote areas. Thus, the existence of such seemingly rational behavior tend enacts a self-fulfilling prophecy regarding drivers’ uncertainty about fuel availability that contributes to the persistence of such asymmetries between urban and rural stations, and increase the threshold for large penetration (Struben 2007). Bi-fuels and in particular flex fuels, while decreasing the risk of getting out of fuel create more of such problems.

Fuel Production and Distribution

Fuel supply chain factors are tightly interconnected with the transportation system. Brazil ethanol producers went through significant learning curves (Goldemberg 1996). Similarly, jobs created in

complementary sectors act to lower fixed cost, or increase support and incentives to keep prices low, as was the case in Argentina. In the model we decompose wholesale fuel cost into primary fuel market price c_f^p and production and distribution cost c_{lf}^d :

$$c_{lf}^w = c_{lf}^d + c_f^p \quad (16)$$

Learning for fuel production and distribution, c_{lf}^d are captured according to the structure of equation (8): fuel production and distribution improves with cumulative fuel throughput (aggregated by fuel over all regions). At the same time, primary fuel price fluctuations have had significant impact on the end-user prices and on how the alternative fuel competition played out, as was the case in New Zealand. Primary feedstock prices depend typically on a myriad of factors, including market dynamics related to scarcity and policies that relate to institutional factors. For example, shocks in the sugar price market the 1990s resulted in a rise of the price of sugarcane, also in Brazil. In response farmers substituted were possible from growing other stocks such as coffee into sugarcane; however, this occurred only gradually and with limited capacity, and the price of sugarcane remained peaking for months; eventually ethanol had to be imported for a while from cheaper, but non-local sources.

Analysis

We have described a set of mechanisms that condition AFV transitions. The main structure in each constituted various forms of increasing returns to scale economies, either within market side (such as automotive learning or scope economies) or cross market side (fueling infrastructure and consumer adoption). The resulting dynamics associated with each are however more complex than basic increasing returns due to a mixture of operational factors such as counterforces. (e.g. knowledge spillovers, competition for social exposure), significant time delays (e.g. in vehicle

replacement, perception updates), heterogeneity and asymmetries (e.g. fuel demand vs supply), and local decision making. Then, what dynamics can we expect from the integrated system, as conceptualized in Figure 2? We begin the analysis with a characterization of the diffusion dynamics for some generic AFV. We simulate an introduction of a hypothetical AFV superior potential performance and fuel economy (each 1.5 times superior to that of the incumbent) but otherwise the potential of each attribute (tank capacity, fuel price) is equivalent to that of the fully penetrated and mature incumbent. We focus on the fundamental dynamics of this system and use typical automotive parameters – for example, consumers replace their vehicles every 10 years.¹⁴ Initial vehicle and fuel production experience with the simulated AFV is moderate (25% compared to a mature technology). Thus, early AFVs are more expensive and perform below their long-run potential; further, consumer consideration has yet to grow. The AFVs are propelled by a fuel that is incompatible with gasoline. Figure 3 tracks simulated diffusion dynamics under moderate, strong, and extreme set of policies with 15 year commitment from OEMS, fuel providers, and government, together acting on all components of the system (see table 2 for the strength of specific policies, which will be discussed in more detail below). We observe from Figure 3 that the positive feedbacks conditioning drivers' adoption of alternative vehicles generate system dynamics characterized by multiple equilibria. The system is attracted to a high equilibrium with high WtC, widespread fueling infrastructure and significant adoption of alternative vehicles and large fuel consumption, or stagnation with low. These fixed points are separated by a threshold, or tipping boundary. The alternative fuel system must exceed a threshold to become self-sustaining. More subtly, during this period, one clear tipping point: some components of the system may improve, while others do not (see for example the strong case). Underlying is the existence of multiple mechanisms that co-

¹⁴ All parameters, technology, technology progress, economic and behavioral are provided in the online appendix; see Struben (2006) and Struben and Sterman (2007) for sensitivity analyses

evolve, but do not have to be in synch. Finally, the difference between the strong and extreme case show that rather the system can stabilize at various low equilibria involving urban adoption clusters, but with limited usage (Struben 2006).

We now examine the conditions for achieving self sustaining market formation. Effective policies act to overcome the barriers imposed by mechanisms. Depending on the alternative technology, such policies focus on infrastructure rollout, establishing an initial vehicle fleet, marketing programs, upfront R&D in the vehicle technology or fuel production and distribution process, and on various forms of taxes and subsidies throughout the fuel and vehicle supply chain. For example, strong marketing helps bringing the system towards the basin boundary. Early on, the impact of direct word of mouth will be limited when AFVs are introduced, due too long vehicle lives that cause the share of alternatives in the fleet to lag significantly behind their share of new vehicle sales, and to the durability of people's emotional attachments to their current vehicle. Likewise, reinvestment in R&D and learning from experimentation during production will be slow early on because of the limited new vehicles sales. In this case we see that under the extreme policy measures takeoff is relatively rapid. Diffusion is mainly constrained by the replacement rate of vehicles. Table 2 shows the policies and upfront activities for the moderate, strong and extreme condition policies corresponding with the simulations in Figure 3. Automotive producers and fuel providers have committed to significant upfront R&D and process organization that helps improve the effective starting knowledge for vehicles fuels (yielding a performance equivalent to 50% of the mature knowledge); retailers receive a significant markup, providing them incentives to enter the business, even when utilization is low; fuel distributors commit to opening fuel stations (5% of incumbents fuel stations), distributed across urban and rural stations equivalent to the incumbent; stations have been mandated to stay in business for 15 years; to stimulate consumer exposure, an aggressive marketing program is put in place (marketing effectiveness=0.05). Parties stay committed for 15 years.

