Sustainable Transportation: Analyzing the Transition to Alternative Fuel Vehicles

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Abstract

The use of motor fuels by light-duty vehicles is a major contributor to oil demand and greenhouse gas emissions. The rate of introduction of alternative fuel vehicles will be an important influence on the time path of fuel use and emissions, and the sustainability of transportation patterns. The Transitional Alternative Fuels Vehicle (TAFV) Model simulates the use and cost of alternative fuels and alternative fuel vehicles over the time period of 1996 to 2010. It is designed to examine the *transitional* period of alternative fuel and vehicle use. It accounts for dynamic linkages between investments and vehicle and fuel production capacity, tracks vehicle stock evolution, and represents the effects of increasing scale and expanding retail fuel availability on the effective costs to consumers. Fuel and vehicle prices and choices are endogenous. The model extends previous, long-run comparative static analyses of policies that assumed mature vehicle and fuel industries. As a dynamic transitional model, it can help to assess what may be necessary to reach mature, large scale, alternative fuel and vehicle markets, and what it may cost. Various policy cases are considered including continued ethanol subsidies, tax incentives for low greenhouse gas emitting fuels, and the absence of transitional barriers.[1] In particular we find that a tax subsidy on low greenhouse gas emission fuels equal to the current $0.54 per gallon ethanol subsidy will yield a 20% reduction in annual greenhouse gas emission by 2010.

[1]Alternative fuel policies are evaluated in the context of gasoline price projections made by the U.S. Energy Information Administration (EIA) in 1996. Since the publication of those projections, the EIA's expected future oil and gasoline prices have been revised substantially down.

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Introduction

Alternative fuels (AFs) and alternative fuel vehicles (AFVs) have been identified both by the Alternative Motor Fuels Act (AMFA) of 1988 and by the National Energy Policy Act of 1992 (EPACT), as providing energy security benefits to the nation. In particular, EPACT requires certain percentages of new vehicle purchases by federal and fuel-provider fleets to be AFVs. At the same time, AFMA provides for favorable treatment of AFV fuel economy ratings in the calculation of each vehicle manufacturer's corporate average fuel economy (CAFE) standard. In addition to their possible energy security benefits, AFs and AFVs continue to be interesting for the reductions in emissions of criteria pollutants (see for example Kazimi, 1997) and greenhouse gases that they may be able to provide. The ability of AFVs to reduce the transportation sector's contribution to global warming is particularly important for long term sustainability because the transportation sector accounts for about 32% of all U.S. CO2 emissions, with motor gasoline making up 67% of the transportation sector total (Davis, 1997; DOE, Tables, 7.9 and 7.11). For AFs and AFVs to achieve substantial energy security and emission benefits, however, it is necessary for them to be widely adopted. This requires a large investments in fuel and vehicle infrastructure.

The Transitional Alternative Fuels Vehicle (TAFV) Model simulates the use and cost of alternative fuels and alternative fuel vehicles over the time frame of 1996 to 2010. As the model's name suggests, the TAFV model is designed to examine the *transitional* period of alternative fuel and vehicle use. That is, the model is a first attempt to characterize how the United States' use of AFVs might change from one based on new technologies available only at a higher-cost and lower-volume, to a world with more mature technologies offered at lower cost and wider scale. It also seeks to explore what would be necessary for this transition to happen, and what it would cost.

Previous studies of alternative fuels and vehicles differ in their estimates of the penetration rates and costs of AFVs. The Alternative Fuels Trade Model (AFTM, USDOE 1996, Leiby 1993) for example, found that there could be substantial penetration of alternative fuels and vehicles in 2010. Many of these studies are limited in that they examine AFVs in a single year. They present a 'snapshot' of AFV use given assumptions about technological maturity and price. The AFTM, notably, assumed mature vehicle technologies produced at large scale and a well-developed alternative fuel retail sector. Other studies, which examine AFVs in a multi-year, dynamic setting (e.g., Fulton 1994, Rubin 1994, Kazimi, 1997, and Bunch et al. 1993, 1997), take technologies and prices as exogenously given. That is, fuel and vehicle prices are determined outside of the model. In particular, they do not examine the important linkages between investments in alternative fuels and vehicles, investment in alternative fuel retailing infrastructure, and the prices and availability of those technologies.

This work follows up on the long-run equilibrium analysis done with the AFTM, which was a partial equilibrium model, used for long-run comparative static analyses. By making endogenous the scale of alternative vehicle and fuel production and the retail availability of alternative fuels, the TAFV model fills a gap in alternative fuel analysis. By endogenous, we mean that the vehicle and fuel prices are determined within the model based upon underlying supply and demand curves. In contrast to the AFTM, the TAFV model specifically characterizes the time path of investment and adjustment, in order to consider whether some of these transitional issues may be important. The results from the TAFV model do, necessarily, reflect its many primary assumptions such as the prices for vehicle and fuel production capital, the costs of raw materials, and input-output assumptions that describe the productivity of a unit of capital in its respective employment.

More generally, the TAFV model provides a methodology for simulating the introduction of new technologies where economies of scale and endogenous feedback effects are important. It is our belief that explicitly modeling these dynamic effects is very important and cannot be ignored for a wide variety of economic and environmental questions that involve either fixed investment in capital or pollution stocks such as greenhouse gas emissions. Other applications potentially include examining the importance of scale economies in the supply of materials for the Partnership for a New Generation Vehicle (PNGV) initiative and infrastructure requirements for fuel cells.

Principal Objectives

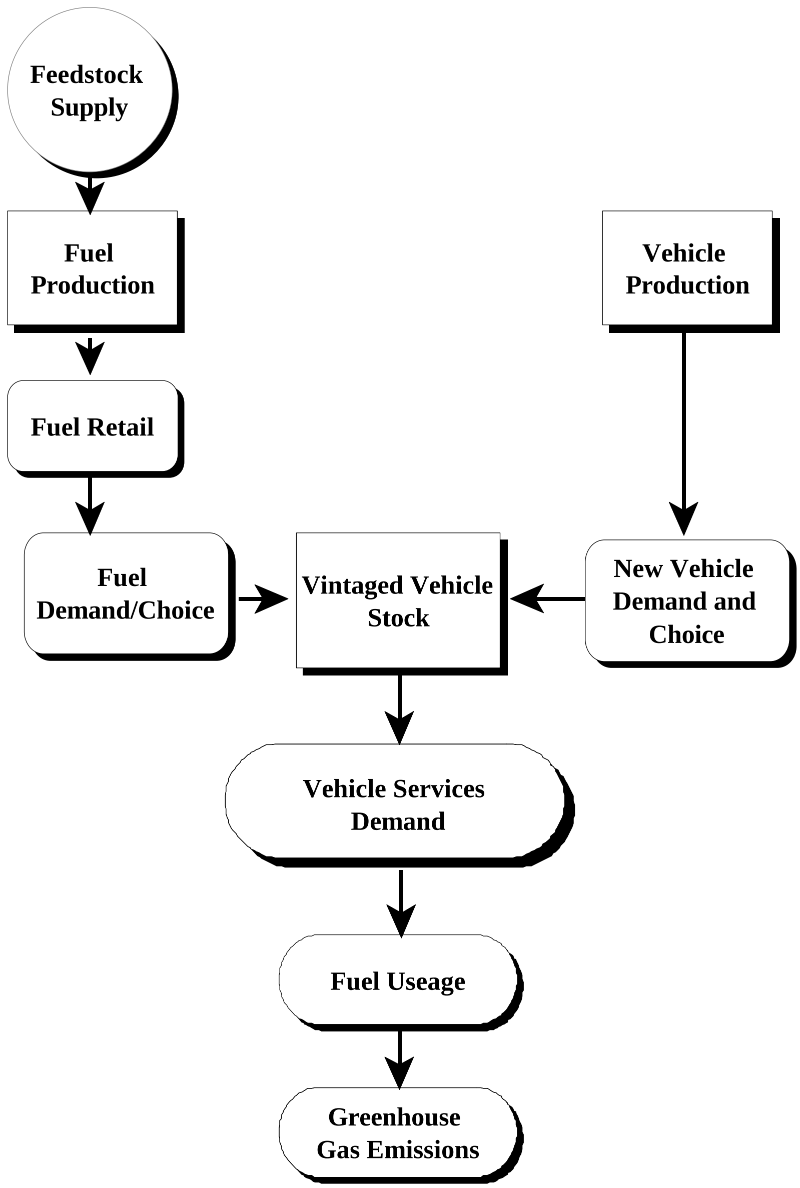
The principal objective of the TAFV model is to provide a flexible, dynamic-simulation modeling tool that can be used for policy analysis. One use of the TAFV model is to assess possible ways in which AFV fleet mandates (authorized under Energy Policy Act) or incentives *may* influence the AFV transition. Because of its flexible design, the TAFV model is also able to examine many other policy scenarios including the effects of taxes, subsidies and possible oil price shocks.

There are a variety of transitional phenomena at work in AFV markets, which might be influenced by policy. As alternative vehicle and fuel producers gain cumulative experience, some cost reductions through learning and economies of scale are expected. If vehicle manufacturers are encouraged to design and introduce new models with AF capability, the number of vehicle models offering AF capability rises, and consumers value this greater choice. Incentives or programs leading to the earlier development of fuel distribution infrastructure can increase fuel availability. This can greatly lower the inconvenience cost associated with refueling, lowering the effective cost of alternative fuels. Promoting the introduction of AFVs may allow consumers to gain familiarity, reducing their uncertainty about fuel and vehicle performance and reliability. Programs calling for the purchase of AFVs by fleets lead eventually to the sale of used fleet vehicles to private consumers, making AFVs available to used-vehicle buyers, increasing consumer familiarity with AFVs and alternative fuels, and possibly leading to expanded private demand for alternative fuels and AFVs. Each of these possible linkages may work slowly, as investments are made and vehicle and capital stocks adjust.

General Model Structure

The TAFV model characterizes, in varying degrees of detail, interactions among the major

Figure 1: Conceptual Diagram of TAFV Model



components shown in Figure 1 below.[2]

As is shown, new vehicles and on-road vehicle stocks are tracked by age. Also tracked are vehicle production capacities and utilization, and wholesale and retail fuel production and

[2]Further details on the general model structure can be found in Leiby and Rubin 1996, 1997.

capacity. Within these modules are endogenous feedback effects from: vehicle economies of scale; the relative richness or "diversity" of vehicle models offered with each AFV technology; economies of scale in fuel retailing; and, the cost to consumers of limited fuel availability. By incorporating the behavior of fuel suppliers, vehicle producers, and consumers the TAFV model can test a wide variety of government and private sector policies. These include AFV fleet mandates authorized under EPACT, tax policies which subsidize or penalize fuels based on their relative greenhouse gas (GHG) emissions, and policies which target the consumer or retail outlets.

Cost Function Representation of Modules

Each module is represented in terms of its current single-period cost function C_{trf}, defined for each year (t), region (r, corresponding to areas that use conventional or reformulated gasoline) and fuel (f). Examples of costs are: 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 sharing costs reflect the welfare loss due to the distortion of choice from the ideally preferred mix of fuel and vehicle non-price attributes, given unequal market prices of fuels and vehicles (Small and Rosen 1981, Anderson, de Palma and Thisse 1988, Leiby and Greene 1995). The cost functions summarize the way in which changing levels of activities, inputs, and outputs affect the costs for each module, and implicitly define the cost-minimizing behavioral relations for those module variables.

