THE GREENISH MACHINE:
On the Road to Reduced CO_2 Emissions via Higher Fuel Economy and Alternative Fuels

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ABSTRACT

This paper addresses the question of how to expediently reduce the carbon dioxide emissions and petroleum dependence of personal transportation in the United States. The focus is on vehicle technologies rather than transportation demand, and is expressly on the near-term. For that reason, the analysis is restricted to fuels and technologies which, assuming appropriate public initiatives, can be reliably and extensively commercialized over the next 10-15 years. The discussion is based on a review of recent studies, which generally examine either efficiency improvement or alternative fuels but rarely address the relation between the two. The alternative fuels considered are methanol and natural gas used in an internal combustion engine and grid electricity used in a battery powered vehicle. Technologies, cost, and performance information are presented for five alternative compact cars, powered by: (1) gasoline at 35 MPG, (2) gasoline at 45 MPG, (3) methanol (M85, flexible fuel), (4) compressed natural gas (CNG), and (5) electricity. There is significant overlap among technologies available for improving fuel economy and technologies needed for alternatively fueled vehicles. Efficiency improvement is found to offer the most cost-effective near-term benefits for reducing both CO_2 emissions and oil use. Alternatively fueled vehicles may be required in the long-term for renewable fuels use and in the near-term for air quality reasons. However, because efficiency improvement is synergistic with alternative fuel technologies, the pursuit of simultaneous investments in both approaches is desirable. A balanced approach, including a variety of complementary public policies, will be needed to pursue an economically efficient path to making a transition to widespread renewable fuel use.

INTRODUCTION

There are two basic approaches to reducing the energy-related impacts of automobile use: cutting the amount of driving and decreasing the impact of each mile driven. This paper focuses on the latter. From an environmental perspective, one can envision the ultimate "Green Machine." Use of the Green Machine would emit no pollutants, be they local air pollutants, acid precursors, hazardous wastes, toxics, or global pollutants like carbon dioxide and halocarbons. The Green Machine would be produced using renewable resources with environmentally sustainable manufacturing processes. The materials would be reused or recycled when the vehicle is scrapped, or perhaps the Green Machine would be indefinitely and cleanly refurbished. For some, the Green Machine is an ambitious goal which automakers should strive to achieve. But others might call it an oxymoron, a contradiction in terms. The truth is likely to lie somewhere in between.

Whichever ultimate assessment one favors, it does seem clear that the environmental impact of each vehicle can be progressively reduced. This notion can be captured by introducing the term "Greenish Machine." The concept of a Greenish Machine emphasizes that much can be done to produce vehicles which, while not fully "Green" in the sense envisioned above, still go a long way toward reducing the environmental impacts of each mile driven. For example, greenhouse gas emissions per mile could be a small fraction of what they are today. The concept of a Greenish Machine also entails a sense of progress, of technological evolution in a direction that leads to progressively "Greener" machines. The focus here is on approaches for reducing oil use and CO_2 emissions. Two types of technologies are clearly needed for such progress: technologies to improve energy efficiency and technologies to utilize alternative (non-petroleum) fuels. This paper explores the relationship between these two in an attempt to identify the best candidate for the Greenish Machine in the near-term (next 10-15 years). Such a first-generation Greenish Machine would provide direct near-term benefits and be an expedient step toward a next-generation, Greener Machine.

The overall carbon dioxide (CO_2) emissions from motor vehicle use depend on the amount of driving, the energy use per distance driven, and the greenhouse emissions associated with each unit of energy used. Analytically, this can be expressed as follows:

$$\begin{bmatrix} TOTAL\ EMISSIONS \\ (tons CO_2/year) \end{bmatrix} = \begin{bmatrix} VMT \\ (miles/year) \end{bmatrix} \times \begin{bmatrix} ENERGY\ INTENSITY \\ (Btu/mile) \end{bmatrix} \times \begin{bmatrix} EMISSIONS\ FACTOR \\ (grams CO_2/Btu) \end{bmatrix}$$

A simpler relation, in which the emissions factor is given directly as grams per mile, is often used for emissions of other pollutants, such as hydrocarbons (HC) and nitrogen oxides (NO_x). Because present CO_2 emissions are intimately tied to energy use, however, it is useful to make the breakdown shown here. The above relation holds for an individual vehicle. On an average basis, it holds for a population of vehicles, be they at a municipal, national, or global level. Recent analysis of the potential for reducing transportation energy use over the next 40 years indicates that about three-fourths of the future reduction potential is from improving vehicle efficiency and the remainder is from reducing vehicle travel demand.[1] A focus on the Greenish Machine involves technology improvement, that is, the second two factors in the above equation.

A vehicle's energy intensity determines how much fuel is needed to run it. It is inversely proportional to a vehicle's energy efficiency, as represented, for example by fuel economy (MPG). A doubling of fuel economy would yield a halving of energy intensity; other things being equal, this would result in a halving of CO_2 emissions. Gasoline has an energy content of 125,000 Btu/gallon, so today's average new cars, which get about 22 mpg on-road, have an energy intensity of 5600 Btu/mile.[2] New light trucks have an average fuel economy of only 17 mpg on-road, or an average energy intensity of 7500 Btu/mile, 33% greater than that of cars. Given the popularity of light trucks as a means of personal transportation in the United States, it is important to fully include them in analyses of potential Greenish Machines.

The emissions factor depends on the fuel used. It includes all emissions associated with production, distribution, and use of the fuel.[3] For example, the current CO_2 emissions factor for gasoline is 86 g/kBtu (grams per 1000 Btu), or about 23 lbs/gal in common units.[4] Electricity from the present grid in the U.S. has an average CO_2 emissions factor of 207 g/kBtu (end-use), or 1.6 lbs/kWh.[5] A completely renewable fuel, at least from a narrow, net CO_2 emissions perspective, would have an emissions factor of zero. This would mean that there would be no net CO_2 emissions if such a fuel is used, thereby eliminating vehicle greenhouse emissions. However, there are other impacts of renewable fuel production and utilization. Fuel production without net CO_2 emissions can be environmentally damaging if it threatens natural habitats and the extent of such damage is related to the scale of fuel production (Cook, Beyea, and Keeler 1991). The

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[1] DeCicco *et al.* (1992), which reports key transportation sector results from the *America's Energy Choices* study (ACEEE *et al.* 1991).

[2] Unless otherwise noted, fuel economy statistics are taken from Heavenrich *et al.* (1991). Estimates of on-road fuel economy reflect a 20% reduction to account for fuel economy "shortfall," that is, the fact that real, on-road driving results in lower fuel economy than indicated by the EPA tests.

[3] Associated greenhouse gases other than CO_2 (such as N_2O and CH_4) are also included in the emissions factors given here, converted to a CO_2 mass-equivalent basis, using the estimates of DeLuchi (1990).

[4] Derived from a CO_2-equivalent emissions factor of 81.3 kg/GJ (10.72 kg/gal or 23.6 lb/gal) based on DeLuchi (1990).

