

**UNDERSTANDING THE TRANSITION TO NEW FUELS AND VEHICLES:  
LESSONS LEARNED FROM ANALYSIS AND EXPERIENCE OF  
ALTERNATIVE FUEL AND HYBRID VEHICLES**

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Additional information transitional analysis of alternative and hybrid vehicles can be found at: <http://pz11.ed.ornl.gov/altfuels.htm>

## **I. Introduction**

Since the energy crisis of 1973 the United States has explicitly sought to moderate the consumption and importation of oil. Initially the dominant concerns were energy conservation and energy security. During the 1980 and 1990's the additional concerns of urban air quality and greenhouse gases took center stage. The transportation sector represents about 28% of total domestic energy use (Davis and Diegel, 2002, Table 2.1). Of the total amount of transportation energy used in the United States the demand is overwhelmingly met by petroleum. As Greene (1996) points out, the almost complete dependence of the transportation sector on petroleum persists today despite the market upheavals of the 1970's and early 1980's. In 1973, at the height of the Arab embargo, the U.S. transportation sector was 95.6% dependent on oil, about 1% less than today. Given geopolitical developments affecting global oil supply and renewed concern about the peaking of world oil production (Campbell and Laherrere 1998), oil dependence is again a major driver of transportation energy policy. The question remains: how should our transportation system transition itself to be more sustainable and secure?

In this chapter we discuss the lessons about transitions that can be learned from past efforts to move to alternative transportation fuels; and what can we learn from the growing introduction of hybrid technology. This is very important since future policies, politics and tax dollars are driven, in part, by expectations regarding the payoffs and costs of emerging fuels and technologies such as hydrogen and fuel cells. Hydrogen fuels and fuel cell vehicles share many of the same attributes, promises, and challenges of other alternative fuel vehicles and electric drive vehicles, only perhaps magnified and compounded.

More particularly, this chapter presents the lessons learned from our modeling and analysis of the transition to alternative and hybrid vehicles. What has worked, or could work in a market-based economy where economies of scale in vehicle production are significant and endogenous network effects are important? For the most part the alternative fuel vehicle (AFV) technologies we examined were mature technologically, though not mature in the market place. For hybrid electric vehicles (HEV's) we explicitly examined the role of technological learning to reduce production costs. It is our belief that explicitly evaluating transition paths, as opposed to static equilibrium outcomes, is very important and leads to compelling insights for a wide variety of economic and environmental questions. This of course implies that policies designed to guide markets must deal explicitly with transitions and not be solely be concerned with future outcomes (that may not occur).

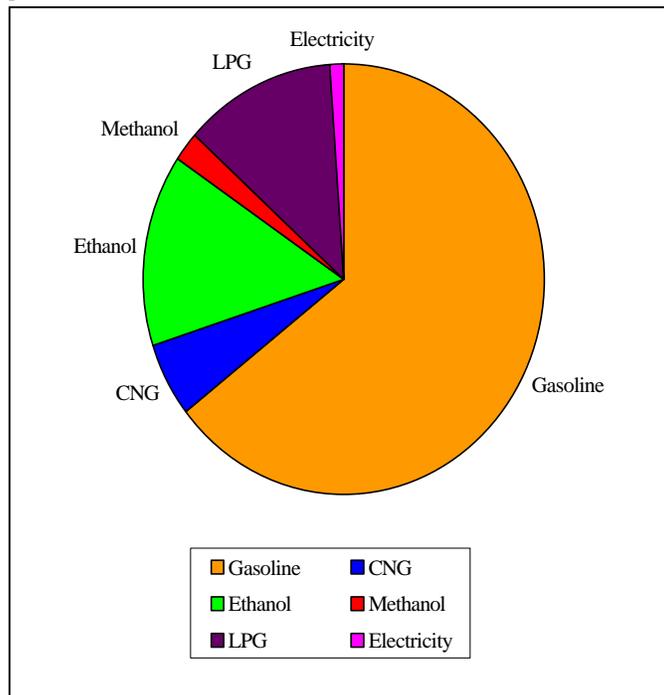
## **II. The Goal of Reducing Petroleum Demand in Transportation**

There are three ways to reduce the amount of petroleum used by cars and light trucks: reduce the amount of driving per year; increase the average fuel efficiency of the vehicle fleet; and substitute alternative fuels for gasoline. The principal fuel efficiency measure in place in the United States is the corporate average fuel economy (CAFE) standards for new cars and light trucks (US Energy Policy and Conservation Act of 1975). CAFE regulations specify minimum fleet average standards for fuel efficiency that vehicle manufacturers must meet. The fuel substitution approach is advocated by Section 502(b) of the Energy Policy Act of 1992 (EPACT), and has been an important impetus for research and demonstration projects and for fleet programs to help alternative fuels enter the US transportation market. Other important alternative fuel incentives include demanding gasoline composition and air quality requirements in the Clean Air Act Amendments of 1990, and large tax credits for ethanol, and CAFE credits

for manufacturing dedicated alternative and flexible fuel vehicles (provided by the Alternative Motor Fuels Act of 1988, or AMFA). A comprehensive listing of measures including tax credits and state and local initiatives can be found in McNutt and Rodgers (2003).

EPACT provides incentives to introduce alternative fuel vehicles (AFVs) and required that the U.S. Department of Energy (DOE) estimate the technical and economic feasibility producing sufficient alternative and replacement fuels to replace, on an energy equivalent basis, at least 10 percent of gasoline use by the year 2000; and at least 30 percent by the year 2010 (EPACT, 502(a), 502(b)). Petroleum is displaced by the use of neat alternative fuels as well as through the use of reformulated and oxygenated gasolines which contain natural gas, hydrogen, and alcohol and ether-oxygenates. Replacement fuels, loosely speaking, are those portions of gasoline which are not gasoline (such as oxygenates) and other non-gasoline fuels that are not alternative fuels (such as gasohol, which is a blend of 10% ethanol and 90% gasoline). The recent strong interest in hydrogen-fueled vehicles reflects its promise for both gasoline substitution, improved end-use fuel efficiency and a set of diverse domestic supply options.

In 1996, DOE published the results of their initial analysis of EPACT'S goals, using the Alternative Fuels Trade Model (USDOE 1996, Leiby 1993). This study determined, among other things, that (p. xii): "For the year 2000, 10 percent replacement of light-duty motor fuel use with alternative and replacement fuels is feasible and appears likely with existing practices and policies." The USDOE report further states: "Displacing 30 percent of light-duty motor fuel use by 2010 appears feasible. However, this estimated feasibility is based upon a number of assumptions that may not be realized without additional alternative-fuel initiatives." These results are shown in Figure 1.



