

Massachusetts Institute of Technology
Engineering Systems Division

Working Paper Series

ESD-WP-2006-06

TRANSITION CHALLENGES FOR ALTERNATIVE FUEL
VEHICLE AND TRANSPORTATION SYSTEMS

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February 2006

Transition challenges for alternative fuel vehicle and transportation systems

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Abstract

Automakers are now developing alternatives to internal combustion engines (ICE), including hydrogen fuel cells and ICE-electric hybrids. Adoption dynamics for alternative vehicles are complex due to the enormous size and importance of the auto industry and vehicle fleet. Diffusion of alternative vehicles is both enabled and constrained by powerful positive feedbacks arising from scale and scope economies, R&D, learning by doing, driver experience, word of mouth, and complementary resources such as fueling infrastructure. We describe a dynamic model of the diffusion and competition among alternative fuel vehicles, including the coevolution of the fleet, technology, driver behavior, and complementary resources. Here we focus on the generation of consumer awareness of alternatives through feedback from driving experience, word of mouth and marketing, with a reduced form treatment of network effects and other positive feedbacks (which we treat in other papers). We demonstrate the existence of a critical threshold for sustained adoption of alternative technologies, and show how the threshold depends on economic and behavioral parameters. We show that word of mouth from those not driving an alternative vehicle is important in stimulating diffusion. Nevertheless, marketing and subsidies for alternatives to ICE must remain in place for long periods for diffusion to become self-sustaining. Expanding the model boundary to include endogenous learning, technological spillovers and spatial coevolution of fueling infrastructure adds additional feedbacks that further suppress the diffusion of alternative vehicles.

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At the end of the 19th century, New York, Boston and Philadelphia were among the cities to welcome clean and silent electric automobiles to replace the polluting horse drawn carriage. Users and inventors, including Thomas Edison, enthusiastically discussed the potential of electrics (The Horseless Age 1896), and an electric car set the world speed record of 61mph in 1899 (Flink 1988). Yet sales of automobiles powered by internal combustion engines (ICE) quickly surpassed electrics and became the dominant design. Internal combustion, the auto, and cheap oil transformed the world, economically, culturally, and environmentally. Today, motivated by environmental pressures and rising energy prices, another transition, away from fossil-powered ICE vehicles, is needed.

Uncertainty abounds. Some envision an electric fleet (MacCready 2004), hydrogen fuel cell vehicles (HFCVs) (Lovins and Cramer 2004; Sperling and Ogden 2004), while others call for ICE-electric hybrids (Demirdoven and Deutch 2004), biofuels (Rostrup-Nielsen 2005), compressed natural gas (CNG), or a mixed fleet (see Greene and Plotkin 2001, MacLean and Lave 2003, Romm 2004 for discussion). Dethroning ICE is difficult: multiple attempts to (re)introduce electric vehicles have failed (Hard and Knie 2001), and initially promising programs to introduce natural gas vehicles stagnated in Italy and withered in Canada and New Zealand after initial subsidies ended (Flynn 2002).

A common explanation for the failure of these programs is that the technologies are still immature and their costs too high (e.g. Flynn 2002; Robertson and Beard 2004). Certainly the high cost and low functionality of alternative fuel vehicles (AFVs) compared to ICE limits their market potential today, particularly in the US, where gasoline is priced below the level that would reflect its environmental and other negative externalities. More subtly, the current low functionality and high cost of alternatives, and low gasoline taxes, are endogenous consequences of the dominance of the internal combustion engine and the petroleum industry, transport networks, settlement patterns, technologies, and institutions with which it has coevolved. The success of internal combustion suppresses the emergence of alternatives, maintaining the

dominance of ICE. These feedbacks mean, as we argue here, that sustained adoption would be difficult even if AFV performance equaled that of ICE today.

Successful diffusion of AFVs is difficult and complex for several reasons. The enormous scale of the automobile industry and fleet creates a wide range of powerful positive feedback processes that confer substantial advantage to the incumbent ICE technology. Important feedbacks include vehicle improvements and cost reductions driven by scale economies, R&D, learning by doing and from field experience, all improving vehicle performance, sales, revenue, scale, and experience still further. Word of mouth and marketing stimulate awareness and adoption, boosting revenue and the installed base of new vehicles, generating still more word of mouth and greater marketing expenditure. Complementary resources play a key role. Alternatives, notably hydrogen-powered vehicles, require new infrastructure incompatible with ICE and petroleum. Drivers will not find AFVs attractive without ready access to fuel, parts, and repair services, but energy producers, automakers and governments will not invest in AFV technology and infrastructure without the prospect of a large market—the so-called chicken and egg problem (Farrell et al. 2003, National Academy of Engineering 2004, Ogden 2004, Bentham 2005). These positive feedbacks mean the evolution of new technologies is likely to be strongly path dependent (David 1985; Arthur 1989; Sterman 2000). Additionally, AFV technologies enable radically new designs and materials (Burns et al. 2002). However, many of these innovations provide spillover opportunities to the dominant platform. For example, lightweight materials and drive-by-wire systems developed for AFVs can be used to improve the performance of conventional vehicles, undercutting AFV adoption. Finally, cars serve not only as transportation but as potent sources of personal identity and social status (Urry 2004). Consumer choice is strongly shaped by cultural norms, personal experience and social interactions (Kay 1997, Hard and Knie 2001, Miller 2001).

The Transition Challenge

The transition to the current ICE-dominated system in the early 19th century provides insights into the challenges of creating an alternative transportation system (Figure 1). The first automobiles generated a huge volume of discussion and press attention. Initial public opinion was often hostile, citing high costs, noise, danger, and high speeds. Experimentation was limited to a few “outsiders” and affluent early adopters (Epstein 1928, Smith 1968, McShane 1994). Although the automobile appeared on the streets of Philadelphia as early as 1804 (McShane 1994), by 1900 the US had 18 million horses but only 8000 registered vehicles in a population of 76 million. More interesting, the fleet consisted mainly of steam and electric vehicles. Steam technology was mature, reliable and familiar, and water and coal were widely available (Geels 2005). Electric power was newer, but electric vehicles proved attractive in cities as taxis, were quiet, started immediately, and did not smell. Battery performance was improving, and the future looked bright (Kirsch 2000; Geels 2005).

The internal combustion engine was a late entrant—Benz demonstrated the first ICE vehicle in 1885 (Epstein 1928). Nevertheless, despite first-mover advantage, electric and steam vehicles were soon overtaken by ICE (Figure 1b). In 1912 registered electric cars peaked at 30,000, while the ICE fleet was already 30 times greater. Why did electrics fail, despite initial success? Changes in driver preferences played a role. The public developed an appetite for “touring”—venturing into the countryside, where the advantages of electrics in cities were of little value. Power to recharge the batteries was not widely available. Because few electrics ventured into the countryside, there was little incentive for entrepreneurs to develop recharging stations outside major cities, further limiting the appeal of electrics (Kirsch 2000). ICE vehicles initially faced a similar situation, but greater range and the ease of fuel distribution through small retail establishments, itself facilitated by the automobile, enabled the gasoline distribution network to grow rapidly. Further, many towns had bicycle shops and mechanics skilled with the mechanical linkages and chain drives used in early ICE vehicles, while experience with batteries

and electric motors was less widely distributed. ICE vehicles also benefited from innovation spillovers, e.g., replacement of the cumbersome hand-crank with electric starting (Geels 2005).

Word of mouth and related network effects also played an important role in overall diffusion and the rise of ICE. The larger the installed base of a platform, the greater the exposure to and familiarity with that platform among potential adopters, increasing the chances that they will choose that platform. Such social exposure to new products, driven by contacts between adopters and potential adopters, is a cornerstone of innovation diffusion theory (Rogers 1962).

More subtly, word of mouth among nondrivers played an important role. Early automobiles were feared due to their speed and perceived risks of explosion, but were also exciting novelties, attracting attention among those who had not yet purchased a car (McShane 1994). These nondrivers would then tell others about what they had seen, rapidly spreading awareness about each type of vehicle. Along with newspaper accounts and new journals dedicated to autos, word of mouth among nondrivers stimulated awareness of ICE faster than ICE vehicles could spread throughout the country (Epstein 1928, *The Horseless Age* 1896).