[5] Equal to 706 g/kWh (196 kg/GJ) end-use, derived from the CO_2-equivalent emissions factors of Fisher (1991), Table VII, but assuming the 1990 U.S. generation mix of 55% coal, 21% nuclear, 10% gas, and 4% oil from EIA (1991), Table 2.6. There is, of course, significant regional variation in the electricity generation resource mix.

amount of fuel required is directly proportional to vehicle energy intensity.[6] Moreover, as will be seen below, consideration of expedient and economical approaches to reducing motor vehicle CO_2 emissions also lend emphasis to the importance of the energy intensity factor of the equation.

IMPROVING FUEL ECONOMY

The U.S. light duty vehicle stock (cars and light trucks, new and used) presently has an average on-road fuel economy of 20 mpg.[7] This corresponds to CO_2 emissions rate of 540 g/mi, counting greenhouse gas emissions throughout the petroleum fuel cycle as well as at the tailpipe. Nationwide, U.S. light duty vehicle use results in annual CO_2-equivalent emissions of 1 billion tons, about one-sixth of total U.S. greenhouse gas emissions.[8] Figure 1 shows historical new light duty vehicle CO_2 emission rates and a policy-dependent range of projected future rates. The solid curve is assumes frozen rated fuel economy but ongoing declines in actual on-road fuel economy, as expected without significant new policy interventions to encourage efficiency improvement.[9] The dashed curve assumes a 40% fuel economy improvement by the year 2001 with a similar rate of improvement subsequently.[10] This 40% fuel economy improvement would imply a 36% cut in light vehicle CO_2 emissions by 2010, accounting for vehicle stock turnover and relative to any assumed growth in vehicle travel.

The level of near-term fuel economy improvement remains speculative unless the needed technological changes have already been identified. Automotive fuel economy improvement potential is a widely discussed but controversial area of technology assessment. Recent studies have estimated cost-effective levels of new car fuel economy for a 10-15 year horizon ranging from 30 mpg to 45 mpg (the present average is 28 mpg).[11] The range spans assessments of little or no increase in fuel economy to improvement rates in excess of that needed to follow the reduced CO_2 emissions curve of Figure 1. The discussion here is based mainly on Ross *et al.* (1991), which

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[6] Some analysts point out a VMT "rebound" effect, whereby improved fuel economy (lowered energy intensity) results in an increasing in driving due to a lower cost per mile of travel. The results of Greene (1990) indicate that this effect is fairly small; it would entail an fuel use adjustment of no more than 5% for the fuel economy improvement levels considered here.

[7] Estimate for 1991, based on new vehicle statistics from Heavenrich *et al.* (1991), the author's stock model, and a 20% shortfall. This 20 mpg estimate is higher than the 18.4 mpg average for 1988 reported by Davis and Hu (1991), but stock average fuel economy would have improved between 1988 and 1991 due to the greater share of newer vehicles. Also, average shortfall may be worse than 20%. New light vehicle fuel economy peaked in 1988 at an average of 21 mpg on-road (25.9 mpg EPA test), so little further improvement in the vehicle stock is currently expected.

[8] Based on 1.9 trillion miles of light duty VMT (FHWA 1991).

[9] DeCicco (May 1992) discusses why a frozen efficiency projection is a likely scenario in the absence of changes from current fuel economy policy.

[10] The fuel economy improvement scenario corresponds to a year 2010 new automobile fuel economy of 51 MPG, which is bracketed by the 45 MPG "low risk" and 55 MPG "medium risk" levels identified by EEA (1991).

[11] Major studies include the analyses based mainly on EEA (1985) and other EEA work, such as Difiglio, Duleep, and Greene (1990) and OTA (1991); the industry-based work such as SRI (1991); Ross *et al.* (1991), which is also partly based on the EEA work; and the recent NRC (1992) report, which draws on the SRI and EEA work.

concludes that significant improvement is possible. These results are chosen because their underlying assumptions are least restrictive regarding market considerations. Concerns about vehicle technology changes which the market may or may not bear are imposed to a greater or lesser degree by other studies in limiting the applicability or refinement of certain technologies.[12] This paper first seeks to explore the horizons of technical and economic feasibility in order to inform policy discussions regarding potential interventions directed toward changing market outcome.

Table 1 shows a breakdown of where fuel economy improvement can be had over the next decade along with a comparison to the improvement level demonstrated in a recent compact car. The largest potential is in engine and transmission improvements. A vehicle's average efficiency--in terms of the amount of energy contained in the fuel that is utilized to move the car--depends largely on how well the engine and transmission work together to deliver energy to the wheels. Load reduction refers to lowering the energy needed at the wheels or by accessories such as air conditioners. Energy loads can be reduced by improved accessories, improved tires, better aerodynamics, and by the use of strong, lightweight materials and structural designs.

This paper compares alternative compact cars, which represent the largest single class of new light duty vehicle sales. The 1992 Honda Civic VX subcompact provides an example of what was recently done to improve advance fuel economy significantly beyond the current average for new cars in its class. The breakdown of how the Civic was made more efficient is fairly close to the generic estimates made by Ross *et al.* The greater potential in the load reduction category is based on fleet average weight reduction level not applied in the 1992 Civic VX relative to the comparable 1991 model. The average fuel economy of new compact cars has been fairly stable for the past several years at just under 30 mpg.[13] The DOE (1990) alternative fuels study chooses a 35 mpg level for a typical compact car in 1995-2000. This fuel economy improvement level is also adopted here as a baseline to which alternative compact cars are compared.

Since technologies are available for efficiency improvement beyond the 35 mpg baseline, the first alternative is a more efficient compact car. Based on Ross *et al.* (1991), it is estimated that 45 mpg would be a cost-effective, technically feasible level for compact cars over the next decade. This 50% improvement over present compact cars is just below the relative improvement suggested

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[12] A discussion of the factors that distinguish some recent fuel economy assessments is given by DeCicco (April 1992).

[13] The 1984-89 compact car average was 29.8 (±0.1) mpg, but fuel economy has recently dipped, with compacts dropping to 29.2 mpg by 1991 (Heavenrich *et al.* 1991). All fuel economy values given here are the 55% city, 45% highway, EPA weighted average ratings, as used for U.S. federal compliance purposes. Note that the values printed on a new vehicle sales sticker average 15% lower, reflecting a downward adjustment to better represent actual on-road driving.

in Table 1.[14] The technology-based fuel economy improvements identified in Table 1 assume no change in the average size, performance, or range of vehicles. In the discussion that follows, it is assumed that vehicle size (interior volume, as it relates to passenger and cargo capacity) is fixed, but performance and range constraints are relaxed for alternatively fueled vehicles. It is also assumed that all vehicles will meet planned emissions standards. The need to reduce emissions of tailpipe pollutants, particularly nitrogen oxides (NO_x), may place a long-term constraint on fuel economy improvement. However, emissions considerations do not constrain the 50% fuel economy improvement considered here.[15] Most alternative fuel vehicle designs are also predicated on meeting or bettering future emissions standards.