**Figure 1 Results of Static Equilibrium Analysis of Alternative Fuel Penetration, Year 2010 Projected Fuel Shares (Leiby, 1993)**

In contrast to these 1993 estimations of long-run gasoline substitution, in 2001 replacement fuels contributed only 2.6 percent of total on-road motor fuel, on a gasoline gallon

equivalent (GGE) basis. This is despite efforts by the Department of Energy to promote alternative fuel use in government fleets and other markets and despite the 1.7 million E85 flexible fuel vehicles (FFVs) on the road by 2001 (EIA, 2000, 2001, 2002). As described in detail below, it is also quite unlikely that the 30 percent displacement goal for the year 2010 will be met. This shortfall from the projections based on comparative-static analyses can largely be attributed to an incomplete understanding of the magnitude and importance of certain key dynamic or transitional impediments to alternative fuels. This earlier work provided critical foundations for our transitional analysis.

### **III. Transitional Analysis**

As recognized in DOE's own analysis, past studies of the alternative fuel (AF) and AFV penetration either assumed mature markets with large-scale vehicle production and the widespread availability of alternative fuels at retail stations, or assumed immature markets and small scale production. Early studies of the AFV market can be grouped into those which are static, single year snapshots (Sperling, 1988; National Research Council, 1990; USDOE, 1996), and those which are multiyear analyses (Fulton 1994, Rubin 1994, and Kazimi 1997a, 1997b), still with limited degrees of dynamic detail. Obviously, the static analyses are limited in that they cannot assess the feasibility or cost of a transition to the new long run equilibrium. Furthermore, in many cases their conclusions, as well as those of most early dynamic models, reflect exogenous assumptions regarding fuel and vehicle prices or AFV penetration rates or both. Those results, in fact, can turn out to be misleading. This is because barriers to new fuels and technologies are real and, for the case of transportation technologies, economically important. Recognizing these issues, DOE commissioned the transitional alternative fuel and vehicle model (TAFV).

The overall objective of the TAFV model is to assess the competitive market outcome over time, without and with possible new policy initiatives. Rather than taking fuel and vehicle prices and penetration rates as an input, they are determined from market conditions. Operationally, this is equivalent to maximizing consumer and producer surplus (well-being) from transportation services provided by the light duty vehicles (cars and trucks) and a variety of possible fuels. The TAFV model characterizes interactions among fuel providers, vehicle producers, fuel retailers, private vehicle purchases and fleet vehicle programs. Each of the supply sectors is represented by a single period cost function defined for each time period, region, fuel, and vehicle type. Examples include: vehicle production costs; fuel production or conversion costs; fuel retailing costs; raw material supply costs; and sharing or mix costs associated with vehicle and fuel choices. The cost functions summarize the way in which changing levels of activities, inputs, and outputs affect the costs for each supply module, and implicitly define the cost minimizing behavioral relationships among the model's variables.

Benefits in this model come from the satisfaction of final demand for transportation services as determined from projections of light duty vehicle fuel use (excluding diesel) for 1996 to 2010 given in the Annual Energy Outlook. The total demand for light duty fuel is satisfied by the use of existing (used) vehicles and the purchase and use of new vehicles. The use of older vehicles is limited by the stock of each vehicle type given a fixed, age adjusted use profile. Each year, to the extent that existing vehicle stocks are insufficient to satisfy the demand for transportation services, a mix of new vehicles is purchased. New vehicles are chosen according to a nested multinomial logit (NMNL) choice formulation, whose parameters come from

(Greene, 1994). Vehicle choice is based on upfront vehicle capital costs, nonprime vehicle attributes and expected lifetime nested fuel choice costs. Fuel choices must be made for the vehicles that are dual or flexibly fueled. Since vehicle and fuel choice is endogenous, it is important to specify which fuel and vehicle characteristics are considered in the fuel and vehicle choice submodules, and which characteristics are endogenously determined. A more detailed presentation of assumptions and data sources can be found in Leiby and Rubin (1997, 2000, and 2001).

#### **IV. Key Transitional Phenomena**

From preliminary analysis and discussions with experts, we identified key areas that could strongly affect the transition to alternative fuels and vehicles. These include the costs to consumers of limited fuel infrastructure and retail availability of alternative fuels; scale economies for vehicle production and fuel retailing; the implications for consumer behavior of initially limited AFV model choice and diversity; the prospect for technological improvement (cost-reduction) through learning-by-doing; and any costs to consumers from being unfamiliar with a new technology. Because of their potential importance, all these transitional barriers, except for those related to consumer unfamiliarity, have been explicitly modeled. We did not model the costs of consumer acceptance for new technologies since we had little information to make realistic parameter estimates. As our results below suggest, omitting this additional possible cost is unlikely to have altered any of our qualitative results, since the AFV market has a difficult time getting started given the transitional barriers that we do include.

##### **IV.1 Effective Costs of Limited Retail Fuel Availability**

Most alternative fuels are currently available at only very few retail stations. First principles and evidence from surveys of diesel car buyers (Sperling and Kurani, 1987) suggest that fuel availabilities (station shares) below 10% can impose large effective costs on consumers. There is, however, little empirical evidence as to the possible size of these costs. Our approach is to use work by Greene (1998) who asked the following question in two national surveys:

"Suppose your car could use gasoline or a new fuel that worked just as well as gasoline. If the new fuel costs 25 (or 10, or 5) cents LESS per gallon but was sold at just one in 50 (or 20, or 5) stations, what percent of the time would you buy this new fuel?"

Greene used a variety of functional forms to estimate a random utility, binomial logit choice model. He found it hard to discriminate among functional forms based solely on the degree of fit to data and noted that we are particularly uncertain about the effective costs of fuel availability at very low levels (less than 5% station share). Besides issues of fit, we have chosen to use his exponential functional form because our intuition tells us that at 50% fuel availability (every other gas station) the cost penalty ought to be small. For the exponential functional form, the cost penalty at 50% availability is 2¢ per gallon. At 0.1% fuel availability the cost per gallon is uncertain, but using the exponential functional form, is conservatively estimated at 35¢ (see Figure 2).