Thus social exposure to the auto, word of mouth among nondrivers, emerging preferences for and the improving convenience of long distance travel, growing scale, experience, installed base and infrastructure, and innovation spillovers all interacted to spell the doom of the early market leaders. These intimate interdependencies between consumer choice and the evolution of technology still exist. The diffusion challenge for alternative vehicles today also differs from the 19th century, when low awareness, the small fleet, undeveloped infrastructure and lack of standards allowed ICE to overtake steam and electric, despite their first-mover advantages and initially superior performance. Over 100 years later, alternative vehicles face a mature industry, fully articulated infrastructure, powerful vested interests, and a society, economy, and culture tightly bound to ICE.

Model boundary

Our research aims to develop a behavioral, dynamic model to explore the possible transition from ICE to AFVs such as hybrids, CNG, and HFCVs. Building on models of the product lifecycle (e.g., Abernathy and Utterback 1978, Klepper 1996), we emphasize a broad boundary, endogenously integrating consumer choice, as conditioned by product attributes, driver experience, word of mouth, marketing, and other channels, with scale economies, learning through R&D and experience, innovation spillovers, and infrastructure (Figure 2).

The fleet is disaggregated by platform (e.g., ICE, hybrid, CNG, HFCV); the model does not represent individual OEMs. Consumer's choice among platforms depends on their consideration set, and, within that set, the relative attractiveness of each (Hauser et al. 1993). Consumers consider a particular option only when sufficiently familiar with it. Familiarity increases through direct exposure to the different platforms, marketing, media attention and word-of-mouth. The attractiveness of each platform in the consideration set is a function of attributes including price, operating cost, performance, driving range, fuel and service availability, and ecological impact. We use standard multinomial logit choice frameworks (Theil 1969, McFadden 1978, McFadden 2001) to model consumer choice among platforms in the consideration set.

Attributes of attractiveness for each platform—performance, cost, range, etc.—improve endogenously through learning by doing, R&D, and scale economies. R&D and learning by doing lead to improvement for an individual platform, but may also spill over to other platforms. Complementary assets such as service, parts, maintenance, and fuel distribution infrastructure critically influence a platform's attractiveness. In turn, the installed base conditions the profitability of such infrastructure. Infrastructure development also requires a fuel supply chain (Ogden 2004), creating additional positive feedbacks through interactions with other industries (e.g., as petroleum replaced coal for home heating, and as HFCVs may coevolve with stationary fuel cells).

Here we focus on adoption generated by consumer awareness through feedback from driving experience, word-of-mouth and marketing, drawing on innovation diffusion models, e.g., Bass (1969), Norton and Bass (1987), Mahajan et al. (1990), Mahajan et al. (2000), and their applications in the auto industry (Urban et al. 1990, Urban et al. 1996). We integrate diffusion with discrete consumer choice models (McFadden 1978, Ben-Akiva and Lerman 1985), models often applied to transport mode choice (Domencich et al. 1975, Small et al. 2005), and automobile purchases (Berry et al. 2004, Train and Winston 2005), including alternative vehicles (Brownstone et al. 2000, Greene 2001).

In other papers we focus on learning, research, and innovation spillovers (Struben 2006b), and model the coevolution of vehicle adoption and fueling infrastructure location decisions in an explicit spatial framework (Struben 2006a). Here we use a reduced form model of these effects. In the discussion we illustrate the impact of disaggregating to include explicit spatial inhomogeneities. We focus on the characterizing the global dynamics and parameter space rather than estimation of parameters for particular AFVs, since (i) these are highly uncertain, and (ii) identifying which parameters are sensitive guides subsequent effort to elaborate the model and gather needed data.

Structure and dynamics of familiarity and adoption

We begin with the fleet and consumers' 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 :

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

Discards are age-dependent. Sales consist of initial and replacement purchases. Initial purchases dominated sales near the beginning of the auto industry, and do so today in China, but in developed economies replacements dominate. Struben (2004) and the online appendix (web.mit.edu/jjrs/www/AFV_Files/AFV_Transition_Appendix1.pdf) treat age dependent

discards and initial purchases; for simplicity we assume the fleet is in equilibrium and focus here on replacement purchases. Thus:

$$s_j = \sum_i \square_{ij} d_i \quad (2)$$

where \square_{ij} is the share of drivers of platform i replacing their vehicle with platform j . The share switching from i to j depends on the expected utility of platform j as judged by the driver of vehicle i , u_{ij}^e . 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,

$$\square_{ij} = \frac{u_{ij}^e}{\sum_j u_{ij}^e} \quad (3)$$

Expected utility depends on two factors: first, while drivers may be generally aware that a platform, such as hybrids, exists, they must be sufficiently familiar with that platform for it to enter their consideration set. Next, for those platforms considered, expected utility depends on (perceptions of) various vehicle attributes. To capture the formation of a driver's consideration set we introduce the concept of familiarity among drivers of vehicle i with platform j , F_{ij} . Familiarity 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. Everyone is familiar with ICE, so $F_{i,ICE} = 1$, while $F_{ij} = 0$ for those completely unfamiliar with platform j ; such individuals do not even consider such a vehicle: $F_{ij} = 0$ implies $\square_{ij} = 0$. Hence

$$u_{ij}^e = F_{ij} * u_{ij} \quad (4)$$

where utility, u_{ij} , depends on vehicle attributes for platform j , as perceived by driver i .

For an aggregate population average familiarity varies over the interval $[0, 1]$. Familiarity increases in response to social exposure, and also decays over time:

$$\frac{dF_{ij}}{dt} = \square_{ij}(1 - F_{ij}) - \square_{ij}F_{ij} \quad (5)$$

where \square_{ij} is the impact of total social exposure on the increase in familiarity, and \square_{ij} is the fractional loss of familiarity about platform j among drivers of platform i .¹

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:

$$\square_{ij} = \square_j + c_{ijj}F_{jj}(V_j/N) + \sum_{k \neq j} c_{ijk}F_{kj}(V_k/N) \quad (6)$$

Here \square_j is the effectiveness of marketing and promotion for platform j . 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 fleet consisting of platform j , V_j/N , and the frequency and effectiveness of contacts between drivers of platforms i and j , c_{ijj} . 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 hydrogen vehicles from the driver of a hybrid.²

It takes effort and attention to remain up to date with new vehicle models and features. Hence familiarity erodes unless refreshed through social exposure. The loss of familiarity is highly nonlinear. When exposure is infrequent, familiarity 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

¹ The full formulation accounts for the transfer of familiarity associated with those drivers who switch platforms (see appendix).

² Eq. 6 can be written more compactly as $\square_{ij} = \square_j + \sum_k c_{ijk}F_{kj}(V_k/N)$; we use the form above to emphasize the two types of word of mouth (direct and indirect).

combustion”—familiarity with ICE =1 and there is no decay of familiarity. Thus the fractional decay of familiarity is:

$$\dot{f}_{ij} = \beta_b f(\dot{f}_{ij}); \quad f(0) = 1, f(\infty) = 0, f'(\cdot) \leq 0. \quad (7)$$

Familiarity decays fastest (up to the maximum rate β_b) when total exposure to a platform, \dot{f}_{ij} , is small. Greater exposure reduces the decay rate, until exposure is so frequent that decay ceases.

We capture these characteristics with the logistic function

$$f(\dot{f}_{ij}) = \frac{\exp(-\beta_b(\dot{f}_{ij} - \dot{f}^*))}{1 + \exp(-\beta_b(\dot{f}_{ij} - \dot{f}^*))} \quad (8)$$

where \dot{f}^* is the reference rate of social exposure at which familiarity decays at half the normal rate, and β_b is the slope of the decay rate at that point. Varying \dot{f}^* and β_b enables sensitivity testing over a wide range of assumptions about familiarity decay.

These channels of awareness generation create positive feedbacks that can boost familiarity and adoption of AFVs (Figure 3). First, a larger alternative fleet enhances familiarity as people see the vehicles on the roads and learn about them from their drivers. Greater familiarity, in turn, increases the fraction of people including AFVs in their consideration set and, if their utility is high enough, the share of purchases going to AFVs (the reinforcing Social Exposure loop R1a). Further, as the AFV fleet grows, people driving other platforms increasingly see and hear about them, and the more socially acceptable they become, suppressing familiarity decay (reinforcing loop R1b).