In some cases the module involves investments I_t in fixed capital stocks K_t with long-lived (multiyear) costs and benefits. If so, the module cost function includes the net cost of current activities (C^v) *plus* the costs of current investments ($I_t\ C_t^K$) minus the estimated discounted future value of all remaining capital stock at the end of the last year. Estimated future capital values are determined taking into account depreciation, discounting, and expected future use value. For the vehicle stock, the future use value declines with vehicle age reflecting the historical decline in miles driven per year as vehicles age.

Market Balancing Conditions

For each year, the objective is to represent a short-run market balancing which results from maximizing consumer and producer surplus. This means that we wish to assure that the following short-run conditions are met:

i. the marginal cost of producing each commodity equals its price;
ii. the marginal benefit of each demand equals its price;
iii. the marginal profitability of each intermediate conversion activity is zero (unless constrained, in which case short-run profits can be positive or negative); and,
iv. the marginal current-year value of investment equals the price of capital minus the discounted expected future value of the equipment from the next year.

We require incremental investment in technology-specific capital to be positive. If new investment is zero, the profitability of existing capital is insufficient to motivate new investment, and the last stated condition is not met. Disinvestment may be desired, but is not allowed.

The partial equilibrium solution is calculated with GAMS (Brooke, Kendrick and Meeraus 1992) and yields market clearing supplies, demands, trade, and conversion process levels. . It requires that supplies, plus net output from conversion activities plus net trades between regions must be greater than or equal to demand. Final demands and basic commodity supplies are "price responsive" in that their quantities will depend on market prices in each year. Fuel blending and conversion, fuel distribution and retail markup, and the combination of fuels with vehicles to provide vehicle services are represented with linear conversion processes. For conversion processes requiring durable capital equipment (such as methanol fuel production or vehicle production), the maximum level of activity is constrained by the amount of installed capital. In addition, a capital stock evolution constraint links depreciated capital and investment in each year to the next year's starting capital stock.[3]

Assumptions and Data

The important assumptions and data sources can be broken down into the following general areas.

- Wholesale fuel supply curves (annual) for
  - Gasoline
  - Natural gas supply (to transportation sector, net of other sector demands)
  - Ethanol supply (corn and cellulosic biomass)
- Wholesale fuel conversion costs and input-output coefficients
  - LPG (based on natural gas price)
  - Methanol (from natural gas)
  - Electricity
- Vehicle production cost curves
- Motor fuels taxes
- Retail fuel supply curves
- Greenhouse gas coefficients
- Fleet sales subject to AFV mandates under EPACT

Many, but not all of these assumptions and data sources are described in the pages below.[4]

Wholesale Fuel Supply Curves

[3]Technical details can be found in Leiby and Rubin (1997).

[4]Technical details can be found in Leiby and Rubin (1997).

Gasoline and Natural Gas

Annual wholesale gasoline and natural gas supply curves pass through the price and quantity projections from Annual Energy Outlook (AEO) (EIA, 1996a) taking into account price-quantity sensitivities as estimated by the AFTM. This methodology insures that the TAFV model uses the standard 1996-2010 AEO base price assumptions, but takes advantage of AFTM's extensive characterization of for the endogenous variation of price with quantity demand. These gasoline and natural gas supply curves can be seen in Figures 2 and 3. Each curve shows the price per gasoline gallon equivalent (GGE) in 1994 constant dollars as a function of the total quantity of fuel (million barrels of GGE per day) supplied in each year.

Figure 2: Gasoline Supply Curves

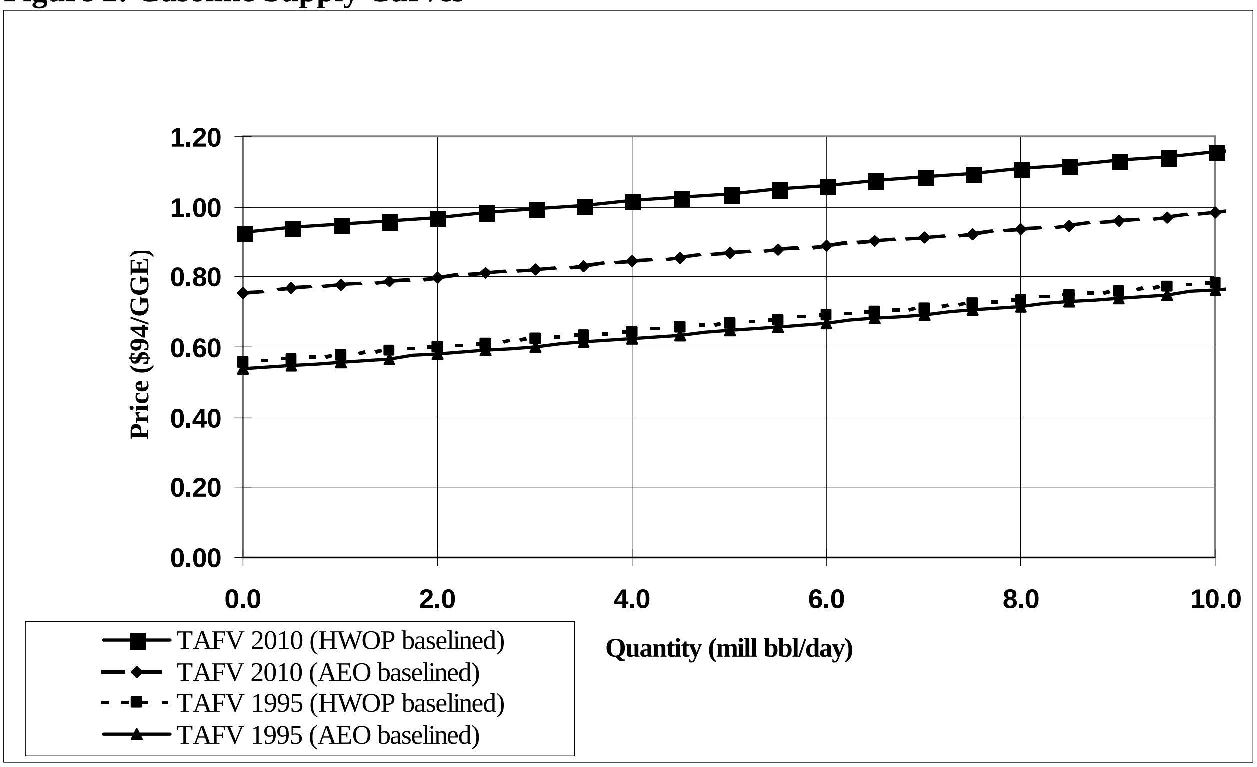
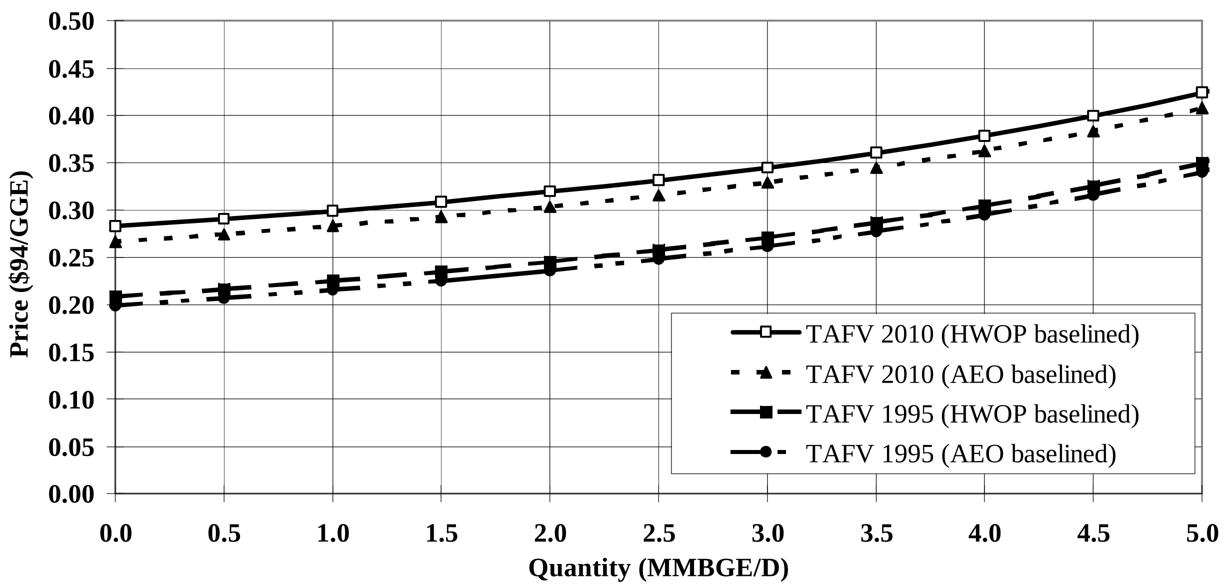


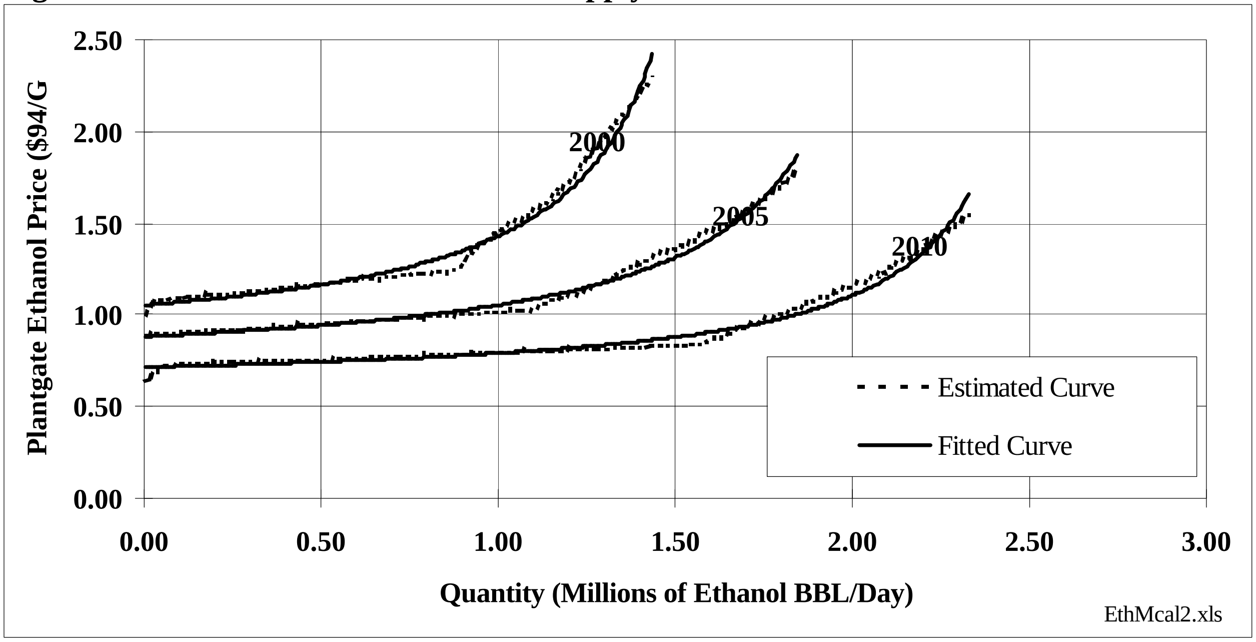
Figure 3: Net Natural Gas Supply Curves for Motor Vehicles



Wholesale Ethanol Supply Curves

Ethanol for use as either a neat fuel or additive can be efficiently derived from two primary sources: grains (corn) and woody biomass. Feedstock supply curves are derived from data provided by Walsh et al (1997), and Perlack (1997). The feedstock and conversion data were used to generate marginal cost curves for ethanol supply at five-year intervals. These aggregate biomass-to-ethanol supply curves reflect the least cost mix of the available biomass feedstocks. The aggregate supply curves were then fitted to a variable elastic functional form convenient for use in the TAFV model. These are shown in Figure 4 as the smooth fitted curves overlaying the more irregular estimated curves. Technical details on the construction of the ethanol supply curves can be found in Bowman and Leiby (1997).