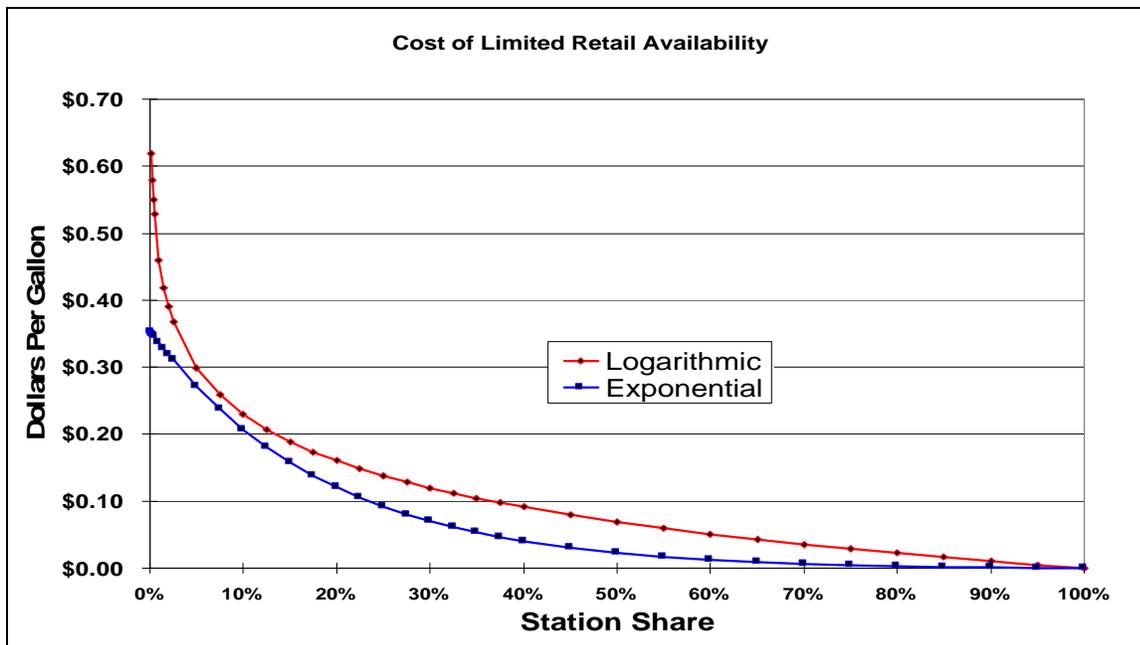


Figure 2 Effective Cost to Consumers vs. Fuel Availability

#### IV.2 Vehicle Manufacturers' Costs per Model and Economies of Scale

The TAFV model is designed to estimate the costs of vehicle production for the following alternative fuels: liquefied petroleum gas (LPG), compressed natural gas (CNG), methanol and ethanol, and electricity. The vehicles are either dedicated to a particular fuel type or are capable of using both gasoline and the respective alternative fuel. The one exception is electricity, which is a direct fuel input only to dedicated EVs. AFV costs are calculated from engineering-economic estimates of the incremental cost of each AFV fuel technology compared to conventional vehicle technology (EEA, 1995). The AFV technologies that we model, except for electric vehicles and HEVs, are assumed to be mature. Here "mature" means that, for a given production scale, further production experience will not reduce per unit vehicle production costs at a rate significantly faster than it would for conventional vehicles.

There do exist, however, substantial economies of scale in vehicle production. That is, there are sharp reductions in per unit vehicle cost with larger scale production. Scale economies occur greatly around 10,000 vehicles produced per year, with full economies are achieved at 100,000 vehicles per year. We therefore model per unit vehicle production costs as a declining function of the installed production capacity available in each year. The volume of production in any given year is constrained by the level of cumulative capacity investment less capacity decay. This means that vehicle prices and manufacturing capacity are endogenous variables. This has the advantage of admitting the positive feedback effects from policies that encourage the early adoption (and hence larger scale production) of AFVs.

#### IV.3 Accounting for Vehicle Model Diversity and the Effective Cost of Limited Diversity

Consumers contemplating buying a new gasoline-fueled car are offered a wide variety of vehicle makes and models with a huge number of features to choose among. The market-wide attractiveness of an alternative fuel or HEV technology will depend on the diversity of vehicle

models for which it is made available. Offering, for example, methanol fuel technology on only a single model will put methanol vehicles at a disadvantage compared to gasoline vehicles, all else equal. At the same time, offering methanol capability on several different models is expensive because it lowers plant scale for any overall level of production. Thus, during the transition period for a new vehicle technology there is an inherent tension between providing model diversity and achieving economies of scale.

Rather than predetermining the number of makes and models offered with alternative fuel capability, we endogenize the level of model diversity by balancing the additional production costs off against the additional consumer satisfaction. This is accomplished by defining a variable that represents the number of makes and models for each vehicle-fuel type produced. On the vehicle production side we divide the total industry production capacity for each vehicle-fuel type by this diversity variable to get average production scale for that vehicle type; on the consumer side we incorporate the diversity variable into our multinomial choice framework.

The value of diversity to consumers depends on the order in which vehicle manufacturers introduce a new fuel or vehicle technology to their existing model lines. This is because different models have market penetrations that vary from a few thousand per year for specialty cars to well over one hundred thousand for some popular cars and pickup trucks. If alternative fuel capability is introduced "randomly" on different vehicle models, then we estimate the cost to be initially \$2080 per vehicle. If instead manufacturers add the AF technology to the most popular model line first, then the effective cost to consumers of limited model-diversity is lower (\$727 per vehicle). When AFV offerings ultimately have the same richness of models as gasoline vehicles, then the limited-diversity cost is \$0 per vehicle. In the simulation model we assume that the AF technology is offered on the most popular model first. Thus the significance of the initially limited model diversity for new vehicle technology depends upon the strategy that manufacturers adopt when introducing the technology. If the technology is introduced on a new, unfamiliar, and made-to-purpose vehicle (such as Honda initially did with the Insight HEV), then the deterrent effect of limited model diversity is far greater than if manufacturer takes a chance by introducing the technology on its most popular vehicle (such as the Honda subsequently did with the hybrid Civic).

#### **IV.4 Technological Cost Reduction and Learning-by-Doing**

Learning-by-doing (LBD) is the process by which the costs of new technologies decline as a function of cumulative experience. This phenomenon is observed in various industrial situations where it is described as a learning curve, progress function, or experience curve. It is important to distinguish LBD, scale economies, and learning by technological progress (the latter is closely related to R&D spending.)