Second, familiarity with AFVs among those driving ICE vehicles increases through word of mouth contacts with other ICE drivers who have seen or heard about them, leading to still more word of mouth (reinforcing loops R2a and R2b). The impact of encounters among nondrivers is likely to be weaker than that of direct exposure to an AFV, so $c_{ijj} > c_{ijk}$, for $k \neq j$. However, the long life of vehicles means AFVs will constitute a small fraction of the fleet for years after their introduction. The majority of information conditioning familiarity with alternatives among

potential adopters will arise from marketing, media reports, and word of mouth from those not driving AFVs. Word of mouth arising from interactions between adopters and potential adopters will become significant only after large numbers have already switched from ICE to alternatives.

Model Behavior: Familiarity

The model generalizes to any number of vehicle platforms and constitutes a large system of coupled differential equations. To gain intuition into the diffusion of alternative vehicles, we analyze a simplified version with only two platforms, ICE ($j=1$) and an AFV ($j=2$). We assume constant driver population and vehicles per driver, so the total fleet, $N = \sum_j V_j$, is constant. Familiarity with ICE can reasonably be assumed to remain constant at 1 throughout the time horizon. Further, AFV drivers are assumed to be fully familiar with it. Thus

$$\mathbf{F} = \begin{bmatrix} 1 & F_{12} \\ 0 & 1 \end{bmatrix}, \quad (9)$$

significantly reducing the dimensionality of the model.

Long vehicle life means the composition of the fleet will remain roughly fixed in the first years after alternatives are introduced. Assuming the fleet of each platform is fixed reduces the model to a first-order system where the change in familiarity with AFVs among ICE drivers, dF_{12}/dt , is determined only by the level of familiarity itself and constant effects of marketing and social exposure to the small alternative fleet.

Figure 4 shows the phase plot governing familiarity for a situation with a strong marketing program for AFVs and a modest initial fleet (table 1 lists model parameters). When familiarity with the alternative is low, word of mouth from nondrivers is negligible, and the gain in familiarity comes only from marketing and exposure to the few AFVs on the road. Since the total volume of exposure is small, the decay time constant for familiarity is near its maximum. As familiarity increases, word of mouth about AFVs among ICE drivers becomes more important, and increasing total exposure reduces familiarity loss.

The system has three fixed points. There are stable equilibria near $F=1$, where familiarity decay is small, and near $F=0$, where word of mouth from nondrivers is small and familiarity decay counters the impact of marketing and exposure to the small alternative fleet. In between lies an unstable fixed point where the system dynamics are dominated by the positive feedbacks R2a and R2b. The system is characterized by a threshold, or tipping point. For adoption to become self-sustaining, familiarity must rise above the threshold, otherwise it (and thus consumer choice) will tend toward the low consideration equilibrium. The existence and location of the tipping point depends on parameters. Sensitivity analysis (Struben 2004) shows the low familiarity equilibrium increases, and the tipping point falls, as (i) the magnitude of marketing programs for AFVs, β_2 , rises; (ii) the impact of word of mouth about AFVs between AFV and ICE drivers, c_{122} , increases; (iii) the size of the initial alternative fleet grows; (iv) the impact of word of mouth about AFVs within the population of ICE drivers, c_{121} , increases; and (v) as familiarity is more durable (smaller β_b and β^* and larger β). Continuing these parameter changes cause the unstable fixed point to merge with the lower stable equilibrium, then to a system with a single stable equilibrium at high familiarity.

A second order model: familiarity and adoption

We now relax the assumption that the share of alternative vehicles is fixed, adding the social exposure loops R1a and R1b. We simplify the dynamics of fleet turnover by aggregating each fleet into a single cohort with constant average vehicle life $\beta_j = \beta$, yielding

$$d_j = V_j / \beta \quad (10)$$

Since $V_2 = N - V_1$, fleet dynamics are completely characterized by the evolution of the alternative, which, from eq. 1 and 2, is

$$\frac{dV_2}{dt} = (\beta_{22}V_2 + \beta_{12}(N - V_2)) / \beta - V_2 / \beta. \quad (11)$$

By eq. 3 and 4, the fraction of drivers purchasing an AFV is

$$\square_{i2} = F_{i2}u_{i2} / (F_{i1}u_{i1} + F_{i2}u_{i2}) \quad (12)$$

As before we assume AFV drivers are fully familiar with its attributes, and that everyone is familiar with ICE. Assuming for now that the perceived utilities u_{ij} are also constant, \square_{22} is constant at $u_{22}/(u_{22} + u_{21})$ and

$$\square_{i2} = F_{i2}u_{i2} / (1 \cdot u_{i1} + F_{i2}u_{i2}). \quad (13)$$

With the equation governing familiarity, the system reduces to a pair of coupled differential equations with state variables V_2 (the AFV fleet) and F_{i2} (the familiarity of ICE drivers with AFVs).

Figure 5 shows the phase space of the system for several parameter sets. In all cases, the utilities of the two platforms are set so that AFV purchase share is 0.5 at full familiarity. Table 1 shows other parameters. The nullclines (dashed lines) are the locus of points for which the rate of change in each state variable is zero. Fixed points exist where nullclines intersect. With moderate marketing and no nondriver word of mouth (Figure 5a) there are three fixed points, as in the one-dimensional case and the state space is divided into two basins of attraction. For small initial alternative fleets, familiarity and the fleet decay to low levels, even if initial familiarity is high. On the other side of the separatrix dividing the basins, familiarity rises and more ICE drivers switch to AFVs, further increasing familiarity and triggering still more switching. Figure 5b shows a case with no marketing but moderate nondriver word of mouth. As in the one-dimensional case, indirect word of mouth among ICE drivers shrinks the basin of attraction for the low adoption equilibrium. In Figure 5c marketing and nondriver word of mouth are large enough so that there is only one fixed point, with high familiarity and diffusion.

In Figure 5 marketing impact is constant. In reality, marketing is endogenous. Successful diffusion boosts revenues, enabling marketing to expand, while low sales limit resources for promotion. Declining marketing effort lowers \square_2 , moving the low diffusion equilibrium toward the origin and enlarging its basin of attraction. Figure 6 illustrates with a set of simulations

beginning with no familiarity or installed base for the alternative. An aggressive marketing campaign ($\beta_2=0.02$) begins at $t=0$. The campaign ends after T years, $10 \leq T \leq 50$ years. When the campaign is short, familiarity and market share drop back despite initial success: the campaign does not move the system across the basin boundary. With the assumed parameters, aggressive promotion must be maintained for roughly 30 years before diffusion becomes self-sustaining.

Such collapse has been observed. For example, attempts to introduce CNG vehicles in Canada, Italy, and New Zealand faltered after initial subsidies expired, despite some initial diffusion.

Expanding the model boundary to recognize that marketing effort and initial subsidies are endogenous closes another positive feedback that hinders diffusion of alternative vehicles. The long life of the vehicle fleet and slow initial development of familiarity imply marketing and subsidy programs must be sustained for long periods before diffusion crosses the tipping point and becomes self-sustaining.

Endogenous Vehicle Performance Improvement

We now relax the assumption that vehicle utility is fixed. Currently alternative technologies are not competitive with ICE. However, scale economies, learning effects, and related interactions with the technology, manufacturing, and fueling supply chains promise to significantly lower costs and improve performance (Figure 2). Positive feedbacks arising from learning, network externalities and complementary lead to path dependency and significantly condition diffusion policies to promote adoption (Arthur 1989, David 1985, Katz and Shapiro 1985; Sterman 2000 describes several dozen positive feedbacks affecting diffusion and firm growth). Struben (2006a, b) examines the impact of such feedbacks in detail; here we aggregate all vehicle characteristics, including purchase cost, fuel efficiency, power, features and range, into a single attribute denoted vehicle Performance, P . Utility takes the reference value u^* when performance equals a reference value P^* :

$$u_{ij} = u^* \exp(\beta P_j / P^*) \quad (14)$$

where α is the sensitivity of utility to performance. The exponential utility function means the share of purchases going to each platform (eq. 3) follows the standard logit choice model.

