Fuel Emission Standards and Cost-Effective Use of Alternative Fuels in California

JONATHAN RUBIN

Possible emission regulations on gasoline suppliers to encourage the use of alternative transportation fuels such as compressed natural gas, methanol, and electricity are examined. A theoretical model based on the concept of marketable emission permits is built for gasoline suppliers. This model shows that a fleet average emission standard on gasoline suppliers will encourage the sale of clean fuels that would otherwise not be profitable because clean fuels will generate valuable emission permits. Next a dynamic empirical model that determines the least-cost solution to meeting emission standards for new vehicles and fuels is built. The empirical model includes emission trading and banking of hydrocarbon, carbon monoxide, and nitrogen oxide permits. Under the assumption that individuals view all types of alternative-fuel and gasoline vehicles as perfect substitutes, the least-cost combination of fuels and vehicles consists mainly of methanol and compressed natural gas vehicles. If consumers favor gasoline vehicles over alternative-fuel vehicles by $350, then the least-cost combination of fuels and vehicles also includes significant numbers of gasoline vehicles.

To reduce pollution from mobile sources the Clean Air Act Amendments of 1990 (CAAA) encourage the use of clean fuels such as methanol, ethanol, and natural gas. Beginning in 1995 the CAAA require the sale of cleaner-burning reformulated gasoline in the nine cities with the worst ozone pollution. The CAAA also establish a clean-fueled-vehicle pilot program in California. This program requires the production, sale, and distribution in California of 150,000 clean-fueled vehicles each year beginning with model year 1996 and 300,000 such vehicles annually in model year 1999 and subsequent years. The CAAA also require the state of California to adopt a program to ensure the production, distribution, and availability of fuels for these vehicles.

Complementary regulations adopted by the California Air Resources Board (CARB) (*1,2*) require the production of low-emission vehicles (LEVs) and the availability of alternative fuels. The LEV regulations for vehicle emissions are based on the concept of marketable permits, whereby hydrocarbon standards are applied to automobile manufacturers, who are allowed to average, trade, and bank emission permits. The averaging, trading, and banking provisions are, however, subject to a number of restrictions (*1,2*). In addition, starting in 1998, 2 percent of all new vehicles sold each year in California must be electric vehicles. The required percentage of electric vehicles sold increases to 10 percent by 2003. In addition California has adopted Phase 2 reformulated gasoline standards for gasoline sold after January 1, 1996.

Department of Economics and Energy, Environment and Resources Center, University of Tennessee, Knoxville, Tenn. 37996.

CARB's answer to the chicken-or-egg problem of matching alternative-fuel vehicles (AFVs) and alternative fuels is to give vehicle manufacturers the right to certify vehicles by using any type of fuel they desire so long as they meet fleet average standards; gasoline suppliers must produce and offer for sale alternative fuels when demand for them reaches specified levels. Gasoline suppliers may produce and offer for sale the specified volumes of alternative fuels themselves, or they may contract out the responsibility to third parties.

The LEV and clean-fuel regulations are a significant improvement in mobile source regulation because they more fully recognize that vehicles and fuels should be treated as a system for cost-effective emission control. Nonetheless there are two serious flaws with CARB's approach. First, the regulations are structured to have gasoline suppliers produce, buy, and sell volumes of alternative fuels. Instead, as argued below, gasoline suppliers should face a volume-weighted *emission* standard.

Second, several factors weaken the link between fuels and vehicles for achieving the least-cost way to reduce emissions. This lack of coordination occurs because the regulations directly control the emissions of vehicles and the emissions of gasoline through its composition, but do not fully coordinate the economic decisions of vehicle manufacturers, fuel suppliers, and drivers. This paper's two main objectives are to describe a better way to introduce alternative fuels and AFVs through the use of emission standards on gasoline suppliers and to estimate the least-cost fuel-vehicle combinations for attaining emission standards.

PREVIOUS RESEARCH

Growing interest in AFVs as a technological fix to urban pollution problems has spawned a large number of studies on the emission impacts and cost-effectiveness of various potential vehicle and fuel combinations (*3–6*). The study described here is the first to combine the environmental and engineering data within the framework of an economic cost-minimization approach that uses the regulatory mechanism of marketable pollution permits. The permit systems described below are also the first to explicitly model the transition of alternative fuels and vehicles through time by use of a dynamic model. A dynamic model for AFVs is important because it recognizes that fuel and vehicle choice decisions in one period are necessarily connected with fuel-vehicle choice decisions of other periods. The decisions must be made jointly and cannot be broken down into a series of period-by-period decisions.

Historically gasoline has been the primary transportation fuel. Hence the regulation of fuels has meant the regulation of the components of gasoline. The design of market incentive mechanisms that incorporate gasoline and alternative transportation fuels requires that a number of additional considerations be taken into account. The permit systems proposed in this paper require that gasoline suppliers meet individual sales volume-weighted standards for the major pollutants emitted by vehicles: nonmethane organic gases (NMOGs) (reactivity adjusted), carbon monoxide (CO), and nitrogen oxides (NO_x).