The theory of LBD was first expounded by Arrow (1962). Empirical studies using historical data suggest learning rates in the range of 5%-20% per doubling of experience (e.g. Lieberman 1984, IEA 2000, McDonald and Schrattenholzer 2001). At the same time, however, these rates must be used with great caution. This is because, as McDonald and Schrattenholzer note, the empirical literature varies in its methodologies and data sources by which learning rates are calculated. For example, the literature does not always disaggregate learning from the effects of scale or research and development (R&D) expenditures. Sometimes the dependent variable is price, rather than cost, and price is influenced by supply and demand factors not related to learning. Finally, the time period chosen for the empirical analysis can also affect the calculated

learning rate. Notwithstanding these limitations, LBD, as documented in the empirical literature, appears to be an important component of technology change and cost reduction. The existence of substantial learning may also be important for determining good public policies designed to spur new technologies.

A concept related to LBD is learning from research and development (R&D). The Partnership for a New Generation of Vehicles and FreedomCAR programs are classic examples of this research-based approach to advanced automotive design. Public policies to encourage new technologies can encourage both R&D and LBD. However, the prospect of learning from R&D can have significantly different policy implications than LBD. As Goulder and Mathai (2000) show in the context of climate change, if knowledge is gained primarily through R&D, then it may be justifiable to shift abatement to the future - i.e. to act later. If cost reductions are also gained via LBD, then the impact of learning and technological change on the timing of abatement efforts is ambiguous. The same reasoning may be applied to policies for promoting new vehicle technologies. Depending on the particular technologies and assumptions, it may be optimal to act sooner, implement technologies, to learn and thereby lower future costs. If the endogenous learning-by-doing rate is sufficiently rapid, LBD proponents argue that forcing a sharp divergence from existing technologies by performance mandates could induce otherwise uneconomic technologies to become economically viable.

For the TAFV modeling results described here we assumed that the prospects for (non-hydrogen) AFV cost reduction through LBD were no greater than those for conventional vehicles, based on the views expressed by those who provided the AFV cost estimates (EEA Inc). This means that the incremental costs for AFVs relative to conventional vehicles did not improve through LBD. For hybrid vehicles, on the other hand, we assumed that given the comparative newness and complexity of the technology a moderate rate of LBD could be gained, a 10% reduction in cost per doubling of cumulative production experience. The net effect implied is that by the time HEV production reaches a significant share of total new vehicles produced, HEV costs (for large plants) could decline to about one-half of their initial level.

## **V. Lessons Learned About the Transition to New Fuels and Vehicles**

Despite the range of federal, state and local initiatives to promote alternative fuel use since the 1980s, there has been little progress in either developing alternative fuel infrastructure, advancing the alternative fuel transition, or achieving alternative vehicle sales and fuel sales. Apart from the mandated sales of AFVs to some fleets, the principal exception has been the sale of over 4 million ethanol flexible-fueled vehicles. This sale of FFVs, mostly to private consumers, is completely understandable (and was predicted by the TAFV model) as the most profitable response of domestic vehicle manufacturers to the federal provision of CAFE credits for FFVs in AFMA (Rubin and Leiby 2000). However, as was also anticipated, these vehicles use little or no ethanol, their FFV property is virtually irrelevant to most owners, and an associated ethanol supply infrastructure has not developed, except in selected states with heavy ethanol subsidies. These historical facts alone provide useful lessons about the prospective transition to hydrogen fueled vehicles. The transitional analyses done with the TAFV model help to explain these outcomes, and allow investigation of possible future outcomes under different policies and incentives, as well as different market conditions and oil price regimes.

In analyzing the transition to other alternative fuels than hydrogen (ethanol, methanol, CNG, LPG, and electricity), analyses with the TAFV model led to some important conclusions

which bear on the proposed hydrogen transition. We find that the transition matters a lot. Furthermore, we can identify some of most important barriers. For AFVs, the most important barriers seem to be limited fuel availability and vehicle scale economies. For HEVs, incremental vehicle costs are large so vehicle scale economies also matter but scale cost reductions are more easily attained by the use of widely shared components (batteries, motors, controllers, etc.) across multiple vehicle platforms. Similar gains should be possible for FCVs. For HEVs, the dominant transitional factor is the uncertain prospect for learning-by-doing.

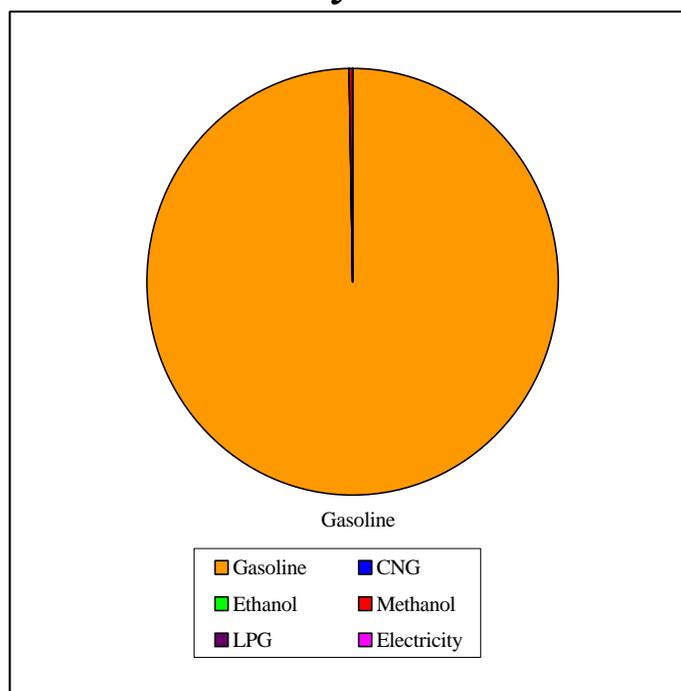
Both the real-world experience with federal and state fleet AFV programs over the last decade and modeling analyses of proposed expanded private and local fleet mandates indicate that forcing vehicle technology adoption by a few doesn't work unless the technology has private appeal. This does not bode well for the strategy of niche introduction.

### **V.1 Transitions Matter (A Lot)**

The barriers to new fuels/technologies are real, and are economically important. Some barriers are transitional, and some barriers will endure so long as overall market conditions (such as oil prices and environmental policies) do not change fundamentally. We find that static equilibrium analysis of the prospects for new vehicle technologies is misleading.

Modeling experiments confirm that transitional barriers, and the particular transition paths pursued, matter a lot for the technology's ultimate market success. Using similar technology and market assumptions as the original DOE (1993) study on alternative fuel vehicles, we re-estimated the likely market penetration of alternative fuels by 2010 using a dynamic analysis and incorporating transitional factors. We incorporate the transitional factors discussed above: vehicle and production scale economies, consumer costs of low retail fuel availability, consumer costs from limited AFV model choice, slow turnover of the on-road vehicle fleet. We did not assume any substantial learning-by-doing for the AFV technologies considered (M85 and E85 dedicated and flex vehicles, CNG and LPG dedicated and dual-fueled vehicles), given the maturity of the technologies. LBD is more likely for electric-drive vehicles (EVs, HEVs, and FCVs).

