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PROJECTED FUEL SAVINGS AND EMISSIONS REDUCTIONS FROM LIGHT-VEHICLE FUEL ECONOMY STANDARDS

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Abstract—This study applies a model of motor vehicle stock turnover to estimate the effect of strengthened fuel economy standards on gasoline consumption, greenhouse gas emissions and hydrocarbon emissions by light-duty vehicles in the United States. Without significant policy change, fuel consumption is projected to grow from a 1990 level of 6.3 million barrels per day (Mbd) to 9 Mbd by 2010. Five policy-driven scenarios are analyzed, ranging up to a new vehicle fuel economy improvement rate of 6% per year. For the 6%/yr scenario, the analysis projects gasoline savings of 2.9 Mbd and emissions reductions of 147 million metric tons per year (carbon equivalent) of greenhouse gases and 495,000 metric tons per year of evaporative hydrocarbons by 2010. The sensitivity of the projections to various factors is also examined. The most critical assumption is the baseline (i.e., the extent of fuel economy change in the absence of stronger standards). Other factors examined, such as growth in vehicle miles of travel (VMT), VMT rebound, credits toward regulatory compliance, rollbacks of standards, upper and lower bounds on a percentage increase standard, possible vehicle market shifts and fuel economy shortfall, were found to have smaller effects. Fuel economy standards are projected to be a reliable mechanism for controlling future gasoline consumption and associated pollution emissions in the United States.

INTRODUCTION

Corporate average fuel economy (CAFE) standards have been the primary policy for controlling energy consumption by cars and light trucks (light vehicles) in the United States. These federal regulations specify a minimum sales-weighted average fuel economy to be met by each manufacturer selling cars or light trucks in the United States. The CAFE standards enacted in 1975 were instrumental in the near doubling of rated automobile fuel economy since that time. Although the impetus for the regulation was the 1973 oil embargo and the energy crises of 1973 and 1979 did temporarily raise fuel prices, CAFE standards provided a steady signal to manufacturers, which has led to the acceptance of more efficient vehicles in the marketplace.

The existing regulatory mandate took effect for automobiles in 1978. The highest level specified in the law, 27.5 mpg,[1] was first established for 1985 and is the automobile standard in effect as of this writing. The standard was rolled back by the Reagan administration for four years, from 1986 through 1989. Figure 1 shows historical average EPA-rated fuel economy of new vehicles through 1993 (along with the future scenarios described later). The average fuel economy achieved by new automobiles peaked at 28.6 mpg in 1988 and has subsequently declined by about 3%. Standards for light trucks were left to the discretion of the Department of Transportation and have greatly lagged behind the standards for automobiles. The 1993 light truck standard was 20.4 mpg, 63% higher than the 1973 new fleet average of about 12.5 mpg; the automobile standard was 27.5 mpg, 94% higher than the 1973 average of 14.2 mpg. New light truck fuel economy peaked at 21.6 mpg in 1987 and subsequently declined; the average was 20.8 mpg in 1993.

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[1] Unless otherwise noted, all fuel economy values cited here are U.S. Environmental Protection Agency (EPA) composite values as used for compliance with CAFE standards, computed as the 55% city and 45% highway-weighted average of unadjusted driving cycle test results. For the purposes of this article, such values are termed *rated* or *compliance* fuel economy values. Historical average fuel economy statistics are from Murrell *et al.* (1993); data on standards and compliance levels by manufacturer are from NHTSA (1993).

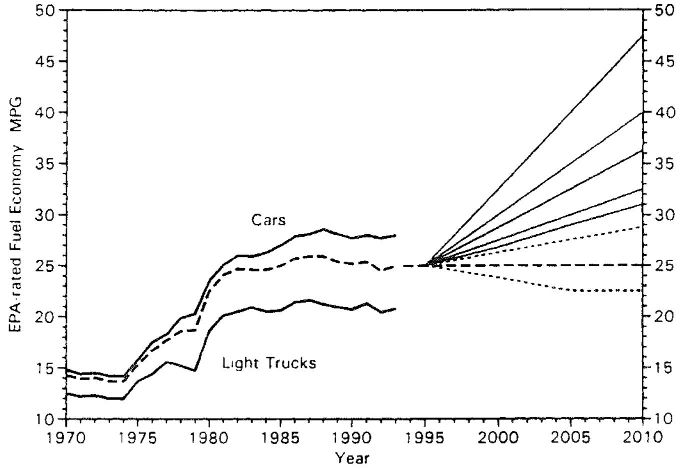

Fig. 1. New light vehicle fuel economy 1970–1993 and scenarios through 2010. Historical data are shown separately for cars, light trucks, and their average (dashed line), from Murrell et al. (1993). Future projections are given as the light vehicle average. The reference baseline of fuel economy frozen at 25.0 mpg is shown as a dashed line. The rising and falling baselines as specified in Table 1A are shown as dotted lines. Solid lines of increasing slope are for linear increase rates of 1.6%/year, 2%/year, 3%/year, 4%/year, and 6%/year, corresponding to cases A–E as specified in Table 1A.

The portion of the new light-vehicle market classified as light trucks increased from 20% in 1977, before CAFE standards took effect, to 33% in recent years. Meanwhile, the gap between the fuel economy of light trucks and that of cars rose from 15% in 1977 to 25% presently. Because most light trucks are used for personal transportation and are substituted for cars in the light-vehicle market, cars and light trucks must be treated together for analysis of overall fuel consumption by light-vehicle transportation in the United States.

There are a number of reasons to reduce light-vehicle petroleum consumption in the United States. Concerns persist about oil import dependence because of its contribution to the trade deficit and national security implications (OTA, 1991c). As of 1992, imports accounted for over 40% of U.S. petroleum consumption and the oil import bill was $45 billion, over half of the merchandise trade deficit (EIA, 1993). Annual motor fuel expenditures average about $1000 per household (EIA, 1990b, Table 7), amounting to just under 4% of the median household income of $26,000 (Bureau of the Census, 1988, Table 715). Thus, although they are a small share of individual consumer expenditures, aggregate motor fuel costs are a large drain on the U.S. economy because the revenues flow to the relatively few oil producers, many of which are overseas. Transportation fuel use is a major source of greenhouse gas emissions, which contribute to risks of global climate disruption (Greene, 1993; OTA, 1991a). A substantial portion of hydrocarbon emissions is directly related to the amount of gasoline consumed (DeLuchi *et al.*, 1992).

Technology for improving vehicle efficiency has greatly advanced over the past decade, and the feasibility of significant improvement is well established. Nevertheless, there is disagreement regarding how much improvement can be made over a given time frame (DeCicco, 1992a; DeCicco & Ross, 1993; NRC, 1992; OTA, 1991b; SRI, 1991). There are ongoing advances in automotive technology, including many technologies that can improve fuel economy but are likely to be applied to enhance other vehicle attributes, such as performance, in the absence of regulatory direction. The greater certainty with which fuel supply requirements can be predicted when vehicles meet mandated efficiency levels is seen by some as a benefit of such standards, apart from the direct benefits of petroleum savings. There has been consistent public opinion support for improving fuel economy standards as a way to address the problems related to motor vehicle fuel consumption. Polls, such as those by Breglio and Lake (1991) and Schneiders (1992), indicate public preference for standards over a gasoline tax, even if efficiency improvements increase the price of a car. The automobile industry, which bears the up-front costs of complying with such regulations, has opposed strengthening of CAFE standards.

The existing law on automotive fuel economy enables the administration to set CAFE standards at a maximum feasible level considering technical practicality, economic impacts and other factors. The Reagan and Bush Administrations (1980–1992) were opposed to fuel economy regulation; the automobile standards were weakened from 1986 to 1989. Strengthening the CAFE standards was not included in the National Energy Strategy issued in 1991. Proposals to increase fuel economy standards were introduced and commanded majorities in several recent U.S. Congresses but were unsuccessful because of filibuster and veto threats. The Clinton/Gore candidacy supported raising CAFE standards during the 1992 election campaign but did not include a proposal to strengthen the standards in the Climate Change Action Plan issued in October 1993. The plan notes that addressing CO_2 emissions from cars and light trucks is a necessary part of a long-term strategy and calls for a 1-year process to develop measures to reduce emissions from personal motor vehicles. The Administration plan specifically calls for examination of "measures to improve new vehicle fuel efficiency . . . at least 2% per year over a 10 to 15 year period" (Clinton & Gore, 1993, p. 31).

A critical question for policy-makers contemplating strengthened CAFE standards is how much reduction in fuel consumption and attendant emissions can be expected. This article estimates the reductions expected to occur under strengthened standards as newer, more efficient vehicles replace older ones in the light-vehicle stock. Computing the savings from fuel economy improvement is a relatively straightforward exercise. The principal inputs needed are estimates of future travel (VMT) and the age distribution of the vehicle population. A number of regulatory provisions can result in achieved CAFE levels being lower than nominal CAFE targets. Therefore, a general analysis is presented that shows the projected savings for various levels of fuel economy achieved by a given year. The effects of regulatory provisions are then examined in terms of their effect on achieved versus nominal CAFE level. Finally, differences among previously reported savings estimates are examined by tracing them to differences in underlying assumptions.