Gasoline suppliers could meet the standards through any combination of fuel production and distribution or by any purchase of permits for emissions from producers or refiners who have generated excess emission reductions. These standards would be defined in terms of vehicle emissions and could be made greater, equal to, or less than those faced by vehicle manufacturers. This permit system is superior to CARB's rules because it is based on the emissions of the vehicle stock, not simply the number of vehicles that use the various fuels, and will therefore better tie emissions to fuel use. Moreover as shown below, it gives economic incentives to supply clean but expensive fuels.

CARB's rules (*1*) allow vehicle manufacturers to meet the fleet average standard by certifying vehicles to any combination of transitional LEVs (TLEVs), LEVs, ultra-LEVs (ULEVs), zero-emission vehicles (ZEVs; ZEVs are expected to be electric vehicles), or conventional vehicles so as long as their sales-weighted hydrocarbon emissions do not exceed the fleet average NMOG emissions standard. Under CARB's plan only NMOG standards are averaged; all vehicles must meet the standards for CO and NO_x applicable to the emissions category to which they certify. The *implied* CO and NO_x standards used in the present study are determined by combining the fleet average NMOG implementation schedule with the CO and NO_x standards for the mix of vehicle classes that CARB believes to be "sensible" (*1*,p.23).

In setting up a fuel permit system the volumes of the different alternative fuels need to be adjusted to achieve gasoline equivalent gallons (GEGs), that is, fuel that provides the same amount of energy as a gallon of gasoline. In addition the average miles per GEG of each type of vehicle must be calculated, taking into consideration the vehicle fleet that uses each fuel. The units of the standards are in grams per GEG. Specifically the emissions of criterion pollutant k (k = NMOG, CO, NO_x) per GEG of each fuel j [Phase 2 gasoline, CNG, M85, etc.) in each time period are calculated as:

$$E_{kjt} = \left(\frac{\text{grams}}{\text{GEG}}\right)_{kjt} = \left(\frac{\text{grams}}{\text{mile}}\right)_{kjt} * \left(\frac{\text{miles}}{\text{GEG}}\right)_{jt} \quad (1)$$

The first term on the right-hand side is the grams per mile for vehicle type j. The second term is the average miles per gallon of each type of vehicle running on fuel j.

Given that emissions for fuels are affected by the vehicle fleet that uses the fuels, permits are generated when a fuel supplier sells fuels with weighted-average emissions less than those of the fleet average standard. The permit system presented below also allows fuel suppliers to bank emission permits. That is if a fuel manufacturer more than meets its emission standards, it can store, or bank, the generated permits for later use. An examination of emission banking for manufacturers of light-duty vehicles has been presented previously (*7*).

Banking allows firms to reduce emissions for some initial period and then release them at a later time. The benefits of banking to firms are the cost savings from being able to smooth out emission rates. This trade-off may be desirable if there are not really thresholds at which environmental or human harm occurs, but rather less pollution is less harmful and more pollution produces greater harm. In addition if firms use banking to smooth emissions over time and if marginal damages from emissions are increasing, banking generates lower total damages. Given that vehicle emission standards are increasing in severity through time, firms will want to have the ability to bank emission permits.

The following equation expresses the number of sellable or bankable permits of emission k in year t.

$$\text{Permits}_{kt} = \check{E}_{kt} * \sum_j \text{MPG}_{jt} * \text{GEG}_{jt} - \sum_j E_{kjt} * \text{MPG}_{jt} * \text{GEG}_{jt} \quad (2)$$

where $\check{E}_{kt}$ equals the fleet average standard of grams of pollutant k per mile for vehicles in year t, and E_{kjt} equals the certified emissions of pollutant k in year t for vehicle type j. Because selling an additional GEG increases a fuel supplier's effective standard, this form of standard encourages fuel suppliers to sell additional GEGs whose use in vehicles produces less pollution per mile than the fleet average standard. Collecting terms, it can be shown that

$$\text{permits}_{kt} = \sum_j \overline{E}_{jkt} * \text{MPG}_{jt} * \text{GEG}_{jt},$$

where $\overline{E}_{jkt}$ is the difference between the fleet average standard and the emissions of vehicles that use fuel j.

PERMIT SYSTEM FOR FUEL SUPPLIERS GIVEN VEHICLE STOCK

In the scenario envisioned here each fuel supplier is assumed to maximize profits from selling various fuels and purchasing or selling permits over a $t = (1, \ldots T)$ period planning horizon, subject to an emission constraint on the fuels sold. For the individual fuel supplier the changes in the stock of vehicles can be taken as exogenous. This problem does not address the question of getting the right mix of vehicles and fuels on the road to minimize the social costs of meeting emission constraints. It has the more modest objective of easing the transition to alternative fuels by rewarding suppliers of clean fuels with valuable permits and penalizing the distribution of dirty fuels. For fuel supplier i the problem can be mathematically expressed as

$$\underset{y^i_{kt}, \text{GEG}^i_{jt}, B^i_{kt}}{\text{Max}} \sum_t \delta_t \left[\sum_j \pi^i_{jt}(\text{GEG}) + \sum_k Z_{kt} * y^i_{kt} \right] \quad (3)$$

subject to:

$$\sum_j E_{kjt} * \text{MPG}_{jt} * \text{GEG}^i_{jt} + y^i_{kt} \leq \overline{S}^i_k, \quad \forall\, k, t \quad (4)$$

$$B^i_{kt+1} = B^i_{kt} + y^i_{kt}, \quad \forall\, k, t \quad (5)$$

$$\text{GEG}^i_{jt}, \quad B^i_{kt} \geq 0, \quad y^i_{kt} \gtreqless 0 \quad (6)$$

where

k = NMOG, CO, and NO_x;
j = fuel type (phase 2 gasoline, methanol, etc.);