## *Transitional Analysis With Barriers*



**Figure 3. Year 2010 fuel shares, accounting for transitional barriers suggests that the market share of alternative fuels may be small, absent significant oil price change or large and new incentives. Compare with Figure 1, the results of analysis omitting transitional barriers.**

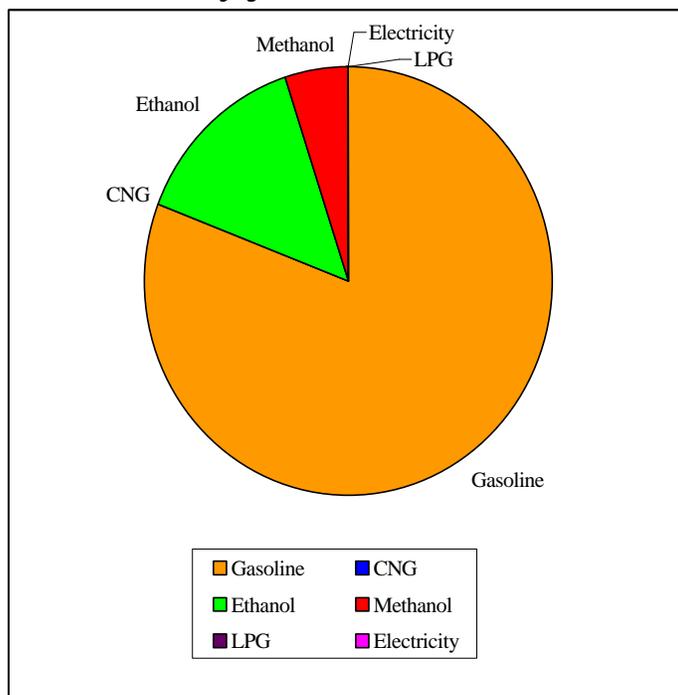
The new results, accounting for the transition and potential barriers to alternative fuels, are strikingly different from the long-run equilibrium analyses (Figure 3). We found that transitional barriers will prevent any significant alternative fuel use by 2010 without sustained, expensive market interventions. Moreover, we estimate that these market barriers are approximately equivalent to a cost of \$1 per gallon now, and persisting at a level of \$0.50 per gallon by 2010. Finally, absent major new government policies to promote alternative fuels or reduce greenhouse gases, it is unlikely that the United States will achieve or even approach EPACT's 2010 displacement goals (Leiby and Rubin, 2001). These transitional barriers are likely to have similar implications for prospects of hydrogen and fuel-cell vehicles.

### **V.2 Coordination, Choice, Scale, Learning**

There is a conflict between diversity of choice and economies of scale and network economies for fuel provision. This means that at the level of vehicle makes and models offered, there is a tradeoff between offering the consumer many vehicle choices and achieving low cost vehicle production levels. For AFVs, initial vehicle costs at low scales are 10% to 50% higher than their full scale costs, and achieving scale economies quickly is essential for profitability. More largely, it means that at the level of the market selection of vehicle and fuel technology, there is a major tension between the merits of producing different AFV technologies for different circumstances and for different consumer regions or market segments, and the *substantial* scale and network economies associated with producing and fueling a single vehicle-fuel technology. This tension proves to be more important than most would think, particularly when we account

for transitional barriers. In the early long-run comparative static analyses of 1993, it was estimated that as many as five different AFV technologies would compete and contribute simultaneously to displace significant fractions of gasoline. The modeling analysis that included transitional issues repeatedly found that not only was it hard for any AFV to gain market share, but that when gasoline was displaced at *most* one or two alternative fuels could simultaneously exist in the market (see Figure 4). This point also has significance for the problematic enterprise of "picking winners," i.e. choosing particular technologies to promote: if only one or two new technologies can survive in the challenging network of vehicles and fuel, the costs of choosing and promoting what might be the wrong one is even higher.

### ***Subsidy for Low-GHG Fuel***



**Figure 4** Year 2010 fuel shares for case of large subsidy for low GHG fuels.

### **V.3 Forcing a Relatively Small Market Segment to buy AFVs will not Work**

The USDOE has the authority under EPACT to require private fleets and those of state and local governments to purchase AFVs, expanding the fleet AFV sales mandate to about 2% of total vehicle sales. The estimated outcome of imposing the private and local (P&L) 2% fleet mandate is that non-fleet vehicle owners are also induced to purchase an additional 2.9% of AFVs by 2010. Thus, under this rule we estimate that a total of 4.9% of new vehicle sales would be AFVs by 2010. Thus, the P&L fleet rule could help reduce transitional barriers by lowering the cost of AFVs. Unfortunately, the vehicles chosen are mainly alcohol FFVs; which use very little alternative fuel given its high cost. Furthermore, the fleet and private demand for AFVs encouraged by the EPACT mandates crowds out induced value of the CAFE credits. That is, the AFV demand induced by the fleet mandate far exceeds the number of AFVs eligible for the CAFE credit, and the credit value falls to zero. As with the base case, fuel price sensitivity analysis shows these results to be quite robust.

More fundamentally, this type of mandate does not work because you have to have a superior product in terms of private value for this to effectively induce voluntary adoption of the technology. This policy does not provide that additional value and does not address the issue of fuel retail availability. Again, absent compelling advantages in *private* value, sustained, significant policy intervention is required. Because the P&L rule did not address this issue, it will not be effective. Moreover, this program is quite costly. As can be seen in Figure 5, the cost of an expanded fleet AFV mandate is as much as \$1.40 per gallon gasoline-equivalent displaced under current oil prices.