Figure 4: Cellulosic Biomass to Ethanol Supply Curve



TAFV Motor Fuels Taxes

Taxes on gasoline and alternative fuels are a significant component of the overall cost of transportation services. Because fuel taxes are *not* equal on a per-mile or per-BTU basis, they can significantly alter the relative attractiveness of the fuels in providing transportation services. The base case results use current federal tax rates (26 USC Sects. 4041, 4081) and a weighted average of state excise taxes (USDOE, 1996, Table IV-1) and, for ethanol, a $0.54 per physical gallon "renewable" tax credit. These tax rates are shown below.

Table 1: Taxes per Physical Gallon (current dollars)

	Federal	State	Renewable Tax Credit	Total
LPG	0.18	0.14	0.00	0.30
M85	0.11	0.15	0.00	0.27
Gasoline	0.18	0.17	0.00	0.33
E85	0.13	0.15	-0.41	-0.09
CNG	0.06	0.15	0.00	0.20

Table 2: Taxes per Barrel of Gasoline Equivalent (current dollars)

	Federal	State	Renewable Tax Credit	Total
LPG	**10.53**	**7.62**	**0.00**	**18.15**
M85	**8.13**	**11.24**	**0.00**	**19.37**
Gasoline	**7.73**	**6.99**	**0.00**	**14.72**
E85	**7.50**	**8.87**	**-26.67**	**-10.28**
CNG	**2.47**	**6.32**	**0.00**	**8.79**

Retail Fuel Supply Curves

Although all of the fuel costs (e.g., taxes, wholesale fuels costs, transportation and retailing costs) enter the model separately, retail fuel supply curves may be constructed to gain an aggregate view of the relative retail costs of the fuels to consumers. Since the price of each fuel is a function of its level of use, each retail supply curve shown below is based on the assumption that all other fuels are held constant at their equilibrium levels. Fuel prices are baselined to AEO96 projections for 1996 and 2010. Looking at these curves, one sees that the retail price of E85 from biomass does become cheaper by 2010. This is due to expected technological advances in biomass conversion efficiencies. Over this same time period, however, the $0.54 per gallon tax credit is scheduled to be phased out. Were this tax credit not phased out (as is assumed in one of the policy scenarios discussed below) the retail price of E85 would be substantially cheaper than that shown below for 2010.

Figure 5: 1995 Retail Fuel Supply Curves

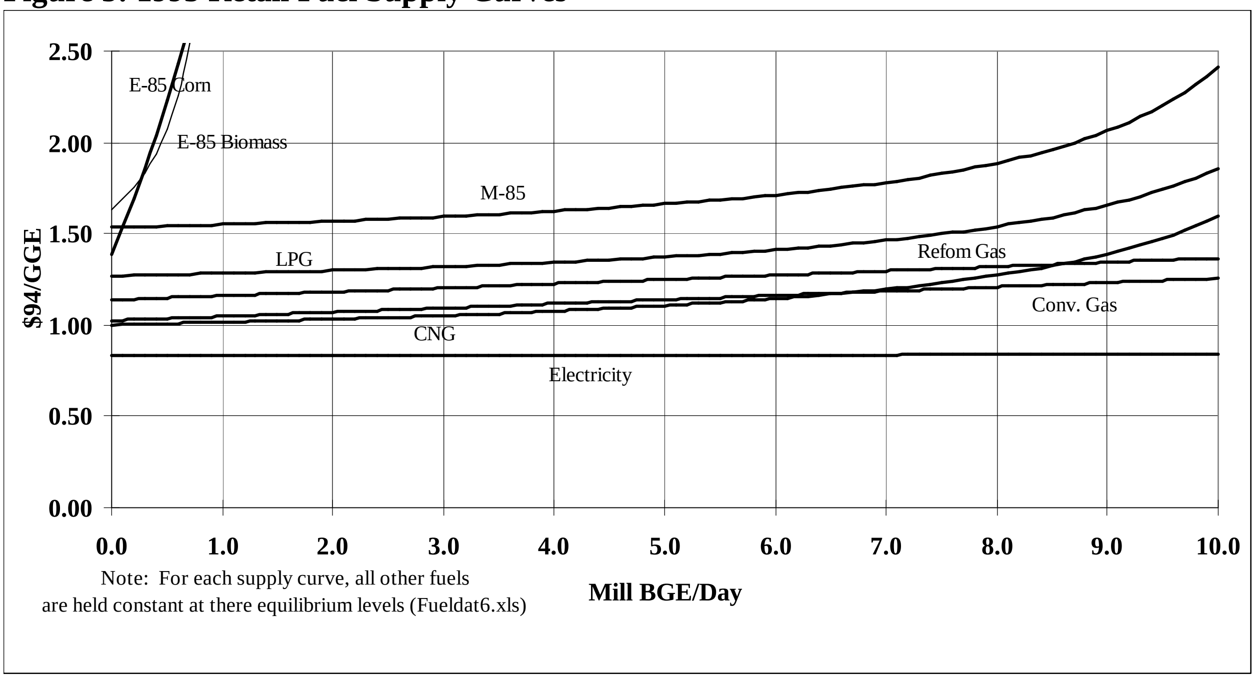
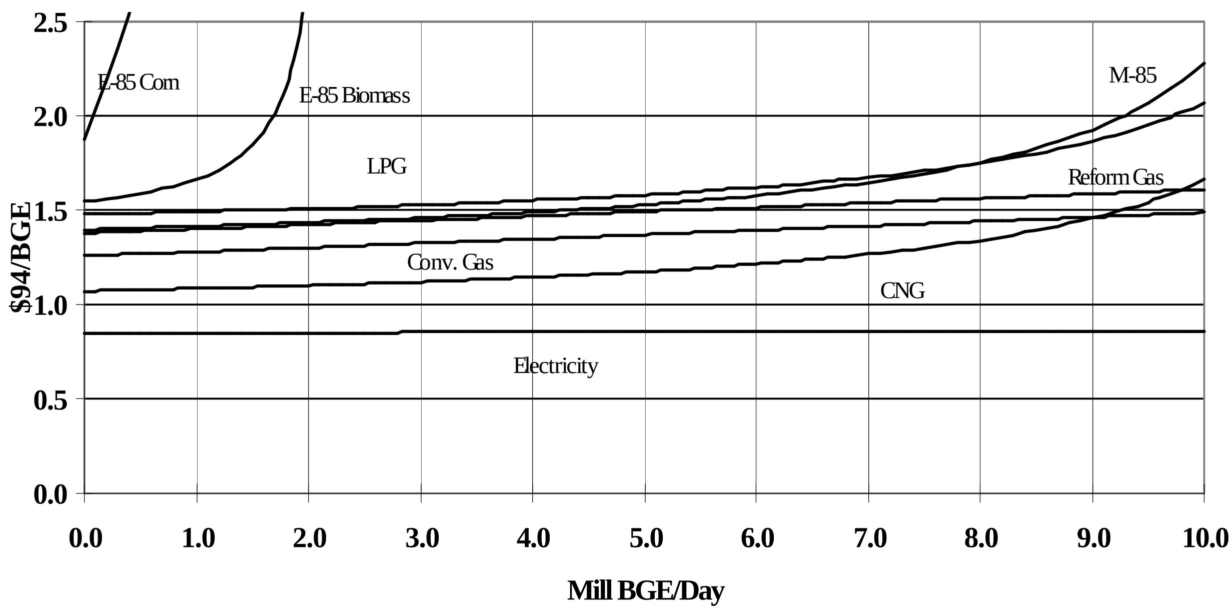


Figure 6: **2010 Retail Fuel Supply Curves**



Note: For each supply curve, all other fuels
are held constant at there reference levels (Fueldat6.xls).

Vehicle Services Demand for New and Used Vehicles

Benefits in this model come from the satisfaction of final demand for transportation services. The total demand for transportation services is specified by a composite demand 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 type given a fixed, age-adjusted use profile.

Each year, to the extent that existing vehicle stocks are insufficient to satisfy demand, a mix of new vehicles is purchased. New vehicles are chosen according to a nested multinomial logit (NMNL) choice formulation, which is a common way of modeling discrete choice behavior. Vehicle choice is based on up-front vehicle capital costs, non-price vehicle attributes and expected lifetime nested fuel choice costs. In this way, long-lived investment consequences are reflected in vehicle choice. For the vehicles that are dual or flexibly-fueled, fuel is chosen based on each fuel's retail price and its retail availability.

Formally, for composite vehicle services demand in year t of vehicle type g the choice fraction for input alternative f will depend upon its (conditional expected indirect) utility, V_{tgf}, which is a linear function of new vehicle price P_{tf} and non-price attributes:

$$V_{tgf} = \beta_g \left(P_{tf} + \alpha_{fR} + \alpha_{fW} + \alpha_{fD} + \frac{\beta_f}{\beta_g} C_{gf} \right) \tag{1}$$

The attributes include, for example:

- β_g cost sensitivity parameter for choice over vehicle types
- P_{tf} vehicle price for fuel technology *f*, at time *t* ;
- α_{fR} vehicle range (distance between refuelings) equivalent cost;
- α_{fW} vehicle weight to performance equivalent cost;
- α_{fD} relative diversity of vehicle models, equivalent cost;
- β_f fuel price sensitivity for vehicle *f*
- C_{gf} expected effective fuel cost over vehicle's lifetime, given current and expected future prices for the fuels vehicle *f* may use, and accounting for expected fuel availability.

The choice of a vehicle is, therefore, made on the basis of endogenous current vehicle and fuel prices and endogenous future fuel prices. The treatment of vehicle and fuel choice parameters in the TAFV model is based on Greene's "Alternative Vehicle and Fuel Choice Model," (Greene, 1994).

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 sub-modules, and which characteristics are endogenously determined. These characteristics are shown in the Table 3.

Table 3: Factors Influencing Fuel and Vehicle Choice		
Factors considered in Fuel Choice	**Endogenous**	**Exogenous**
Fuel Price	X	
Fuel Availability (fraction stations offering fuel)	X	
Refueling Frequency[5] (based on range)		X
Refueling Time Cost		X
Performance Using Fuel (HP:weight ratio changes)		X
Factors Considered in Vehicle Choice	**Endogenous**	**Exogenous**
Vehicle Price	X	
Fuel Cost (incl. effective cost of non-price fuel attributes)	X	
Performance (changes in HP-to-weight ratios)		X
Cargo Space (loss due to space required for fuel storage)		X
Vehicle Diversity (number of models offering AFV technology)	X	

Given equal fuel prices and the exogenous vehicle and fuel characteristics shown above, Table 3 gives the default shares of fuels and vehicles based upon the value of vehicles to consumers (Leiby, 1993).

[5]All vehicles, except electric vehicles, are assumed to use commercial refueling stations.