$\delta_t = 1/(1 + r)^t$, or the discount factor in year t;
Z_{kt} = the per unit price of permits y_{kt} of emission k in year t, $y^i_{kt} > 0$ represents sales, $y^i_{kt} < 0$ are permit purchases;
$\pi(\text{GEG})^i_{jt}$ = the profit function of gasoline supplier i from supplying fuel j in year t;
MPG_{jt} = average mile per GEG of vehicles using fuel j at time t; and
B^i_{kt} = ith firm's stock of banked emissions k in year t (in g).

The objective function (Equation 3) of this problem says that individual fuel suppliers will maximize the profits from selling the various fuels and selling (or purchasing) permits over the T period time horizon. The first constraint, Equation 4, requires that emissions of each pollutant from all fuels sold by this fuel supplier plus the quantity of pollution permits bought or sold at time t must be less than the standard for that pollutant at time t. Equation 5 defines the stock of the emission bank in each year as the total amount bought or sold in any year plus the level in the bank from the previous year. By setting the initial stock of the bank at zero ($B_{kt} = 0$) and requiring that the stock be nonnegative in each year ($B_{kt} \geq 0$), borrowing against the future is disallowed.

From the first-order conditions it can be shown that fuel suppliers should equate the present value of marginal profit from supplying each fuel to the weighted sum of the pollution cost of that fuel. The marginal profits of clean fuels can be negative, because clean fuels generate credits that can be sold. In contrast the marginal profits from the sale of dirty fuels must be positive or else (from the Kuhn-Tucker conditions) the quantity sold must be zero. Moreover for any two consecutive time periods when the stock of banked pollutants is positive, firms will equate the discounted value of permits with the marginal value of being able to pollute one more unit of pollutant k. This type of fuel permit system gives fuel suppliers an incentive to produce expensive, but clean fuels because they can sell pollution permits from the sale of the clean fuels.

EMPIRICAL MODEL OF EMISSION TRADING FOR FUEL SUPPLIERS

Marketable emission permits derive their optimality properties from allocating abatement activities such that the marginal cost of abatement is equated across all sources. Savings are generated because of differences in the marginal costs of abatement between different suppliers. In the scenario described savings are generated when gasoline producers have different marginal production and distribution costs for the various fuels.

Except for reformulated gasoline, alternative fuels either are produced by only one supplier or are not currently produced in a way that is representative of wide-scale use. In the long run wide-scale use of alternative fuels can be expected to lead to multiple suppliers. For now, though, the cost savings from trading emission credits can be calculated by assuming only one supplier of each fuel, but allowing the quantity of each fuel chosen to be determined by a cost-minimizing model that allows fuel suppliers to use any combination of fuels so long as the resulting emissions meet given standards. Cost savings are determined by comparing this outcome with other outcomes, such as electric vehicle (EV) mandates or vehicle penetration scenarios expected by air quality management plans.

To fairly compare fuel-vehicle systems the model must incorporate differences in vehicle costs in the choice of fuels. This is done by determining the incremental cost differential between AFVs and gasoline vehicles, annualizing this incremental capital cost over an assumed vehicle lifetime, and adding this annualized vehicle cost to incremental operation and maintenance costs and to the respective fuel costs. This cost then represents the fuel cost to manufacturers; the cost of fuel j to consumers is the production and transportation costs of fuel j minus the annualized incremental vehicle costs of vehicles that use fuel j.

Mathematical Representation of Empirical Model

The equilibrium model shown below determines the least-cost solution to meeting emission standards for new vehicles and fuels. Consistent with focusing on fuels it is written from the fuel suppliers' perspective. This model, though, explicitly makes vehicles a separate choice variable and takes vehicle vintages into account. Since fuel emission standards are based on the vehicle stock that uses the various fuels, the optimal solution is the same as if vehicle manufacturers took fuel costs into consideration and optimally chose fuels, but faced standards based on the whole fleet of vehicles from the time that the standards are set and into the future.

The empirical optimization model is mathematically represented as follows:

$$\min_{\text{GEG}_{jt}, V_{ajt}, B_{kt}, I_{kt}} \text{TC} = \sum_t \sum_j \delta_t P_{jt} * \text{GEG}_{jt} \quad (7)$$

subject to:

$$\sum_j E_{jt} * \text{MPG}_{ij} * \text{GEG}_{jkt} + I_{kt} \leq \bar{S}_{kt}, \quad \forall\ K, t \quad (8)$$

$$B_{kt+1} = B_{kt} + I_{kt}, \quad \forall\ k, t \quad (9)$$

$$Q_{jt} \sum_a V_{ajt} = \text{GEG}_{jt}, \quad \forall\ j, t \quad (10)$$

$$V_{ajt+1} = V_{ajt}, \quad \forall\ j, t \quad (11)$$

$$\sum_j \text{GEG}_{jt} = \text{tsale}_t, \quad \text{for } t = 1, \ldots T \quad (12)$$