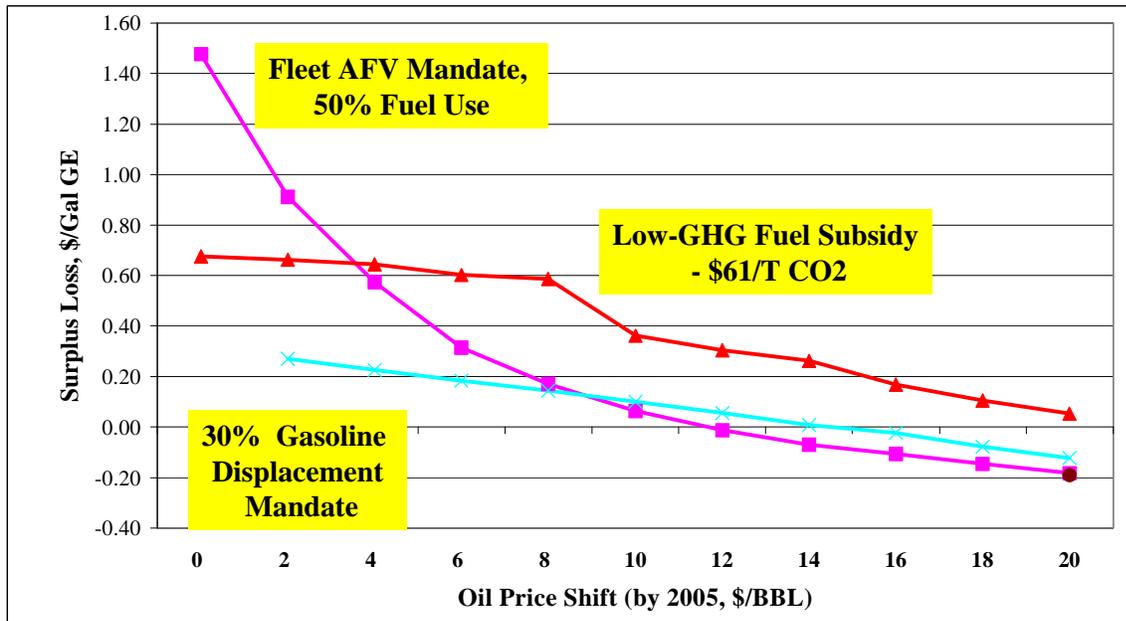


Figure 5. The cost AFV policy tools versus oil price levels. Cost is measured as net social surplus loss per GGE of gasoline displaced, excluding externalities.

Both the real-world experience with federal and state fleet AFV programs over the last decade and modeling analyses of proposed expanded private and local fleet mandates indicate that forcing vehicle technology adoption by a few doesn't work unless the technology has private appeal. This does not bode well for the strategy of niche introduction, given the experience to date and the model implication that is hard for niche vehicles to move out of the niche. Moreover, statements by fleet managers and vehicle manufacturers emphasize that fleet owners are very sensitive to the life-cycle economics of their vehicles, including their "residual" or resale value in the general market after a few years of service. Commercial and government fleets, which often rely on quite conventional passenger vehicles, prove to be a demanding market for new vehicle types, rather than a natural or easy market.

#### V.4 Importance of Oil Prices as a Long-run Barrier

The comparatively low price of oil projected by many government agencies (e.g. U.S. DOE/EIA 2003), both relative to the history of the last few decades and relative to the current and projected price of alternative fuels, presents a significant and sustained barrier to new transportation fuels. Overall, without compelling private advantages, large and sustained policy intervention is required to attain substantial market share for new fuel and vehicle technologies,

particularly AFVs or advanced (e.g. full 300V) HEVs. Modeling analyses also indicate that a temporary oil market shock, even when coupled with moderate subsidies or vehicle sales mandates, cannot induce significant AFV market share so long as consumers anticipate that the oil price increase will fade away after two years.

Without eliminating this long-run cost barrier, transitional policies can be ineffective and costly. Figure 5 shows how the cost of gasoline displacement by AFV declines as the relative cost of oil increases. Alternatively, under sustained higher oil prices, transitional policy can work. In these circumstances, both price and non-price incentives can be effective, as shown in Figure 6. Figure 6 shows the estimated share of gasoline displaced in 2010 by (non-hydrogen) alternative fuels for a range of higher oil price levels. The horizontal axis labeled "Oil price shift" refers to the increase of oil prices above the EIA base path, achieved gradually over the next 5 years, and sustained thereafter. Similar market share results hold if sustained higher costs are imposed for carbon emission, at levels that provide an equivalent price differential for alternative fuels.

However, some strategies which are quite costly and ineffective under current market conditions become quite efficient at inducing new vehicle technologies when coupled with a permanent oil price increase or a major change in environmental policy. Early vehicle *and* fuel use mandates in selected fleets, and possibly other niche applications, are costly under current market conditions but appear to set the groundwork for rapid technology gains and infrastructure development if market conditions (such as oil price or the price of carbon emissions) change radically and enduringly. Thus these high-cost programs have option-value in the face of energy market and environmental uncertainty.

Simulations also suggest that a deployment mandate or niche application can be an effective strategy *if* one anticipates substantial technological LBD. This is relevant for hydrogen problem.

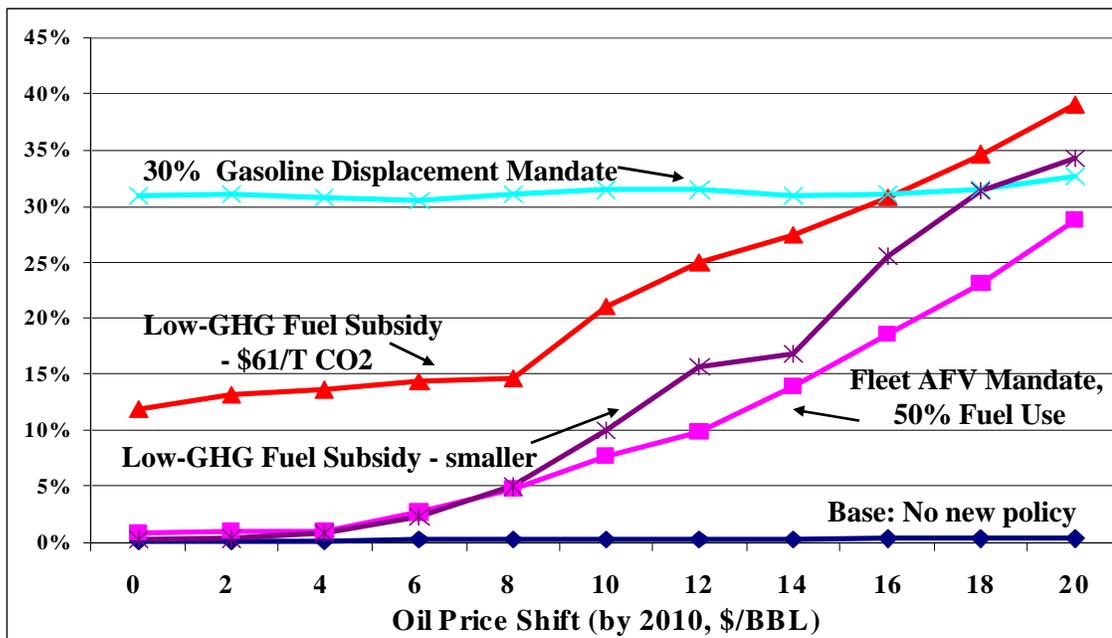


Figure 6 Effectiveness Policy Tools at Different Oil Price Levels (2010 Alternative Fuel Share vs. Oil Price)