Effectiveness of a policy is not likely to be independent from the presence of others and the current state of the system. For example, investing in consumer awareness is not likely to generate much demand when fueling infrastructure is virtually absent; few consumers find vehicles sufficiently attractive compared to their current vehicle type of choice yielding very little adoption and further exposure. More formally, policies are highly complementary. Implications of this complementarity is the sensitivity To illustrate, the bar graphs in table 2 show the sensitivity of the equilibrium entrant installed base share to a univariate modification of one policy measure. The open dots shows the effect of eliminating a policy, leaving the others at the strong level while the grey dots show the result of individual policies being moved to its maximum value, with the other policies remaining at their moderate level. We observe that downward sensitivity of the equilibrium is strong, while upward is limited. We can also relate these two scenarios to the definitions of the technology diffusion at time zero: the moderate scenario is in an inert state, while the high policy scenario is in a fragile state. Further, while the policies may not be eliminated after 10 years, after 15 years the active policies have brought the system into one of robust growth.

The existence and location of the tipping point and the size of the basin of attraction of the low diffusion equilibrium depend on technology, starting condition of the incumbent technology and its institutional context. Thus, these factors, with the employed policies determine the time and efforts required to bring the system past the fragile state depend. For example, ICE/electric hybrid vehicles do not require an alternative fueling infrastructure; further, much of the production techniques are relatively known – either from the gasoline vehicle, or from other applications in electric systems applications. Thus for this technology relatively little experience will already produce a reasonable performing and cost competitive technology that may be attractive to a sufficient customer base to have its market share allow for sufficient revenues and reinvestment for the vehicle to climb further

in market share. That is, the basin of attraction of the low diffusion equilibrium is relatively small. In contrast, HFCVs require the buildup of entire new fuel infrastructure, and significant modifications in the fuel production and distribution supply chain and involve wholesale redesign of the vehicle and maintenance capabilities. Plug-in hybrids can partially rely on a fueling infrastructure at the home, but require much exposure and learning; further, many spillovers will exist with more traditional plug-in and mono-fuel vehicles. Vehicles that run on biofuels such as E85 ethanol involve moderate adjustment to the vehicles, but require a large scale adjustment to the fuel supply chain. Analysis of historical cases further inform our understanding. However, little data exists of failed attempts. Here we study three cases of alternative fuel and vehicle introductions in Argentina, New Zealand and Brazil.

As discussed above, in each of the cases the subsidies have been in place for a long time (Table 1). Organizing the analysis around the mechanisms and simulating of the cases is helpful to propose and explore internally consistent hypotheses for critical behind important factors that conditioned the observed regularities. A detailed calibration goes beyond the purpose of this work. Further, many of the institutional factors and their coevolution with the transport sectors that played a role in the different countries (R5,B5 in Figure 2) are not captured. However, using representative parameters the model is already able to generate the many patterns of behavior for the historical data of the various cases. The case specific parameters, such as demographics and those that represent the competing vehicle platform type, and the policy parameters are listed in the online companion. We briefly discuss and compare the introduction of CNG in Argentina and New Zealand, after which we will focus on ethanol in Brazil.

Figure 4 shows the data for vehicle adoption, fueling infrastructure and fuel consumption in Argentina and New Zealand. The government of New Zealand, an economically advanced country,

with strong mentality for independency, desired to seek independence from foreign oil by 2000 (Sperling 1988). Commitment from all parties was strong. CNG vehicles offered a clear economic advantage – with an estimated payback period for an average driver of 2 years. From the start we can observe a rapid climb of the CNG conversions, achieving conversions at a rate of 50% of new vehicles sold in 8 years and a 5% installed base. The NGVs in New Zealand, as was the case in the first two decades in Argentina, came about through conversions of existing gasoline vehicles. Compared to situations where alternative fuel vehicles can only diffuse through new vehicle purchases, in this process a driver can make a replacement for a much lower investment (the order of ten times less) and without having to search for a new vehicle. Thus, the theoretical upperbound for the installed base growth rate for such conversion technologies is much higher than cases where alternative fuel vehicles. As the installed base can grow faster, so can consumer exposure and production experience, having great implications for the effort required to pass any low basin of attraction (Struben and Sterman 2007 discuss the role of the vehicle life on tipping dynamics). Then, given the economic advantages of CNG, the growth rate can be considered modest from a narrow consumer adoption perspective. First, the large market share is a poor indicator of what is going on – the cumulative sales of and experience with vehicles, total vehicles on the road and their drive experience and exposure, and fuel production and distribution consumption and experience were all still very limited 8 years after the introduction. While conversion capacity grew easily, quality conversion was not straightforward. Absent large a scale automotive experience and the novelty of natural gas, the fast growth implied significantly constraint the capabilities of all the involved production and distribution capabilities. Further, the rapid adoption rate by those for whom the economic advantage was greatest, did not imply that sustained and large scale consumer acceptance is not guaranteed. Effectiveness of the marketing program had been limited – a large fraction of the population had not been reached. Several incidents during that period resulted in questioning the safety of CNG infrastructure and driving. Thus, at that time many of the technical challenges had

remained unresolved and CNG had remained considered a second grade fuel throughout. In particular fuel stations, while present in the main urban areas, provided limited coverage in the more remote regions. More important than the growth rate, despite the fact that CNG had gained a 10% market share in fuel transportation consumption in 1986, when the program of incentives and awareness building seized conversion rates collapsed rapidly. Despite the fact that driving on CNG was economically favorable compared to gasoline, on several other aspects the system had not achieved the necessary maturity to be able to withstand a privatization and a subsequent fall of the gasoline prices a decade after its introduction: while the stock of converted vehicles would remain high for significant time, drivers of the bi-fuel vehicles swiftly turned to refueling of gasoline; utilization and profitability of the gas stations that carry natural gas reduced. Many natural gas filling stations, marginally profitable during the foregoing period, were converted back to gasoline stations. As this occurred, even fewer people went through the hassle to convert their vehicle, setting in motion the downward spiral of natural gas in New Zealand. In New Zealand, while most policy makers and industry stakeholders were excited about the S-shaped diffusion trajectory of natural vehicles, they had underestimated the market complexity, and with it the fact that natural gas in transportation had never escaped the fragile state.