$$B_{kl} = 0;\ 0 \leq B^t_k;\ \text{GEG}_{jt} \geq 0, \quad \forall\ j, k, t \quad (13)$$

$$V_{Ajt} = 0 \quad (14)$$

where

TC = total fuel and incremental vehicle costs;
Q_{jt} = the per vehicle quantity of fuel j used by vehicles in year t;
P_{jt} = per unit of production, transportation, and distribution and incremental vehicle cost of fuel j in year t;
V_{ajt} = number of vehicles of vintage a using fuel j in year t, where A is the terminal vintage for vehicles; and
tsale_t = total quantity of fuel use (on a gasoline equivalent basis) in year t.

The other symbols are as defined previously.

The objective function (Equation 7) minimizes the total fuel and incremental vehicle costs of all vehicles introduced over the T period time horizon. Equation 8 requires that the sum of emissions of pollutant k from all fuels plus the net amount of pollution k banked at time period t must be less than the standard for pollutant k at time t. The standard is equal to the product of the fleetwide vehicle emission standards and the expected equivalent sales quantity of gasoline. Equation 9 defines the stock of the emission bank in each year as the total amount invested (positive or negative) in any year plus the level in the bank from the previous year. Equation 10 allocates the quantity of fuel j used in time period t to the vehicles of the various age classes that use it. Equation 11 specifies that vehicles grow in age each year with no mortality until the end of their expected lifetimes. Constraint Equation 12 requires that the sum of all efficiency-weighted GEGs equals the predicted volumes of fuel used in period t on the basis of forecasts of vehicle miles of travel (VMT). Finally Equation 14 specifies that when vehicles reach the vintage age A they are taken out of service.

Data and Implementation

This model is specified for the South Coast Air Basin for the years 1996 to 2010. The year 1996 is when California Phase 2 gasoline must be introduced; it also reflects early stages of LEV technology. The year 2010 reflects the time period when vehicle and fuel production technology can reasonably be assumed to have advanced and when many of the problems of implementation have been solved. The vehicle-fuel systems examined in the present study include gasoline, methanol blends, neat methanol, CNG, and electricity.

On the basis of the fuel economy projections of the on-road vehicle fleet by the Office of Technology Assessment of the U.S. Congress (*8*), the present study assumes an annual rate of increase of 2.57 percent in fuel efficiency for the 19 years between 1991 and 2010. To give some perspective, the annual rate of increase in fuel efficiency for passenger cars for the 16 years from 1975 to 1991 was 3.59 percent. The annual rate of increase of 2.57 percent is applied to the average fuel efficiency of 25.0 mi/gal (MPG) for the combined fleet (cars and light-duty trucks) in the 1991 model year (*9*) to yield the average MPG of the fleet used in the present study.

The annual quantity of GEGs used by light-duty vehicles from 1996 to 2010 is determined by combining the vehicle age, mileage relationships, and vehicle mix from California's on-road mobile source computer simulation model, EMFAC7E (*10*), with projected VMT and MPG rates. VMT projections are by the South Coast Air Quality Management District (*11*) for spark-ignition passenger cars and light-duty trucks. Finally the emissions of vehicles used in the present study are the 50,000-mi certification standards for light-duty vehicles. These certification standards can be found in CARB (*1*).

PHYSICAL PROPERTIES OF FUELS

The physical properties of the different alternative fuels are very important determinants of their emissions, performance characteristics, and energy equivalency factors. Determination of the volume of each alternative fuel that could be used in the time frame of the present study involves determination of the volumetric energy equivalency of each of the alternative fuels in terms of GEGs. The estimation of GEGs consists of two portions: one part is due to the pure energy content of the fuels, and one part is due to thermal efficiency differences among different vehicle types.

The pure energy conversion factors for the various fuels are shown in Table 1. In the case of CNG the multiplier is for one therm; the others are based on 1 gal.

These volumetric energy conversion factors need to be adjusted to account for engineering efficiency differences. These differences represent the gains in effective heating value of alternative fuels relative to Phase 2 gasoline. Efficiency gains for intermediate years are interpolated assuming equal annual rates of change. These energy efficiency factors have been chosen after consulting the available literature, but they still represent subjective judgment. These efficiency adjustments are shown in Table 1.

FUEL COSTS

The estimation of the future prices of different transportation fuels needs to consider many factors including the costs of feedstocks, the technological maturity of processes to convert feedstocks to final products, and assumptions about the political and economic environments. Indeed there is no one correct price for each fuel. The best that can be done is to narrow the range of uncertainty and make sure that the various estimates are made on a consistent set of assumptions.

The present study assumes that energy markets are global and well connected. In particular the present study uses the approach taken by the National Research Council (*5*) in defining prices for the various energy and nonenergy feedstocks (where appropriate) as functions of the price of crude oil. This approach has the advantage of providing a unifying structure over the price forecasts of each fuel's costs. Simulation results are then interpretable as being due to emissions benefit and cost differentials of the various fuels rather than to the different assumptions made in different price forecasts. The drawback to this approach is that it can overstate the degree to which fuel markets are linked, and it does not allow for relative changes in the prices of fuels.