Shift)

### **V.5 The Ability of Conventional Technology to Adapt can Forestall the Transition**

The U.S. historical experience since the 1988 AFMA and the 1990 Clean Air Act amendments created a serious interest in alternative fuels has shown how hard the transition to new motor fuels can be. It has also shown that established, or "conventional" technologies and industries can and *will* respond to the challenge of a substitute vehicle or fuel. The pressure for clean and alternative fuels was answered by the development of reformulated gasolines. Some of the newly formulated conventional fuels embodied alternative fuel components and blends, providing a path for a measure of renewable and alternative fuel use in existing vehicles without the need for wholly new fuel distribution infrastructures or markedly new vehicle designs. Vehicle manufacturers also demonstrated the ability to produce increasingly clean gasoline-burning engines, sharply reducing the air-quality motivation for alternative fuel vehicles. Manufacturers ultimately produced near Zero-emission vehicles (near-ZEV) that challenged the need for the ZEV mandates in some states and diminished the pressure to produce electric vehicles. This demonstrated ability of the fuels and vehicles industry to respond by adapting conventional systems was not including the TAFV modeling analyses, which considered a range of vehicles but took vehicle designs as static. However, provision for this natural market response should be made in the planning and analysis of potential future transitions.

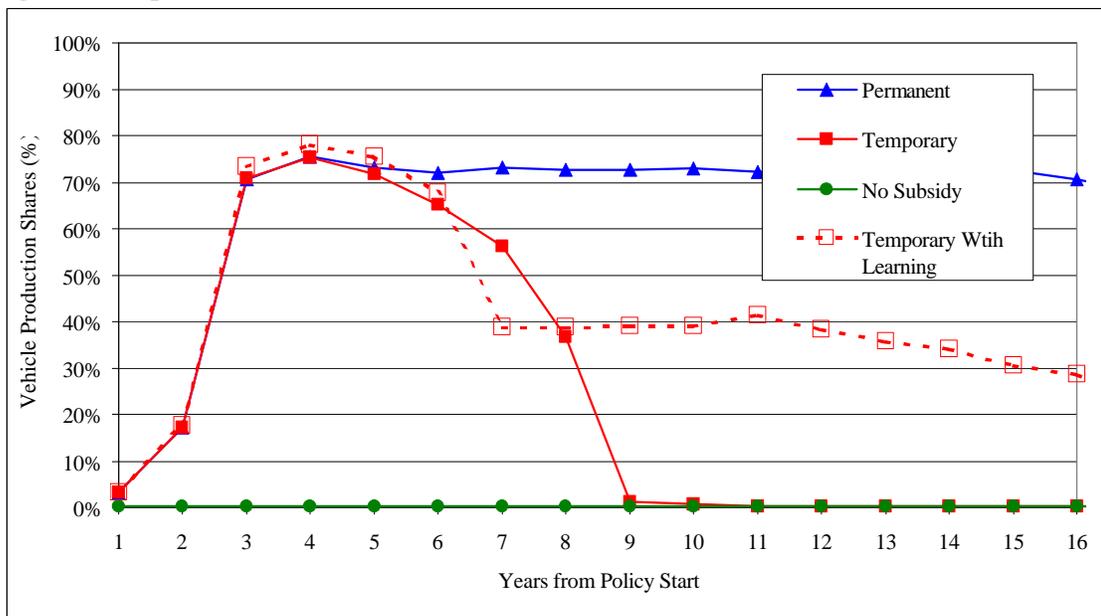
### **V.6 Technology Change Important, Yet a Poorly Understood Issue for the Transition to Hydrogen**

Learning curves are widely believed to be important and significant for many new technologies. But representing learning is tricky and its magnitude and timing is not well understood. In addition, if one accounts for cost reductions through learning by doing (LBD) when assessing policy for a technology transition, a balanced approach would also consider the potential for two countervailing effects: the learning or adaptability of conventional technology and its ability to also get better; and the potential for "forgetting," the flip-side of learning

The choice of an index of experience to use for LBD has long been of topic of research. In TAFV, there are several ways to model cumulative experience: as cumulative new production capacity or new vehicles sold, or as total installed production capacity or number of vehicles on the road (total stock). Given that production capacity and vehicles are scrapped over time, these later two methods allow for "forgetting" as well as learning. Globerson and Levin (1987) have argued that we should incorporate both learning and forgetting into institutional environments. Benkard (2000), drawing on data from the aircraft industry, showed that in certain industries there is evidence of organizational forgetting: "production experience actually depreciates over time, and knowledge gained from building one product doesn't necessarily spill over to the next generation." Benkard found that a model that includes depreciation of experience accounts for the data much better than the traditional learning model. We model LBD in terms of total installed vehicle production capacity. This assumption allows both accumulation and depreciation of experience, and does affect our results. Short-lived vehicle subsidies, if they are insufficiently large or long in duration, may be unable to induce a sustainable HEV production sector. Such temporary subsidies may only temporarily lower vehicle production costs from learning.

Without subsidies we project no substantial penetration by HEVs, based on their

prospective fuel efficiency gains and costs. This may reflect an overly pessimistic assessment of the costs of hybrid technologies. If so, our results should be interpreted to hold with lower levels of subsidies than indicated. Hybrid subsidies (on the order of \$2000 per vehicle) can induce substantial hybrid penetration and gasoline demand displacement under EIA's 2001 oil price projections (see Figure 7). This result is quantitatively different from the result achieved for AFVs. The efficacy of HEV subsidies is much greater than for AFVs because of the latter's huge infrastructural needs. The HEVs sold are primarily of the "mild" hybrid type, a 42-volt system that achieves modest fuel efficiency gains (15%) with greater cost effectiveness than more extensive hybrid designs. Temporary HEV subsidies are effective at inducing hybrid vehicle penetration, but do not have long-term effects once they are removed *unless* there are cost reductions due to LBD. With LBD we found that a high enough temporary subsidy can be effective in assisting hybrid vehicles to overcome transitional barriers and to become self-sustaining in a competitive market.