Table 4: Market Choice Shares Given Equal Prices, Fuel Availability and Vehicle Diversity			
Vehicle	**Fuels**	**Fuel Share**	**Vehicle Share**
Conventional	Conventional Gasoline		16.9%
Flex-Fuel	Conventional Gasoline	19.0%	
Flex-Fuel	M85	40.20%	
Flex-Fuel	E85	40.20%	16.8%
CNG Bifuel	Conventional Gasoline	90.8%	
CNG Bifuel	CNG	9.2%	7.1%
LPG Bifuel	Conventional Gasoline	76.0%	
LPG Bifuel	LPG	24.0%	13.8%
CNG Dedicated	CNG		9.7%
LPG Dedicated	LPG		15.6%
Alcohol Dedicated.	M85	50.0%	
Alcohol Dedicated	E85	50.0%	19.4%
Electric	Battery EV	0.0%	0.6%
Total			100.0%

Key Transitional Phenomena

From our preliminary analysis, we have identified some key areas that are likely to strongly affect the transition to alternative fuels and vehicles. Because their potential importance, these areas have been modeled in detail.

- Costs to consumers of limited retail fuel availability for some alternative fuels

- Capital stock durability and turnover
  - Vintaged vehicles
  - Durable vehicle and fuel production plants

- Scale economies for vehicles and fuels

- Endogenous vehicle model diversity
  - costs to producers
  - value to consumers

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 below 10% can impose large implicit 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 (1997,1998) who models availability using a random utility, binomial logit choice framework. Within this framework, the value, or utility, that the *j*th individual receives from choosing fuel option *i* is given by

$$U_{ij} = A_i + B \cdot P_i + C \cdot g(\sigma_i^R) + \varepsilon_{ij} \tag{2}$$

where A_i are non-price attributes of the fuel, P_i is the price of the fuel, $g(\sigma_i^R)$ is the perceived retail availability of the *i*th fuel and ε_{ij} is a random error term. The term B converts the market price of fuels into consumer satisfaction or utility and, hence, can be interpreted as the marginal utility of a dollar. The log of the odds in favor of purchasing fuel option 2 rather than fuel option 1 is given as:

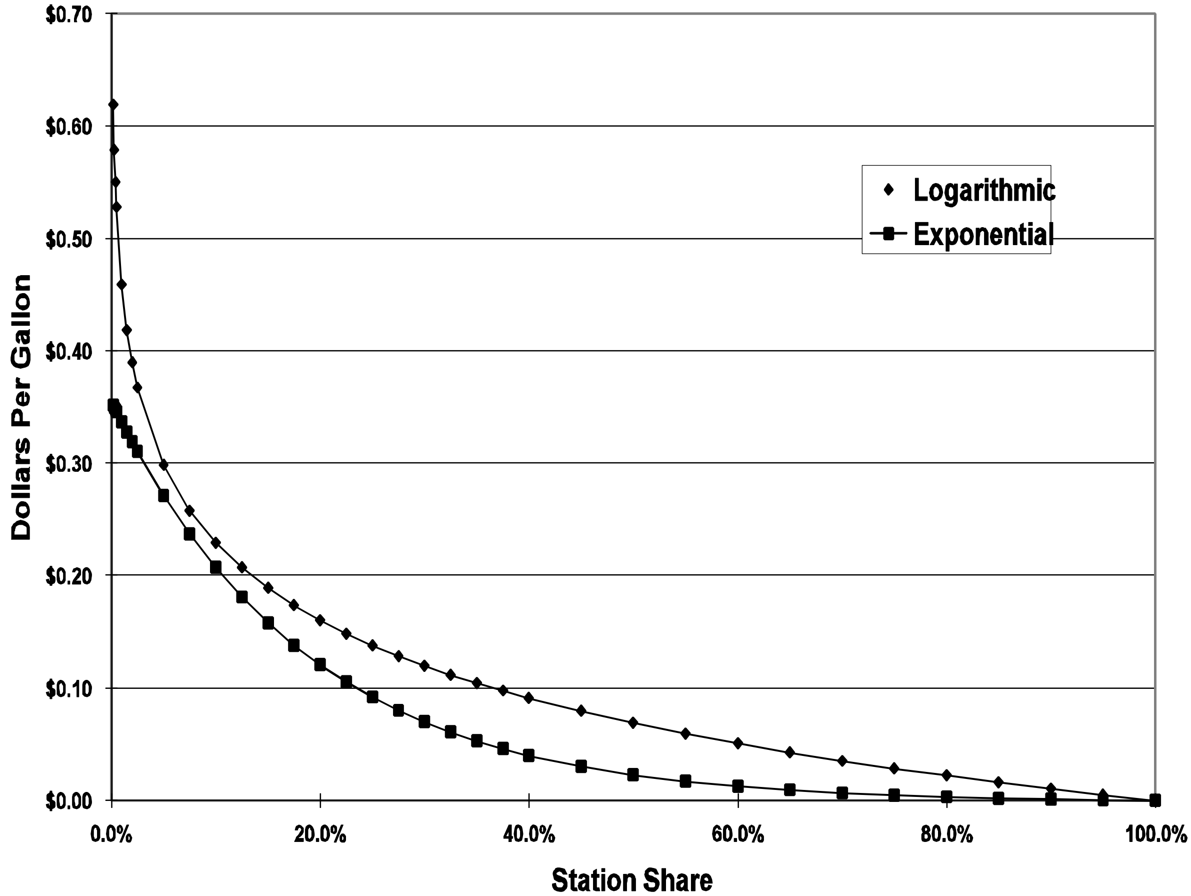
$$\ln\left(\frac{Prob_2}{Prob_1}\right) = A_2 - A_1 + B(P_2 - P_1) + C(g(\sigma_2) - g(\sigma_1)). \tag{3}$$

To determine what percentage of the time consumers would choose to use one fuel rather than another given different fuel prices and availabilities, Greene 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 (10, 5) cents LESS per gallon but was sold at just one in 50 (20, 5) stations, what percent of the time would you buy this new fuel?"

The results from these surveys were used to estimate equation 3. In order to do the estimation, a functional form must be chosen for $g(\sigma)$. Greene estimated four forms: linear ($g(\sigma) = \sigma$), exponential ($g(\sigma) = e^{b\sigma}$), power ($g(\sigma) = \sigma^{b}$), and logarithmic ($g(\sigma) = \ln(\sigma)$). The costs per gallon for limited fuel availability using the two better-fitting functional forms are shown in the Figure 7.

Figure 7: Costs of Limited Retail Availability



Greene notes (p. 34) that it is not possible to definitively discriminate among the alternative functional forms, but that the exponential functional form fits the data best and behaves reasonably over the whole range of fuel availabilities. Besides issues of fit, we have chosen to use the 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, the next lowest fuel availability cost is 7¢ per gallon found using the logarithmic functional form. At 0.1% fuel availability the cost per gallon, using the exponential functional form, is 35¢.

Vehicle Manufacturers' Costs per Model (Line)

The TAFV model is designed to estimate the costs of vehicle production for the following alternative fuels: LPG, CNG, alcohols, and electricity. The vehicles are either dedicated to a particular fuel type or are capable of using both gasoline and the respective alternative fuel.[6] AFV costs (shown in Table 5) are calculated from engineering-economic estimates of the incremental cost of each AFV fuel technology compared to conventional vehicle technology (EEA , 1995c). EEA believes that AFV technologies, except for electric vehicles, are mature. Here "mature" means that, for a given production scale, further production experience will not reduce per-unit production costs at a rate significantly faster than conventional vehicle production costs will decline. There do exist, however, substantial per-unit cost savings with larger scale production.

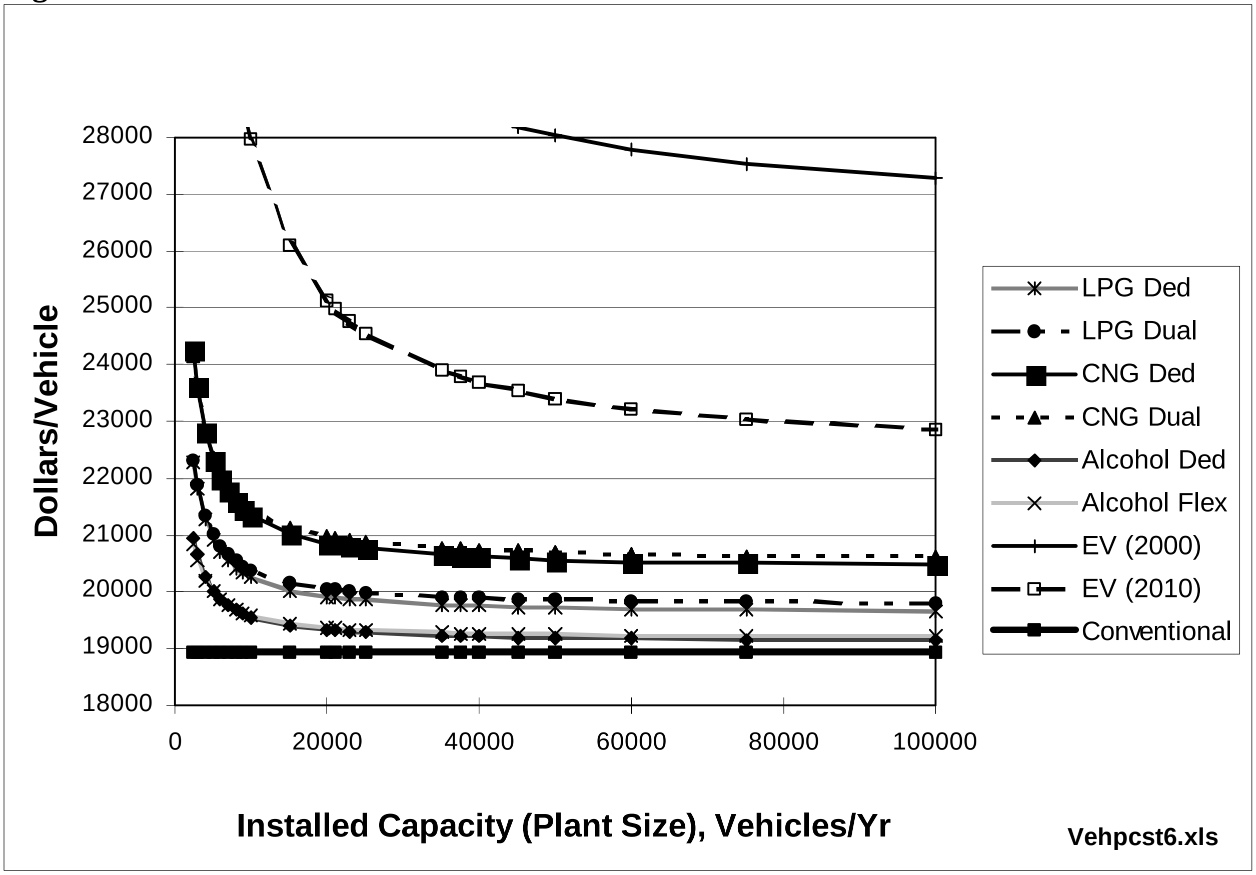
We therefore model per-unit vehicle production costs as a declining function of the installed production capacity available in each year. The volume of production in any given year is constrained by the level of cumulative capacity investment less capacity decay. This means that vehicle prices are endogenous variables. This has the advantage of admitting the positive feedback effects from policies (such as AFV fleet programs) that encourage the adoption (and hence larger scale production) of AFVs.

[6]The one exception is electricity. Hybrid electric vehicles are currently not characterized in the model, but we plan to include them in the future.