Other analysts have reported projections of fuel savings from higher automotive fuel economy over time spans similar to those considered here (CRA, 1991; DOE, 1991; Farmer, 1991a, 1991b; Greene, 1990b; Greene and Duleep, 1993; Ledbetter & DeCicco, 1991; OTA, 1991b). A major source of differences among projections is the assumed baseline fuel economy (i.e., the future CAFE levels in the absence of higher standards). Differences also arise because of uncertainties in the VMT projection, including the effect of improved fuel economy on the amount of driving. There are also issues regarding the extent to which mandated fuel economy improvements might raise the cost of new cars so that older, less efficient vehicles remain in the stock for a longer period of time. There is also a related issue of attribution—namely, the extent to which the fuel savings are an effect of the regulatory intervention rather than a market response to changes in fuel price. This latter issue has been examined in retrospective analyses of the existing CAFE regulations (Greene, 1991; Leone & Parkinson, 1990). Given the variety of assumptions that can be made about all of these factors, it is not surprising that the range of predicted savings estimates is wide. Estimates regarding the Bryan (1991) proposal, for example, have been reported as varying by as much as a factor of 5, from 0.5 Mbd (million barrels per day) to 2.5 Mbd (Dillin, 1991; OTA, 1991b, pp. 99ff).

This article focuses on the direct gasoline savings from future CAFE increases without revisiting the broader issues of technical feasibility and economics. This introductory section closes with a brief review of the past savings attributable to standards. A methodology section describes the analytic approach and scenario definitions. The results are presented in two sections: consumption and savings estimates for the set of primary scenarios with varying baseline assumptions; and the effect on estimates of underlying assumptions regarding the form of the standards and other factors.

Savings from past CAFE standards

Various analysts have estimated the fuel savings due to past improvements in automotive fuel economy, ranging from 2 Mbd to 4 Mbd depending on the period and vehicle classes covered (Greene *et al.*, 1988; OTA, 1991b; Ross *et al.*, 1991; Schipper *et al.*, 1990). None of these analyses explicitly broke the savings down by cause (standards or fuel price). For calculating the effect of the existing standards, an appropriate base year is 1977. This is the year before the automobile standards went into effect and is after the immediate response to the 1973 oil crisis, which caused an initial round of fuel economy improvement prior to CAFE standards. The average on-road fuel economy of cars and light trucks subject to CAFE regulation rose from about 13 mpg in 1977 to 20 mpg in 1991, when annual travel (VMT) by light vehicles subject to CAFE regulation reached 1.9 trillion miles. The savings estimate relative to frozen fuel economy is therefore

$$\frac{(1.9 \times 10^{12}\,\text{miles/year})}{(42\,\text{gal/bbl})(365\,\text{days/year})}\left(\frac{1}{13\,\text{mpg}} - \frac{1}{20\,\text{mpg}}\right) = 3.3\,\text{Mbd}$$

For this calculation, new vehicle fuel economy statistics are from Murrell *et al.* (1993). Stock average fuel economy is estimated as described later using the author's stock model and a shortfall of 20%, with VMT derived from FHWA (1992).

The question of how much of the savings is attributable to CAFE standards as opposed to changes in fuel price was addressed by Greene (1990a), who found a strongly significant CAFE effect but only a marginally significant price effect. This is not surprising because prices fluctuated and, through mid-1990, were lower in real terms than they were in 1973. Greene's coefficients suggest about a 75% effect for CAFE, but he could not reject the hypothesis that price had no effect. It is therefore reasonable to attribute 75% to 100% of the reduction of CAFE standards, resulting in a savings estimate of 2.5 Mbd to 3.3 Mbd. Thus, light-vehicle fuel consumption would be 40% higher if CAFE standards had not been enacted and over 50% higher if no improvement in fuel economy (CAFE induced or otherwise) had occurred.

METHODOLOGY

The basic relation for fuel use by a population of motor vehicles is

$$\text{Fuel Use} = \frac{\text{VMT}}{\text{MPG}} \tag{1}$$

Vehicle fuel economy, represented by MPG (miles per gallon), refers to the stock average of the vehicle population under consideration. Actual on-road fuel economy must be used for MPG in eqn (1) rather than the compliance fuel economy ratings, which are biased high (see the following subsection). Stock average MPG depends on the fuel economy of all vehicles in the stock, weighted according to their usage by vehicle age (vintage) and other attributes that might be used to classify vehicles for the purpose of analysis (such as cars versus trucks). Vehicle miles travelled (VMT) depends on the size of the driver population, their income and the cost of driving, as well as structural factors (related to land use and availability of alternative modes of transportation). VMT's cost-of-driving dependence links it to fuel economy (MPG), because

$$\text{Fuel Cost per Mile} = \frac{\text{Fuel Price}}{\text{MPG}} \tag{2}$$

Thus, an improvement in fuel economy may induce additional driving—what is known as the "rebound" effect (Greene, 1991)—thereby offsetting some of the potential fuel savings.

Shortfall in on-road fuel economy

Because of increasing congestion, urbanization, higher road speeds and other factors, actual on-road fuel economy is less than the EPA-test fuel economy used for CAFE compliance purposes. The gap between on-road MPG and EPA test values is termed fuel economy shortfall. The fuel economy estimates given in the *EPA Gas Mileage Guide* and printed on new-vehicle sales stickers reflect an average downward adjustment of 15%, based on EPA analysis from the early 1980s, which at least partly corrects for shortfall. Mintz *et al.* (1993) place the average shortfall at close to 20%, noting that it may be worse for some light trucks. For the U.S. light-vehicle stock, the average on-road fuel economy in 1990 was 19.4 mpg (Davis & Strang, 1993). The age-weighted average EPA test fuel economy of the light-vehicle stock in 1990 was 24.3 mpg, also suggesting a shortfall of 20%. It has been projected that shortfall could grow to 30% by 2010 (Westbrook & Patterson, 1989), but this is yet to be confirmed by empirical trends. A constant shortfall of 20% is assumed for this analysis. An underestimate of shortfall implies a proportionate underestimate of both fuel consumption and fuel savings; the reverse is also true. Note that shortfall is considered to depend on the year in which a vehicle is used, not the year in which it was made.

Fuel economy projections

Baseline. Estimating the savings due to a policy such as CAFE standards involves computing the difference between two projections of fuel use (i.e., fuel use projected under some baseline assumptions minus fuel use projected under assumptions of the CAFE standard). For the purpose of comparing several potential policy changes, such as a variety of CAFE proposals, fuel taxes or other options, it is sufficient that they be compared to a common baseline. Ideally, the baseline should represent an expectation of what would occur in the absence of policy change (a null policy case). The issue of what changes in new-vehicle fuel economy would occur in the absence of policy change is often contentious. Three baseline cases are examined in this article: a middle case that holds new light-vehicle rated fuel economy frozen at the 1993 light-vehicle average of 25.0 mpg, plus cases of slowly falling and slowly rising trends.

The justification for a frozen fuel economy baseline is as follows. The 1990–1991 Middle East crisis had a relatively small and temporary impact on oil prices. There appears to be no market expectation of a lasting or severe supply disruption. Price rises are expected to be modest; for example, the Department of Energy projects a real gasoline price increase rate of 1%/yr through 2010 (DOE, 1993). New light-vehicle rated fuel economy peaked at 25.9 mpg in 1987–1988 and has since declined, coincident with increases in power performance, weight and other vehicle amenities. Light truck market share has also increased. Recent announcements in the automotive trade press suggest a continuation of such trends for the indefinite future. Although there may be small fluctuations in the average from year to year, there is little indication of a trend either upward or downward. From 1981 to 1993, average new light-vehicle fuel economy has been within 0.9 mpg of 25.0 mpg, which is the baseline fuel economy chosen in this article.

A falling baseline case assumes that new-fleet fuel economy is fixed through 1995 and then declines at 1%/yr from 1996 to 2005, reaching a new plateau at 22.5 mpg, which is then held through 2010. A downward trend might be expected with ongoing low oil prices if CAFE standards are terminated, if they are administratively rolled back or if enforcement is weakened. Ongoing increases in light truck market share while the light truck standards are essentially flat would also result in a decline in the new light-vehicle average.

A rising baseline case assumes that new-fleet fuel economy is fixed through 1995 and then improves at 1%/yr through 2010. A rationale for this scenario would be an expectation that technology advances and a diminishing marginal value of vehicle amenities adverse to fuel economy could allow the market to yield a slow improvement. A higher rising baseline (e.g., 2%/yr increase, so that new cars reach 33 mpg in about 10 years without stronger standards) appears unsupportable given current trends and an expectation of slowly rising fuel prices.

Policy scenarios. The five principal scenarios of policy-driven fuel economy improvement are summarized in Table 1. The scenarios are identified by their rates of improvement in light-duty fleet average fuel economy. Percent increases are relative to the base year (1993) average, which is assumed to hold for 1994–1995 as well. In all

Table 1. Scenarios of light-vehicle fuel economy for varying degrees of regulatory pressure

Scenario	Percent Increase by 2005	Percent Increase by 2010	Ten-year (2005) Targets Cars	Ten-year (2005) Targets Light Trucks	Ten-year (2005) Targets All LDVs
Frozen efficiency baseline	0	0	28.0	20.8	25.0
(A) DOE 1993 projection	16%	24%	32.5	24.1	29.0
(B) 2% per year	20%	30%	33.6	25.0	30.0
(C) 3% per year	30%	45%	36.4	27.0	32.5
(D) 4% per year	40%	60%	39.2	29.1	35.0
(E) 6% per year	60%	90%	44.8	33.3	40.0

Fuel economy values are EPA composite 55% city, 45% highway unadjusted test ratings in miles per gallon (mpg).

scenarios, the increases start in 1996 and continue linearly through 2010. The same percent improvement rates are assumed for light trucks as for cars, and the light truck market share is held at the recent average (34%) level. This is a reasonable assumption if light trucks receive regulatory pressure equal to that of cars, as has been specified in recent Congressional proposals (in contrast to past CAFE standards).