**Figure 7. HEV Production share with permanent and temporary (\$2400) subsidy, and with temporary subsidy given Learning By Doing.**

Clearly LBD is an important factor. Its importance for costs has been validated in the literature and confirmed in empirical studies of many industries. Its importance for new vehicle policy was validated again here. But, while important, learning is very tricky to represent. For this reason, in order to better understand the prospects for transitions to new vehicle technologies, including AFVs, hybrids, and fuel cell vehicles, further work is needed to refine the estimates of technology costs and learning rates.

**V.7 Lessons and Challenges for Hydrogen Fuel Cell Vehicles: Is H2 different?**

One might ask whether the challenge of the transition to hydrogen vehicles is different from that of other alternative fuel vehicles or hybrid vehicles. In some ways the answer is "Yes," particularly since there are substantial prospects for non-transportation applications of hydrogen and fuel cells, and the opportunity for some synergistic development and efficiency gains

between the sectors. Also, FCVs involve a host of new supply, distribution, storage, and vehicle technologies, some of which still have the possibility of marked improvement and cost reduction. On the other hand, one could argue that hydrogen FCVs are much the same as AFVs, facing all of the same challenges, "only more so" FCVs face the same monetary and business plan challenges of new technologies (like HEVs), and the same fuel system challenges of AFVs, exacerbated by the particular properties of hydrogen gas. Finally, they face the same doubts about political sustainability.

One clear lesson from our analysis of AFVs and hybrids is that an assessment of hydrogen's potential as a fuel for FCVs (FCVs) must consider transitional barriers; a simple mature scale cost assessment will be misleading. Although there has been considerable speculation, and some scenario development, there has been little rigorous analysis of alternative ways the transition to hydrogen could take place. At present, no modeling system exists that can integrate the development of infrastructure (production, distribution, storage, and retailing), motor vehicle production, the evolution of demand, as well as the necessary policy context, over time and geographically within the United States. Potentially important interactions with other energy sectors such as electricity generation and the spatial and geographic detail in the location of production, delivery and demand are very important issues that are clearly essential for a fully satisfactory representation of the transition to hydrogen. As with hybrid vehicles, modeling endogenous LBD and exogenous R&D will be important.

On the hydrogen production side, the existence of multiple potential supply pathways and technologies is important to consider in the context of economics. One of the results from the AFV transition analysis was that cost savings attainable with specialization of vehicle production and fuel infrastructure outweighed the benefits of diversity of fuel and vehicle types. This may be true for hydrogen production pathways. On the other hand, the diversity of potential feedstocks across the nation may allow different regions to specialize in particular pathways. One possible issue for consideration is whether early movement to a small-scale onsite production system would advance or impede larger scale hydrogen use over the long term.

Given the magnitude of the costs involved in transitioning to hydrogen FCVs and the possible links to the electricity generating sector, transitional modeling may require a general equilibrium framework as is currently common in models evaluating the regional and global effects of GHG reduction policies such as MERGE (Manne, et al. 1995). Such a framework would account not only for the interactions among many economic activities in multiple sectors, but also for the aggregate effect of large scale investments in the hydrogen system on tax flows and on the availability of capital for investment in other important competing economic activities (such as consumer goods production, health care or environmental management).

From the demand side, there an important transitional modeling issue involves how to account for the additional amenity value of fuel cells vehicles including, quiet operation, standby electricity generation power, and "green" value. At the same time, our AFV modeling work has shown the importance of recognizing the important disamenity of limited model choice and limited fuel retail availability. A good characterization of these issues would hopefully be able to indicate which fuel pathways and vehicle technologies provide the greatest value to consumers.

Finally, given the magnitude of costs involved in a transition to hydrogen FCVs, an important consideration (not explicitly addressed in the TAFV model) is likely to be of role of political commitment. Political commitment, or perceived lack thereof, will have a direct economic cost in terms of increasing uncertainty which will raise costs for fuel and vehicle

suppliers who make investments in equipment that will require use for many years to justify.

## **VI. Conclusions**

Overall, the market barriers to significant alternative fuel and vehicle use are substantial. We find that in the absence of any new and substantial policy initiatives, it may be difficult for the alternative vehicle and fuel markets to get started. Hydrogen FCVs face the same transitional barriers problems and barriers that are shared by AFVs, only more so. Our results lead us to several observations. First, in a market economy where vehicle manufacturers, fuel suppliers, and consumers all make independent decisions, the efficacy of government policies to reduce the dependence of the United States transportation sector on petroleum is highly dependent on the world price of petroleum. Second, the penetration of alternative fuels and AFVs depends on the fuel retail infrastructure, the ability of AFVs to achieve scale economies, and other transitional barriers. Third, governmental policies, if sufficiently large, can effectively reduce these barriers and can allow alternative fuels to compete in the marketplace with gasoline. However, given the current and expected low price of petroleum in the world today, doing so would be costly.

Given the world-wide nature of energy markets, there is a need to assess the competition from conventional vehicles and fuels and consider the response. Since the marginal production cost of oil is \$2-\$5/bbl in the Middle East, and transportation costs are low (in the \$1-\$2/BBL range) there is a persistent threat that the economics of alternative fuels, including hydrogen, could be undercut by oil supplier actions. If significant quantities of gasoline and diesel are displaced, their prices can and will most likely decline substantially. This is a natural consequence of the multi-product nature of the refining process, and limits to the flexibility of product mix during refining operations. This may be offset, however, by rising demand for petroleum in China and other developing nations.

Lest we appear too definitively negative about the transition towards AFVs and FCVs, we would like to make a few cautionary notes. First, there is obviously a large potential role for advances in technology to bring down the costs and increase the benefits of hydrogen fuel cell vehicles. In addition, we have tried to model the existing vehicle market within the current and possible future regulatory context. Growing energy security or environmental concerns could motivate sufficiently strong policies to achieve the transition. For example, were the United States to ratify the Kyoto protocol and require reductions in greenhouse gases from the transportation sector on the order of 20% by 2010, then the whole price regime for transportation would be fundamentally altered, potentially allowing AFVs and FCVs to be much more competitive.

Efforts to pick winning alternative fuel technologies have fared poorly, as demonstrated with California's experience with M85. Furthermore, the network nature of the fuel-vehicle market, large economies of scale and the prospect for learning through experience all indicate that the least-cost and natural market outcome is for a single vehicle and fuel technology to dominate (or a few closely related technologies). This suggests that policies for transitions should address targets, not technologies, since unexpected technologies may be superior to meet the goals, and second-best technologies may have little long-term market prospect.

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