Table 5 Cost Data for Vehicle Production and Fuel Retailing			
Incremental Vehicle Production Costs (Capital and Variable, Compared to a Gasoline Vehicle)			
	Plant Scale (Vehicles per Year)		
Vehicle Type	2,500	25,000	100,000
Alcohol Dedicated	$2,038	$363	$223
Alcohol Flexible	$1,911	$409	$284
CNG Dedicated	$5,349	$1,841	$1,548
CNG Dual	$5,792	$2,015	$1,701
LPG Dedicated	$3,745	$972	$741
LPG Dual	$3,778	$1,109	$887
Electric Dedicated (1996)	$42,125	$11,060	$8,471
Electric Dedicated (2010)	$29,627	$5,974	$4,003
Note: these figures reproduce the estimated IRE based on EEA's accounting methodology, "Specification of a Vehicle Supply Model for TAFVM," Sept., 1995, p.1-2. They differ slightly from some numbers in EEA's Table 5-2.			

For each fuel technology, vehicle costs increase as the richness of offerings (the number of models) increases. Vehicle diversity is a choice variable under the control of the vehicle producer. Note that while model diversity adds to the vehicle producers' costs, there is a motivation for producing diversity since it makes a vehicle (fuel) type more attractive to consumers. Representative total (not incremental) cost curves for these vehicle types and for conventional gasoline vehicles are shown in Figure 8. As is seen, AFV costs decline sharply with the number of vehicles produced each year.

Figure 8: Vehicle Production Cost vs. Scale



Endogenous Vehicle-Model Diversity and the Effective Cost of Limited Diversity

Consumers contemplating buying a new gasoline-fueled car are offered a wide variety of models with a huge number of features to choose among. The attractiveness of an alternative fuel technology will depend, in part, on the diversity of vehicle models for which it is 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. Rather than predetermining the number of models offered with alternative fuel capability, we endogenize the level of model diversity by balancing additional production costs against additional consumer satisfaction.

This is accomplished by defining a variable n_f which represents the number of models of fuel type f produced. On the vehicle production side we divide the total industry production capacity for vehicles of fuel type f by n_f. On the consumer side we incorporate n_f into the our multinomial choice framework by adapting a framework suggested by Greene (1997). In our approach, the unit consumer benefit from having n_f models to choose between given fuel type f, is

$$B_f = \frac{a}{\text{ß}}\ln\left(\frac{n_f}{n_1}\right) \tag{4}$$

where

n_1 is the number of models of gasoline vehicles offered based on current data,
ß is the NMNL choice parameter for choice among vehicle-types, and
a reflects the popularity-order in which manufacturers choose vehicle models to offer the fuel technology f.

If alternative fuel capability is introduced "randomly" on different vehicle models, then the appropriate value for a is a = 1. On the other hand, if the new technology is offered on the most popular vehicles first, then we can estimate a based on the current distribution of conventional vehicle model popularities (sales) (a . 0.37). Numerically, this implies that the unit costs of limited diversity per AFV range over the following magnitudes:

$0/vehicle (when diversity matches conventional vehicles);
$770/vehicle (if fuel technology is offered only the most popular model), and
$2080/vehicle (if fuel technology is offered on only one random model AFV).

Simulation Results

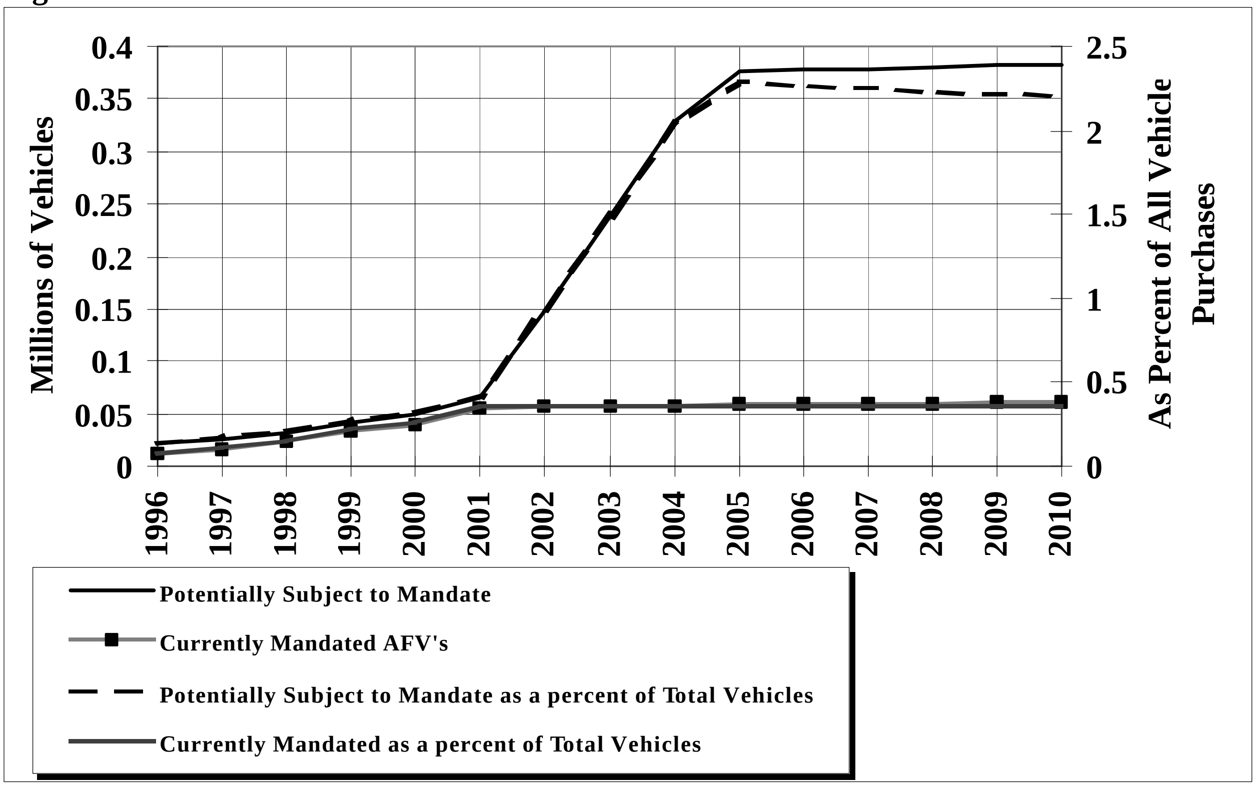
We now present four simulation scenarios, including the base case (no new policy), a long-run analysis (no transitional barriers) and two policy cases. In each of these cases, all assumptions that pertain to the base case, except those explicitly changed in a particular policy scenario, are maintained throughout. Detail differences in the assumptions can be seen in Table 7 in the appendix.

Case 1: Base Case (No New Policies) Scenario

This case characterizes the possible market evolution starting from the current limited alternative fuel availability and low AFV production scale. Fuel production costs vary over time, reflecting DOE Annual Energy Outlook (AEO) Base projections. Alternative fuel taxes reflect current treatment, with a phase-out of the ethanol incentive by 2001. There are two existing federal AFV policies: existing mandates under EPACT for fleets to buy AFVs, and CAFE credits for producers of AFVs. The existing EPACT fleet mandates that require certain percentages of new vehicle purchases by federal and fuel-provider fleets to be AFVs. Both the existing EPACT fleet mandates and possible additional fleet mandates which may be required under a "late rulemaking" are shown in Figure 9.

A second important policy driver included in the base case is the favorable treatment received by AFVs pursuant to AMFA in the calculation of each manufacturer's CAFE standard. When calculating a vehicle manufacturer's CAFE, for the purposes of complying with the CAFE standards, AFVs are treated as highly fuel-efficient. According the AMFA (including revisions contained in EPACT) a gallon of alternative fuel used in a dedicated alternative fuel vehicle shall be considered to contain 15% of a gallon of gasoline (on an equivalent fuel basis). For dual-fueled vehicles the AMFA assumes that the gasoline and the alternative fuel are each used half of the time. Our analysis indicates that this yields per-vehicle marginal values of $225 - $457 for dual and dedicated vehicles (respectively), up until AFVs make up 1% of new vehicle sales in each year (Rubin and Leiby 1997). Beyond that point the CAFE standards are unlikely to be binding.

Figure 9: Fleet New Vehicle Purchases



The results of the base case scenario are summarized in Figures 10 and 11. The figures display the time paths for alternative fuel demand shares and vehicle production shares for each AFV type. As is seen, in the base case there is almost no use of alternative fuels and almost no production of AFVs. These results are in marked contrast to DOE's 1996 long-run analysis, which concluded that if the necessary infrastructure for a mature alternative fuel and vehicle industry were present, then "alternative fuels, as a group, appear likely to sustain a 30-percent market share under equilibrium conditions." (DOE 1996:13). However, the modeling results here suggest that the necessary infrastructure may *not* evolve smoothly, fuel and vehicle prices may not benefit from economies of scale, and gasoline displacement may be very limited in the absence of any additional policies.