Retail incremental vehicle costs were estimated by using published sources and conversations with experts in the field. These costs (in present-value dollars) are given in Table 2. They represent the additional costs to consumers over those for conventional vehicles. For example gasoline vehicles with TLEV technology emission levels are estimated to have retail costs equal to an ad-

TABLE 1 Volumetric Conversions and Engineering Efficiency Gains of AFVs

Fuel-Vehicle System	Volumetric Fuel Multiplier	1996 Model Year	2010 Model Year
M85 FFV	1.74	5%	5%
M85 dedicated	1.74	10%	15%
M100	1.99	15%	20%
Phase 2 gasoline	1	0%	0%
CNG dual-fuel	1.26	0%	0%
CNG dedicated	1.26	5%	10%

TABLE 2 Retail Incremental Vehicle Costs Used for Present Study (Per Vehicle Costs, 1992 U.S. Dollars)

Fuel/ Vehicle	TLEV	LEV	ULEV	ZEV
Phase 2	70 - 200	200 - 300	500 - 1000	na
Methanol FFV	200 - 300	276 - 400	nc	na
Methanol Ded.	0 - 200	100 - 300	400 - 600	na
CNG Dual-Fuel	1532 - 2544	1532 - 2544	1532 - 2544	na
CNG Dedicated	900 - 1500	1050 - 1650	1250 - 1850	na
EV	na	na	na	4,179 - 15,869

na: not available.
nc: not considered.

ditional \$70 to \$200 over those for gasoline vehicles with conventional emission abatement equipment and emission levels.

One problem with these cost numbers is that they sometimes represent different stages of technological development. That is they are reasonable estimates, but they represent technology at different points in time. The exceptions to this are EVs. The EV numbers are explicitly based on different assumptions about the applicable technology. To compensate for different technological maturities, ULEVs are not allowed to exist until 1998. As it turns out the more expensive ULEVs are generally not chosen by the model until later years, when standards become tighter.

Fuel taxes are added to fuel costs and combined with incremental vehicle costs to yield the low-cost and high-cost prices for the various fuels. Incremental vehicle costs are converted into cents per gallon by dividing the costs by the total number of miles driven by each type of vehicle and multiplying by the MPG of the vehicles in each year. The low-cost estimates are given in Table 3. Each price represents the cents per gallon (1 gal equals 3.785 L) of fuel on an efficiency-weighted basis. For example under the low-cost scenario the CNG used in dedicated vehicles with LEV technology will cost \$1.30 in 1996 on a gasoline equivalent basis. This cost includes fuel costs and incremental vehicle costs. For this same fuel and year the high-cost estimate is \$1.44. Additional details are provided elsewhere (*12*).

SIMULATION RESULTS FOR JOINT-COST MODEL

A number of simulation scenarios were run by using the model identified in Equations 7 to 14 and the data described above. As a first look into the implications of the model, Figure 1 shows the optimal choice of fuels and vehicle technology for fuel-vehicle systems introduced in 1996 through 2010 under the high-cost scenario, when the banking of HC, CO, and NO_x is allowed. These fuel-vehicle systems represent the least-cost means of attaining the fleet average standard for HC and the implied fleet average standards for CO and NO_x emissions for the new vehicle fleet introduced starting in 1996. That is the emission standards and fuel and vehicle use are based on the entire fleet of vehicles of model year 1996 and beyond. As discussed previously the standards used in this model are different from those for California vehicle manufacturers, who face an HC fleet average standard based only on vehicles sold in each model year.

The units in Figure 1 are 100 million GEGs. The fuel volumes shown represent the aggregate volumes in each year for each fuel type used by all vehicles that use each fuel (e.g., the sum of all fuel used by vehicles of all model years and all age classes). The total fuel volume (the top curve in Figure 1) increases greatly from 1996 to 2010. This reflects the fact that as time passes a greater percentage of the on-road fleet is composed of vehicles produced after 1996. By 2007 100 percent of fuel use is attributed to vehicles produced in 1996 and beyond. The small decline in fuel use in the years 2008 to 2010 reflects predictions that annual fuel efficiency gains increase at a greater growth rate than VMT. The total costs for the fuels (including incremental vehicle costs and taxes) are \$34.22 billion and \$39.24 billion for the low- and high-cost scenarios, respectively. Table 4 shows these costs and the costs from additional scenarios.

As seen in Figure 1 dedicated vehicles that use 100 percent methanol (M100 vehicles) and dedicated CNG vehicles that use LEV and ULEV technology use the bulk of the fuel in each year in the high-cost scenario. This is also true for the low-cost scenario, although the results are not shown. EVs are also chosen, even though no explicit number of EVs was required. Absent are gasoline vehicles that use conventional or any of the various LEV technologies. Thus if these AFVs are viewed as close to or perfect substitutes for gasoline vehicles and can be made for the incremental costs indicated above, then it appears that AFVs represent a viable low-cost means of attaining emission goals. Especially for the EVs, but also for the CNG vehicles, the high capital costs are effectively offset by the low fuel costs over the vehicles' life spans. Changing the real discount rate in a range of 0 to 15 percent did not appreciably change the chosen mix of fuels and vehicles. Running the model with low incremental vehicle costs for gasoline vehicles (conventional, TLEV, LEV, and ULEV) and the high-cost scenario for AFVs does not bring gasoline vehicles into the solution set.