In Argentina the growth of the NGV market share was much slower: limited marketing efforts were in place early on as the hope was that natural gas would replace the bus fleets in the urban centers. While the government offered limited financial incentives, with exception to the fuel, much effort was done to achieve conversion quality. Economic favorability of conversion was guaranteed as natural gas fuel price were guaranteed below to remain 40% below that of gasoline; favorability was further helped by the abundant experience and exposure with natural gas technologies: there was a natural gas at the home culture. Further, the distribution took place over an extensive network reaching most of the cities. Technological challenges such as with fuel compression and dispensing

at the station sites could relatively easily be overcome. Further, with the large scale of the market and concentration of the population in some areas, the quality of service and fuel availability could improve effectively. In the late 1990s as the scale increased conversion shops had generated many jobs. As the standardization and experience grew OEMS became actively involved and started to offer pre-market natural gas vehicles, producing them locally and relying local inputs from within the emergent conversion industry. Argentina now also exports much of its fuel station compression technology. In 1994 stations were state owned by "gas del estado" and their numbers could be controlled and increased; during the subsequent privatizations franchised fuel stations received a guaranteed gross margin that was 3 to 5 times larger than for gasoline, but many stations went out of business. Yet, many unprofitable fuel stations were closed and the following years turned out to be nearly devastating for natural gas in transportation. But demand remained growing, eventually also inducing further expansion of the fueling infrastructure. Argentina was endowed with several institutional and natural resources, and had enacted policies that created significant advantages for natural gas in transportation compared to New Zealand. A slow diffusion path, experience in related industries, economic need and willingness to accept inconveniences by the consumers allowed the building of confidence that CNG could offer sustained economic advantages over gasoline. As acceptance and experience grew, gradually the Argentinean natural gas transport sector amalgamated into the established natural gas and automotive industry sectors, which established further legitimation for commitment from various parties and developmental support. While it is yet to be decided whether Argentina's natural gas vehicle market is fragile or robust, several economic crises have been overcome. We now turn to Brazil.

Brazil has currently achieved an energy balance absent of oil imports, an often cited success story and example. This transition been possible, in part due to foreign oil being substituted by internally produced petroleum after discovery of major oil fields. However, the largest share of current fuel

consumption (40%) derives from internally produced ethanol. How did Brazil achieve this large number? Figure 5 shows some main data related ethanol use in transportation: the ethanol vehicle (EthV) sales and in use share, ethanol production, and an estimate of the fraction of fuel stations with ethanol pumps. While no detailed data on ethanol fueling infrastructure was available, every village larger than 1500 people was obliged to provide fuel. The large share of ethanol in transportation has three contributors: the share of ethanol in gasoline has improved from 5% in the 1970s to 20-24% in 2005. Further, a significant share of vehicles runs on pure ethanol (nearly 4 million, or 15% of the LDVs), accounting for about 40% of the total ethanol consumption. Finally, flex fuel vehicles became available around 2001, achieving a sales share of over 60% in 2005. Currently, a small but steeply growing number of flex-fuel vehicles (~ 5%) can rely upon both gasohol and the ethanol. The forces that have been at work to achieve these large sociotechnical shift have been enormous and in place for a long time. In order to decrease Brazil's dependency on foreign oil, the government had established the PROALCOOL program in the 1970s (explain government and program). Early focus had been on helping the ailing agricultural sector. During the late 70s, with their early successful steps into alcohol, the government increased its commitment to increase the use of alternative fuels – declaring an “economy war” (Sperling 1988). With plenty capacity in the local agriculture industry, the government targeted to produce and use about 20% of expected gasoline demand through bio-mass based fuel, with a particular focus on increasing the alcohol share in gasoline. Fuel distribution could make use of the same infrastructure; this was not the case for vehicles: while an ethanol fuel mix of until 10% requires only minor vehicle adjustments, a larger ethanol share, such as 20-24% requires significant adjustments. The research that occurred in the 1970s in combination that built on the earlier long history with ethanol (dating back to the early 20th century) allowed new vehicles to be ready for this market. By 1980 the government had achieved its goals.

While this initiative was considered a success, at the root of the necessary conversions lies however what suggests being on itself a far greater success: the rate of diffusion of ethanol vehicles after its launch in the early 1980s is unprecedented. The shift to pure ethanol was not part of the early program plans, but pressured by the high oil prices and an Iran-Iraq war that furthered the long-term uncertainty about foreign oil supply, causing the government to shift its focus to neat alcohol vehicles. In this case major modifications to the vehicles were required (**). To the domestic automobile industry production of AFVs offered potential opportunities for export, but risks were very high. They were willing to get involved though for several reasons: first, one technology (fuel) had been selected that would serve to replace gasoline. second, already in 60s research on pure ethanol vehicles had started and with the increased experience in gasohol vehicles, automobile companies committed to have a large number of models available in 1979; further, the government had shown its commitment to alcohol in the 1970s, providing confidence it was serious about making fuel available at a large scale; the government also made fuel widespread available, forcing the monopolist energy provider, Petrobras, to provide the fuel at stations in each village larger than 1500 people; to stimulate production and distribution of the fuel itself, Petrobras had to guarantee the majority of ethanol purchase from the producers. Besides guaranteed sales, the producers were also guaranteed a price, which would reduce gradually over the years. Consumers had not been forgotten either. Massive campaigns that played in on the patriotic feeling of the consumer, and supported by large exposure programs, in combination with large tax breaks, were well received, especially during the economic downturn. Further, with the experience of the recent success of alcohol in transportation consumers were easily interested to consider these alternatives. The centralized organization had made several significant steps towards overcoming several chicken and

egg problems and paved the way for contracts with the final component, the automobile industry that were to develop these vehicles.¹⁵

The model, though a stylized representation of the dominant mechanisms, generates a similar adoption pattern, when introducing an extensive marketing program, the widespread availability of ethanol fueling stations, a significant vehicle portfolio generate the speedy adoption correspond with the policies in place and result in a similar adoption (see the appendix for details). Deviations between the data and the simulation lay in various factors not critical for the purpose of this discussion. For example, the extreme spikes in ethanol market share in the real data correspond with the economic collapse, and the reduction in the absolute number of vehicles. Further, a large share of the early sales involved taxis for which incentives were provided that significantly reduced the purchase and operation cost of ethanol vehicles to half of gasoline (Sperling 1988); the total number of “taxi drivers” increased enormously during the first years. The collapse of the ethanol program in the early 90s came with two shocks. First, the world sugar price skyrocketed, resulting in producers substituting from ethanol to sugar production, which increased ethanol price and uncertainty by consumers and automakers about sustained fuel availability at affordable price; eventually ethanol had to be imported. This coincided with the realization by the newly democratically elected government that abolished many of the incentives, convinced that the subsidies were unsustainable.