Figure 10: Fuel Demand Shares - Base Case

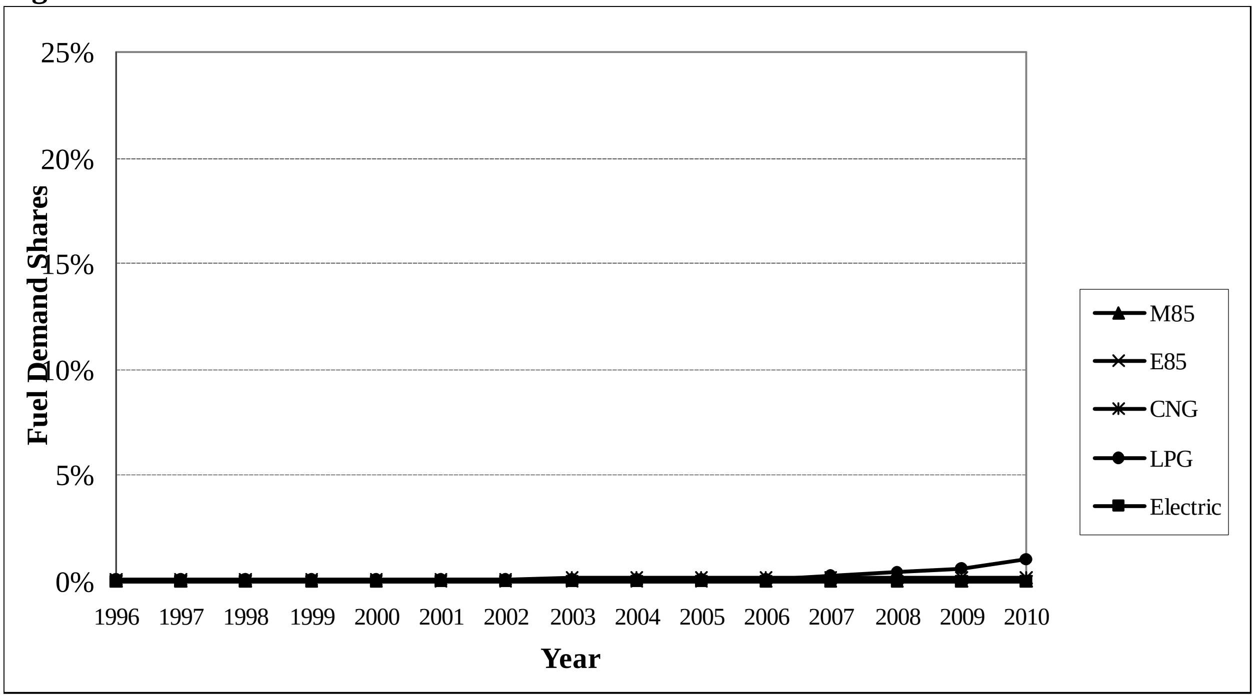


Figure 11: Vehicle Production Shares - Base Case

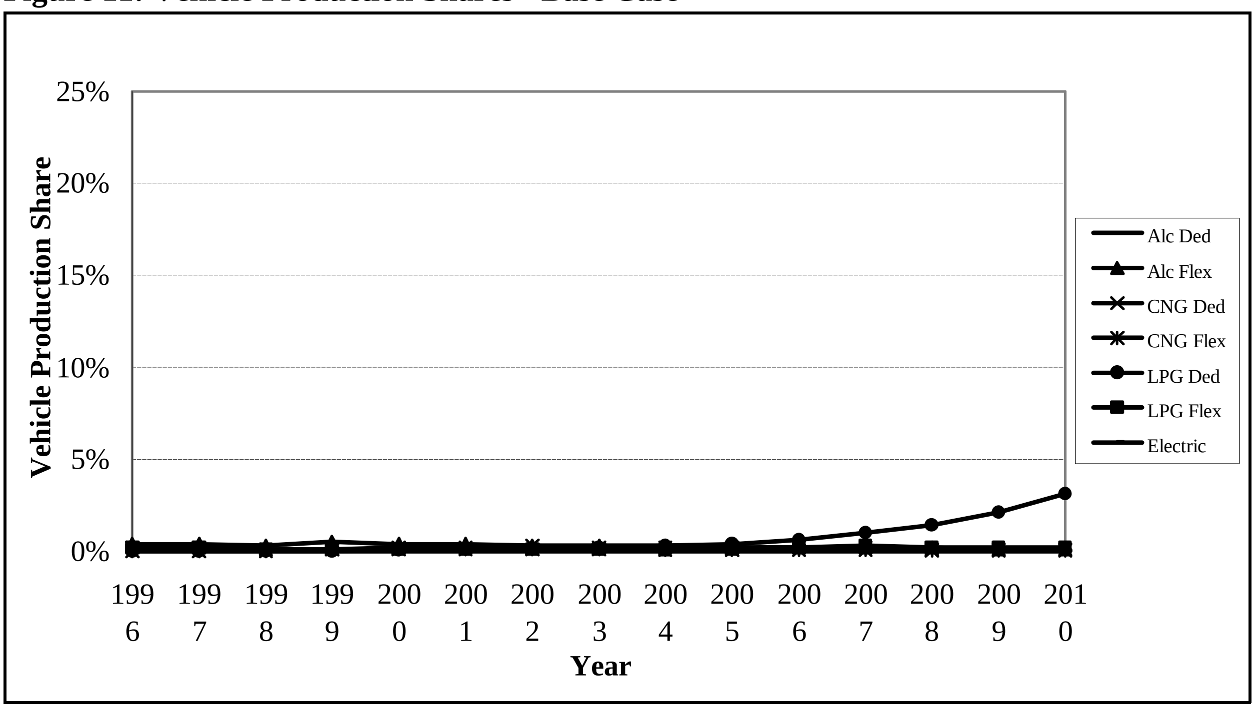
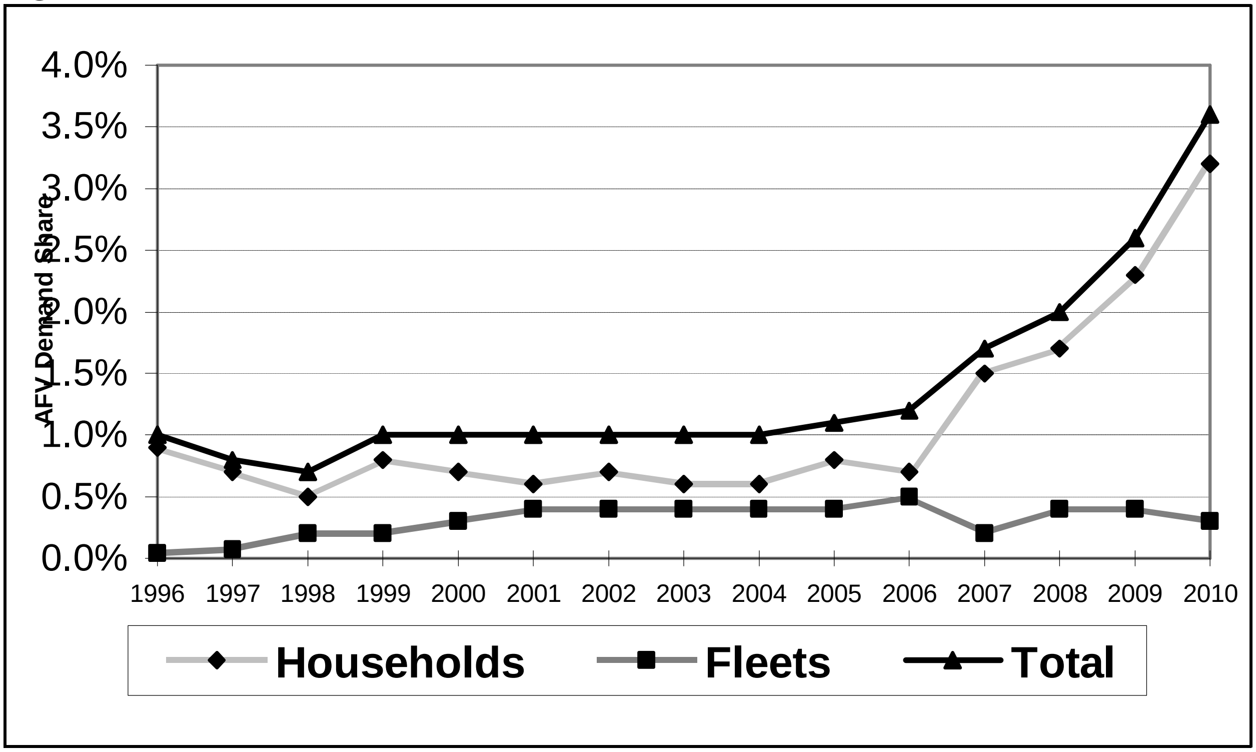


Figure 12: AFV Demand Shares - Base Case

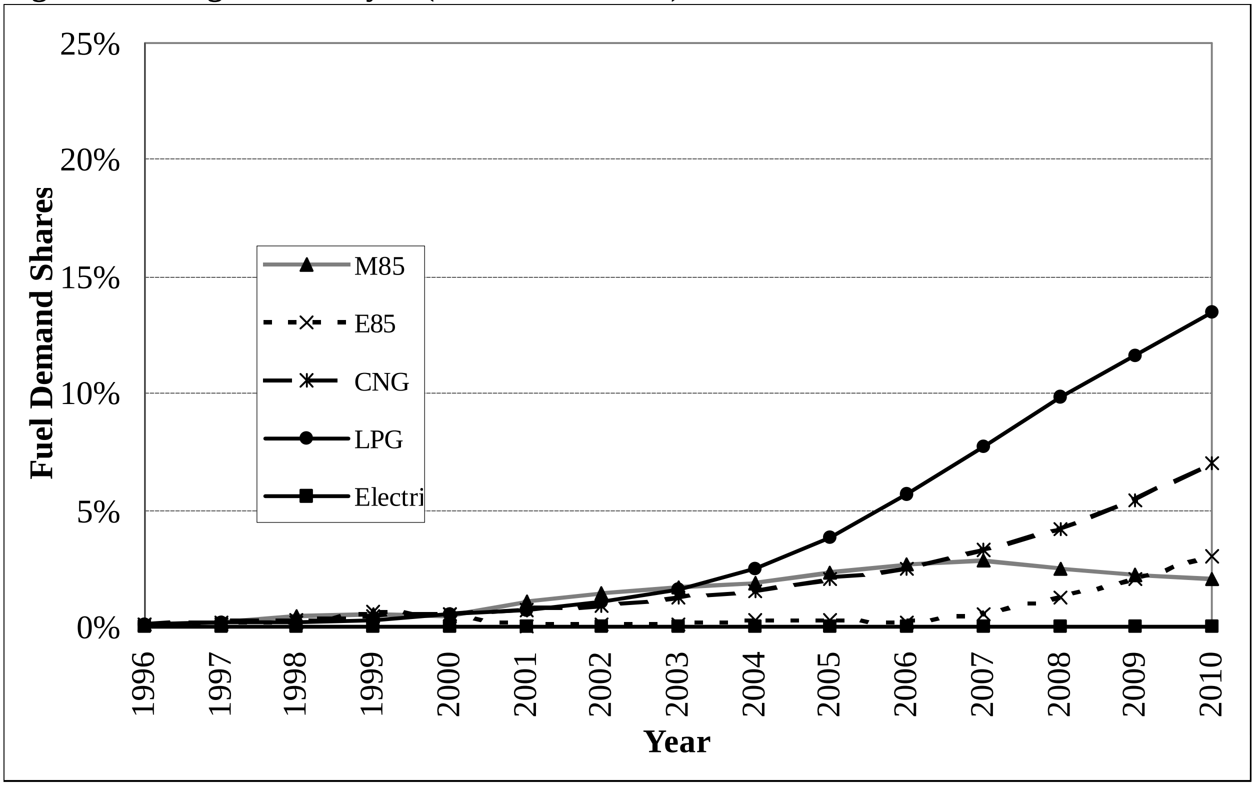


As Figures 10 and 11 do show, however, there is some small percentage of fuel and vehicle use. Expanding the scale on Figure 11 to highlight the path of vehicle purchases by ownership category yields Figure 12. Interestingly, we see that the combined AFV sales hover around 1% for the first 10 years, consistent with the subsidies received due their favorable treatment under CAFE regulations. Although not shown in Figure 12, the vehicles chosen are FFVs running on gasoline. The cumulative, mandated fleet purchases do help induce private vehicle demand by driving down the price of AFVs. This effect, as noted above, is however too small to have a significant impact on overall sales.

Case 2: Long-Run Analysis

As a comparison to our base case, we are interested in determining what the fuel and vehicle paths would be in the absence of transitional barriers. This case allow us to compare our results with those of the earlier DOE study (1996) and presents us with an opportunity to demonstrate the importance of explicitly modeling transitional barriers. In this case we assumed that all vehicles and fuels attain their large-scale production costs. In addition, we assume that there is a well-developed fuel retail infrastructure (all fuels are widely available) and that limited vehicle diversity is not an issue for AFVs. That is, we remove all transitional barriers to alterative fuels. Otherwise we retain the base case assumptions. The results from this case are seen in Figure 13.