Estimates of the cost of technology-based fuel economy improvement may be presented in the form of an energy conservation supply curve. The estimates of Ross *et al.* (1991) are adapted here in Figure 2 to show the estimated cost of reaching a given level of fuel economy. Cost-effectiveness estimates vary even more than the estimates of feasbible MPG level. Important determinants of cost-effectiveness include assumptions regarding the scale of production and whether improvement involves a premature plant or equipment retirement (i.e., requirements for new retooling investments prior to the end of the useful life of older tooling investments), as well as parameters such as the amortization period and discount rate. The estimates shown in Figure 2 are lower than some reported elsewhere, but are adopted here under assumptions of a full scale of production, avoidance of premature plant retirement costs for the 10-15 year time horizon, and valuation of fuel savings over a full-vehicle lifetime at a societal discount rate (3% real). The Figure 2 cost curve represents an average of all automobile classes. Assuming the same cost per percentage improvement for the compact class, the estimated average cost of improving to the 35 mpg baseline is $170 per vehicle. The estimated cost to reach the 45 mpg level is $750, or about $600 above the baseline.

EFFICIENCY AND ALTERNATIVE FUELS

Improved fuel economy will clearly reduce vehicle CO_2 emissions. For example, a 45 mpg, improved efficiency compact car would emit one-third less CO_2 per mile than the typical 30 mpg compact car of today. However, as long as a fossil fuel such petroleum is the primary energy source, significant CO_2 emissions will remain (unless a way is found to sequester the CO_2 or utilize only the hydrogen in the fossil fuel). To eventually eliminate net CO_2 emissions, motor vehicles

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[14] The Honda Civic VX, rated at 60 mpg, already greatly exceeds this level, although it is a subcompact with a manual transmission. Adjusting the Honda Civic VX improvements to reflect subcompact class average characteristics implies a 59% improvement potential relative to 1990 fuel economy (Plotkin 1992).

[15] Calwell (1990); Ross *et al.* (1991). The 49-state (60 mpg) version of the Honda Civic VX does, for example, face a NO_x constraint. However, the California (55 mpg) version meets the more stringent NO_x standard while demonstrating a fuel economy level still in excess of that assumed here.

would need to be powered by a renewable fuel. In the near term, alternative (but not necessarily renewable) fuels hold promise as ways to alleviate local and regional air pollution problems caused by petroleum fueled vehicles. Research, development, and investment resources are always limited. Is it worth putting significant resources into improving gasoline powered vehicles rather than focusing investments directly on alternative fuel technologies that could directly utilize clean and renewable fuel energy sources?

It is argued here that improving efficiency and promoting alternative fuels are mutually reinforcing strategies. More pointedly, it is suggested that significant investments to improve conventional vehicle fuel economy are not at all lost to the cause of promoting alternative fuels and may in fact be the most expedient and cost-effective way to make the transition away from a petroleum based transportation system. Programs to promote efficiency and alternative fuels in a complementary fashion will both reduce transportation oil consumption. There are a number of other reasons why efforts to improve the fuel economy of conventional vehicles to be mass-produced over the coming decade will help pave the way for alternatively fueled vehicles of the future:

(1) Alternatively fueled vehicles are likely to have a more limited range than gasoline vehicles (see Table 2, discussed below). Therefore, high efficiency can help extend the range and will be important for widespread consumer acceptance.

(2) Improved efficiency can enable use of smaller motors and fuel or battery storage requirements, benefiting vehicle performance and leaving more space for passengers and cargo.

(3) Because the scale of use is so large and still growing--with 200 million motor vehicles in the U.S. and nearly 600 million worldwide (MVMA 1991)--no conceivable fuel or power source, no matter how clean or renewable, can be truly sustainable in an ecological sense if it is used inefficiently.

(4) The direct fuel costs of near-term alternative fuels, still produced from fossil sources, are likely to be very competitive with current gasoline prices (see Table 2, below). However, the production of renewable fuels is likely to involve higher costs, reflecting environmental and other externalities that are neglected in current fossil fuel prices. At these higher prices, higher vehicle efficiencies will bolster consumer acceptance.

(5) Improving fuel economy to the level identified here would provide a direct economic benefit of significant fuel savings. Income that would otherwise be spent on consumption of oil would be made available for other uses, including investments needed for enabling more extensive renewable fuels use.

(6) Finally, many of the technologies for improving the fuel economy of conventional vehicles are also applicable to alternatively fueled vehicles. Putting technologies to use as soon as they are developed provides valuable experience. This will familiarize consumers with new technologies and designs as well as provide an on-road track record that engineers can use for the next round of refinements.

This paper will not go into detail about the various alternative fuel options, which have been extensively discussed elsewhere.[16] Rather a summary of published cost and performance estimates for near-term efficiency and alternative fuel options is presented.[17] This is followed by an elaboration of point (6), namely, the technological synergisms between fuel economy and alternative fuels. As pointed out by Gordon (1992), it would be premature to single out one particular alternative fuel vehicle design as the ultimate choice. In the short run, the best options may vary from region to region, depending on the local resources and environmental constraints. State and local initiatives to promote alternative fuel use, for example, in municipal or company fleets, will provide an early market and valuable experience needed before there can be extensive replacement of petroleum in the long run.

Cost and Performance Comparisons

Table 2 compares five different types of compact cars that could conceivably be made available in large numbers over the next 10-15 years. In addition to the improved efficiency car introduced above, three alternatively fueled compact cars are also presented. Comparisons are made relative to the 35 mpg compact car which is taken as the near-term baseline. The detailed assumptions behind the estimates are given in the table's notes. As noted earlier, all vehicles are considered to have the same size in terms of passenger and cargo capacity.[18] The alternatives considered are thus assumed to be potentially competitive in a broad, near-term automotive market, which will still include gasoline powered vehicles. These premises regarding the baseline vehicle selected for comparison purposes should be kept in mind, since "selecting different baselines will drastically alter the results" of alternative vehicle comparisons.[19]

All of the alternative vehicles will cost more than the baseline 35 mpg compact car. The methanol option appears to be the least expensive alternative in terms of vehicle cost. An electric car is significantly more expensive, due entirely to the high battery costs, which are presented here as a first cost adder which covers battery replacements that might be needed over the vehicle's lifetime. In other words, all battery costs are treated as a capital expense, rather than as an operating expense such as fuel or electricity consumption. Not explicitly considered here is the electric hybrid design, which couples a combustion engine with an electric motor and battery. Hybrid designs are very promising--some consider electric hybrids as the next major step for

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[16] See, for example, Sperling (1988); OTA (1990); Gordon (1991); Fisher (1991).

[17] The DOE assessment effort is documented in DOE (1990) and related technical reports. Corroborations and adjustments were obtained from Sperling (1988), Hamilton (1989), OTA (1990), DeLuchi (1990), Wang *et al.* (1990), EPA (1990), and discussions with a number of analysts of alternative fuel vehicle technologies.