The rapid revival of ethanol vehicle sales, through flex-fuel vehicles, may seem a surprise, in particular because this was stimulated with limited incentives. Flex-fuel vehicles differentiate

¹⁵ Refuting alternative explanations: product succession of neat-ethanol vehicles by flex-fuels (while neat vehicles were critical for flex-fuels, their sales collapsed more than a decade before the conception of flex-fuels), inferiority of products, chasms (early sales included many types of consumers, including the mass-market).

themselves from pure ethanol or gasoline vehicles as they provide flexibility of fuel choices under constraints in fuel availability or fuel price fluctuations. However, this advantage is only useful when the performance is sufficient and the choice option is useful. Their success can be explained by the working of the mechanisms that produced an important inheritance from the pure ethanol failure: experience with the use and production of ethanol and their vehicles, existing demand, and fueling infrastructure together have enabled the rise of flexfuel vehicles. For example, production cost of ethanol was reduced through a significant learning curve (Figure 5c). Experience is built also through the large ethanol content in gasohol, but the largest share derives from ethanol vehicles (Figure 5d), as the rise and fall of ethanol vehicles resulted in an installed base still being around 3 Million vehicles. This not only sustained production of the fuel, but also of vehicle R&D, production techniques and consumer exposure. Further, the installed base and its demand for fuel enabled the ethanol fuel network to remain in place (Figure 5b).

Counterfactual analysis for flex-fuels generate some different pictures (Figure 5d), suggesting that flex-fuel rely heavily on the rise and fall of neat ethanol vehicles. Shown are (top) the simulation in Figure 5b), extended towards 2030, with fueling infrastructure, fuel production experience and consumer acceptance to represent the original simulated case. Fuel demand declines with the depletion of the stock of ethanol vehicles, fueling infrastructure becomes initially more sparse over time, but as the flex-fuel vehicles flood the market, their increased fuel demand more than compensates this, and fueling infrastructure recovers. The other two simulations show counterfactual runs assuming ii) reduced fuel production experience and i) reduced fueling infrastructure. In both cases, while ethanol vehicles still take off, as familiarity and vehicle performance are high, ethanol fuel consumption is significantly suppressed in both cases: drivers of flex fuel vehicles increasingly convert to gasoline, which results in a further decline of the ethanol fueling infrastructure, increasing the attractiveness of gasoline even further.

These results illustrate how strongly the alternative builds upon the previous experience and earlier diffused network. While experience with ethanol in transportation in Brazil dates back at least 75 years, an analysis that goes back 30 years suggests that current penetration and fuel consumption levels are deeply rooted in the institutional arrangements, in the historical context and the system level interactions. Thirty years of strong commitment was necessary to achieve 40% displacement and a potentially self-sustaining market for ethanol. Policies have been in place that aligned infrastructure, technology performance, vehicle availability, and consumer interest. Even after a period of seemingly smooth take-off, elimination of some important policies and price shocks resulted in program failure. Unintentionally this failure provided the institutions, technology experiences, fueling infrastructure, production networks, acceptance that set the stage for the emergence of a flexfuel market. Expanding the boundary further opens more questions on the long-term robustness of the current flex-fuel path. Some effects act to push the system further towards robustness. For example, an increase of fuel export opportunities (especially US and Japan), raises experience, and creates employment. Other factors act to push the system towards fragility. For example, land constraints in the agricultural sector have already resulted in substitution away from other resources (coffee), of which the growing activities have moved upward towards the Amazon. Thus, a growth in the ethanol production scale results in ecological degradation, with potential backlash.

Discussion of fuel transition challenges

Diffusion trajectories of AFVs are determined only to limited extent by their intrinsic technological characteristics. The competition takes place not at the technology level but at the level of the system. Many actors and mechanisms play a role in this system. For such complex technologies – the

dynamics are determined by a set of endogenous factors that change over time. This framework reveals system level thresholds and substantially longer times required for AFV markets to become self-sustaining than decision makers expect and allow for with introduction programs. Argentina also illustrates the long duration that such systems are found in a fragile state: it took 15 years to reach an 8% installed base, even though vehicles. Diesels failed in the US and took 20 years to achieve a 25% share in Europe (Schipper 2002). The existence of challenges – the role of infrastructure, consumer and investor acceptance and uncertainty, and technology learning are well known (e.g. Sperling 1988). However, to understand the diffusion dynamics entails a focus on the mechanisms, historical context and institutions. The first one implies the highly path dependence, the second two argue for carefulness in transferability of outcome. Implications are significant: successful formation of markets for AFVs requires strategies and policies that are based upon an understanding of the collective dynamics, coordination, commitment and flexible policies, and the role of the time delays.

Further during the early stages success is conditioned the institutional developments as well, by the character of the alternatives, and historical preconditions, including competition with other vehicles. Different AFVs provide different challenges. Such a situation was the case with the transition towards the horseless carriage, with EVs having the burden of a slow developing support infrastructure, and steamers experiencing a liability of public acceptance from earlier times. This allowed ICE vehicles to gain market share, build experience and innovate more, and keep learning from its slower developing competitors. Similarly, in the modern transition, HFCVs will be subject to strong learning curves and the various hybrid technologies might be well positioned. Platforms also vary widely in their compatibility of the technologies and attributes, such as is the case for hybrid electric vehicles or hydrogen fuel cell vehicles. For example, mono-fuels, such as neat ethanol are incompatible with the current fueling infrastructure and are fully dependent on sufficient

availability of the alternative fuel. The dual fuel NGVs vehicles in New Zealand and Argentina comprised predominantly of converted petrol vehicles and thus did not require replacement of retired of a market vehicle, which is the case for original equipment manufacturer developed AFVs and which strongly reduces the theoretical replacement rate. Finally competitive dynamics between AFVs are highly dependent on what platforms are in the market, which determines the variety in infrastructure compatibility, technological similarity and spillover potential. Thus, different AFVs, different histories and different institutional settings suggest different likelihood for success and require a different blend of policies. We close with a discussion on the implication for diffusion theory.