Several investigators (*13–15*) have performed work that suggests that individuals prefer the attributes of gasoline vehicles to the hypothesized attributes of AFVs. To test the magnitude of this bias toward gasoline vehicles, a number of simulations were run with low incremental costs for gasoline vehicles, with the high-cost scenario for AFVs, and with the price of reformulation lowered by 10 cents (equal to about \$350 in incremental vehicle costs). In this scenario significant numbers of gasoline vehicles that use LEV and ULEV technology (with incremental vehicle costs equal to \$200 and \$500, respectively) displace CNG and M100 vehicles that use ULEV technology (costing \$1,850 and \$600, respectively). Gasoline reformulation costs are not, however, expected to be this low. Nonetheless if consumers view gasoline vehicles as providing additional value over M100 and CNG vehicles equal to 10 cents per gallon (\$350 incremental vehicle costs), then gasoline vehicles become a cost-effective alternative to achieving emission standards. This observation should be viewed as conservative (favoring the status quo of gasoline vehicles), however, since this uses the low-cost estimates for gasoline vehicles and the high-cost estimates for AFVs. Interestingly the inclusion of gasoline vehicles only slightly affects the optimal number of EVs. Nonetheless M100 (and to a lesser extent CNG) remain important fuels in vehicles that use LEV technology (using the high incremental vehicle cost estimates). When the price of gasoline is lowered by 16 cents (zero reformulation costs equal to

TABLE 3 Cents Per GEG Including Incremental Vehicle Costs, Low-Cost Scenario[a] (1992 U.S. Dollars)

Year	EV	CON. GAS	GAS TLEV	GAS LEV	GAS ULEV	M85 DED. TLEV	M85 DED. LEV	M85 DED. ULEV	M85 FFV TLEV	M85 FFV	M100 TLEV	M100 LEV	M100 ULEV	CNG TLEV	CNG LEV	CNG ULEV
1996	463	152	154	157	164	162	164	171	174	176	164	167	174	127	130	135
1997	440	157	158	161	169	164	167	174	177	179	166	168	176	130	134	139
1998	418	161	163	166	174	166	169	177	180	182	168	170	178	134	138	142
1999	398	166	167	171	179	169	171	179	183	185	169	172	180	138	142	147
2000	380	171	172	176	184	171	174	182	187	189	171	174	182	142	146	151
2001	362	174	176	179	187	171	174	182	187	189	170	173	181	146	150	155
2002	346	177	179	183	191	171	174	182	188	190	169	172	181	150	154	160
2003	331	181	183	186	195	171	174	183	189	191	168	171	180	155	159	164
2004	316	184	186	190	199	171	174	183	189	192	168	170	179	160	164	169
2005	303	188	190	194	203	171	174	183	190	192	167	170	179	164	169	174
2006	291	192	194	198	207	171	174	184	191	193	166	169	178	169	174	180
2007	279	196	198	202	211	171	174	184	192	194	165	168	177	174	179	185
2008	268	200	202	206	216	171	175	184	193	195	164	167	177	180	184	190
2009	258	204	206	210	220	171	175	185	194	196	163	166	176	185	190	196
2010	248	208	210	215	225	171	175	185	194	197	162	166	176	192	196	203

a. 1 gallon equals 3.785 liters.

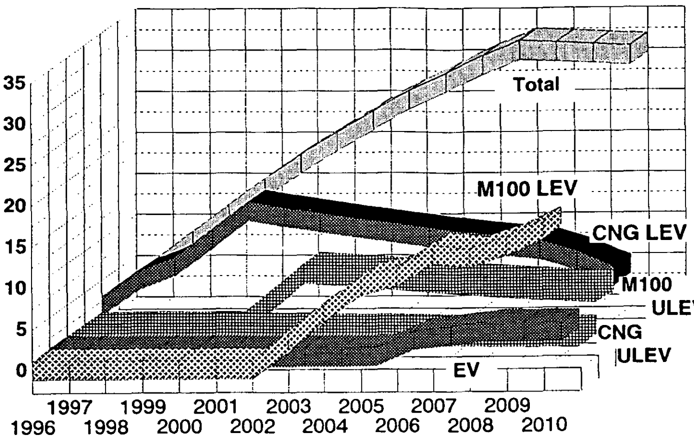

FIGURE 1 Fuel-vehicle combinations for high-cost scenario (100 million gallons; discount rate = 5 percent; 1 gal = 3.785 L).

$566 in incremental vehicle costs), the optimal mix of vehicles includes mainly gasoline vehicles that use LEV and ULEV technologies. At this price for gasoline, M100 LEVs still continue to contribute to fuel needs in the latter part of the time horizon.