[18] The compact car class is defined by EPA as having a passenger plus cargo interior volume of 100-109 ft^3 and is generally considered capable of carrying 4-5 passengers.

[19] OTA (1990), p. 29, which provides a discussion of how choice of a baseline vehicle for comparison purposes must be carefully linked to the policy question being addressed.

improving "conventional vehicle" fuel economy beyond the levels discussed here.[20] However, performance estimates for hybrids have a very wide range depending on the assumptions used. Even though the technologies may be just as available as those of the other alternative fuel options considered here, it appears that significant further analysis is needed to provide a cost and benefit assessment of potential electric hybrid vehicles.

Vehicle fuel economy is shown in Table 2 on an energy end-use equivalent basis. That is, the energy used only at the vehicle (e.g., not including what is needed to produce and distribute the fuel itself) is converted to an equivalent number of gallons of gasoline.[21] Also shown are CO_2 emissions on a full fuel cycle basis.[22] The difference in ranking according to fuel end-use and full fuel cycle CO_2 emissions is most pronounced for electricity, since the average efficiency of electricity generation and transmission is about 30%. If renewable feedstocks were used for the fuels or the electricity were generated from largely non-greenhouse emitting sources, the net CO_2 emissions from the alternatively fueled vehicle could be much lower (DeLuchi 1990; Fisher 1991). However, extensive use of renewable feedstocks and electricity generation cannot be counted on over the 10-15 year time horizon posited here.

Regarding direct fuel costs, natural gas and electric vehicles are lowest, assuming conventional feedstocks and neglecting environmental externality costs. However, greater vehicle costs, particularly for electrics, and significant infrastructure costs must also be considered. A full economic analysis that would incorporate all relevant costs and benefits is beyond the scope of this paper. Nevertheless, inspection of the estimates in Table 2 suggests that added efficiency improvement is a very attractive near-term option for reducing per vehicle CO_2 emissions. The investments in vehicle technology needed to displace 1 Mbd of oil use are no more than half those of any alternative fuel option and there are no new infrastructure costs. Of course, it would be possible to incorporate more efficient technologies into the alternative fuel vehicle designs. This will, of course, compound the up-front costs. However, the high cost-effectiveness of efficiency improvement by itself as well as the potential for synergistic technology development may make the total cost of highly efficient alternatively fueled vehicles lower than a simple sum would indicate. We leave this as a suggestion for future analytic work.

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[20] MacCready (1991); EEA (1991). Hybrids could, of course, utilize an alternative fuel such as methanol in their combustion engine. Fuel cell electric vehicles have also been identified as promising (DeLuchi, Larson, and Williams 1991), but this technology is at an earlier stage of development and does not qualify for inclusion among the "near-term" options discussed here.

[21] The standard energy content of gasoline is 125,000 Btu/gallon (higher heating value, Davis and Hu 1991).

[22] Based on DeLuchi (1990), including the global warming effects of methane and nitrous oxide emissions, which add 15%-20% to the average impact based on the fossil fuel CO_2 emissions alone.

Technological Commonalties

The significant overlap between the technology developments that can be used to improve conventional vehicle fuel economy in the short term and those that will be needed for practical alternatively fueled vehicles is illustrated in Table 3. Combustion engine technologies, of course, apply only to new vehicles that will have such engines. This includes electric hybrid vehicles, which will be important in making the transition to zero-emission type vehicles such as pure battery and fuel cell electric vehicles. Technologies for improving engine efficiency will be particularly critical to the success of any of the alternative combustion fuels, such as natural gas and alcohols, which can also be used in hybrid electric vehicles. Natural gas is not a renewable fuel and neither are alcohols as currently produced in the United States. However, biomass-based supply systems could eventually produce alcohol or synthetic gaseous fuels that could replace petroleum over the course of a number of decades.[23]

Engine efficiencies much higher than those of current new vehicles will help to maximize vehicle range and minimize environmental impacts of alternative fuel production. Most of the potential refinements mentioned above for todays' standard spark-ignition four stroke engine will also find critical use in engines optimized for alternative fuels. The same is true for new emissions control technologies, such as electrically heated catalysts and NO_x-reducing catalysts. Modern alternative engine designs, such as the two-stroke and DI diesels, can also be used with alternative fuels. For example, General Motor's *Ultralite* concept car is being designed to enable use of a variety of alternative fuels in its two-stroke engine module.[24] Transmission technologies also apply to any alternatively fueled vehicle that uses a combustion engine, as well as to some electric hybrid designs. Transmissions play a critical role in maximizing the amount of time the engine operates in its most efficient regime. All of the load reduction technologies--aerodynamics, better tires, weight reduction, improved accessories--will enhance the performance and viability of any alternatively fueled vehicle. Load reduction has played a very prominent role in the development of prototypes such as General Motor's *Impact* electric vehicle and the *Ultralite*.

Expedience and Economics

The synergisms between fuel economy improvement and alternative fuel utilization reenforce the suggestion from Table 2 that encouraging efficiency improvement is likely to be the most expedient and least expensive path to reduced CO_2 emissions. In other words, the best candidate for a first generation "Greenish Machine" is a conventional gasoline vehicle of significantly

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[23] DOE (1990) estimated the infrastructure and supply requirements for various alternative fuels to displace 1 Mbd of U.S. transportation oil use by about 2005. ACEEE *et al.* (1991) projected solar or biomass derived transportation fuel availability of 1.3 Mbd or more by 2010 and up to 3.5 Mbd by 2030. Current U.S. light vehicle gasoline consumption is about 6.5 Mbd (13 Quads; 1 Mbd oil equivalent equals about 2 Quads [10^{15}Btu/yr]).

[24] Keebler (1991), and pers. comm. with GM *Ultralite* project staff.

improved fuel economy. Technologies for efficiency are available now and do not require the time to build a new fuel supply infrastructure. As shown in Figure 1, even modest goals for fuel economy improvement can start the country on a path of decreasing light vehicle CO_2 emissions and oil consumption. This will also provide a head start on the longer term efforts to replace petroleum with a renewable fuel. Moreover, because atmospheric CO_2 concentrations are increasing and CO_2 remains in the atmosphere for a long time, a ton of emissions reduction 10 years from now will be much more effective towards stabilizing climate than a ton of emissions reduction 20-30 years from now (Krause *et al.* 1989); Lashof and Tirpak 1990). As indicated in Table 2, significant investments in vehicle technologies and infrastructure are needed to displace 1 Mbd of oil over the next 15-20 years, and this is even without developing renewable supplies for the alternative fuels. Cost-effective fuel economy improvement of conventional vehicles will yield larger, assured reductions in CO_2 emissions over the same time frame.