Conclusion

Technological change has an enormous impact on economic and societal development. From an economic lens the aggregate of technological change may be viewed as a Schumpeterian process of creative destruction and the resulting winners can be seen to follow the S-shaped diffusion patterns. Within this realm of thinking understanding under what condition certain technologies may diffuse is not a central question if one assumes that the aggregate of progress exhibits constant returns to scale (Romer 1986; Aghion and Howitt 1992). However this question becomes central for inquiries of sociotechnical systems change, observing that sociotechnical systems are frequently locked into inferior systems (Arthur 1989). For example, Energy Technology Innovations (ETIs) are sought to address three great challenges: energy independency to avoid economic (and social) disruption, modern energy services, providing energy for mankind, without entraining disruption of global climate (Gallagher et al. 2006). History illustrates the difficulty of establishing large scale self-sustaining markets for such technologies, whether it concerns AFVs, winds power, nuclear energy or synfuels. With such challenges it is not only critical to understand what alternative technologies may

break through, but also the time scales within which they may provide significant contributions to society.

The S-curve literature has shaped the thinking of strategy- and policymakers and scientists alike. Such a concept while valuable for mobilizing resources that drive innovative efforts (**) also spurs focusing on end-states, technological constraints, and oversimplified pictures of increasing returns. It induces assumptions that once critical economic and technological bottlenecks have been overcome, the forces of the invisible hand will take care of the establishment of a market. For example short term price signals are tools popular among policy and strategy makers, but they do not reflect long term potential, institutions, legitimation (e.g. Sperling 1988, p50 on synfuels in 1973, or nzl).

For complex market technologies however, a successful transition requires an understanding of how the actions of actors together shape a trajectory of a technology with recognition of the physiological characteristics of the system. A working market involves clusters of aligned elements such as complimentary products, infrastructure, maintenance- and supply networks, consumers' behavior, producer experience, and various institutions. Within this system distributed decision makers continuously influence how others update their assumptions about various aspects of the market which influences their future decisions in turn. A limited understanding by the actors how the system evolves as a whole over time does not necessarily negate a successful introduction of a new technology. However, highly reciprocal systems of nested multi-sided markets, policies devised to diffuse a new technology may yield perverse dynamics.

The mechanisms by which complex technologies succeed or fail are ill-understood, and in order to address questions regarding how technological systems may break through it is just as critical to

understand why promising technologies fail. This framework begins with the acknowledgement that such systems exhibit a variety of diffusion patterns. While the Argentinean experience suggests economic and technological viability of NGVs, the New Zealand experience illustrates the fragility of an AFV system in the early stages. This study has attempted to provide a framework for studying how the process by which alternative technology systems such as EITs, and in general for complex market technologies. While simple market technologies, such as walkmans, are fragile only for a short period after introduction, complex market technologies are fragile, and sensitive to path dependency for a much longer period.

A series of subtle behavioral feedbacks in which actors attempt to improve their situation may have long run implications. In the case of AFV transitions, endogenous topping-off is such an example exhibiting perverse dynamics. Further, the physiological aspects of the system of study must be clearly understood. For example, even attractive vehicles take a long time to penetrate; change of perceptions regarding complex and emotional technologies such as vehicles require alternatives to multiple and repeated exposures before individuals become to consider them as a serious alternative, technology improvement require investments, infrastructure buildup. The prevalence of such long delays, throughout the system fundamentally alter the prospect for the self-sustaining market to emerge. Technologies are increasingly dependent on infrastructure and on other platforms (Grübler 1994; Parker and Van Alstyne 2005). Associated with this the potential modes of behavior are much more complex. In such cases, absence of deep understanding of early stage market mechanisms, actions of those who seek to introduce and stimulate adoption of a technology may contribute to its demise (Flink 2002).

The institutions, formal as well as temporal partnerships, are highly important drivers of the early stage dynamics. A thorough understanding of some of the main decision makers involved is critical

for a successful transition. The political process may itself contribute to the failures: in many of the failed alternative energy cases, low levels of stagnation, the desired technologies results in governments entering in technology development business in a major fashion, only to lose interest after a few years, with any infrastructure quickly being dismantled and mothballed without any learning transferred to the next cycle (Vietor 1985; Crow 1985). As Nelson envisions in 1994 when describing the need for models that include the coevolution of technology, industry and supporting institutions: “a society’s institutions – both general and specific to the broad sector that contains the developing industry – will influence the parameters of the model, and perhaps even its broad shape”. Institutions involve policies, existing complementarities, historical practices and cultural influences.

While the inferences that result from the analysis in this paper bear the usual cautions and their generalizations are limited by the number of cases involved, the integration of this with existing bodies of literature provides initial shaping of a theory of diffusion of technology systems. Most of all any such theory should be able to explain multiple modes of behavior of technology adoption. The diffusion of technology is a dynamic process that induces substantial changes within the system it is introduced into, resulting in different patterns of interactions, depending on the context in which this takes place. The coevolution of actions, beliefs and structure can trap the system in a state of low penetration. Ingredients of such a theory should include critical aspects that allow analyzing the broad boundary that may reflect the dynamic of such systems; the explicit presence, decisions and learning of key actors; a focus on the mechanisms that drive the behavior modes; the system physiological characteristics, including the rate at which they may change, the institutional contexts, and most of all the multitude of decision makers.