Performance follows a standard learning curve, rising as relevant knowledge of and experience with the platform, K , improves,

$$P_j = P_j^0 (K_j / K^0)^\alpha \quad (15)$$

where performance equals an initial value P^0 at the reference knowledge level K^0 .

Much of the knowledge gained for one platform can spill over to others. Spillovers can be modeled several ways (Jovanovic and MacDonald 1994, Cohen and Levinthal 1989). Since knowledge is multidimensional (e.g., powertrain, suspension, controls), one firm and platform may lead on certain aspects of technology and lag on others, simultaneously being both the source and beneficiary of spillovers. To allow for varying substitution possibilities, the knowledge base for each platform is a CES function of the platform's own experience, E_j , and the (perceived) experience of other platforms, E_{ij}^p :

$$K_j = K^0 \left[\alpha_j \frac{E_j}{E^0} + (1 - \alpha_j) \sum_{i, i \neq j} \beta_{ij} \frac{E_{ij}^p}{E^0} \right]^{1/\sigma} \quad (16)$$

where E^0 is the reference experience level, $\alpha_j = (1 - \beta_j)/\sigma$ and σ is the elasticity of substitution between the firms' own experience and the experience of others, α_j is the fraction of knowledge arising from the platform's own experience, and β_{ij} is the strength of spillovers from platform i to j . Constraining $\sum_{i, i \neq j} \beta_{ij} = 1$ ensures constant returns to scale.

Imitation, reverse engineering, hiring from competitors and other processes enhancing spillovers take time. Hence spillovers depend on *perceived* experience, which lags actual experience. For simplicity we assume first-order exponential smoothing with spillover adjustment lag τ_j :

$$\frac{dE_{ij}^p}{dt} = (E_i - E_{ij}^p) / \tau_j. \quad (17)$$

Spillover time constants may differ across platforms. Small firms may lack the resources to imitate innovations as quickly as their large rivals.

Finally, we proxy a platform's experience and learning from all sources with cumulative sales:

$$\frac{dE_j}{dt} = s_j \quad (18)$$

Parameters will depend on differences in the technologies. For example, ICE experience is relevant to biodiesel vehicles, but less relevant to General Motors' HyWire HFCV (Burns et al. 2002), which radically alters most design elements. We assume a 30% learning curve and moderately high elasticity of substitution, $\sigma=1.5$. Initial conditions are as in Figure 6; Table 1 lists other parameters.

Figure 7 illustrates the impact of performance improvement. For comparison, the trajectory labeled "Equal Performance" shows diffusion when the AFV enters the market with experience, and therefore utility, equal to ICE—learning has already leveled the playing field. The other simulations assume, more realistically, that AFVs begin with low experience and immature technology, yielding low initial performance relative to ICE. In the "No Spillover" case each platform improves only through its own experience. AFV adoption stagnates at a low level. Poor initial performance limits sales, suppressing the accumulation of experience that could boost performance. The system is trapped in the low-diffusion basin of attraction. The "Spillover ICE->AFV" case activates spillovers from ICE to AFVs (but not vice-versa). AFVs quickly benefit from the large experience base of ICE (through transfers of engineers, patents, access to suppliers, and other resources). Performance rises quickly, and diffusion, though still requiring many decades, becomes self-sustaining. The "Spillovers to Both" case allows AFV innovations to spill over to the incumbent (e.g., lighter materials, drive-by-wire systems). ICE vehicles now improve even as the alternative does, reducing AFV attractiveness and slowing diffusion. If such spillovers are strong enough, the performance gap between ICE and AFVs

may never close enough for the system to escape the low-diffusion basin of attraction. Due to the strength of the many positive feedbacks governing the system dynamics, diffusion patterns are quite sensitive to the strength of the learning curve and spillovers, suggesting benefits from disaggregating the many sources of performance improvement (R&D, learning by doing, spillovers, scale economies, etc.) and empirically estimating their impacts.

Spatial coevolution with fueling infrastructure

The analysis above did not include the development of fueling and maintenance infrastructure, and therefore applies to AFVs, such as hybrids, that use the existing gasoline distribution system. For others, such as HFCVs, fuel and other infrastructure must be built up together with the fleet. Often stereotyped as “chicken-egg” dynamics, these co-evolutionary dynamics are more complex. The local scale of interactions is paramount. Fuel availability differs for each driver, based on their location and driving patterns relative to the location of fuel stations.

Struben (2006a) develops a dynamic vehicle-infrastructure model with explicit spatial structure. A region is divided into small patches. The location of fueling infrastructure is endogenous. Station entry and exit are determined by the expected profitability of each location, which, in turn, depends on the demand for fuel at that location and the density of competition from nearby stations. Households within each patch choose AFVs according to the structure described above, except that the perceived utility of each platform also depends on the effort required to find fuel. Refueling effort is a function of (i) the risk of running out, which depends on vehicle range and the location of fuel stations relative to the driver’s desired trip distribution, and (ii) expected refueling time, which includes the time spent driving out of the way to reach a fuel station and crowding at fuel stations. Driver behavior is also endogenous. For example, the number and length of trips increases as fuel availability rises. Effective vehicle range is also endogenous: drivers who perceive refueling effort is high, say because fuel stations are sparse or crowded, will seek to refuel before their tanks near empty. Such topping-off requires more frequent refueling stops and increases congestion at fuel stations. Refueling effort rises, reducing both

AFV purchases and their use for longer trips, creating additional positive feedbacks that can suppress diffusion.

Figure 8 shows a simulation calibrated for California. The initial ICE fleet and infrastructure distribution are set to current California values (16 million vehicles and 8000 gas stations, concentrated in urban areas). To emphasize the spatial coevolution of vehicles and infrastructure, we assume full familiarity with AFVs and set AFV performance equal to that of ICE. The simulation begins with an AFV fleet of 25,000 vehicles and about 200 fueling stations (approximate values for CNG in California in 2002, including private fleets and stations). We assume, optimistically, that all AFV fuel stations are accessible to the public. Losses for fuel stations are heavily subsidized for the first 10 years.

Figure 8 shows alternative fuel stations and fleet. Despite performance equal to ICE and full familiarity with the AFV, overall diffusion is slow, and after 13 years has largely saturated. Fuel stations grow roughly with the fleet, though many are forced to exit when subsidies expire in year 10. Though not shown, miles driven per year for the typical AFV are also far less than for ICE vehicles. The spatial distribution after 13 years shows essentially all AFVs and fueling stations are concentrated in the major urban centers. Limited diffusion is a stable equilibrium in the cities, because high population density means fuel stations can profitably serve the alternative fleet, and low refueling effort induces enough people to drive the alternative vehicle. However, though a few AFV fuel stations locate in rural areas during the period they are subsidized, rural stations are sparse, so rural residents and city dwellers needing to travel through them find AFVs unattractive. Further, urban adopters, facing low fuel availability outside the cities, use their AFVs in town, but curtail long trips. Consequently, demand for alternative fuel in rural areas never develops, preventing a profitable market for fuel infrastructure from emerging, which, in turn, suppresses AFV adoption and use outside the cities.

While islands of limited diffusion might be sustained in the cities, broad adoption of AFVs can easily founder even if their performance equals that of ICE. While not considered in the simulation, low diffusion limits knowledge accumulation that can improve AFV performance. Further, auto OEMs would likely respond to the demand for AFVs in cities by offering small, efficient, inexpensive models adapted for commuting but ill suited for touring. Such behavior further reduces their attractiveness in rural areas, and likely restricts adoption to affluent households who can afford an AFV for commuting and an ICE vehicle for weekend excursions. These feedbacks would further constrain diffusion.

Discussion

Modern economies and settlement patterns have coevolved around the automobile, internal combustion, and petroleum. Successful introduction and diffusion of alternative fuel vehicles is more difficult and complex than that for many products. The dynamics are conditioned by a broad array of positive and negative feedbacks, including word of mouth, social exposure, marketing, scale and scope economies, learning from experience, R&D, innovation spillovers, complementary assets including fuel and service infrastructure, and interactions with fuel supply chains and other industries. A wide range of alternative vehicle technologies, from hybrids to biodiesel to fuel cells, compete for dominance; the lack of standards increases uncertainty and inhibits investment. And the large role of the automobile in personal identity and social status means purchase decisions involve significant emotional factors.