Figure 1 illustrates the scenarios as increases in the overall new light vehicle (combined car and light truck) average fuel economy. Scenarios B, D, and E are similar to proposals introduced in the 102nd Congress, except that 10-year target dates are pushed forward from 2001 to 2005. Detailed fuel economy values (EPA-rated new fleet and stock averages and estimated stock on-road average) for key projection years (2000, 2005, 2010) are given in Table A1 in the Appendix.

Scenario A corresponds to the DOE (1993) projection, which gives a market-driven increase in fuel economy averaging 1.6%/yr. Earlier DOE projections (e.g., the National Energy Strategy and previous editions of the *Annual Energy Outlook*) also had market-driven increases, which have been contradicted by data observed through 1993. Scenario A is used to facilitate comparison to other published analyses which adopt similar projections as a baseline. The judgment that such a trend is unlikely in the absence of policy change is consistent with the statement by a DOE official that there "may be unmet CAFE needs" in testimony regarding National Energy Strategy projections (Stuntz, 1991).

Scenario B specifies a 2%/yr increase in new-fleet fuel economy, the minimal rate of increase targeted by policies to be developed in support of a U.S. Climate Action Plan (Clinton & Gore, 1993). This rate of increase is similar to the rate corresponding to the NRC (1992) "lower confidence, technically achievable" fuel economy levels (the higher levels in that report) and to the levels proposed in the Johnston (1991) amendment.

Scenario C (3%/yr) is an intermediate case, which corresponds to the level that would be achieved under the Bryan (1991) bill with an administrative rollback of its 10-year target.

Scenario D is similar to the full 10-year improvement proposed by the Bryan bill, except that the year for achieving a 40% improvement is moved forward from 2001 to 2005 and the 4%/yr rate of improvement is continued to 2010.

Scenario E (6%/yr) is the most ambitious case, similar to the Boxer (1991) bill with the dates moved forward and ongoing improvement through 2010. The 10-year target of Scenario E is slightly less than the intermediate fleet average (Level 2, for new cars reaching 46 mpg) identified as cost-effective by DeCicco and Ross (1993). The 2010 new-car level of 53 mpg is just below the 55-mpg "medium risk" level identified by EEA (1991) for that year.

VMT growth

Historical and projected VMT are graphed in Fig. 2, and estimates for key years are listed in Table A1. Light-duty vehicle miles of travel (VMT) estimates are based on

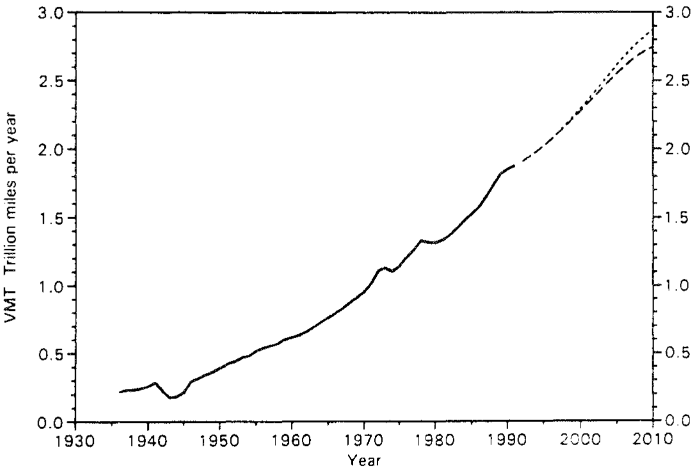

Fig. 2. Past and projected U.S. light duty vehicle miles of travel. VMT for cars and light trucks covered by CAFE regulations, in trillion (10^{12}) miles/year. Past data based on FHWA Highway Statistics; projections based on ACEEE analysis, with an average growth rate of 2%/year 1990-2010. The dashed projection is without cost of driving adjustment; the dotted projection is maximum estimated "rebound" effect, based on fuel economy improvement Scenario E (6%/year) and a fuel cost of driving elasticity of −0.10.

statistics from FHWA (1989, 1992). To project future travel, average VMT growth rates of 2.1%/yr through 2000 and 1.9%/yr from 2000 to 2010 are used, based on UCS *et al.* (1991) but adjusted downward for the dampening effect of the 1990–1991 recession (annual VMT growth dropped to 1.4% between 1990 and 1991). The resulting projection is cumulative VMT growth of 48% from 1990 to 2010. DOE (1993) projects cumulative light-duty VMT growth of 41% over this same period. Even fairly aggressive measures to dampen travel demand are likely to cut no more than 16% from VMT by 2010 (UCS *et al.*, 1991). Therefore, a substantial increase in stock fuel economy will be needed to return light-vehicle fuel consumption to the 1990 level over this period.

Many factors determine the overall amount of driving. The most important is the size of the driving age population, often taken to be ages 16 to 80. Neither the projections of this analysis nor that of DOE (1993) reflect the recent upward revisions in projected U.S. population growth, largely due to immigration. Compared to the Spencer (1989) projections, the more recent Day (1992) projections indicate an increase in driving age population of 1.0% by 2000, 3.4% by 2010 and 7.1% by 2020. Travel demand is strongly linked to economic activity (e.g., gross domestic product). The foregoing projections assume average economic growth of 2.0%/yr for 1990-2010, as used by DOE (1993). Geographic factors are important. For example, higher VMT will result from greater suburban sprawl or a greater diffusion of the population and commerce into areas that are now largely rural. VMT can decrease through factors or policies that reduce the need for motor vehicle travel, increase vehicle occupancy or increase alternate modes of travel. Finally, VMT depends on the cost of driving and therefore on fuel price and fuel economy. Although it is beyond the scope of this analysis to account for the many influences on travel demand, the sensitivity of the estimates made here to projected VMT must be kept in mind.

Rebound. The base projection of VMT shown as the dashed line in Fig. 2 does not reflect changes in the cost of driving, either through increased fuel prices or increased fuel economy. VMT can be related to the cost per distance of travel through an empirically determined elasticity parameter. Using C to represent the cost of driving (eqn 2; e.g., cents per mile) and subscripts 1 and 2 to represent base and adjusted projections, respectively, the definition of elasticity implies

$$\frac{\mathrm{VMT}_2}{\mathrm{VMT}_1} = \left(\frac{C_2}{C_1}\right)^{\epsilon} \tag{3}$$

The elasticity ϵ is taken to be -0.1, at the low end of the -0.10 to -0.15 range estimated by Greene (1991) using historical data. However, it is consistent with the downward trend indicated by Greene's analysis, which suggests that an elasticity as small as -0.05 may be appropriate for more recent conditions. If fuel prices are relatively stable as fuel economy goes up, then fuel cost becomes an ever smaller share of overall operating cost, and one would expect a lower sensitivity. That is, elasticity is not constant but is proportional to expenditure share. This effect is not modeled in this article; a constant elasticity is sufficient because VMT rebound is a second-order effect (much smaller than the uncertainties in baseline fuel economy and VMT projections). The maximum rebound effect under the fuel economy increases analyzed in this article is shown as the dotted line in Fig. 2. Because the effect of reduced U.S. fuel demand on oil prices is not modeled, the fuel price projection is fixed and the cost of driving adjustment depends only on vehicle fuel economy.

Vehicle stock turnover

The improvement in the fuel economy of the vehicle stock (all cars and light trucks in use, new and used) lags behind that of new vehicles depending on the rate of stock turnover (replacement). Stock fuel economy is computed as the harmonic average of fuel economy by vehicle age, weighted by the average number of miles driven annually by vehicles of a given age. Historical data on new light-vehicle fuel economy are from Murrell *et al.* (1993), as plotted in Fig. 1. Statistics on mileage and survival fraction by vehicle age are from Davis and Strang (1993); the product of mileage and survival probability used as the stock turnover weighting factor is plotted in Fig. 3. It is assumed that the mix of light vehicles on the road remains fixed over the projection years with respect to vehicle age and miles driven by age. New-vehicle market shares by vehicle class and manufacturer are also assumed to be fixed. Under these assumptions, new-vehicle sales growth tracks VMT growth, and there is no need to make an explicit projection of new-vehicle sales. In any given year, sales of new motor vehicles are strongly dependent on the state of the economy, which is also a key factor in determining VMT. Because this study cannot attempt to project economic growth, the stock model represents only vintaging effects. Business cycles would introduce unevenness in the rate of stock turnover but do not affect the long-term trends which are of interest here.

Other assumptions

The response to fuel economy regulation is affected by other factors, such as manufacturers' compliance behavior and the structure of the standards. It is assumed here that the overall fleet average fuel economy targets are exactly achieved (i.e., that the major

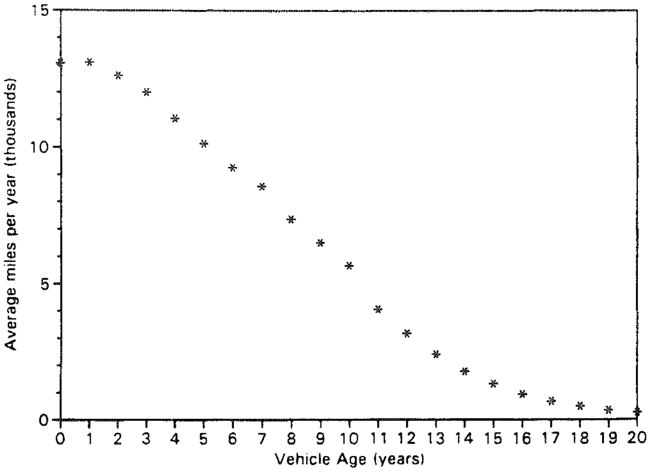

Fig. 3. Survival-adjusted travel of light vehicles by age. Each point is the product of average annual travel by vehicles of a given age and the probability of a vehicle remaining on the road at the given age, based on statistics from Davis and Strang (1993).