It has been argued that significant greenhouse gas emissions reductions can only come at a high price and that such investments are not warranted considering the uncertainties surrounding global warming.[25] However, Figures 1 and 2 indicate that a major CO_2 emissions reduction can be obtained by investing in automotive efficiency improvements that more than pay for themselves in fuel savings. The large direct fuel cost savings indicate that pursuit of automotive efficiency is a "no-regrets" strategy, which has significant net economic benefits irrespective of the avoided CO_2 emissions. From Figure 2, the estimated first cost increment for a 50% efficiency improvement in the average new compact car is $750, corresponding to a 7% increase over the average retail price. Comparing the fuel savings to the investment cost, the annual rate of return is 26%.[26] That is a quite attractive investment even without accounting for trade deficit reduction, national security benefit, and pollution decreases associated with reduced oil use.[27]

The positive results of the foregoing lifecycle cost analysis for efficiency improvement may mean little to a new car purchaser, who is likely to only keep the vehicle for part of its useful life and who attaches much greater importance to first cost than to operating cost. Indeed, if fuel economy improvement were a strong market factor, there would be little need for policy makers to address the issue. The situation regarding efficiency improvement is similar to that which justifies policy interventions to promote alternatively fueled vehicles, which are also not an expected outcome given near-term automotive market conditions.

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[25] Such arguments have been made on numerous occasions by the Bush administration to justify U.S. inaction on setting specific CO_2 reduction targets.

[26] Internal rate of return computed for a future gasoline price of $1.30/gallon, 12,000 miles per year of driving for 10 years, and an investment cost of $750 to improve from 30 mpg to 45 mpg at 20% shortfall.

[27] Some of these benefits as well as other costs are estimated by Greene and Duleep (1992).

POLICY IMPLICATIONS

Based on the forgoing assessment, one would have great optimism about the potential for improving the automobile. It is less clear that such changes in automotive technology could happen quickly. Present market conditions do not favor improvements in any of the factors: automotive efficiency, alternative fuels use, or reduced travel demand. Public policy intervention is needed.[28] This need is generally recognized and has resulting in significant initiatives for promoting alternative fuels, such as the Alternative Motor Fuels Act of 1988 (AMFA), the California programs for alternative fuels and a number of other state-level programs, and the alternative fuel provisions of the energy legislation currently being considered in the 102nd Congress. Success in establishing policies for promoting alternative fuels is at least partly due to the fact that there have been significant alternative fuel supply industry interests as well as environmental interests which have been able to ally themselves to promote alternative fuels, particularly as a way to address air pollution.

The principal public policy for promoting automotive efficiency improvement is the Energy Policy and Conservation Act of 1975 (EPCA), which established Corporate Average Fuel Economy (CAFE) standards. The highest level delineated by Congress was 27.5 mpg for automobiles, which was first set for 1985. The standard was rolled back in 1986-89 and stands at 27.5 mpg today. CAFE standards have been very effective in advancing the fuel economy of U.S. automobiles.[29] Legislation to strengthen the standards or complement them with other policies for promoting efficiency has been introduced in each of the past three Congresses. However, such efforts have been thwarted by the combined opposition of the automobile industry and federal administrations ideologically opposed to regulations that affect industry. There have even been calls to eliminate CAFE standards. The automotive industry recommends modest gasoline taxes as a way to promote fuel conservation,[30] however, recent administrations have generally opposed increased taxation.

In contrast to alternative fuels, there is no focussed business interest in advancing fuel economy. Thus, "efficiency has no constituency" even though there is broad support among environmental and consumer groups for measures to promote automotive fuel economy. Measures to promote vehicle efficiency are absent from the National Energy Strategy. The energy legislation progressing in Congress[31] contains numerous provisions for improving energy efficiency in

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[28] The limitations of market forces regarding personal transportation energy use have been widely discussed; see, e.g., Stobaugh and Yergin (1979); Bleviss (1988); Bleviss (1990); Ross *et al.* (1991); DeCicco (July 1991); and the article by Gordon (1992).

[29] Greene (1990), in both *Forum* and *The Energy Journal.*

[30] See, e.g., Liberatore (1990); industry sponsored studies such as Leone and Parkinson (1990) and CRA (1991); and any recent Congressional testimony on this issue by auto industry representatives.

[31] Comprehensive National Energy Policy Act, H.R. 776, 102nd Congress, Washington, DC, 1992.

residential and commercial buildings, the utility sector, and in manufacturing, but contains nothing to improve motor vehicle efficiency. Lack of measures for effectively advancing automotive energy-efficiency thus remains a gap in current U.S. energy policy.

The technological synergisms between improving efficiency and developing alternatively fueled vehicles presented above suggest that there could be synergisms in the policy arena. In fact, the efforts to develop alternatively fueled vehicles are already creating spin-offs in terms of efficient technologies. For example, vehicles like the GM *Impact* and *Ultralite* prototypes, demonstrate efficiency levels far in excess of those of the current new car fleet. The *Impact* is an electric vehicle and the *Ultralite* was initially developed with a methanol engine, but has a modular engine design that could be adapted for other alternative fuels, such as electricity as well as gasoline.[32] Battery limitations have resulted in electric vehicle designers putting a premium on efficiency in the rest of the car by making extensive use of load reduction technologies (better aerodynamics, low rolling resistance, lightweight materials). Policies to put alternatively fueled vehicles on the road can therefore help put efficient technologies on the road.

Nonetheless, the forgoing analysis suggests that relying only on alternative fuels promotion policies may amount to putting the cart before the horse. For achieving a significant near-term impact in reducing oil use and CO_2 emissions, efficiency should lead. Efficiency will help pull alternative fuel technologies along. The range and performance limitations of the alternatively fueled vehicles that can commercialized soon, along with their limited potential for reducing CO_2 emissions, imply that neglect of conventional vehicle efficiency improvement will result in no timely progress toward reducing vehicle related CO_2 emissions.[33]

Major policy options for encouraging automotive efficiency improvement are fuel economy standards, price incentives (guzzler taxes, feebates) for vehicles, fuel pricing measures, governmental vehicle purchase commitments, and a competition or challenge for commercializing ultra-efficient vehicles. The particulars of such options are discussed at length elsewhere.[34] The focus here will be on considerations for coordinating the promotion of automotive efficiency and alternative fuels.

They worked in the past and strengthened standards will work again. As a way to promote alternative fuels, the CAFE regulations were amended to provide manufacturers with a CAFE credit for alternative and flexible fuel vehicles. These provisions let automakers add a specified MPG increment toward meeting their fleet average requirements for each alternatively fueled

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[32] General Motors Corp., press releases and brochures on the *Impact* and *Ultralite* vehicles, and pers. comm. with GM project staff.

[33] A stark confirmation of this assessment is provided by McCosh and Brown (1992), based on recent tests of state-of-the-art alternatively fueled vehicles.