We developed a behavioral, dynamic model to explore the diffusion of and competition among alternative vehicle technologies. The full model has a broad boundary and captures the spatial distribution of vehicles and fueling infrastructure. To gain insight into the dynamics, we explored a simplified version, focusing on the generation of consumer awareness of alternatives, and choice among platforms once they enter consumers' consideration set. We introduce the concept of familiarity with a platform to capture 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. Familiarity can be generated by marketing and media, by direct social exposure and word of mouth created by contacts between ICE and AFV drivers, and by indirect word of mouth arising from conversations about AFVs among ICE drivers.

The positive feedbacks conditioning driver familiarity with and consideration of alternative vehicles generate system dynamics characterized by multiple equilibria. The system is attracted to high familiarity and significant adoption of alternative vehicles, or stagnation with low familiarity and adoption. These fixed points are separated by a threshold, or tipping point. Awareness and adoption must exceed the threshold to become self-sustaining. The existence and location of the tipping point and the size of the basin of attraction of the low diffusion equilibrium depend on parameters. Stronger marketing and direct word of mouth favor diffusion. However, the impact of direct word of mouth will be small when AFVs are introduced, due to 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. In such settings, indirect word of mouth about alternative vehicles among ICE drivers can significantly lower the threshold for sustained adoption.

Endogenous improvement in vehicle attributes from learning, R&D, scale economies, etc. adds important additional positive feedbacks that can further suppress the diffusion of alternative vehicles. Current AFVs (e.g., hybrids) are expensive and offer lower performance relative to ICE; many are not yet commercially available (e.g., HFCVs). Though AFVs undoubtedly would improve with scale and cumulative R&D and experience, these innovation drivers remain weak as long as there is substantial uncertainty, low familiarity, and limited adoption. Further, technology spillovers from alternative vehicle programs to the incumbent can further suppress adoption. Heywood et al. (2003) estimate that the performance of hydrogen vehicles will not equal that of ICE, hybrids or clean-diesel for 20 years. During this time, the dominant ICE technology can benefit from many innovative ideas—lighter materials, performance-enhancing

software—that might emerge from alternative vehicle programs. Finally, the local, spatial coevolution of adoption and fuel infrastructure can significantly impede broad scale diffusion, even if AFVs equal ICE in cost and features.

While the analysis here characterizes the system dynamics in terms of the parameters and model boundary, empirical work is needed to estimate the relative strength of marketing, direct social exposure, and indirect word of mouth in conditioning familiarity and consumer choice. Vehicle features and performance should be disaggregated, and interactions with other industries and the fuel supply chain should be captured. The results suggest, however, that a broad model boundary is required to capture the wide array of interactions and feedbacks that determine the dynamics of alternative vehicle diffusion.

Acknowledgments

Financial support provided by the National Renewable Energy Laboratory (grant XCO-5-55516-01) and the Project on Innovation in Markets and Organizations at the MIT Sloan School of Management. We thank Nelson Repenning, Derek Supple, Cory Welch and seminar participants at NREL, the 2005 International System Dynamics Conference, and MIT for helpful comments, and Cory Welch for data access.

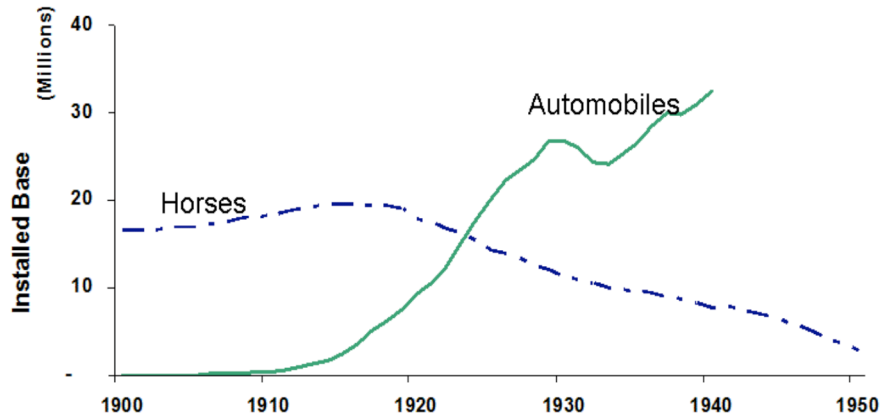
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Figure 1 (a) automobile and horse populations, US (Source: US Bureau of the Census 1997); (b) Share of auto producers for each platform (ICE, steam, electric), with number of active producers. Source: Kimes and Clark (1996).



**Producing firms per platform
1876-1942**

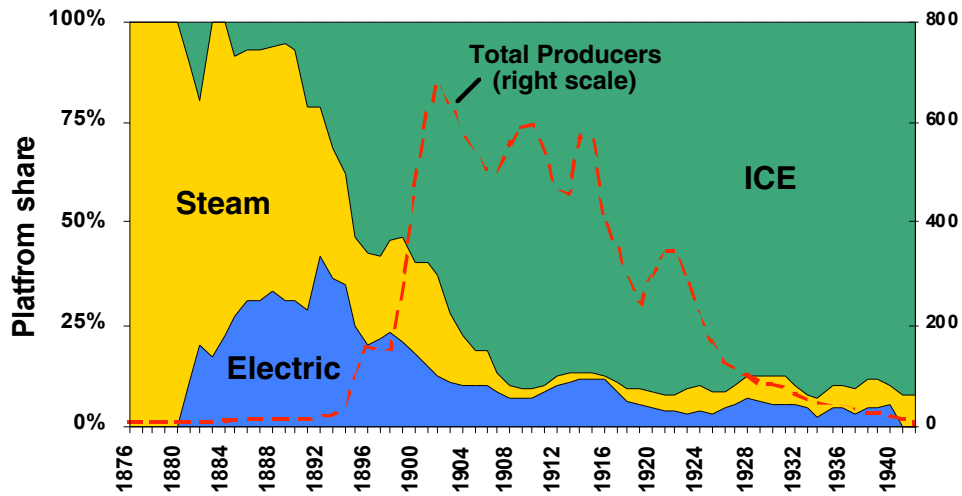


Figure 2 Model boundary, stakeholders, and interdependencies.