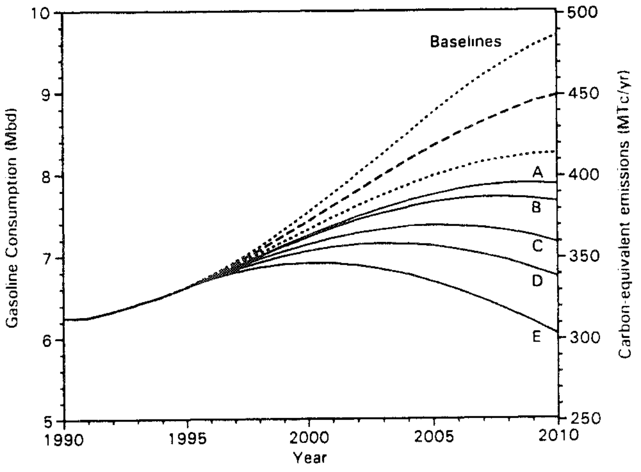

Fig. 4. Projected U.S. light duty vehicle fuel consumption, baselines, and fuel encomy improvement scenarios. Gasoline consumption is in millions of barrels per day (Mbd) and greenhouse gas emissions are full fuel cycle carbon-equivalent in millions of metric tons per year (MTc/year). The dashed line is the reference baseline projection used for savings calculation, corresponding to the dashed line projections in Figs. 1 and 2. The dotted lines are consumption projections for the rising fuel economy baseline (lower dotted line) and falling fuel economy baseline (higher dotted line). The solid lines are for fuel economy improvement scenarios A-E as labeled (see Table 1).

manufacturers, in terms of sales volume, comply with the law). This has been the case historically; only limited volume luxury and specialty producers have been in noncompliance and their low CAFE values have been offset by producers with above-average CAFE values. In fact, the overall new-fleet average achieved by manufacturers has exceeded the CAFE standards by a margin of 0.3 mpg. The effect of such a compliance margin is small; for example, for the ranges examined here, which mostly exceed a fleet average of 30 mpg after 2005, a 0.3-mpg compliance margin would have a 1% effect on fuel consumption. The structure of standards refers to the relative fuel economy increase required of each manufacturer. The current separation of domestic from imported fleets is one such structural factor. The uniform percentage increase structure of most recent proposals is another (discussed later). To analyze a uniform percentage increase CAFE structure, including the effects of floors and ceilings, base year CAFE and sales data by manufacturer are used. Tabulations of these statistics and other model inputs are given in DeCicco (1992b).

SCENARIO RESULTS

Table A1 in the Appendix lists the principal results for each scenario and three key years (2000, 2005, and 2010). Given in the table are the assumed fuel economy levels for new cars and light trucks and the average fuel economy of the light-duty stock (all vehicles on the road, new and used), with both EPA-rated and estimated on-road values. Also listed are aggregate light vehicle fuel consumption and savings estimates for the key projection years. The fuel consumption projections are plotted in Fig. 4. U.S. light vehicle fuel consumption in 1990 was 6.3 Mbd, of which 98% was gasoline. By comparison, total U.S. petroleum consumption in 1990 was 17.0 Mbd, of which 7.2 Mbd (42%) were imported (DOE, 1993). The middle (frozen efficiency, in the absence of CAFE standards increases or other policy changes) baseline projection is that overall light-duty vehicle fuel consumption is expected to rise to 9.0 Mbd by 2010, a 41% increase over the 1990 level. The rising and falling fuel economy baselines, shown as the dashed lines in Fig. 4, give a variation of about ±8% from the frozen efficiency projection for 2010.

Scenario A barely begins to balance growth in VMT by 2010; the stronger scenarios begin to overcome VMT growth. In Scenario C (3%/yr fuel economy improvement) consumption peaks at 7.4 Mbd in 2005 and then begins to decline slowly as the rate of improvement is larger than the expected rate of VMT growth. Scenario D (4%/yr), which corresponds to the fuel economy improvement rate proposed by the Bryan (1991) bill but delayed by 4 years, is not sufficient to return consumption to the 1990 level by 2010. This goal can be met by Scenario E (6%/yr). In this case, fuel consumption peaks by 2000 at a level 7% below the baseline projection and 11% higher than the 1990 level. Thus, a steady rate of new-fleet fuel economy improvement can have a significant effect even by 2000 in spite of the lags in stock turnover.

A savings estimate is obtained as the difference between a scenario's consumption projection and whatever baseline is selected. Savings projections relative to the middle baseline are shown in Fig. 5. All policy scenarios result in some fuel savings, which become substantial by 2010 for higher improvement rates. A 4%/yr CAFE improvement (Scenario D) yields gasoline savings of 2.2 Mbd in 2010, a 25% reduction relative to the middle baseline projection of 9.0 Mbd by 2010. The highest fuel economy improvement considered here (Scenario E) yields projected savings of 2.9 Mbd by 2010, cutting projected consumption by nearly one-third and achieving a 3% absolute reduction from 1990 consumption level by 2010. Thus, within the uncertainty range for this analysis, it can be said that a new-fleet fuel economy improvement rate of 6%/yr is needed to return light-vehicle fuel consumption to the 1990 level by 2010, in the absence of measures to dampen growth in VMT significantly by that time.

A gasoline consumption rate of 1 Mbd is equal to 15.3 billion gallons per year. The gross value of the gasoline savings to consumers may be found by multiplying the savings estimate by an assumed future retail fuel price. Based on a 2010 gasoline price projection of roughly $1.60/gal (1993$, DOE, 1993), for example, the gross annual savings for Scenario D would be $54 billion in 2010. These direct consumer cost savings include taxes and would also have to be balanced by the investment costs associated with making the fuel economy improvements to estimate the net benefit. Such estimates are beyond the scope of this article (see, e.g., DeCicco & Ross 1993; Greene & Duleep 1993; Greene & Liu 1988).

Table 2 summarizes the effect of higher and lower fuel economy baselines on savings estimated for the years 2000 and 2010. A higher baseline fuel economy results in lower savings and vice versa. For example, with the 4%/yr improvement scenario, the higher baseline reduces the projected 2010 savings from 2.2 Mbd to 1.5 Mbd (32% lower) and the declining baseline raises the savings estimate to 3.0 Mbd (33% higher). Thus, these fairly modest variations in baseline assumptions imply a one-third variation in the savings estimated for this particular case. Similarly significant variations in savings occur for the other cases, as shown in Table 2.

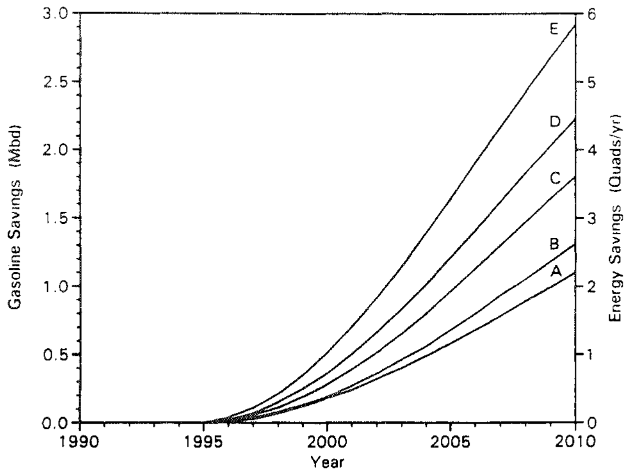

Fig. 5. Projected fuel savings by fuel economy improvement scenario. Gasoline savings are in millions of barrels per day (Mbd) and the equivalent energy savings are in Quads (10^{15}Btu) per year. Savings are computed relative to the middle (frozen fuel economy) baseline; see Table 1 for scenario definitions and Table A1 for other assumptions.

Table 2. Variation of projected savings according to assumed baseline fuel economy

(a) Projections for 2000 MPG Improvement Scenario	Savings (Mbd) Relative to Baseline Fuel Economy (a) Fixed	(b) Falling	(c) Rising
(A) DOE/AEO'93, 16% by 2005	0.18	0.29	0.08
(B) 2%/yr rise, 20% by 2005	0.21	0.32	0.10
(C) 3%/yr rise, 30% by 2005	0.28	0.39	0.18
(D) 4%/yr rise, 40% by 2005	0.38	0.49	0.27
(E) 6%/yr rise, 60% by 2005	0.52	0.63	0.42

(b) Projections for 2010 MPG Improvement Scenario	Savings (Mbd) Relative to Baseline Fuel Economy (a) Fixed	(b) Falling	(c) Rising
(A) DOE/AEO'93, 16% by 2005	1.1	1.8	0.4
(B) 2%/yr rise, 20% by 2005	1.3	2.1	0.6
(C) 3%/yr rise, 30% by 2005	1.8	2.5	1.1
(D) 4%/yr rise, 40% by 2005	2.2	3.0	1.5
(E) 6%/yr rise, 60% by 2005	2.9	3.7	2.2

Based on stated VMT growth projections and −0.10 VMT rebound elasticity.

Direct comparisons of these results to those published by others is difficult because of the later implementation of new fuel economy standards assumed here. However, earlier analyses by the author applied the model used here to scenarios similar to those published elsewhere. Applying the model to a CAFE standards increase reaching 40% by 2001 (4 years earlier than targeted by Scenario D of the present analysis) yields a savings projection of 2.4 Mbd for 2005. The combination of the "max tech." and "mpg gap" scenarios of Greene (1990b) matches many of these assumptions but yields a savings projection of 1.8 Mbd for 2005. Reasons for the difference include lower base level and growth rate for VMT and a higher fuel cost-of-driving elasticity than used here. Farmer (1991b) also made savings projections, reporting an estimate of 0.88 Mbd in 2006 from a 40% CAFE increase by 2001. The range of estimates he reports for 2006 is 0.45 Mbd to 1.42 Mbd; his lower estimate ("low CAFE impact" scenario) appears to reproduce the DOE (1991) estimate. Reasons for such significantly lower estimates include a much higher baseline fuel economy, which continues to rise while the standards increases are assumed to level off after 2001; lower initial VMT and lower VMT growth over the next decade; a higher rebound elasticity; and a rebound calculation based (incorrectly) on new vehicles rather than the entire stock.