Figure 13: Long-Run Analysis (As If No Barriers)

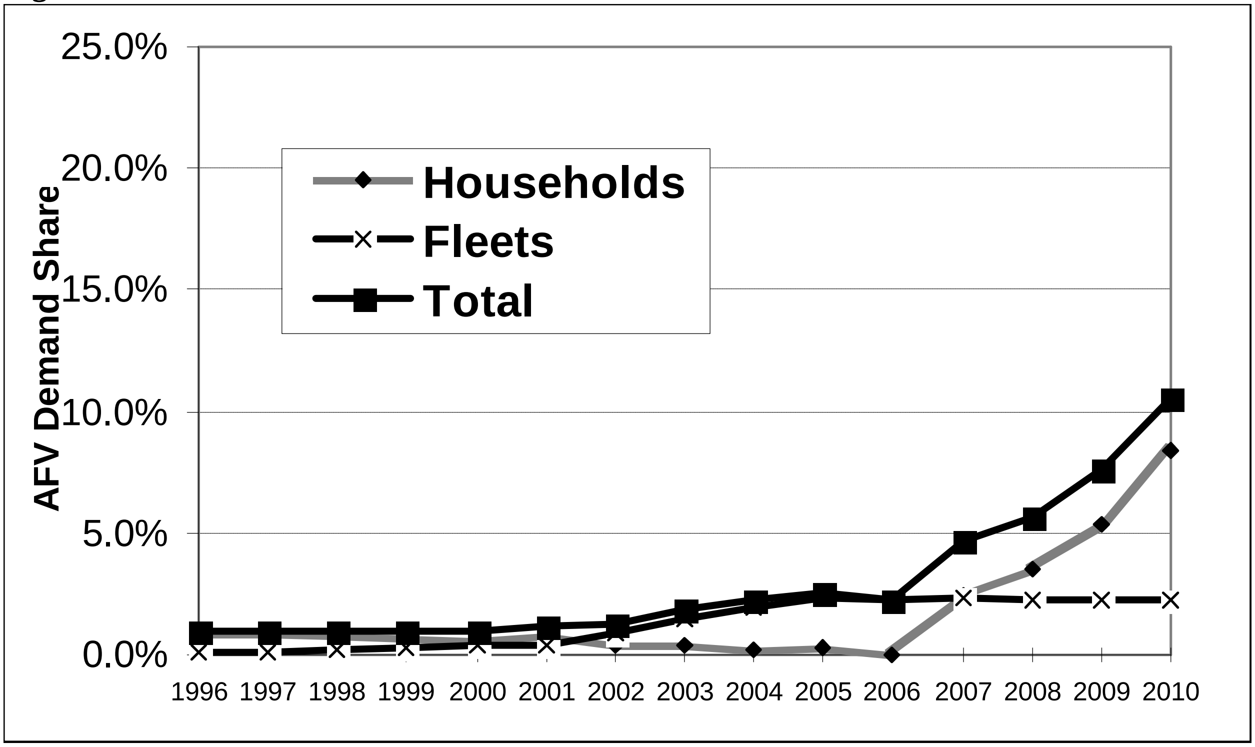


In stark contrast to our base case results, all the fuels except electricity gain at least some market share by 2010. Combined, the alternative fuels displace a total of 25% of gasoline demand by 2010 even in the absence of any new policy initiatives. This amount of fuel displacement is roughly equivalent to what DOE predicted in their 2010 analysis. This is a very important finding. It shows the importance of modeling transitional barriers when examining new, emerging technologies. Simply doing static, short-run analyses ("snapshots") is likely to lead to misleading results.

Case 3: EPACT Late Rule Making

As mentioned earlier, the USDOE has the authority under EPACT to require private fleets and those of state and local governments to purchase certain percentages of AFVs (as shown in Figure 9) if it determines that this is necessary to attain EPACT's fuel displacement goals. This policy case maintains the base case assumptions, but imposes the "late rulemaking" fleet mandate. The outcome of this case is seen in Figure 14 which shows two interesting results. First and foremost is that the mandated fleet sales induces private (non-fleet) vehicle owners to purchase AFVs for about 8% of their new vehicle needs by 2010. Not shown in this figure is that most of these vehicles are dedicated LPG vehicles (although there are also a few early alcohol and CNG FFVs). By the year 2010 however, these vehicles only displace about 3.5% of the gasoline demand. Thus, we see that even though consumers desire a diversity of alternative fuels and vehicles (as indicated by the equal price shares used in the NMNL, see Table 4) vehicle economies of scale

Figure 14: AFV Demand Shares - Late Private Rule



encourage the market to focus on a particular alternative technology. The second major policy outcome shown in Figure 14 is that the private household demand for AFVs once encouraged by their favorable treatment for CAFE purposes, is crowded out by the larger number of fleet AFVs required under the late rulemaking.[7] This is an example of the well-known, and often all-to-frequent occurrence of the law of unintended consequences. Here one policy designed to encourage AFV use is canceled out by a second policy with a similar goal.

Case 4: Tax credits for low GHG fuels

Of particular interest for the long-run sustainability of transportation is the ability to stabilize, or actually decrease, the transportation sector's contribution to global warming. This is especially important since the transportation sector is responsible for about 32% of the emissions of CO_2 in the US, and gasoline contributes 63% of the transportation sector's total (Davis, 1997, Tables 7.9, 7.11). One of the interesting policies suggested for reducing GHG emissions from the transportation sector, is to offer a tax credit for low GHG emission fuels equal to that currently available to ethanol, namely $0.54 per physical gallon, or about $0.80 per GGE. The tax credit is

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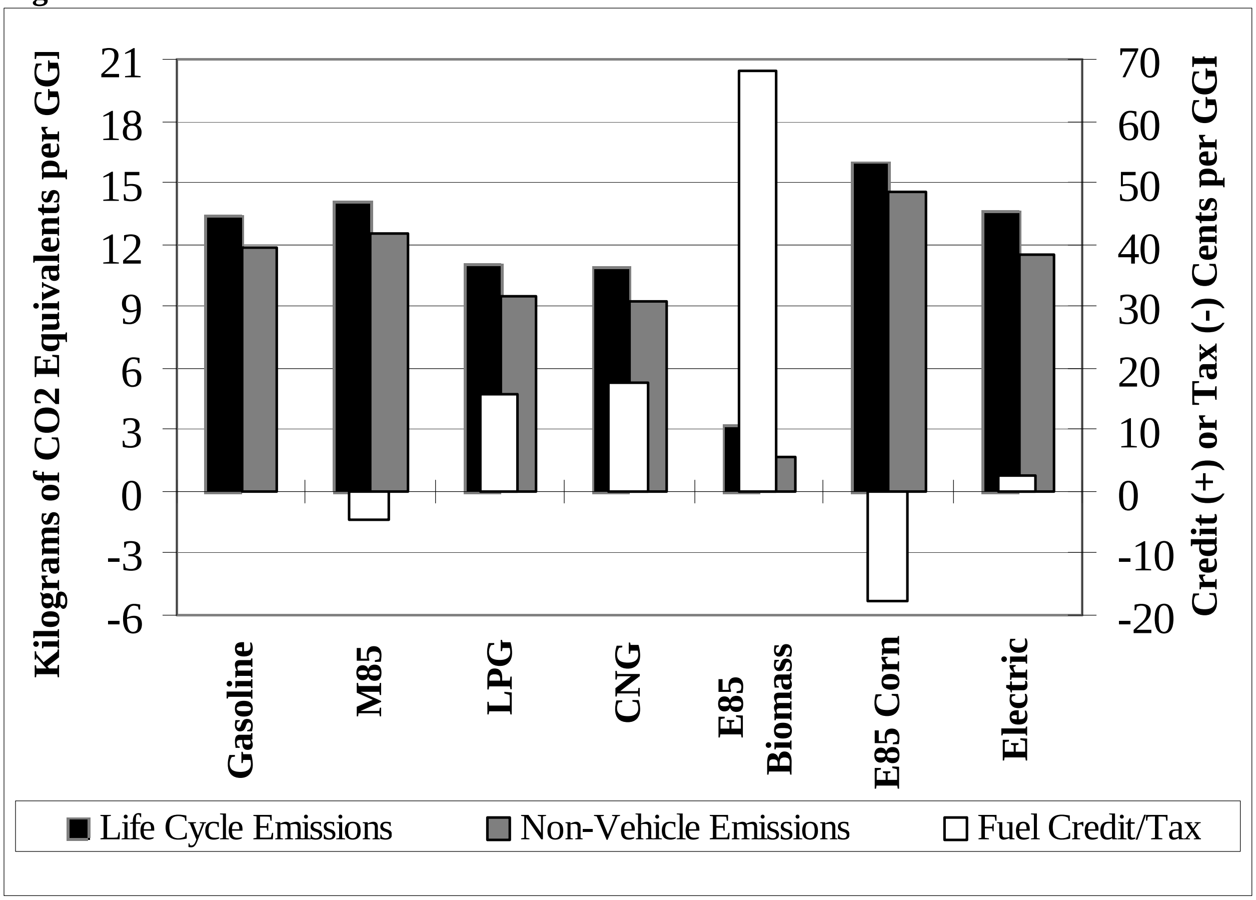
[7]Vehicle manufacturers can gain all available CAFE credits for AFVs through their production for the fleet program. Since the EPACT fleet mandate is larger that the number of CAFE credits available, there is no longer an induced AFV subsidy from manufacturers to households due to CAFE credits.

structured such that a zero GHG emission fuel (pure ethanol from biomass) would gain the full $.80 per GGE credit and gasoline would receive a credit of zero. Other fuels would receive a prorated credit or tax depending on whether their GHG emissions are less or greater than those of gasoline. Shown in Figure 15 are the "lifecycle" GHG emissions of each fuel based on estimates by the US DOE (1996). Additionally shown are the GHG emissions from fuel production and use only; excluding emissions from vehicle production. Lastly shown are the cents per gasoline gallon equivalent (GGE) credits or taxes based on the GHG emissions from fuel production and use.[8]

Figure 15: GHG Emissions and Credits or Taxes



The results of this Low-GHG Fuel Tax Credit policy case are shown in Figures 16 and 17. We find that the GHG credit significantly increases the fuel shares of E85 and LPG by 2010. E85 from biomass, receiving a very large ($0.68 per GGE) credit is the dominant alternative fuel while LPG receiving a smaller ($0.16 per GGE) credit also is a significant fuel. This credit is able to accomplish EPACT's goal of a 30% fuel displacement by 2010. The new vehicle production shares tell a similar story. However, it is interesting to note the importance of the long lead times

[8]The taxes and credits are based on only the fuel production and use portion of the lifecycle emissions since this most closely captures our understanding of suggested legislation.

in purchasing the new vehicles before they are able to make a significant impact on overall fuel use. Alcohol vehicles come in earlier than the LPG vehicles but eventually the sales of new LPG vehicles overtake and surpass those of alcohol vehicles. We attribute this phenomenon to increasing returns to scale in LPG vehicle production which are larger than those for alcohol vehicles due their large incremental retail costs. This interpretation is supported by the fact that the number of models of LPG vehicles (i.e., LPG vehicle diversity) is always significantly smaller than that for alcohol vehicles which reaches full diversity by 2003. A lower equilibrium level of model diversity suggests that scale economies are more significant, since the market outcome trades diversity for scale.