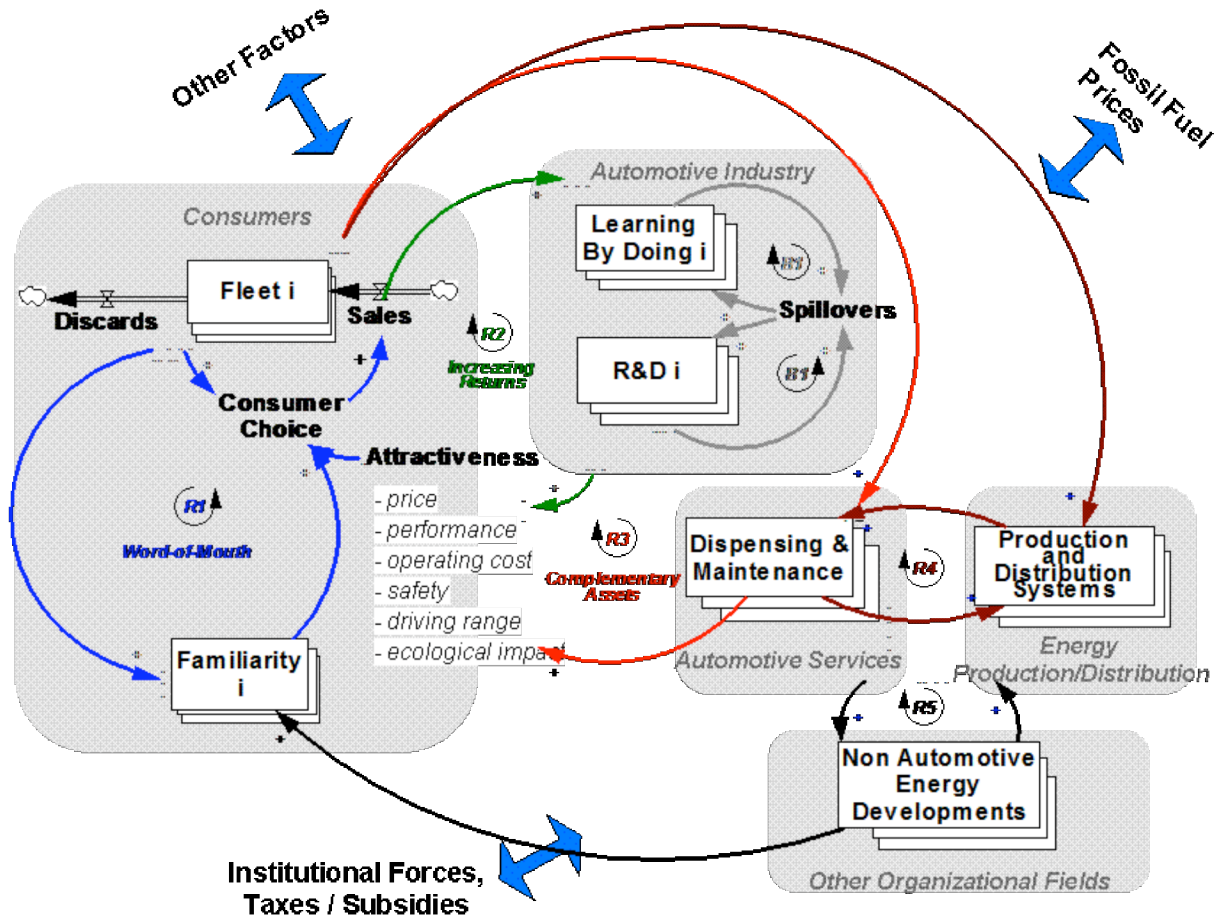


Figure 3 Principal positive feedbacks conditioning familiarity and consumer choice, with expected modes of behavior.

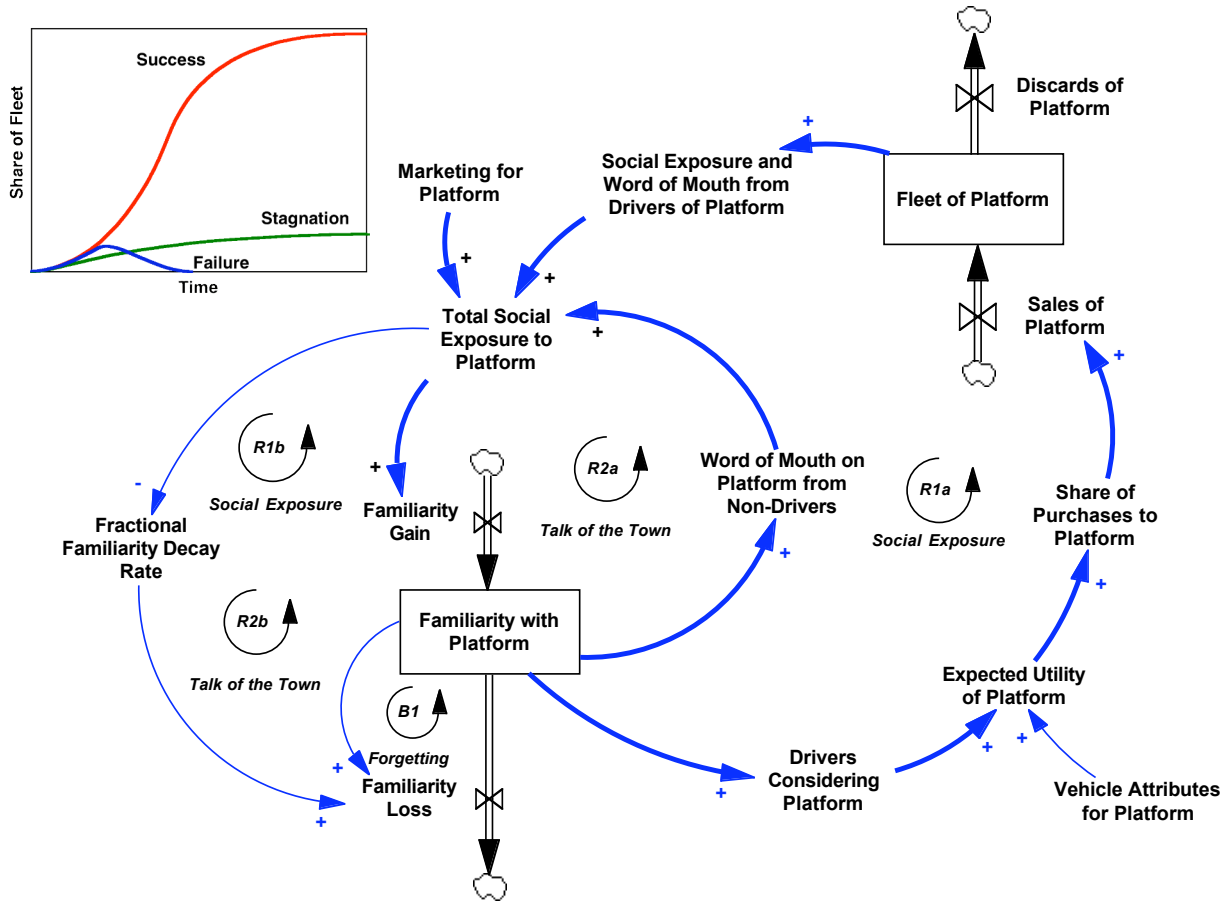


Figure 4 Phase plot for one-dimensional system showing two stable and one unstable fixed points for familiarity of ICE drivers with AFVs (parameters in Table 1).

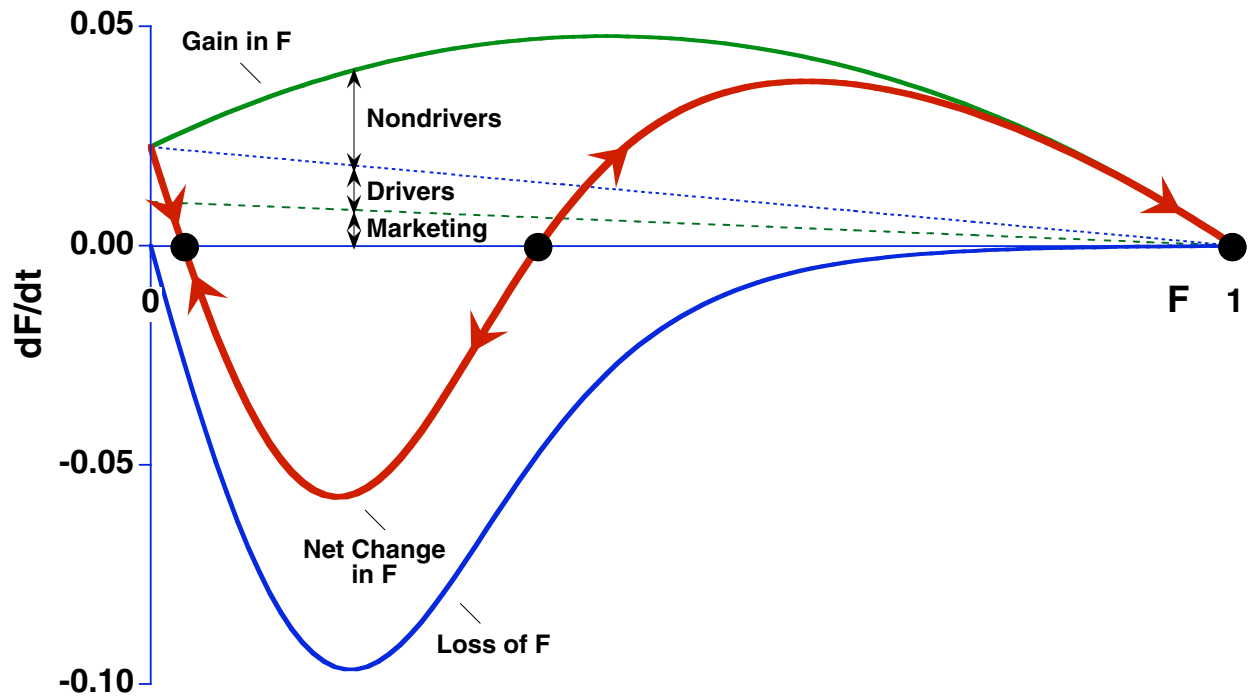


Figure 5 Phase space for two-dimensional system with endogenous familiarity and fleet. Fixed points exist at intersections of nullclines; sample trajectories shown as dots. Grey area shows basin of attraction for the low-diffusion equilibrium. Strength of marketing and nondriver word of mouth as shown. Other parameters as in Table 1.