[34] A recent, integrated transportation energy strategy was developed as part of an overall national strategy for efficiency and renewable sources in ACEEE *et al.* (1991); see Gordon (1990); Ledbetter and Ross (1991).

vehicle sold. This credit effectively reduces the fuel economy requirement for an automakers conventional (gasoline) vehicles, creating a trade-off between the two objectives. In the absense of an ongoing strengthening of CAFE standards, the credits can result in lower new fleet fuel economy. The flexible fuel credit provision is particularly problematic because it is based on the assumption that the alternative fuel (instead of gasoline) is used at least half the time, which is probably unrealistic for the next decade or two. Thus, based on the existing provisions, the flexible fuel CAFE credit is expected to result in an *increase* in light vehicle oil consumption compared what would happen in the absence of the credit.[35] This is because the lost efficiency in conventional vehicles results in more gasoline use than is likely to be displaced by the flexible fuel vehicles. Proposals to raise the current cap on the CAFE credit would aggravate the situation. This is an example of policies working at cross purposes. A flexible fuel vehicle CAFE credit will create such a problem unless there is a mechanism to tie it to actual alternative fuel use. For example, a pool of available credits could be developed according to the amount of nationwide alternative motor fuel use (which would have to be reported), and made available to automakers on this basis.

The U.S. federal gas guzzler tax has played a role in post-1983 fuel economy improvements (Ross *et al.* 1991). However, the MPG rating below which the U.S. gas guzzler tax applies needs to be raised to keep upward pressure on the low end of the fleet; the tax should also be extended to light trucks. A gas guzzler tax create a market incentive for buyers to avoid the least efficient vehicles. The mechanism would become even more powerful if extended to provide a subsidy to the most efficient vehicles. This leads to the concept known as a *feebate* (contraction of "fee" and "rebate").[36] A feebate can also take the form of a sliding-scale sales tax, so that high-mpg vehicles are taxed less than low-mpg vehicles.

Feebates would be a valuable complement to CAFE standards because they would address manufacturers' concerns about achieving a sales mix which satisfies their CAFE targets. In general, feebates are a particularly promising policy tool because they can be flexibly designed to meet other policy objectives, such as revenue neutrality or revenue generation, promotion of domestic vehicle production, as well as rational treatment of alternative fuel options (DeCicco *et al.* 1992). Ideally, a feebate system would be based on full fuel cycle CO_2 emissions, since this permits an even-handed and environmentally sound way to compare the performance of vehicles that use different fuels. The rebate portion of a feebate program should be coordinated with subsidies for alternatively fueled vehicles. Alternative fuel vehicles may warrant a subsidy beyond a rebate level that might be set from strict energy efficiency, CO_2 emissions, or other

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[35] An analysis which demonstrates the adverse nature of this trade-off is given by Farmer (1991).

[36] Feebate concepts and policy considerations are discussed by Levenson and Gordon (1990); Geller and DeCicco (1991); Calwell *et al.* (1992); Davis and Gordon (1992); and DeCicco *et al.* (1992).

environmental considerations, particularly to offset high first costs due to limited initial vehicle production. A broader-based feebate system can also be developed, such as the California DRIVE+ proposal, which provides incentives for vehicles that have both lower tailpipe emissions of criteria pollutants as well as higher fuel economy (Levenson and Gordon 1990).

Fuel pricing is another form of market incentive. An added gasoline tax would be a useful complement to both incentives and standards. However, a small tax (e.g., 5¢-10¢ per gallon) will have only a trivial effect on vehicle purchase decisions and driving behavior. Fuel taxes in the $1.00 per gallon range would be effective, resulting in an oil use reduction as much as 2 Mbd (Chandler and Nicholls 1990). A tax on petroleum fuels (rationalized, e.g., by the national security externality) would, of course, make alternative fuels more attractive. A more general fuels tax could be carbon based; this would be a way to favor those fuels which result in the lowest CO_2 emissions. Although taxation policies, particularly higher petroleum fuels taxes, make economic sense, they are politically difficult to obtain and potentially regressive. A higher gasoline tax may become more politically feasible if proposed as tax shifts (e.g., with offsets to income taxes) rather than new, added taxes.

Another option for increasing the effective price of driving is to incorporate some or all of the payment for automobile insurance through a "Pay As You Drive" (PAYD) plan. PAYD involves collecting on a actual miles-driven basis the variable cost portion of insurance premiums, better relating consumers' costs to the hazard exposure due to distance driven. This would increase the marginal cost of driving without increasing the overall cost and without resorting to a tax increase. Two versions of PAYD have been discussed, paying at the gas pump or paying based on annual odometer readings.[37] Because PAYD would cause a significant increase in the cost of driving another mile, total miles driven, total fuel consumption, and most likely the number of accidents will decrease. The pay-at-the-pump version would also induce vehicle fuel economy improvement.

The "Green Machine Challenge" is a proposal to encourage the development and mass marketing of a vehicles that give very significant advances in fuel economy and emissions performance.[38] In essence, the challenge would be a coordinated, nationwide promotional program for ultra-efficient vehicles. The requirements for a qualifying Green Machines could be fuel neutral, for example, by specifying energy use and emissions criteria that represent a significant advance over those characteristics in current production vehicles. Part of the incentive could be prizes to winning manufacturers or significant rebates for each such vehicle actually sold. An important way to get a challenge started would be purchase commitments from governmental and

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[37] See NICO (1992) and El-Gassier (1990) on paying insurance through a gasoline price adder; see Butler (1990) on paying insurance based on annual odometer readings.

[38] See DeCicco (1991) for an outline of the concept.

private fleet operators, which would offer a further inducement to manufacturers by providing an assured initial market for the vehicles. For example, the City and County of Denver, CO, is developing a "Green Fleets" concept, which gives efficiency guidelines for municipal vehicle purchases. Such a program could link and leverage strategic procurement programs by states and municipalities wishing to promote fuel economy and alternative fuels.

There are two other general points regarding policy formation. The first is that strong, ongoing research programs are a prerequisite for any promotional policies directed toward getting improved technologies on the road. Secondly, the various policy options for promoting alternative fuels and fuel efficiency should be viewed complementary. In terms of the broad objective of reducing transportation oil use, it is likely that their effectiveness in combination will be greater than the sum of their effects in isolation. For example, without complementary market incentives, CAFE standards and alternative fuel vehicle promotions both have to swim upstream against market forces that disfavor fuel economy and new fuels. Market incentives--feebates plus fuel pricing measures--could at least weaken if not turn the "oil carrying" tide that now disfavors both efficiency and alternative fuels.

CONCLUSION

Improving automotive technology to lessen the environmental impact of each mile driven is an essential part of an overall strategy to reduce the environmental impacts of transportation. This is particularly true for addressing the problem of rising greenhouse gas emissions. The realization of a completely "Green Machine" that emits little or no net CO_2 is many years (perhaps at least a generation) away. This paper introduces the term "Greenish Machine" to emphasize that much can be done in the near term to make a vehicle which, while not fully "Green," goes a long way to reducing environmental impacts. Thus, the Greenish Machine need not be an exotic, futuristic vehicle requiring breakthrough technology. Rather, it is a moving target, starting with the production vehicles of today which achieve fuel economies significantly higher than average by applying state-of-the-art engineering toward efficiency improvement. The Honda Civic VX is an example, but Greenish Machines need to be produced in all vehicle classes, including pickup trucks, van, wagons, and large cars.