Figure 16: Fuel Production Shares - Low GHG Credit

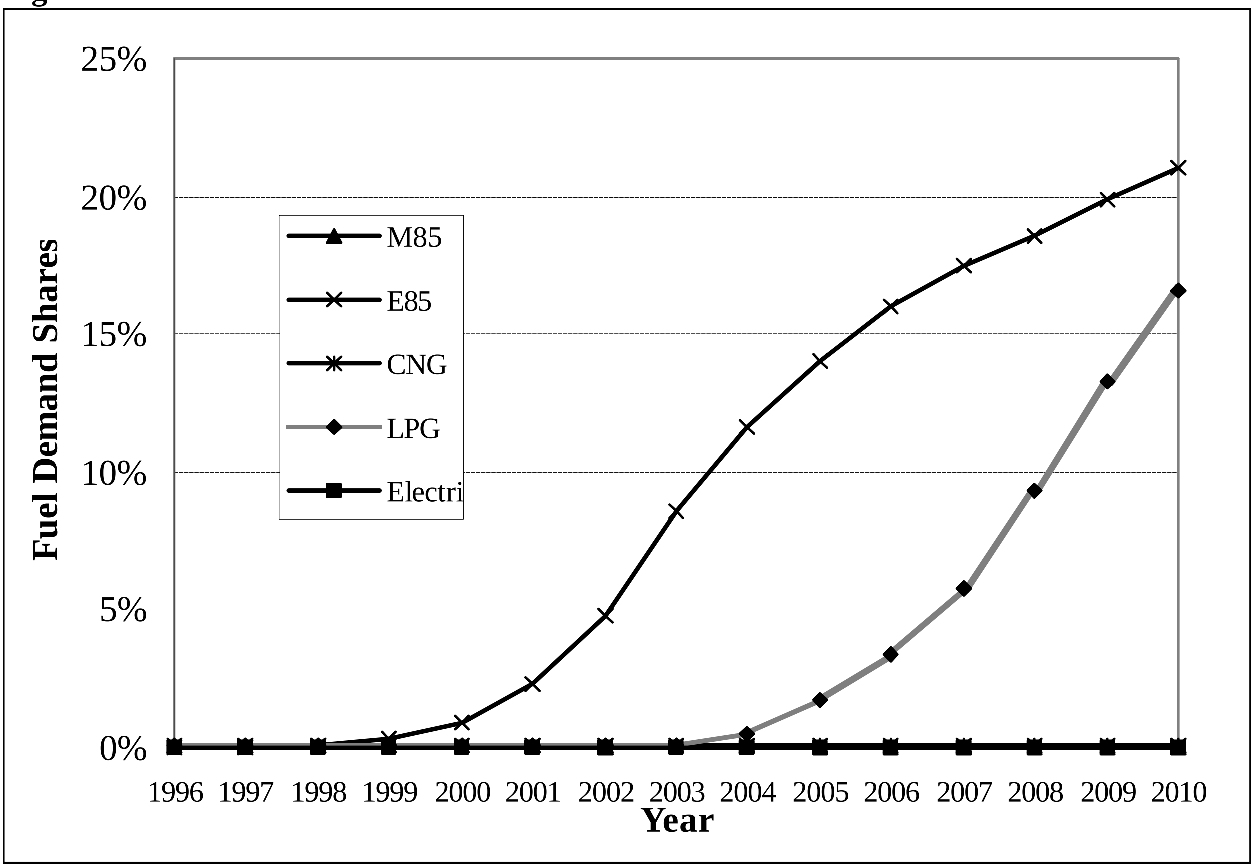
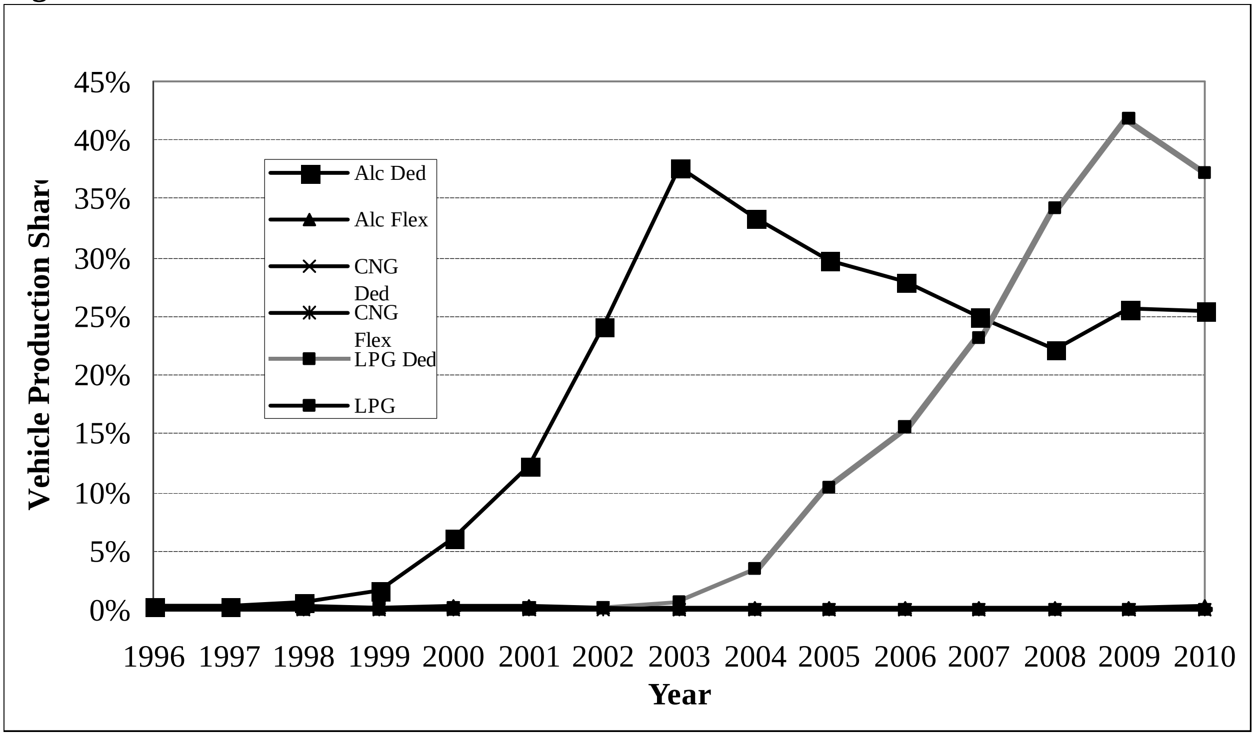


Figure 17: Vehicle Production Shares - Low GHG Credits



As a variation on the low GHG policy case, we simply assume that the current ethanol tax credit, due to be terminated in 2001, will be continued in its current form through 2010.[9] In this case, E85 achieves an 85% fuel share by 2010, with no other alternative fuel having any significant market penetration.

Table 6: Summary Results Across GHG Cases				
	NPV Incremental Benefits ($ Billions)	GHG (Billions Metric Tons)	Tax/GHG ($/MT)	Cost/GHG ($/MT)
Tax Cut for Low GHG Fuels	-25.5	-0.915	66.65	27.84
Continue Renewable Fuel Credit	-25.2	-0.759	63.84	33.24

The costs per metric ton and the overall effectiveness of the two alternative GHG policies are

[9]In this case, corn and cellulosic ethanol are treated (subsidized) equally. In the previous low-GHG fuel credit case, cellulosic ethanol is given the maximum subsidy, while corn ethanol is penalized slightly relative to gasoline.

shown in Table 6. When comparing the cost per ton of the two policies, it is important to make the distinction between the costs in terms of tax dollars foregone (column 4 in Table 6) and the costs per ton to the nation's economy after subtracting out transfers that benefit the fuel producing sectors (column 5). As is seen from the table, continuing the ethanol tax credit in its current form is not as effective as the tax cut for low GHG fuels in reducing GHG emissions (since the E85 is derived from corn in the early years), or in attaining EPACT's gasoline displacement goal (since LPG qualifies for a subsidy in addition to E85). In addition, continuing the ethanol tax credit is more expensive to the economy on a per-ton basis than a tax policy specifically targeted to reduce GHG emissions. Nonetheless, it is still an effective second-best policy. We cannot comment on whether either of these policies is, in fact, desirable from a national perspective. In our view that judgement is a political decision.

Conclusions

In contrast to earlier work, we find that transitional impediments are very important to the transportation sector and may overshadow theoretically attainable production costs and market penetrations scenarios. In particular, the long run penetrations for alternative vehicles and fuels anticipated in the earlier EPACT 502B (DOE 1996) study are not likely to be achieved without measures to encourage the expansion of vehicle production and fuel availability. Limited retail fuel availability is important, as are vehicle production scale-economies and limited model diversity. These features lead to substantially higher *initial* effective costs of alternative fuel vehicle services than were estimated for the long-run mature market outcomes in the EPACT 502b analysis for 2010.

More specifically, it may be hard for the alternative vehicle and fuel markets to get started. In terms of a policy tool, we do find that private (non-fleet) AFV purchases respond to fleet policies. We observe the expansion of household sector AFV demand in cases where fleets are induced or required to buy more AFVs. In part, this reflects vehicle production scale economies at work and our assumption that fleets refuel commercially. While we have not tried to determine the size of fleet mandates that may be necessary to attain EPACT's goals, it does appear that this is a viable policy tool. In the absence of any specific requirement that fleet AFVs use alternative fuel, fleet AFV purchase mandates may be met with dual or flex-fueled vehicles, and little alternative fuel may be used. However, if fleet AFVs are also mandated to use some fraction of alternative fuel, and if they refuel at publicly accessible commercial stations, then the barrier of limited retail fuel availability is diminished.

New technologies often require a network of specialized infrastructure, have scale economies of production, and may have a value which depends strongly on their compatibility with some other the existing product or technology ("hardware-software" compatibility). In these cases, the market tends toward specialization and the dominance of a single technology alternative. Alternative fuels and vehicles have each of these features to some degree. However, consumers have distinct tastes and circumstances, and thus collectively place a substantial value on having a diversity of product choices. Thus there is a tension between the cost-reducing effects of specialization and the utility-increasing effects of technology diversification. Given the costs and benefits estimates used in our model, we find that even in those cases where there is substantial AFV penetration due to policies (e.g., GHG-tax credit case), the costs of supplying technological diversity outweigh the benefits such that only one or two alternative fuel technologies are able to successfully enter the market.[10]

Finally, we would like to state that our estimates show that the federal government does appear to have technically feasible policies at hand to lead the transportation sector towards a sustainable path, if sustainable transportation is defined in terms of the transportation sector not increasing, or even decreasing, its contribution to global warming. Specifically, the use of GHG tax credits or a continuation of the renewable fuel (ethanol) tax credit on the order of $0.80 per GGE does appear to be sufficient incentive to stabilize GHG emissions from the transportation sector.

[10]It has been pointed out to us that while this result obtains in our deterministic analysis, in a world of great uncertainty the hedging and option value of diversity may sustain more AF technologies in the market, at least for a while.

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Table 7: Scenario Assumptions					
Case Name	Price paths (oil and gas)	Fleet program	Fuel Taxes	Other Alternative Fuels or Vehicles Policies	Comments
Base (No Policy)	Base, see text.	Existing programs (Note 1)	Existing (Note 2)	None	All of the following scenarios use these Base assumptions unless specifically noted otherwise.
No Transitional Barriers (Long-Run) - Higher LPG Costs	Base, see text.	Existing programs (Note 1)	Existing (Note 2)	None	The long-run analysis assumes: full vehicle model diversity, no cost of limited retail fuel availability, full scale fuel and vehicle production costs.
Late Private Rule	Base, see text.	Late Private Rule (Note 3).	Existing (Note 2)	None	The late private rule would expand fleet AFV purchases starting in 2001. In later years (2005 to 2010) it is estimated to require fleets to purchase about 380,000 new AFVs per year, representing 2.2% of total new light duty vehicle sales, in 2010. See Figure 9 for additional details.
Low-GHG Fuel Subsidy	Base, see text.	Existing programs (Note 1)	Low-GHG fuel subsidies, declining with inflation (Note 4)	None.	The $0.54 per physical gallon ethanol subsidy is worth $0.68 per GGE for E85 made from biomass. Not shown in the fuel use graph is the changing mix of E85 from corn to biomass through time.

1. Existing programs only - no private fleet mandates. See Figure 9
2. Ethanol subsidy in real (constant) dollars, standard (Federal Highway Fund and state) motor fuel taxes remain constant in real terms.
3. Private fleet are required to purchase AFVs under the EPACT "Late Private Rulemaking" authority, see text.
4. Low-GHG fuel subsidies: Beginning 2001, $0.54 per physical gallon ethanol subsidy ends, replaced by subsidy (tax reduction) for low GHG fuels. Cellulosic ethanol, viewed as having near-zero GHG emissions, still receives full $0.54 per physical gallon subsidy. All other fuels receive tax reduction in proportion to their GHG reduction from gasoline, see Figure 15. Low-GHG fuel subsidy declines with inflation.