U.S. Department of Energy *Annual Energy Outlook* projections of the past several years (DOE, 1993, and previous since 1985) have all projected rising baseline fuel economy, although the rate of rise projected by DOE has been lower in the more recent editions. As noted earlier, average new-vehicle fuel economy has been essentially flat for some time now (actually declining slightly from its shallow peak in 1987–1988). Rising baseline fuel economy was also assumed for the National Energy Strategy analysis (EIA, 1990a) and more recently for the Climate Action Plan (Clinton & Gore, 1993, using analysis similar to that of DOE, 1993). Farmer (1991a, 1991b) also chooses this high rate of improvement for his "low CAFE impact" scenarios. The DOE analyses also use lower VMT growth rates than used here. Comparisons to observed VMT growth rates (prior to the 1990–1991 recession) indicate a consistent DOE underprojection of VMT, although VMT projections are reasonably more arguable than fuel economy projections. Rising fuel economy baseline and lower VMT growth both yield low projected fuel savings impacts from proposed standards or other policies to improve new vehicle fuel economy. Continuing to assume near-term rises in fuel economy to represent what is likely to happen in the absence of policy change appears to be misleading given the available data and recent market trends.

Dependence on achieved CAFE and year

The projected gasoline savings by year are shown in Fig. 5 for the five scenarios of new-fleet fuel economy improvement. Some savings are obtained from any increase in achieved CAFE. A 4%/yr new-fleet fuel economy increase yields savings of 2.2 Mbd in 2010. A 2%/yr rate of increase, one-half as large, yields savings of 1.3 Mbd, or 41% lower. The 6%/yr rate of increase, half again as large as the 4%/yr rate, yields savings of 2.9 Mbd in 2010, or 31% higher. This is because CAFE measures the inverse of fuel consumption, so that a given percentage increase in fuel economy corresponds to a smaller percentage decrease in fuel consumption. Note that these results are for an achieved value of CAFE increase. As discussed later, a number of factors can result in achievement of lower CAFE levels than targeted by legislation.

Figure 5 also shows how savings grow with time, as newer, more efficient vehicles displace older vehicles in the on-road stock. Achievement of steadily increasing standards results in steadily increasing savings relative to a fixed frozen-efficiency baseline. If standards were increased to a certain level (say, by 2005) and then not increased further, savings would continue to rise for a while but then level off, as they have in recent years as the fuel economy improvements of the 1980s have leveled off. Delays in the standards would have the effect of shifting the curves to the right, so that comparable savings are achieved in a later year. The dependence of the fuel savings achieved in a given year on the rate of fuel economy improvement follows the pattern illustrated in Fig. 6, which gives the results in terms of the emissions reductions which are proportional to fuel savings.

Table 3 lists the cumulative savings in 2000, 2005, and 2010. Cumulative savings continue to grow through time. For example, if a 40% CAFE improvement is achieved by 2005, cumulative savings would be 1.8 billion barrels by 2005 and would exceed 5 billion barrels by 2010. To put these savings estimates in context, this domestic conservation potential can be compared to leading new U.S. oil extraction options that have been proposed. For example, opening the Arctic National Wildlife Refuge to oil production offers a possible total of 3.6 billion barrels, and Outer Continental Shelf regions offer 3.1 billion barrels (NES, 1991). In both of these cases, finding economically recoverable oil is less than certain and would entail environmental damage that is avoidable through conservation approaches, such as higher fuel economy standards. Annual demand reductions obtainable from incremental fuel economy improvement are also generally larger than delivery from new domestic supply sources; for example, NES (1991) estimates an Arctic National Wildlife Refuge Production rate of 0.87 Mbd (at a 46% probability level) in 2005. Demand reductions achieved through vehicle efficiency improvement will continue to grow as VMT grows, whereas oil supply from any given source will shrink as reserves are depleted.

Emissions reductions

In addition to reducing petroleum use, fuel economy improvement will reduce emissions of greenhouse gases and some local air pollutants. Calculating the carbon dioxide

Table 3. Cumulative gasoline savings by rate of fuel economy increase

	Billion (10^9) Barrels* Saved Cumulatively from 1995 through Year		
MPG Improvement Scenario	2000	2005	2010
(A) DOE/AEO'93, 16% by 2005	0.1	0.6	1.6
(B) 2%/yr rise, 20% by 2005	0.2	1.0	2.9
(C) 3%/yr rise, 30% by 2005	0.2	1.4	4.1
(D) 4%/yr rise, 40% by 2005	0.3	1.8	5.2
(E) 6%/yr rise, 60% by 2005	0.4	2.6	7.0

Relative to frozen fuel economy baseline, −0.10 rebound elasticity, and other assumptions as in Table A1.

*Energy end-use conversion is 5.25 Quads per 10^9 bbl gasoline.

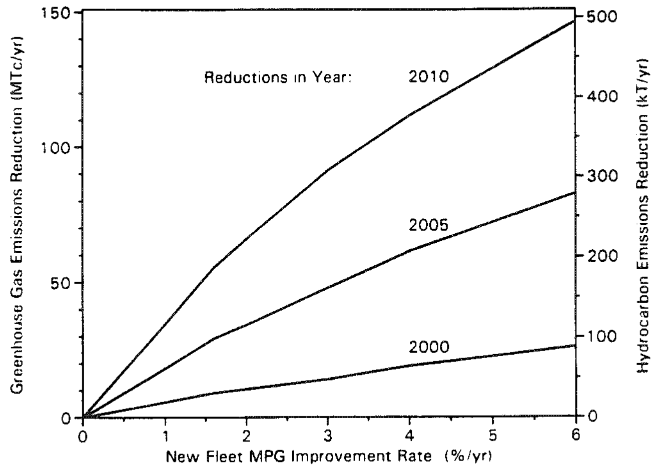

Fig. 6. Reductions of greenhouse gas and hydrocarbon emissions as a function of rate of fuel economy improvement. Projections are relative to the middle (frozen fuel economy) and other assumptions as given in Table 1A. Greenhouse gas emissions reductions are given as full fuel cycle carbon-equivalent, in million metric tons per year (MTc/year), based on 12 kg_c/gallon (50.3 × 10^9 kg/year per Mbd). Fuel fuel cycle evaporative HC (VOC) emissions, not including tailpipe component, are given in thousands of metric tons per year (kT/year), based on 11 g/gallon (0.17 × 10^9 kg/year per Mbd).

(CO_2) emissions reductions from reduced petroleum fuel consumption is straightforward, because CO_2 emissions are essentially proportional to the amount of the fuel used based on its carbon content. A full determination will also include "upstream" petroleum consumption in the extraction, refining and transportation processes, as well as the effects of associated methane (CH_4) and nitrous oxide (N_2O) emissions. These indirect factors increase the greenhouse impact by about 20% above that of the direct CO_2 emissions of fuel combustion (DeLuchi, 1991; MacDonald, 1990).

One might also expect that improved fuel economy will yield a reduction of other pollutants generated in the combustion process—the carbon monoxide (CO), hydrocarbons (HC), and nitrogen oxides (NO and NO_2, i.e., NO_x) that are local air pollutants. Practically speaking, however, the relation between emissions and fuel economy is more complex. This is because of the dominance of catalytic control for tailpipe emissions, combustion process-control trade-offs for engine-out emissions (particularly NO_x) and the various factors affecting volatile hydrocarbon (HC) emissions in vehicle fueling systems, both on-board and in the supply system. As for tailpipe emissions, a properly functioning catalytic converter can eliminate up to 90% of the HC, CO and NO_x from the exhaust stream, but this degree of emissions control does not occur during much real-world driving (Calvert *et al.*, 1993). However, because significant evaporative hydrocarbon emissions occur on-board the vehicle and throughout fuel supply processes (literally, between the oil well and the intake manifold), there is a strong link between evaporative HC emissions and fuel economy.

Regarding CO_2 emissions, each million barrels per day of gasoline end-use results in 50.3 million metric tons per year (MTc/yr) of greenhouse gas emissions, expressed on a CO_2-equivalent carbon mass basis and including upstream emissions during the production and transportation of petroleum products (DeLuchi, 1991). According to estimates developed for the U.S. Climate Change Action Plan (Clinton & Gore, 1993), total U.S. greenhouse gas emissions were 1462 MTc/yr in 1990. About 320 MTc/yr, or 22%, are from cars and light trucks. The middle baseline projection implies light-vehicle greenhouse gas emissions growing to 450 MTc/yr by 2010.