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Figures and Tables

Alternative Fuel Consumption Shares

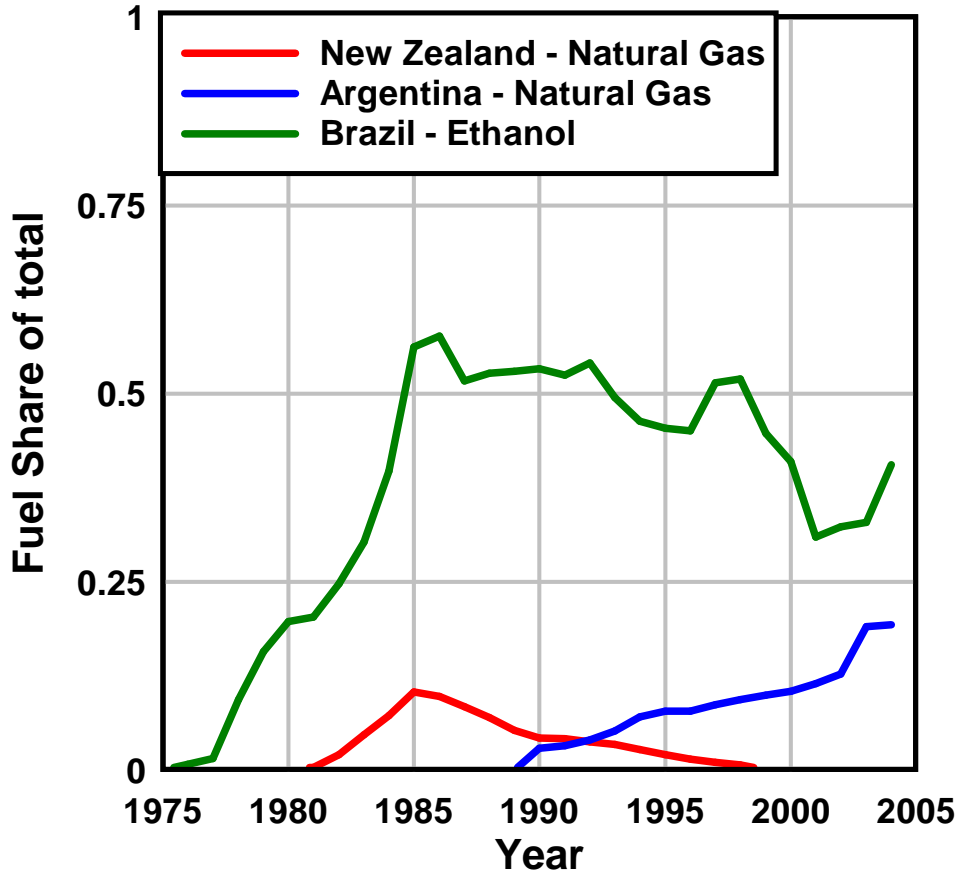


Figure 1 Alternative Fuel Consumption Shares in Transportation

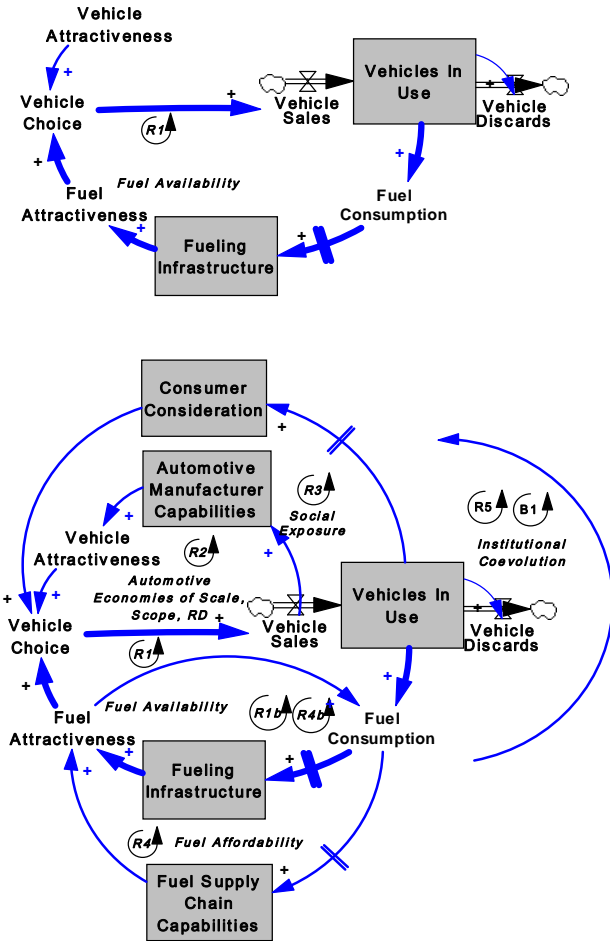


Figure 2. Principal feedback loops driving adoption in alternative fuel vehicle transition model. Top the coevolutionary dynamics between fueling infrastructure and vehicle adoption. Bottom a more complete picture of transition mechanisms