All of the technologies that can be used to achieve near-term improvements in the efficiency of conventional vehicles are also applicable to one or more alternatively fueled vehicle designs. Encouraging efficiency will aid the move toward renewable fuels because of these design synergisms. Moreover, most alternative fuels will require greater vehicle efficiency for acceptable performance and range. The sheer scale of global automobile use will require high efficiency in utilization of any fuel, no matter how clean. Fuel economy improvement is very cost-effective, both to individual consumers and the U.S. economy as a whole. Therefore, pursuing efficiency and pursuing alternative fuels are essential complements to each other. Efficiency improvement will provide the far greater near-term benefits while providing transferable technologies and economic savings that will assist the long-term transition to renewable fuels. In short, improving the fuel economy of conventional vehicles is the most important near-term action for starting a serious transition away from a petroleum-based transportation system.

In spite of the many reasons for technological optimism about the potential for Greenish Machines, it is also clear that progress will be very slow unless new public policies are instituted to encourage manufacturers to pursue efficiency improvements. Policy options include fuel economy standards, vehicle pricing incentives such as feebates, fuel pricing measures such as a carbon tax or pay-at-the-pump insurance, fleet purchase commitments for efficient vehicles, and a competition for producing ultra-efficient vehicles. Care must be taken in coordinating efforts to promote efficiency and alternative fuels, so that adverse trade-offs (such as the flexible fuel vehicle CAFE credit) are not created. All of the forgoing options should also be backed by strong, on-going research programs. The policy options are complementary, so that a package of multiple, coordinated options will be most effective. With a concerted, coordinated national strategy to simultaneously advance vehicle efficiency and alternative fuels, the U.S. motor vehicle fleet can start heading down a road leading to real reductions in oil consumption and CO_2 emissions.

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Table 1. Breakdown of potential near-term improvements in automotive fuel economy

Measures for:	Projected by Ross *et al.*	Achieved in the Honda Civic VX
Engine efficiency	23%	20%
Transmission efficiency	17%	15%
Load reduction	15%	9%
Total MPG Improvement	55%	44%

The Ross *et al.* (1991) projections work from a 1987 new car fleet average of 28 mpg (EPA-rated), for a total cost-effective potential estimate of 44 mpg by 2000, using existing technologies and assuming a 1987 performance level.

The Honda estimates compare a 1992 Civic VX (60 mpg EPA-rated) with a similarly equipped 1991 Civic (41 mpg), based on information from Honda (1991) and OTA (1991). The California model VX fuel economy is 8% lower (55 mpg), since the more stringent NO_x standard (0.4 g/mi) precludes use of the lean-burn mode.

Table 2. Cost and performance of various alternatively fueled compact cars compared to improved gasoline fueled compact cars

The estimates are for near-term fuel sources and dedicated fuel technologies, based on what can be reliably commercialized by 2000-2005.

Vehicle characteristic	Baseline gasoline	Efficient gasoline	Methanol (M85)	Nat.Gas (CNG)	Battery Electric
Added cost per vehicle (\$)(a)	--(b)	600(c)	300	800(d)	6300(e)
New vehicle cost (\$)	11,000(f)	11,600	11,300	11,900	17,300
Fuel economy (MPG equiv)(g)	35	45	37(h)	35(i)	73(j)
Range (miles)	420(k)	540	300	160	80
Performance (+ is faster)(l)	--	same	+10%	-30%	-50%
CO_2 emissions (g/mi)(m)	380	300	420	350	350
Annual per vehicle fuel cost (\$)(n)	530	410	500(o)	200(p)	250(q)
Fuel cost savings (10^9\$/year)(r)	--	23	2(s)	10(t)	10(u)
Investment costs (10^9\$):(v)					
Vehicle technology(w)	--	13(x)	27(y)	33(z)	220(aa)
Infrastructure	--	0	4	8	22

(a) All costs are 1990\$ and are rounded to the nearest \$100. Unless otherwise noted, estimates for alternative fuel vehicles are based on DOE's Flexible and Alternative Fuel Assessment, Technical Report 4, August 1990.

(b) Baseline vehicle is zero by definition; estimates of the cost to reach this level from a typical 1987 vintage vehicle range from \$170 (Ross *et al.* 1991) to \$450 (DOE 1990); we assume \$170. This cost applies to all vehicle types and is included in the underlying \$11,000 cost assumed for the baseline vehicle.

(c) Based on the Ross *et al.* (1991) estimate of \$750 per vehicle for a 50% fuel economy improvement relative to a 1987, subtracting the \$170 needed to reach the 35 MPG level assumed here.

(d) OTA (1990) reports \$700-\$800; DOE (1990) reports \$900.

(e) Added first-cost equivalent, covers battery replacements needed over vehicle lifetime (10-12 years, same as for conventional vehicles).

(f) The \$9639 (1987\$) price for a baseline compact car from DOE (1990), adusted to 1990\$, with \$170 added for cost of bringing fuel economy up to 35 mpg.

(g) On an equivalent energy end-use (fuel pump or power plug) basis, at 125 kBtu/gallon of gasoline.

(h) As reported by both DOE (1990) and OTA (1990).

(i) Assumes dedicated CNG engines; fuel economy about 10% lower would result from gasoline vehicles converted to CNG (DOE 1990). Some analysts project an even higher efficiency or no performance trade-off for optimized CNG vehicles; however, no such vehicles have yet been built and tested, so these projections are not used here (OTA 1990; pers. comm., E. Durbin, Princeton University, and C. Weaver, EFEE Inc.).

(j) Assumes an all-electric vehicle with an average charger input rate of 0.5 kWh/mile, which is the mid-range battery performance identified in DOE (1990) and Hamilton (1989). A range of 0.4-0.5 kWh/mile is given by Wang *et al.* (1990); the results are extremely sensitive to the projected battery performance and efficiency.

(k) Assumes a 15 gallon tank for both gasoline vehicles and an 18 gallon tank for the methanol vehicle, with 20% fuel economy shortfall.

(l) Given as the negative of percent change in 0-60 mph time.

(m) Based on emissions factors, in grams of CO_2-equivalent greenhouse gas emissions per kBtu delivered end-use energy, of: 86 for gasoline, 99 for methanol (natural gas feedstock), 79 for natural gas, and 207 for electricity (derived from DeLuchi 1990).

(n) For the new vehicles only, based on 10,000 miles of driving, 20% MPG shortfall, and prices of $1.49/gallon for gasoline, $3.70 per Mcf for natural gas at wellhead, and 8.2¢/kWh for residential electricity (DOE Annual Energy Outlook 1992).

(o) It is assumed that the retail price of methanol fuel (M85) is priced per Btu on a par with gasoline, presuming that any realistic large-scale effort will involve fuel taxes or subsidies to more or less equalize the consumer cost.