Table 4 shows the projected annual reductions in greenhouse gas emissions for selected levels of CAFE improvement. The 4%/yr CAFE increase scenario (Case D) would result in CO_2 emissions reduction of 61 MTc/yr by 2005 and 112 MTc/yr by 2010. This is a 25% reduction compared to U.S. car and light truck greenhouse gas emissions otherwise

Table 4. Projected reductions in greenhouse gas emissions resulting from light-duty vehicle CAFE increases

MPG Improvement Scenario	Carbon-Equivalent Emissions Reductions (Millions Metric Tons per Year) in 2000	in 2005	in 2010
(A) DOE/AEO'93, 16% by 2005	9	29	55
(B) 2%/yr rise, 20% by 2005	11	34	66
(C) 3%/yr rise, 30% by 2005	14	48	91
(D) 4%/yr rise, 40% by 2005	19	61	112
(E) 6%/yr rise, 60% by 2005	26	83	147

Relative to frozen fuel economy baseline and other assumptions as in Table A1, with full fuel cycle carbon-equivalent emissions of 26.5 lb/gal (50.3 MTc/yr per Mbd).

projected for 2010. Figure 6 shows emissions reductions in 2010 by percent fuel economy improvement rate; the dependence on year follows the pattern shown for fuel savings in Fig. 5. A reduction in 2010 emissions of 130 MTc/yr would be needed to return to the 1990 level by that year; a 6%/yr fuel economy improvement rate would do slightly better than that.

Hydrocarbon (HC) vapors contribute to smog and regional air pollution. The particular hydrocarbons regulated for air pollution control are termed volatile organic compounds (VOC). Highway vehicles accounted for 5.5 million metric tons, or 27% of nationwide VOC emissions, in 1992 (EPA, 1993); the majority of these emissions are from light vehicles. Another 650,000 metric tons of VOC are emitted by petroleum-related industries. Because increased fuel economy will lead to a decrease in the overall quantity of gasoline consumed, there will be a corresponding decrease in VOC emissions during refueling, fuel distribution and refining. There will also be reductions in emissions due to gasoline vapors escaping from vehicle fuel tanks and other on-board mechanisms before fuel reaches the engine. Tailpipe emissions are, however, a complex function of engine operating condition, catalyst performance and driving patterns. The 1993 federal standard for automobile tailpipe HC emissions is 0.41 g/mi; following the 1990 Amendments to the Clean Air Act it will drop to 0.25 g/mi for nonmethane hydrocarbons (NMHC) over a phase-in period of 1994–1996 (EPA, 1990). The actual emission reduction resulting from this tightening of tailpipe standards is highly uncertain, however, because the emissions test procedure so poorly reflects real-world vehicle operating conditions (Calvert *et al.*, 1993; Ross, 1994).

DeLuchi *et al.* (1992) estimate full fuel-cycle HC emissions in the United States as a function of fuel economy, accounting for expected future improvements in air pollution controls. A mid-range estimate is that average evaporative HC emissions of 11 grams/gallon are associated with light-vehicle gasoline use, based only on the fuel supply system and nontailpipe portion of vehicle emissions. Over 80% of these emissions occur in the locale of vehicle use. Including correlations of fuel economy to tailpipe HC emissions would raise the impact further; however, this effect is uncertain. DeLuchi *et al.* (1992) note that the empirical evidence is weak, and Ross *et al.* (1991) point out that it may be an artifact of a few cars which are outliers in terms of tailpipe emission and fuel economy characteristics. The nontailpipe estimate of 11 grams/gallon could be lower or higher depending on the effectiveness of air pollution controls yet to be implemented in response to recent Clean Air Act amendments, but current evaporative emissions per gallon of gasoline consumption are much higher.

Projected HC emissions reductions associated with fuel economy improvement are shown in Table 5. The right axis of Fig. 6 shows the projected nationwide HC emissions reductions as a function of fuel economy improvement rate. For the 4%/yr CAFE increase scenario, HC emissions reductions would reach 207,000 metric tons/yr by 2005 and 377,000 metric tons/yr by 2010. On a per vehicle mile basis, a 40% improvement of

Table 5. Projected reductions in hydrocarbon emissions resulting from light-duty vehicle CAFE increases

MPG Improvement Scenario	HC Emissions Reductions (Thousands of Metric Tons per Year) in 2000	in 2005	in 2010
(A) DOE/AEO'93, 16% by 2005	31	99	186
(B) 2%/yr rise, 20% by 2005	35	116	223
(C) 3%/yr rise, 30% by 2005	48	161	307
(D) 4%/yr rise, 40% by 2005	65	207	377
(E) 6%/yr rise, 60% by 2005	89	279	495

Relative to frozen fuel economy baseline and other assumptions as in Table A1, with fuel cycle nontailpipe HC emissions computed at 11 g/gallon (0.17×10^6 metric tons/yr per Mbd).

the average light-duty vehicle from the present on-road average of 20 mpg to 28 mpg would yield an average HC emissions reduction of about 0.15 g/mi, a magnitude comparable to the 0.16 g/mi tailpipe emissions reduction required by the 1990 Amendments to the Clean Air Act. Moreover, because current emissions test procedures so poorly reflect in-use emissions, it is likely that HC emissions reductions resulting from fuel economy improvement will be obtained with greater certainty than the reductions projected from a tightening of emissions standards under current test procedures.

SENSITIVITIES AND DISCUSSION

There are a number of provisions that enable a manufacturer to comply with CAFE regulations at an achieved fleet average fuel economy level less than the standard set for a given year. The mechanism for determining compliance levels below the standard is the CAFE credit, measured in miles per gallon. The current CAFE law provides for carry-forward credits, which manufacturers earn by exceeding the standard in a given year and which can be applied against their standards requirement in a future year. Japanese manufacturers currently have such credits available because of their historically higher CAFE averages. The Alternative Motor Fuels Act provides credit for vehicles that can operate on a fuel other than gasoline, including a more limited credit for vehicles that can use either gasoline or an alternative fuel (flexible fuel vehicles). Other types of credit schemes have been proposed (e.g., allowing manufacturers to trade credits among each other or among separately regulated fleets, and credits for certain safety devices, such as airbags). Another provision of fuel economy current and proposed regulation is the ability of the administering agency to roll back the standard, lowering the level that had been targeted by law. Legally speaking, only a rollback changes the standard level that applies to a manufacturer; credits are added to a manufacturer's achieved CAFE when determining compliance with the standard.

CAFE credits

Several analysts have examined the potential impact of CAFE credits. Farmer (1991a) estimated the impact of credits for alternative and flexible fuel vehicles. OTA (1991b) discussed existing credits and the concept of marketable CAFE credits but did not quantify fleet impacts. Ditlow (1991) estimated the potential impact of available carry-forward and alternative fuel credits. It is difficult to determine the extent to which manufacturers will avail themselves of various credit options. More broadly, there is the question of whether the existence of strengthened standards will itself induce automaker decisions (such as provision of flexible fuel vehicles) that would not occur with weaker or abolished standards. The Clean Air Act Amendments of 1990 and California Air Resources Board regulations are likely to require some number of alternatively fueled vehicles in areas that have severe difficulty in attaining air quality standards, such as parts of California.

For a CAFE improvement scenario similar to the aforementioned Case B, Farmer (1991a) found that the credits could lower achieved CAFE levels enough that gasoline consumption would be higher than it would under CAFE regulation without the flexible fuel vehicle credits. The reason is that, under the most likely assumptions, there would be insufficient alternative fuel use to offset the reduced fuel economy of most vehicles. Farmer projected that the vehicles earning CAFE credits, particularly over the next decade, will mainly be flexible fuel vehicles which continue to operate primarily on gasoline. Credits are not linked to the amount of gasoline actually displaced but do serve to lower the fuel economy requirements for the whole vehicle fleet. Therefore, overall gasoline consumption can be higher than it would be under CAFE standards without flexible fuel vehicle credits. This perverse outcome (of a policy rationalized as a way to displace petroleum use resulting in higher petroleum use) applies strictly to the credits for flexible fuel vehicles; credits for dedicated nonpetroleum-fueled vehicles would not have this effect.

Table 6 shows the effect of CAFE credits as the difference in achieved fuel economy for various scenarios. Although the extent of alternative fuel credit utilization may depend on the stringency of standards, for simplicity only two levels of alternative fuel vehicle credits are analyzed here. A lower level of credit utilization is used for baseline cases, shown as the first row in Table 6. The higher level shown in the second row is for cases of strengthened standards. The same level of carry-forward credits is used in all cases, because carry-forward is limited to three years and all manufacturers use up their earned credits by 2006. Under these assumptions, only alternative fuels credits affect new-fleet fuel economy in the later projection years. These changes in achieved fleet average fuel economy were applied as adjustments to the fuel economy scenarios analyzed here to estimate the effect of credits on overall light-vehicle gasoline consumption. In analyzing the effect of CAFE credits, only petroleum fuel consumption is considered here; changes in consumption of nonpetroleum fuels are not modeled. The impact of credits should be judged relative to a baseline which also accounts for credits. Accounting for credits increases the projected gasoline consumption by approximately the same amount in all scenarios, about 0.2 Mbd in 2005 and 0.3 Mbd in 2010. Therefore, credits alone have little effect on the absolute value of a savings projection.

Carry-forward credits represent fuel economy improvements achieved in advance of standards increases. The fact that such credits have been earned is reflected in the baseline average fuel economy (e.g., the overall 1990 average), which would otherwise be lower. Therefore, baseline consumption would otherwise be higher, because fleets more efficient than the standard would not have already entered the vehicle stock as they in fact have. One can expect manufacturers who would otherwise be constrained by a future standard eventually to avail themselves fully of any credits they have earned. Carry-forward credits were found to have a small effect, increasing gasoline consumption by less than 1% in 2005 and negligibly in 2010, when such credits would be exhausted.