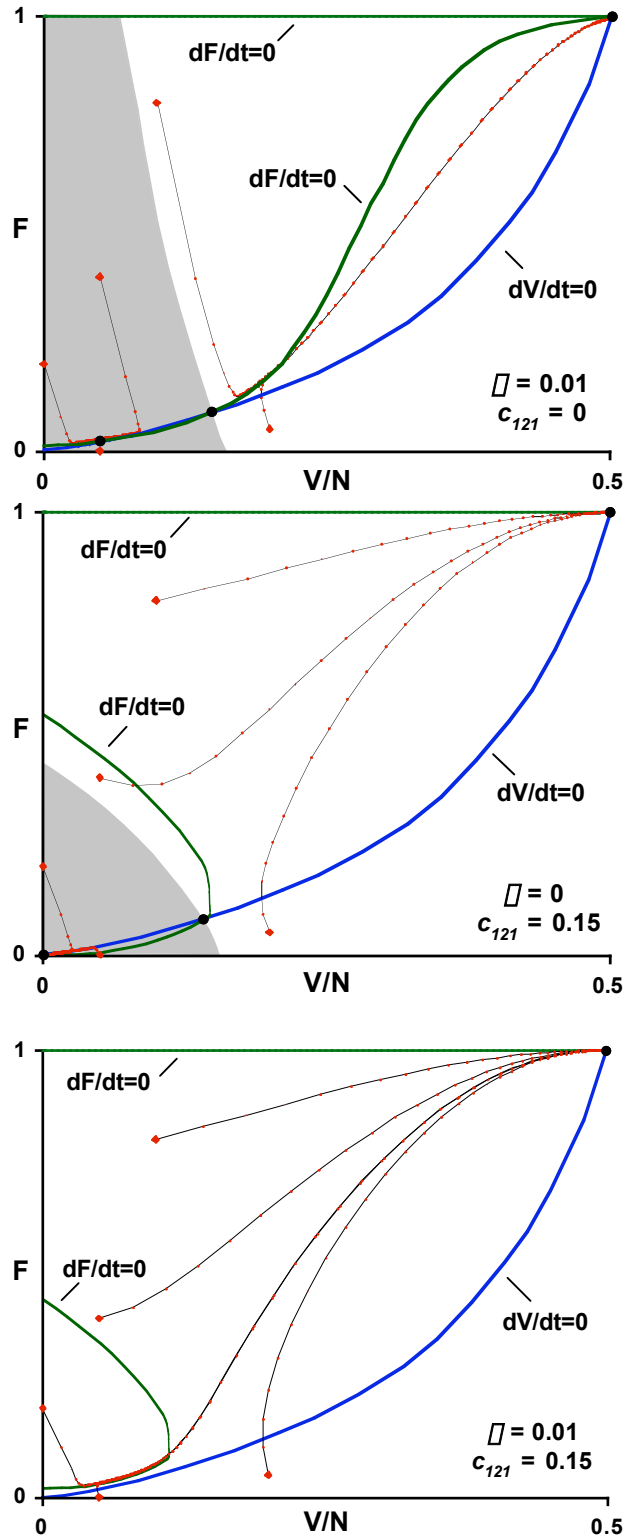


Figure 6 Alternative vehicle familiarity and fleet with an aggressive marketing and promotion program. Duration of high marketing impact ($\tau_2 = 0.02$) varies between 10 and 50 years.

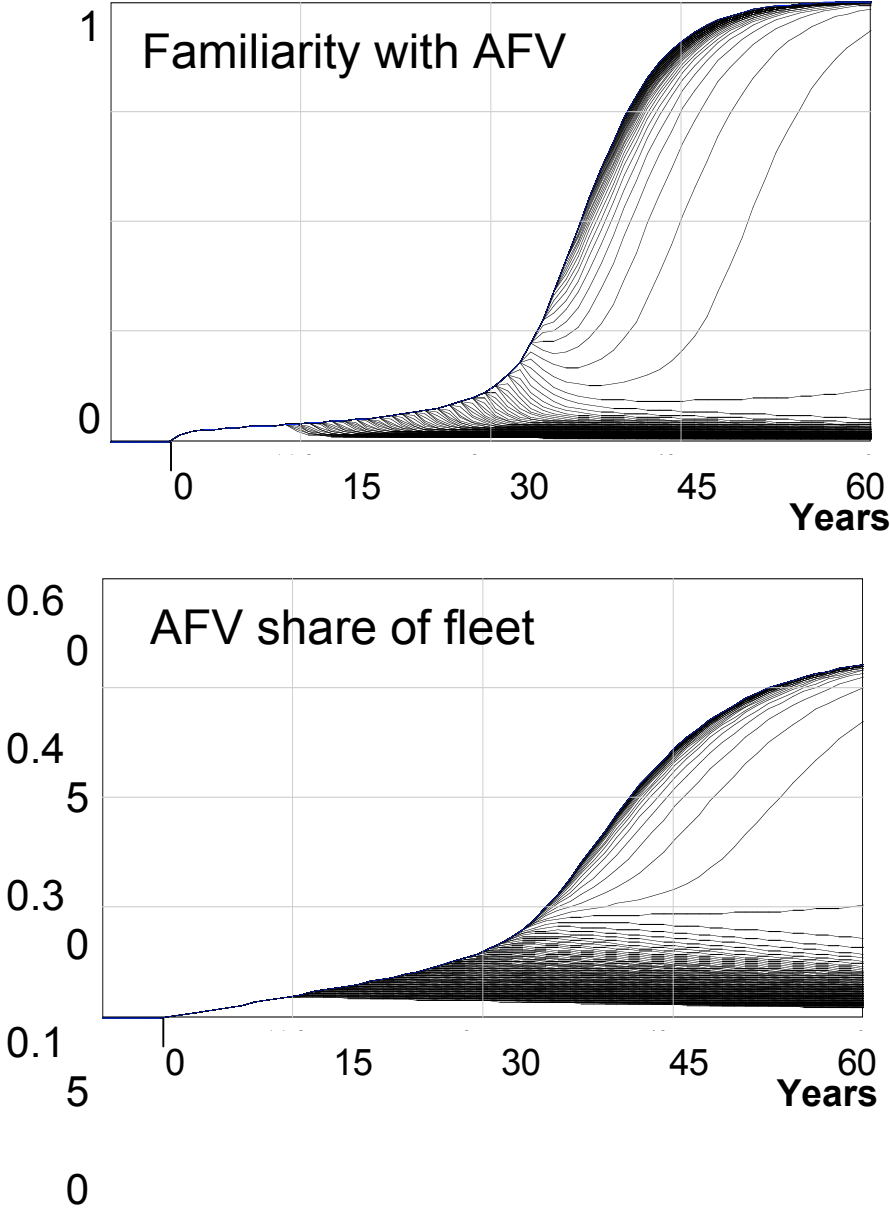


Figure 7 Alternative vehicle familiarity and fleet with endogenous learning and innovation spillovers.