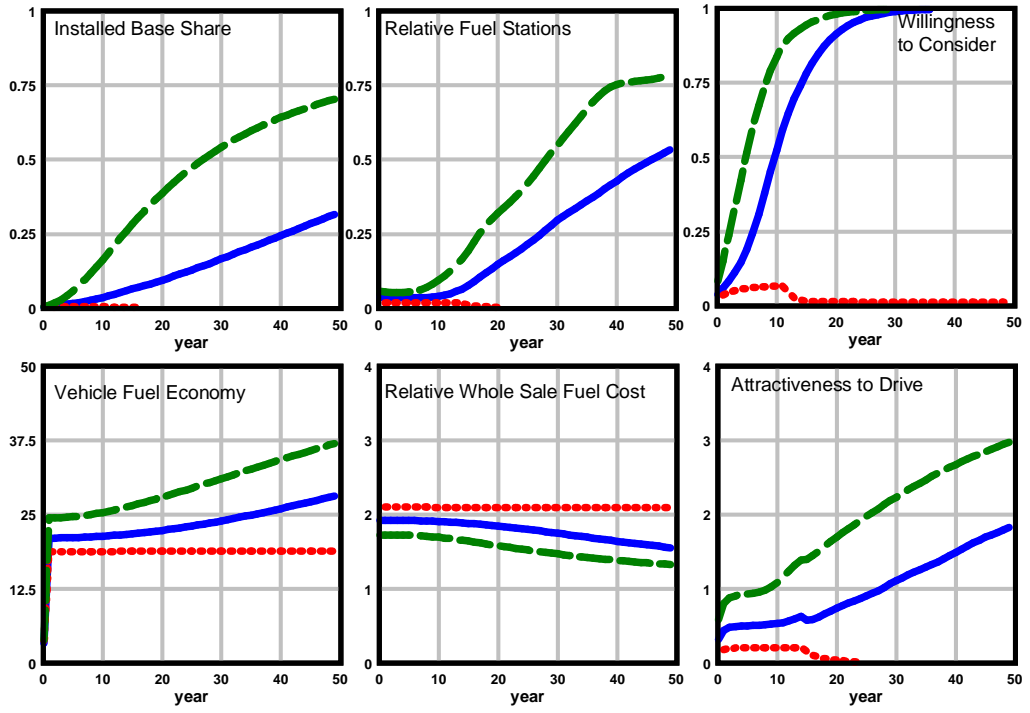


Figure 3. Policies and impact of base case simulations: Moderate (dotted), strong (line), and extreme (dashed) policies

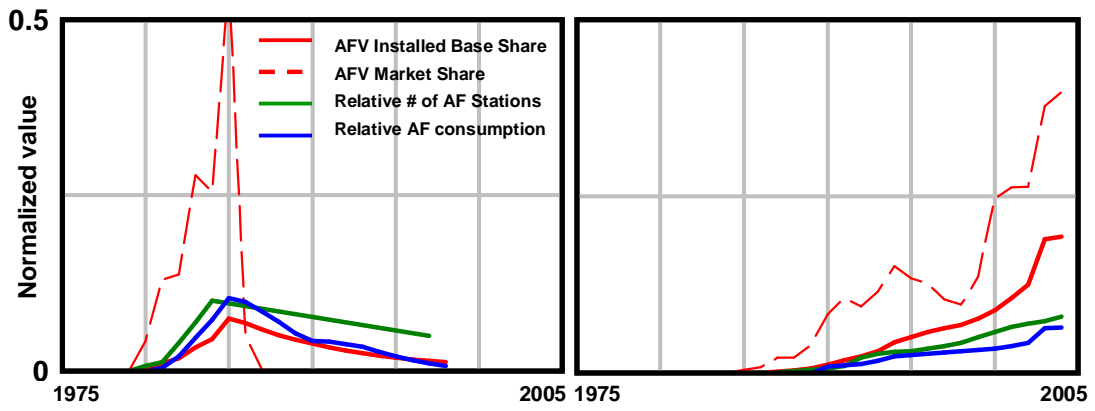


Figure 4. Diffusion patterns of natural gas vehicles in New Zealand (left) and in Argentina (right). Values normalized to incumbent technology.