EVs are chosen as a cost-effective means for meeting emission standards for two reasons. First, EVs are treated under CARB's regulations and in the present model as having zero emissions, even though their use generates additional power plant emissions [power plant emissions have been estimated previously (*6*)]. Thus EVs are given an unfair advantage in the regulations, which explains why some are used in 1996 when standards are at their least-stringent levels over the time horizon. Second, the implied emission standards used here have such tight NO_x emission restrictions for 2003 and beyond that they can only be met with the use of some EVs. That is the CARB's HC standard combined with its expected implementation schedule for LEV technologies implies an NO_x standard that can be met only through the use of some EVs.

As discussed CARB requires a certain percentage of the new vehicle fleet to be EVs in each model year starting in 1998. When these EV requirements are imposed on the model, the number of EVs chosen increases; the cost of meeting the emission standards also increases. For both the low- and high-cost scenarios the costs rise about 1 percent, varying slightly with the discount rate. These results are shown in Table 4.

All the above scenarios were conducted by using the basic model that allows emissions of HC, CO, and NO_x that are less than the standards to be put into separate emission banks and carried forward to be used in later periods. When emission banking is not allowed the cost of meeting the standards rises. For both the low- and high-cost scenarios, the cost savings from being able to bank the three separate emissions range between 2.5 and 5.5 percent, depending on the interest rate. The cost savings represent the savings due solely to allowing the mix of fuels and vehicles to be chosen such that emission reductions are made in early periods, to be used later to relax emission standards.

Since CARB's regulations, in strict terms, require only an HC fleet average standard, it is also interesting to examine the cost savings and the mix of fuels and vehicles from this scenario. In this case HC emissions become the only banked pollutant and the total costs of the fuels and incremental vehicle costs falls to $33.08 billion (representing a 3.30 percent decrease in costs) and $36.43 billion (representing a 7.14 percent decrease in costs) for the low- and high-cost scenarios, respectively. The cost savings from banking fall to 0.75 to 1 percent of total costs, depending on the interest rate and assumed costs. Banking of HC emissions is thus 2.5 to 5 times less valuable than banking of CO and NO_x emissions in the presence of all three constraints.

As discussed earlier for the scenarios in which all three pollutants had their own constraints, significant numbers of EVs were voluntarily chosen. With only an HC constraint, no EVs are voluntarily chosen. Imposing CARB's EV mandates (for the case of only an HC standard) raises the costs of meeting the HC pollution standard by about 3.11 and 7.5 percent for the low- and high-cost scenarios, respectively (Table 4). When banking is also restricted the EV mandates cost an additional 3.88 to 8.33 percent for the low- and high-cost scenarios. Under the base case assumptions (HC, CO, and NO_x standards and banking is allowed) the percent cost increases for EV mandates could be viewed as fairly small (approximately 1 percent of costs). However the 3.11 to 7.59 percent cost increases found in the HC-only constraint or the 3.88 to 8.33 percent cost increases found in the HC-only constraint, no-banking scenario bring into question the burden imposed by the EV mandates. The additional burden of EVs is all the more rel-

TABLE 4 Present-Value Cost Estimates for Various Scenarios[a] (5 Percent Discount Rate, US$1 Million, 1992)

HC, CO, and NOx Standards	Base Case	No Banking	EV Mandates	EV High-Cost, All Else Low
Low-Cost	34,218	35,202 (2.88%)	34,524 (0.89%)	36,062 (5.39%)
High-Cost	39,236	41,394 (5.50%)	39,635 (1.02%)	na
HC Standard Only	**Base Case**	**No Banking**	**EV Mandates**	**EV Mandates No Banking**
Low-Cost	33,088	33,381 (0.88%)	34,117 (3.11%)	34,372 (3.88)
High-Cost	36,435	36,745 (0.85%)	39,200 (7.59%)	39,470 (8.33%)

[a]The numbers in parentheses represent the percent cost increases from the "low-cost" and "high-cost" scenarios as applicable; na: not applicable.

evant considering that EVs are falsely assumed (by California regulations) to produce zero emissions. This suggests that CARB's EV mandates are an excessively expensive way to achieve emission goals; the same emission standards could be met more cheaply with other low-emission fuels and vehicles.

That scenario, with only the HC constraint, no banking, and mandated quantities of EVs, most closely matches CARB's regulations. It still differs significantly from CARB's regulations, though, that require vehicle manufacturers to meet standards on vehicles in each model year independently; in contrast these simulations ensure that the fleet average standard is based on the whole fleet in every time period.

FINAL REMARKS

There is widespread agreement that both vehicle emission control systems and fuel type simultaneously affect mobile source emissions. This paper argues that placing emission regulations on fuel suppliers will encourage the use of alternative transportation fuels such as CNG, methanol, and electricity. By using marketable emission permits, these regulations can be designed to minimize the cost of meeting emission standards. It was argued that the regulation of fuels should be based on the emissions of vehicles that use the fuels.

Previous studies that have looked at alternative transportation fuels have made single-period, "snapshot" estimates of the costs and emission impacts from their introduction. The research presented here has examined the impact of meeting emission goals for transportation fuels with a multiperiod dynamic model that includes emission banking and the coordination of the on-road stock of vehicles and fuels.