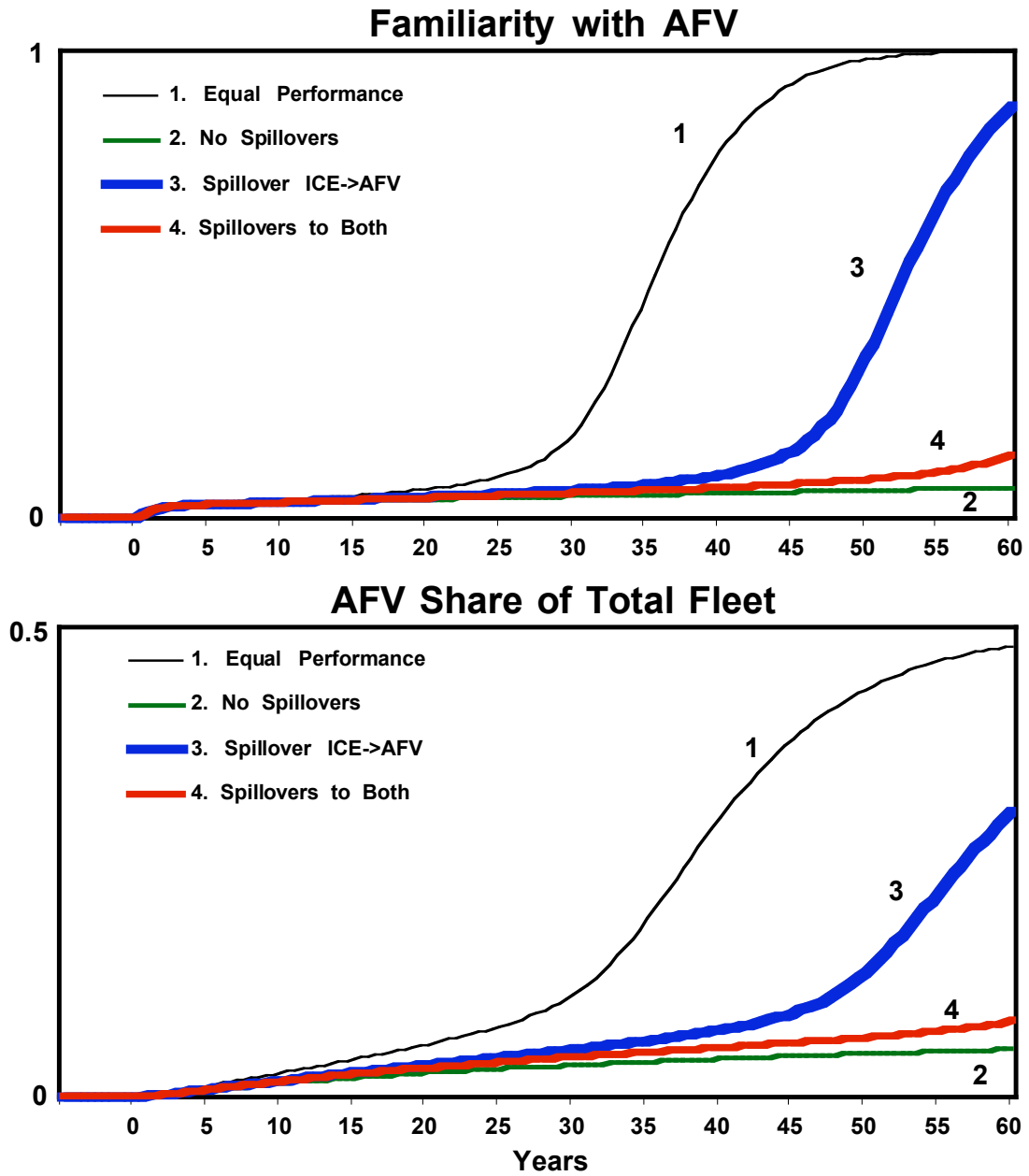


Figure 8 Behavior of spatially disaggregated model calibrated for California.

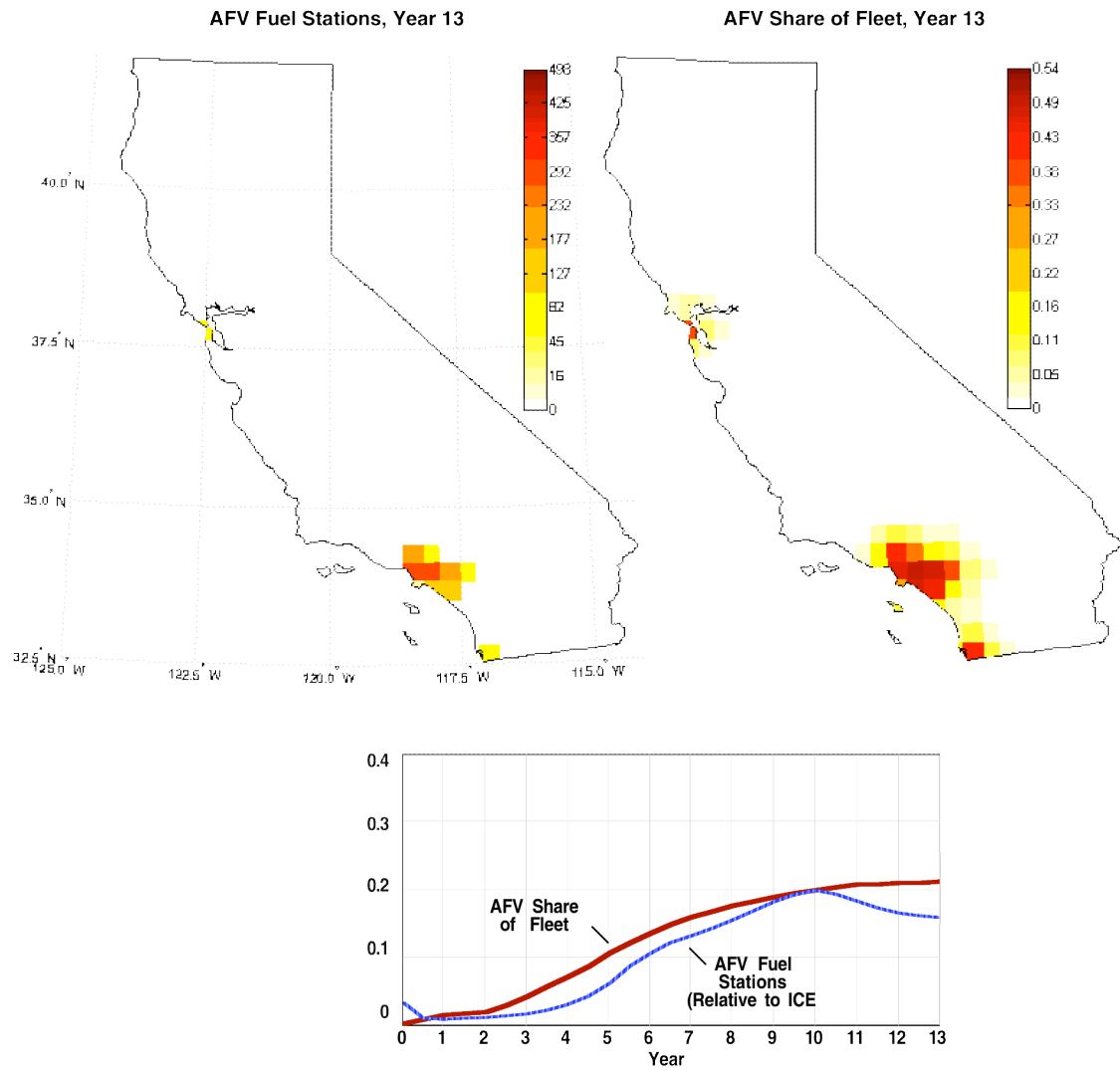


Table 1. Parameters used in simulations.

	Definition	unit	value
β_2	AFV marketing effectiveness	1/year	0.01
c_{122}	Strength of word of mouth about AFVs for contacts between ICE and AFV drivers	1/year	0.25
c_{121}	Strength of word of mouth about AFVs for contacts between ICE and other ICE drivers	1/year	0.15
β_0	Maximum familiarity loss rate	1/year	1
β^*	Reference rate of social exposure	1/year	0.05
β	Slope of decay rate at reference rate	year	20
β	Average vehicle life	year	8
u^*	Reference utility	dmnl	1
β	Sensitivity of utility to performance	dmnl	0.3
β	Elasticity of substitution	dmnl	1.5
P_0	Initial Performance	dmnl	1
K_0	Reference knowledge level	dmnl	1
β	Learning curve strength	dmnl	0.379*
E_0	Reference years of effective experience	years	20
β_{ij}	Experience spillover time	years	8

* The learning curve exponent β is calculated from the assumed fractional performance improvement per doubling of knowledge, $(1 + \beta)P_0 = P_0(2K_0/K_0)^\beta$, or $\beta = \ln(1 + \beta)/\ln(2)$. We assume a 30% learning curve, $\beta = 0.3$, so $\beta = 0.379$.