For flexible and alternative fuel vehicle credits, consumption is higher than it would be without such CAFE credits. The flexible fuel vehicle credits would increase consumption by about 2% in 2005, rising to 3% in 2010. These results are qualitatively consistent

Table 6. Potential fuel economy decrements due to CAFE credits

	Number of MPG by which New Light-fleet Average Could be Lowered, in Year			
Type of CAFE Credit	1996	2001	2006	2010
Alt. fuel, with baseline	0.2	0.4	0.5	0.5
Alt. fuel, with standards	0.3	0.7	1.4	1.5
Carry forward, all cases	0.5	0.2	0	0

Alternative fuel credits are for both flexible and dedicated fuel vehicles, from Farmer (1991a), Table 3. Carry-forward credits are author's estimates, based on current CAFE achievement levels and assuming that manufacturers follow an improvement path which uses up their earned credits by 2006.

with those of Farmer (1991a), because his alternative fuel vehicle credit assumptions were used here, although his significantly different assumptions for other factors result in lower overall differences between consumption levels with and without standards. Farmer also estimated that removing the current cap on flexible fuel vehicle credits would cause further increases in gasoline consumption. In any case, the general conclusion is that the small amount of alternative fuel use likely over this time period is not enough to offset the increased gasoline use due to the lower conventional vehicle fuel economy permitted by the credits.

A comment on CAFE credit trading

Currently, CAFE credits may only be applied to the manufacturer's fleet on which they are earned. Credits cannot be moved from one fleet to another (e.g., between an automaker's car and light truck fleets) and there are no provisions for trading of credits among manufacturers. Credits trading is seen as a market mechanism which can be used to improve the economic efficiency of environmental regulations. For example, the recent Clean Air Act Amendments include provisions for banking and trading of air pollution emission allowances (EPA, 1990). There have also been proposals for CAFE credits trading to incorporate similar flexibilities into the framework of CAFE standards. Nevertheless, under current and proposed CAFE penalty systems, there may not be much incentive for manufacturers to make credits available for trading (OTA, 1991b, p. 84).

If tradeable CAFE credits are measured in MPG (miles per gallon), credit trading could result in lower overall average fuel economy and therefore higher gasoline consumption. Fuel use is gallons consumed, not miles per gallon, so credits measured in MPG units (as in current law) will result in lost savings whenever the credits are transferred from a fleet of higher fuel economy to a fleet of lower fuel economy. For example, consider a fleet that achieves 35 mpg rather than a hypothetical future requirement of 30 mpg (actual on-road fuel economy), thereby earning a credit of 5 mpg. Assuming lifetime driving of 100,000 miles per vehicle, the expected fuel savings represented by this 5-mpg difference would be 476 gallons per vehicle. Now consider the effect of applying this 5-mpg credit to a fleet averaging 20 mpg, so that it is treated for compliance purposes as if its average fuel economy were 25 mpg. A similar calculation shows that the additional consumption would be 1000 gallons per vehicle. The added consumption of the lower mileage fleet is therefore more than double the fuel savings of the higher mileage fleet, resulting in an expected net excess consumption (lost savings) of 524 gallons per vehicle. (Because of the inverse relation between fuel consumption and fuel economy, it can be shown that when trading credits from a higher to lower fleet, the ratio of differences in expected fuel consumption increases with the square of the ratio of the respective fleet CAFE values.)

The correct way to value the added fuel economy is in terms of the fuel savings expected over the life of an average vehicle. In this example, the higher fleet's expected savings of 476 gallons would then allow an offsetting increase of only 2.1 mpg in the lower fleet, so that it would be treated at 22.1 mpg rather than 25 mpg. Therefore, to avoid compromising potential fuel savings, a system for trading CAFE credits should be based on the expected number of gallons saved or wasted (or equivalently, gallons/mile or liters/100 km) rather than differences in MPG. This is consistent with proposals for emissions trading, which are based on expectations of avoided air pollution emissions as measured, for example, in tons per year. In fact, automotive fuel use credits based on avoided CO_2 emissions would work correctly, because CO_2 emissions are directly proportional to fuel consumption. Use of CO_2 emission rates (e.g., grams/mile) is also one way to permit exchange of credits among vehicles that utilize different fuels.

Rollbacks

As noted earlier, CAFE law includes provisions for the administering agency to set a standard lower that the legislatively targeted standard by conducting a rule-making proceeding to determine a maximum feasible average fuel economy level under various considerations. Such rollbacks were used when the 27.5-mpg automobile standard first set for 1985 was lowered to 26.0 mpg for 1986–1988 and 26.5 mpg for 1989. The standard was returned to 27.5 mpg as of 1990. Applying the stock model retroactively yields an estimate of 50,000 barrels/day for the additional 1992 fuel consumption due to this rollback, because vehicles less efficient than would otherwise have been required still remain in the fleet. For fuel economy standard proposals similar to cases D and B, the proposed rollback levels are for a 30% rather than 40% targeted increase and a 15% rather than 20% targeted increase, respectively, in 10 years. The Bryan (1991) proposal, for example, limited the rollback in 2001 so that the standard would specify at least a 30% improvement in CAFE. A full rollback of this extent would increase fuel consumption by 0.3 Mbd in 2005, or 4%, for example. The effect of rollbacks as assumed here can also be seen in Table A1 (e.g., by comparing cases D and C). If the present CAFE standards were rolled back 1 mpg, there would be an increase in gasoline consumption of 0.15 Mbd (and in CO_2 emissions of 7.5 MTc/yr) by 2000 if stronger standards were not restored in the intervening years.

Floors and ceilings

A CAFE standard formulated as a uniform percentage increase may contain floors and ceilings, which set lower and upper bounds, respectively, on the CAFE standard pertaining to any manufacturer. For example, the Bryan (1991) proposal specifies that manufacturers achieve by 2001 a CAFE increase of 40% above their 1988 CAFE values but that passenger car fleets must reach at least 33 mpg (the floor) and are not required to exceed 45 mpg (the ceiling). In this case, then, the range of manufacturers' CAFE standards is constrained from 7 mpg below to 5 mpg above the 40-mpg average that would be achieved if all manufacturers increased their CAFE by 40%. There is a continuous range of floor and ceiling levels consistent with a given average improvement in fuel economy. In the limiting case, the floor meets the ceiling at a single standard for all manufacturers, like the present CAFE standards. Tightening the floor and ceiling boundaries could be considered as a way to change the relative burden among manufacturers presently having lower or higher fleet ratings. It would also make the achieved fleet fuel economy more resistant to changes in market shares. The particular floor and ceiling adjustments needed to maintain a given average CAFE level depend on the market share mix by manufacturer, so maintaining simple numerical symmetry of the bounds may not maintain a given overall average.

The stock model was modified to perform a manufacturer-by-manufacturer analysis, permitting explicit specification of floors and ceilings. This analysis was done only for the 4%/yr increase scenario similar to the Bryan proposal. Comparisons of CAFE standards for varying the floors and ceilings around an average CAFE of 40 mpg by 2001 are tabulated by manufacturer in DeCicco (1992b). Averaged over all manufacturers, the effect of floors and ceilings on projected fuel consumption is small. For example, removing the ceilings would decrease consumption by 1%, increasing the savings relative to frozen fuel economy by about 4% in 2005. Savings decrease 2% when the ceiling is lowered by 2.5 mpg without raising the floor. The narrowness of the MPG range specified by the floors and ceilings affects the relative burden of improvement on manufacturers. This depends on the fuel economy mix of their current fleets, which is related to the size class mix of their fleets. To the extent that the relative burden is seen as a less than ideal compromise among the requirements on manufacturers, an adjustment can be made by changing the floors and ceilings. Such changes can be made while the expected fuel savings resulting from the legislation are essentially preserved.

Uncertainties

Any projections such as these involve a number of uncertainties. For savings projections, the largest uncertainty has to do with the baseline assumption (i.e., the projection of what will happen in the absence of policy change). The largest remaining uncertainties pertain to the current and future levels of VMT. VMT depends on demographic factors, economic activity and fuel prices. It also depends on transportation planning policies, particularly those for controlling congestion or determining land use patterns—factors well beyond the scope of this article. Projections become less certain farther into the future. If the uncertainty of the present VMT estimate is ±5% and the uncertainty of the future growth rate is ±20% (e.g., ±0.4%/yr out of the 2%/yr average rate assumed through 2010), then the uncertainty of VMT projections is ±7% after 5 years and ±11% after 15 years. Uncertainty of VMT propagate directly to uncertainties in projections of fuel consumption or fuel savings. Another aspect of VMT uncertainty is the rebound effect, which is estimated here using a price elasticity of −0.10. For a 6%/yr fuel economy improvement through 2010, a zero rebound effect would result in a 4% decrease in gasoline consumption and an 8% increase in projected savings; doubling the rebound effect would have reverse impacts of similar magnitude.

The analyses presented here hold market shares constant at 1988 levels. Changes in prices, consumer tastes, marketing strategies of manufacturers, CAFE standards and other factors could result in a different mix of vehicles. Changes in manufacturers' market shares will affect the outcome of a percentage increase type of standard. For example, consumption will be reduced if fleets that are now more efficient than average gain market share; the converse is also true. Historical changes in manufacturers' market shares have had a small effect, amounting to a 1% to 2% effect on new light-vehicle fleet average fuel economy (DeCicco, 1992c). The effect of market share changes would be damped by floors and ceilings, as noted earlier. Larger effects can occur from marketwide shifts in vehicle attributes. The magnitude of market shift effects can be estimated by examining historical changes in the mix of cars and light trucks as fractions of the total light-duty fleet.