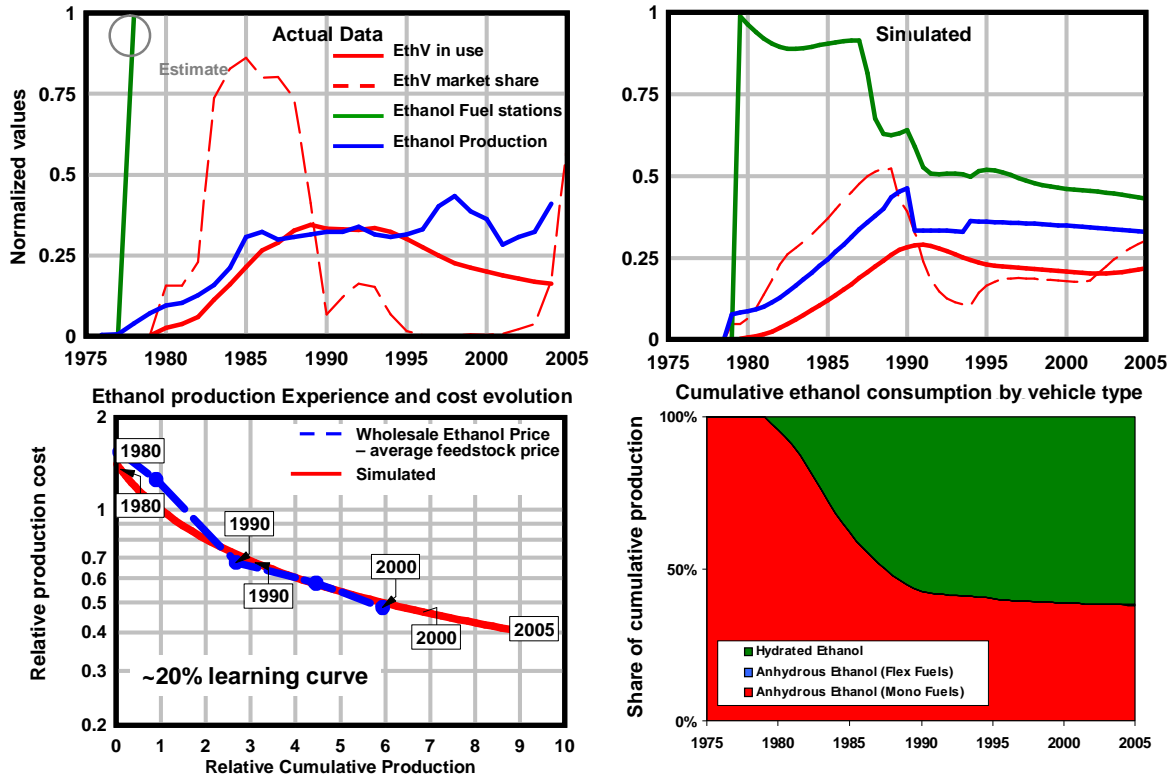


Figure 5. Brazil's experience with ethanol: overview and fuel production

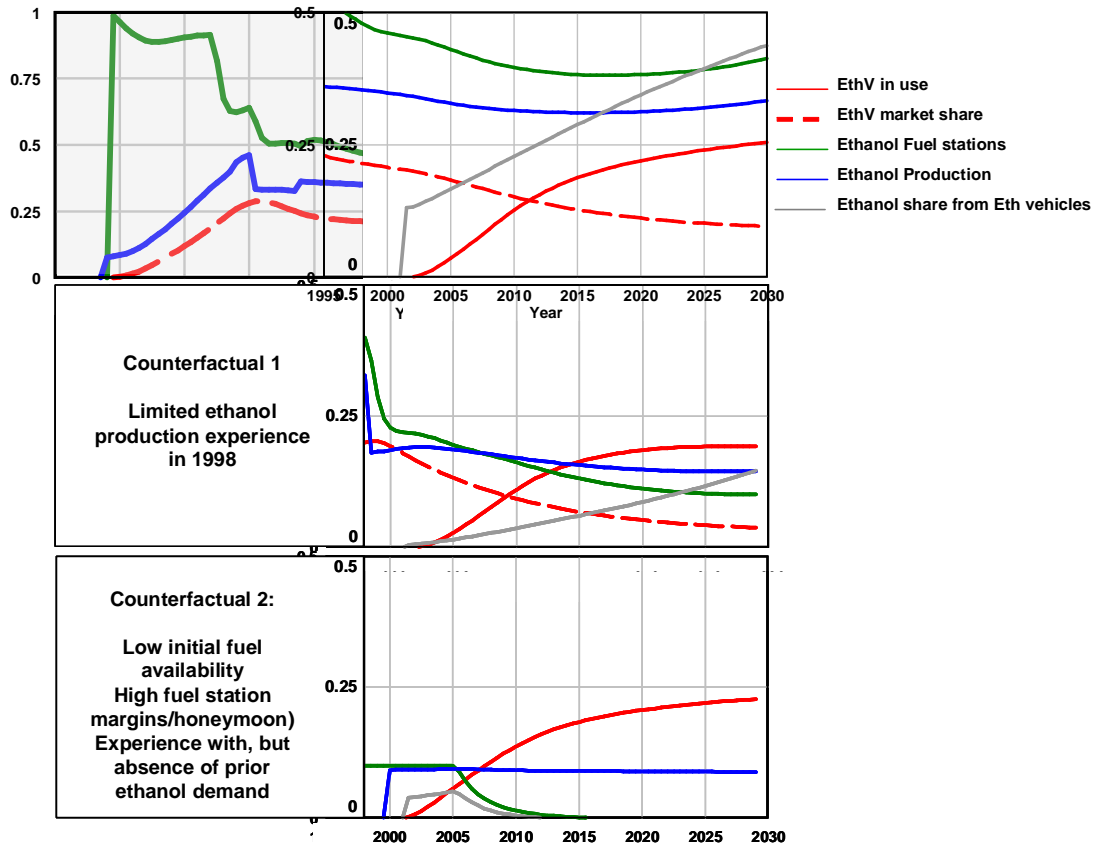


Figure 6. Forward simulation of current situation (top) and of counterfactuals assuming respectively reduced fuel production experience (middle) and reduced fueling infrastructure

Table 1. Alternative Fuel Vehicle introduction programs in New Zealand, Argentina and Brazil

		New Zealand	Argentina	Brazil
Introduction year		1979	1984 "Liquid Fuels Substitution Program"	1976 "PROALCOOL"
Main Motivation		Reduce dependence on foreign oil	Reduce dependence on foreign oil and urban pollution	Reduce dependence on foreign oil
Dominant vehicles at introduction		ICE petroleum and diesel	ICE petroleum and diesel	ICE petroleum
Introduced technology		Conversion of vehicles in the marketplace into bi-fuel CNG	Conversion of vehicles in the marketplace into bi-fuel CNG	Alternative vehicles driving on pure ethanol
Explicit Goals at Introduction		20% vehicles in 1990	1995: 2,000,000 OET/year; 134,000 converted vehicles (mainly from diesel); 270 fuel stations	970 Million Gallons/year in 1979
Enabler		Discovery of 3 natural gas fields in 1960s/1970s	Abundant natural gas resources and natural gas network for residential applications; new gas fields	Overcapacity in large agricultural sector, especially sugar; history with ethanol
Policies to stimulate diffusion	Consumers (economic)	Loans, tax incentives; guaranteed fuel price differential	Guaranteed fuel price differential; Gasoline fuel tax; natural gas subsidies	Tax exemption; guaranteed fuel price differential
	Consumers (acceptance)	Promotion campaigns to consumers	Promotion campaigns to consumers	Promotion campaigns to consumers
	Automotive Industry	Tax incentives for assembly workshops; enable acceptance for standards	Standard development for retrofitted kits	Contracts with automakers to make models available by 1980
	Fuel Retailers	Loans, tax incentives, guaranteed markups	Standard development for fuel station technology	Mandated fuel stations in every city over 1500 inhabitants
	Fuel Producers and Distributors	Guaranteed markups		Guaranteed price and sales for producers

Table 2. Policy values (relative to a max value) for moderate, high and full scenarios in column 3-5 and the resulting installed base (bottom). The bar graph shows how equilibria are affected of moderate (high) scenarios individual policies are adjusted to maximum (eliminated).

Policy	Definition	Med	High	Full	Equilibrium installed base with policy adjustment
		Parameter Value relative to Max			
Vehicle R&D	Initial Knowledge (Relative to incumbent) Max = 0.75	0.32	0.48	0.80	
Vehicle Portfolio	Initial Models (Relative to incumbent) Max=0.15	0.16	0.48	0.80	
Fleet Conversions	(Relative to incumbent) Max=0.08	0.27	0.53	0.80	
Fuel Production R&D	Initial Knowledge (Relative to incumbent) Max=0.75	0.32	0.48	0.80	
Infrastructure Rollout	Launch (Relative to incumbent) Max = 0.08	0.27	0.53	0.80	
Marketing Program	Marketing effectiveness (fraction/year) Max = 0.06	0.32	0.48	0.80	
Policy Duration	Policy Duration (year) Max=20	15	15	15	
Equilibrium Installed base		-	0.37	0.70	