A theoretical model based on the concept of marketable emission permits was built for gasoline suppliers, given that the current and future stock of vehicles is not a choice of gasoline suppliers. This model shows that a fleet average emission standard placed on gasoline suppliers will encourage the production and distribution of clean fuels that would otherwise not be profitable because clean fuels will generate valuable emission permits. This permit system, however, does not minimize the total (fuel and vehicle) costs of meeting emission standards because the fuel and vehicle production decisions are made by different decision makers.

Next a multiperiod empirical model was built. That model determines the least-cost solution to meeting emission standards for new vehicles and fuels. The model explicitly makes vehicles a separate choice variable and takes vehicle vintages into account. The base simulations use three independent constraints for HC, CO, and NO_x emissions. Under the assumption that individuals view all types of alternative-fuel and gasoline vehicles as perfect substitutes, both the low- and high-cost scenarios determined that the least-cost combination of fuels and vehicles consists mainly of dedicated methanol vehicles and dedicated CNG vehicles that use LEV and ULEV technology. Some EVs were also chosen.

Absent from the selected fuel and vehicle systems are any vehicles that use Phase 2 reformulated gasoline, which will be the required fuel for all gasoline vehicles in 1996 and beyond. Only when the price of reformulation was dropped by 10 cents per gallon, equal to $350 in incremental vehicle costs, were significant numbers of gasoline vehicles chosen. This suggests that if consumers view gasoline vehicles as providing $350 in additional value over methanol and CNG vehicles, then the use of gasoline vehicles that use LEV and ULEV technology becomes a cost-effective means of achieving emission standards.

Although there are CO and NO_x standards implied by California's LEV program, only HC emissions have a predefined schedule. When the model is estimated with only the HC constraints, fuel and incremental vehicle costs fall by 3.30 and 7.14 percent for the low- and high-cost scenarios, respectively. In addition the cost savings from banking fall to about 1 percent, but the costs of the EV mandates rise substantially to 3.11 to 7.59 percent for the low- and high-cost cases, respectively. The low value of banking is understandable given that the fuel volumes covered under the emission regulations are a fairly small proportion of fuel sales in the early years of the scenario. The fairly substantial percent cost increases for EV mandates found in the HC-only constraint scenario (3.11 to 7.5 percent) bring into question the burden imposed by the EV mandates. This suggests that CARB's EV mandates are an excessively expensive way to achieve emission goals.

REFERENCES

1. *Proposed Regulations for Low-Emission Vehicles and Clean Fuels.* Staff report. California Air Resources Board, 1990.
2. *Proposed Regulations for Low-Emission Vehicles and Clean Fuels.* Technical Support Document. California Air Resources Board, 1990.
3. Sperling, D. *New Transportation Fuels: A Strategic Approach to Technological Change.* University of California Press, Berkeley and Los Angeles, 1988.
4. *Alternative Transportation Fuels: An Environmental and Energy Solution.* (D. Sperling, ed.) Quorum Books, New York, 1989.
5. *Fuels to Drive Our Future.* National Research Council, National Academy Press, Washington, D.C., 1990.
6. Wang, Q., D. Sperling, and J. Olmstead. *Emission Control Cost-Effectiveness of Methanol-, Ethanol-, Liquified Petroleum Gas-, Compressed Natural Gas-, and Electricity-Fueled Vehicles.* Institute for Transportation Studies Report. University of California, 1993.
7. Rubin, J., and C. Kling. An Emission Saved Is an Emission Earned: An Empirical Study of Emission Banking for Light-Duty Vehicle Manufacturers. *Journal of Environmental Economics and Management*, Vol. 25, No. 3, Nov. 1993, pp. 257–274.
8. U.S. Congress, Office of Technology Assessment. *Improving Automobile Fuel Economy: New Standards, New Approaches.* OTA-E-504. U.S. Government Printing Office, Washington, D.C., Oct. 1991.
9. Heavenrich, R. M., J. D. Murrell, and K. H. Hellman. *Light-Duty Automotive Technology and Fuel Economy Trends Through 1991.* EPA/AA/CTAB/91-02. Environmental Protection Agency, May 1991.
10. *Methodology to Calculate Emission Factors for On-Road Emission Factors for On-Road Motor Vehicles*, EMFAC7E. California Air Resources Board, 1991.
11. *Future Baseline Emissions for the South Coast Air Basin: Average Annual Day, Final Appendix III-B.* Final Air Quality Management Plan. 1991 Revision, South Coast Air Quality Management District, July 1991.
12. Rubin, J. *Marketable Emission Permit Trading and Banking for Light-Duty Vehicle Manufacturers and Fuel Suppliers.* Ph.D. dissertation. University of California, Davis, 1993.
13. Beggs, S., S. Cardell, and J. Hausman. Assessing the Potential Demand for Electric Cars. *Journal of Econometrics*, Vol. 16, 1981, pp. 1–19.
14. Bunch, D., M. Bradley, T. Golob, R. Kitamura, and G. Occhiuzzo. Demand for Clean-Fuel Vehicles in California: A Discrete-Choice Stated Preference Pilot Project. *Transportation Research*, Vol. 27A, 1993, pp. 237–253.
15. Walls, M. Differentiated Products and Regulation: The Welfare Costs of Natural Gas Vehicles. Discussion paper ENR92-01. Resources for the Future, 1991.

Publication of this paper sponsored by Committee on Alternative Transportation Fuels.