The market share of light truck classes increased from about 20% in 1975–1977, just before CAFE standards took effect, to about 33% presently (Murrell *et al.*, 1993). The 1991 average new car and light truck fuel economies were 27.8 mpg and 20.8 mpg, respectively, yielding an average of 25.0 mpg. If the light truck market share dropped back to 20% while fuel economy levels were the same, the average would be 26.0 mpg, or 4% higher. In 1975–1977, light truck fuel economy averaged 15% lower than that of cars; the gap is now 26% (1988–1991 average). If both market share and the truck/car fuel economy ratio were restored to the earlier level while keeping the same new car fuel economy level, the light-duty fleet average would be 26.9 mpg, or 7% higher than the actual 1991 value. The increased sales share of light trucks is considered a significant market shift, and so this 4% to 7% effect on fuel economy is suggestive of the potential impact of future market shifts. Therefore, with a significant strengthening of CAFE standards (e.g., a 4%/yr improvement rate), a continuing adverse (to overall fuel economy) market shift of such a magnitude would reduce the savings but not severely. A reverse of the past car-to-truck shift would have a beneficial impact on overall fuel economy. Such a shift is conceivable if, in response to new standards requiring the same percentage increases in cars and light trucks, manufacturers found it easier to comply by reducing the market share of less efficient trucks.

Their discrepancy between rated and on-road fuel economy is another potential source of error. As noted earlier, the projections given here assume constant 20% shortfall. Westbrook and Patterson (1989) projected ongoing increases in shortfall, reaching 30% in 2010. Fuel consumption and savings projections are both inversely proportional to one minus the assumed shortfall. If shortfall is 30% rather than 20% in 2010, the resulting projections would be 8/7 of (14% higher than) the given projections.

A minor uncertainty is introduced because manufacturers might meet the CAFE standards with some safety margin (i.e., the fleet averages will actually be a little higher than what is actually mandated by the standards). The "zero overshoot" assumption used here has manufacturers exactly meeting the overall average CAFE targets. Historically, manufacturers as a whole have exceeded CAFE targets by 0.7 mpg for passenger cars, 0.2 mpg for light trucks and about 0.3 mpg on average. The effect of a safety margin would be small, resulting in an increase in projected savings of 2% or less.

Other sources of uncertainty involve the rates of vehicle stock turnover and the annual miles driven by vehicles of different ages. These effects are not analyzed here; historical data suggest that they are relatively small and, in any case, their impact would simply be to delay achievement of a given savings level by a year or two. There may be relationships among several sources of error, and some effects may balance out. The overall error in a projection can be calculated by taking the geometric mean of the uncertainties from each source, assuming independence of error sources (Tukey, 1958). Combining the sources of error considered here yields a net uncertainty of roughly ±15% for 2010, not considering the uncertainty in the baseline projection of fuel economy. The effect of the assumed baseline is large, changing the projected savings in 2010 by ±25% for the 6%/yr improvement case and as much as ±50% for the 2%/yr case (which is closer to the baseline, magnifying the proportionate difference in savings). Combining the baseline uncertainty with that from the other factors increases the overall uncertainty to about ±30% for the 6%/yr scenario in 2010. Uncertainties are smaller for earlier years.

For the 4%/yr CAFE improvement scenario (a 40% increase in new car and light truck fuel economy by 2005), for example, the mid-range estimate of fuel savings is 2.2 Mbd and the overall uncertainty level is ±36% in 2010. Thus, there is reasonable confidence that the actual savings will be between 1.4 Mbd and 3.0 Mbd, compared to the situation in absence of stronger fuel economy standards. For policy-makers, this should provide sufficient assurance that improving CAFE standards will be effective in addressing the problems of imported oil dependence and environmental impacts from petroleum use by motor vehicles.

CONCLUSION

Strengthening the CAFE standards for light-duty vehicles in the United States will result in significant reductions in petroleum fuel consumption and attendant reductions in carbon dioxide (CO_2) and hydrocarbon (HC) emissions. A number of factors affect the consumption and savings projections, but in all instances the expected savings increase with the stringency of the standards. These results are based on an analysis of five CAFE standards scenarios, some of which are similar to recent legislative proposals. These scenarios cover rates of CAFE increase ranging up to 6%/yr through 2010, with fuel consumption and savings projections reported for the years 2000, 2005 and 2010. Light-duty fuel consumption is projected to grow from 6.3 Mbd in 1993 to 9 Mbd in 2010 without a strengthening of CAFE standards or other substantive changes in policy. The most rapid rate of fuel economy improvement examined here (6%/yr) would suffice to return light-vehicle fuel consumption to the 6 Mbd level by 2010.

The most critical underlying assumption regarding savings projections is that of the baseline (i.e., the extent of fuel economy improvement or decline in the absence of strengthened standards). Considerations regarding the choice of a baseline were discussed, and a baseline of frozen-rated fuel economy was chosen as the middle case for the analyses presented here. Alternative baselines of rising and falling fuel economy give a ±8% variation in light-vehicle fuel consumption around the middle baseline projection for 2010.

For the 6%/yr CAFE increase scenario, the mid-range projections are gasoline savings of 1.6 Mbd in 2005 and 2.9 Mbd in 2010. In 2010, the corresponding emissions reductions are 147 million metric tons per year of carbon-equivalent greenhouse gases and 495,000 metric tons per year of evaporative hydrocarbons. Assumption of a higher or lower baseline gives a ±25% change in the projected savings. Other factors affecting the achieved levels of fuel economy and overall fleet fuel consumption were also examined, including timing, CAFE credits, potential rollbacks of standards, upper and lower bounds on a percentage increase standard and uncertainties regarding light-duty vehicle market shifts, growth in vehicle miles of travel (VMT), VMT rebound and fuel economy shortfall. Compared to the baseline assumption, these other factors have smaller effects on the projections. In summary, there is a high degree of confidence that strengthening fuel economy standards will be effective in controlling future gasoline consumption and associated emissions by cars and light trucks in the United States.

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APPENDIX

Table A1. Summary of consumption and savings projections by scenario

	1990	2000	2005	2010
Base VMT (10^{12} mi/yr)	1852	2279	2553	2748
Light truck share of miles	25%	34%	34%	34%
Shortfall, on-road vs. EPA	20%	20%	20%	20%
Baseline Scenarios				
(a) Reference (middle)				
New automobile EPA mpg	27.8	28.0	28.0	28.0
New light truck EPA mpg	20.6	20.8	20.8	20.8
New LDV average EPA mpg	25.2	25.0	25.0	25.0
Stock average EPA mpg	23.8	25.0	25.0	25.0*
Stock average on-road mpg	19.3	20.0	20.0	20.0
Fuel consumption, Mbd	6.35	7.43	8.33	8.96
(b) Falling (lower)		−5.0%	−10.0%	−10.0%**
New automobile EPA mpg		26.6	25.2	25.2
New light truck EPA mpg		19.8	18.7	18.7
New LDV average EPA mpg		23.8	22.5	22.5
Stock average EPA mpg		24.6	23.7	22.9
Stock average on-road mpg		19.7	19.0	18.3
Fuel consumption, Mbd		7.54	8.74	9.70
Savings relative to (a), Mbd		−0.11	−0.41	−0.74
(c) Rising (higher)		5.0%	10.0%	15.0%
New automobile EPA mpg		29.4	30.8	32.2
New light truck EPA mpg		21.8	22.9	23.9
New LDV average EPA mpg		26.3	27.5	28.8
Stock average EPA mpg		25.4	26.3	27.4
Stock average on-road mpg		20.3	21.0	21.9
Fuel consumption, Mbd		7.33	7.96	8.25
Savings relative to (a), Mbd		0.11	0.37	0.71

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Table A1. Continued

	1990	2000	2005	2010
Policy Scenarios				
(A) 16% by 2005 (DOE/AEO'93)		7%	16%	24%
New automobile EPA mpg		30.0	32.5	34.7
New light truck EPA mpg		22.3	24.1	25.8
New LDV average EPA mpg		26.8	29.0	31.0
Stock average EPA mpg		25.7	27.1	28.9
Stock average on-road mpg		20.6	21.7	23.1
Fuel consumption, Mbd		7.25	7.74	7.87
Projected savings, Mbd		0.18	0.58	1.10
(B) 2%/yr		10%	20%	30%
New automobile EPA mpg		30.8	33.6	36.4
New light truck EPA mpg		22.9	25.0	27.0
New LDV average EPA mpg		27.5	30.0	32.5
Stock average EPA mpg		25.8	27.5	29.8
Stock average on-road mpg		20.6	22.0	23.8
Fuel consumption, Mbd		7.23	7.64	7.65
Projected savings, Mbd		0.21	0.68	1.31
(C) 3%/yr		15%	30%	45%
New automobile EPA mpg		32.2	36.4	40.6
New light truck EPA mpg		23.9	27.0	30.2
New LDV average EPA mpg		28.8	32.5	36.3
Stock average EPA mpg		26.1	28.6	32.1
Stock average on-road mpg		20.9	22.9	25.7
Fuel consumption, Mbd		7.15	7.38	7.16
Projected savings, Mbd		0.28	0.95	1.81
(D) 4%/yr		20%	40%	60%
New automobile EPA mpg		33.6	39.2	44.8
New light truck EPA mpg		25.0	29.1	33.3
New LDV average EPA mpg		30.0	35.0	40.0
Stock average EPA mpg		26.5	29.8	34.3
Stock average on-road mpg		21.2	23.8	27.4
Fuel consumption, Mbd		7.05	7.11	6.74
Projected savings, Mbd		0.38	1.22	2.22
(E) 6%/yr		30%	60%	90%
New automobile EPA mpg		36.4	44.8	53.2
New light truck EPA mpg		27.0	33.3	39.5
New LDV average EPA mpg		32.5	40.0	47.5
Stock average EPA mpg		27.1	31.9	38.7
Stock average on-road mpg		21.7	25.5	31.0
Fuel consumption, Mbd		6.91	6.69	6.05
Projected savings, Mbd		0.52	1.64	2.91

*Calculated by stock model runs.

**Percent changes relative to 1993 new-fleet average. Assumes −0.10 for elasticity of VMT with respect to fuel cost of driving.