(p) Based on adding $0.64 to the wellhead price of gas to account for transmission and distribution (Paul Leiby, Oak Ridge National Laboratory, pers. comm.), for a consumer price of $4.46/MBtu, or $0.56 per gallon of gasoline equivalent.

(q) For charger input rate of 0.5 kWh/mile (no shortfall) and assuming a 40% rate discount for off-peak charging (Hamilton 1989). Note that possible battery replacement are covered in the vehicle first-cost increment.

(r) For national aggregate direct consumer fueling costs, at a 1 Mbd oil replacement level, using the numbers of alternatively fueled vehicles assumed by DOE (1990) and the direct consumer fuel cost savings equivalent to 1 Mbd of gasoline for the efficient conventional vehicles.

(s) For 60 million flexible fuel vehicles on the road operating 75% of the time on M85.

(t) For 23 million CNG cars and light trucks only; the 1 Mbd oil diplacement scenario of DOE (1990) also includes another 7 million heavier trucks and light trucks in fleets larger than 6 vehicles.

(u) Assuming 36 million electric vehicles, based on DOE (1990), Table A-5, by scaling up the all-electric vehicle contribution to oil displacement (DOE's hyrbrid vehicles are not considered here).

(v) Investment costs needed to displace 1 Mbd (1 million barrels per day) of petroleum use; 1 Mbd is equivalent to about 2 Quads (10^{15} Btu) of energy end-use.

(w) Aggregation of added purchase costs per individual vehicle.

(x) Estimated by assuming linear improvement of new car fleet from 1996-2001 at an average cost of $375 per vehicle (one-half the total improvement cost of $750 from the 1987 baseline) and average sales of 11 million new cars per year. This cost is the Ross *et al.* average for all new cars. Assuming comparable level of improvement for all new cars (not just compacts), the investment cost is $21x10⁹. The resulting total oil savings would be 1.6 Mbd (assuming 15% VMT growth and 10% rebound effect by 2005). Scaling to a 1 Mbd level yields $13x10⁹ as shown.

(y) DOE (1990) estimate of $17x10⁹ for 60 million M85 vehicles, plus $170 per vehicle for underlying efficiency improvement.

(z) DOE (1990) estimate for CNG vehicles, which includes some heavy trucks, plus $170/vehicle for the 23 million CNG cars and light trucks assumed by DOE (1990).

(aa) Based on the DOE (1990) $6300/vehicle estimate only, for 36 million electric vehicles (EVs). EVs may require improved aerodynamics, structure weight reduction, and improved tires to bring their underlying efficiency up to the assumed baseline level. However, it seems reasonable to assume that, for an optimized EV design, such costs could be included in the $6300/vehicle difference already assumed.

Table 3. Technologies for improving automotive efficiency that are also needed for alternatively fueled vehicles.

Technologies for improving fuel economy:	Methanol & Ethanol	Natural Gas	Electric Hybrid	Electric (grid)	Electric Fuel Cell
Engine refinements (a)	X	X	X		
Variable valve timing	X	X	X		
Two-stroke engines	X	X	X		
DI diesel engines	(c)	(c)	X		
Electronic transmission control	X	X	(d)		
Continuously variable transmission	X	X	(d)		
5-speed lockup automatic trans.	X	X	(d)		
Idle off	X	X	X		
Aerodynamic improvements	X	X	X	X	X
Weight reduction, materials	X	X	X	X	X
Weight reduction, packaging	X	X	X	X	X
Improved lubricants	X	X	X	X	X
Advanced tires	X	X	X	X	X
Accessory improvements	X	X	X	X	X
Regenerative braking (b)			X	X	X

(a) Includes fuel injection, overhead cams, roller cam followers, multi-valve cylinder heads, and engine friction reduction.

(b) Regenerative braking generally requires an electric drive train, and so it is not likely to be used in vehicles with only combustion engines.

(c) Neat alcohols have poor compression ignition characteristics, but could be used with ignition accelerating additives or glow plugs.

(d) Hybrid designs based on direct motor drives do not require transmissions, but transmissions would be used in certain "parallel" hybrid designs.

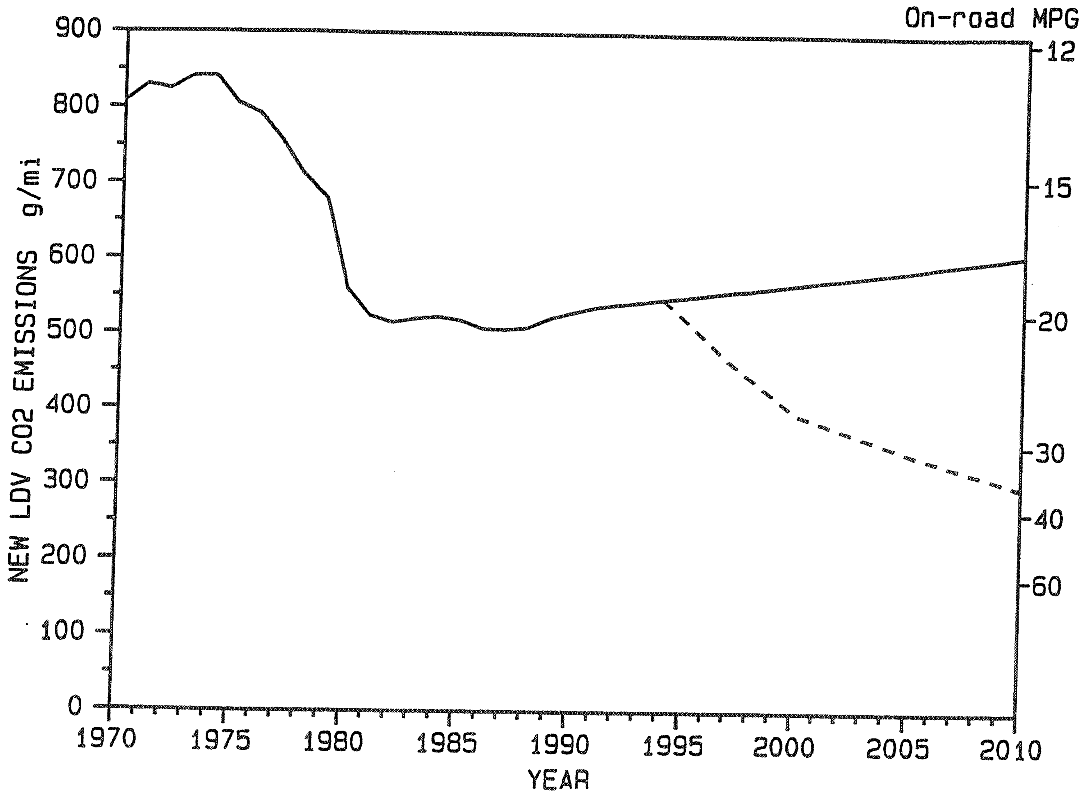
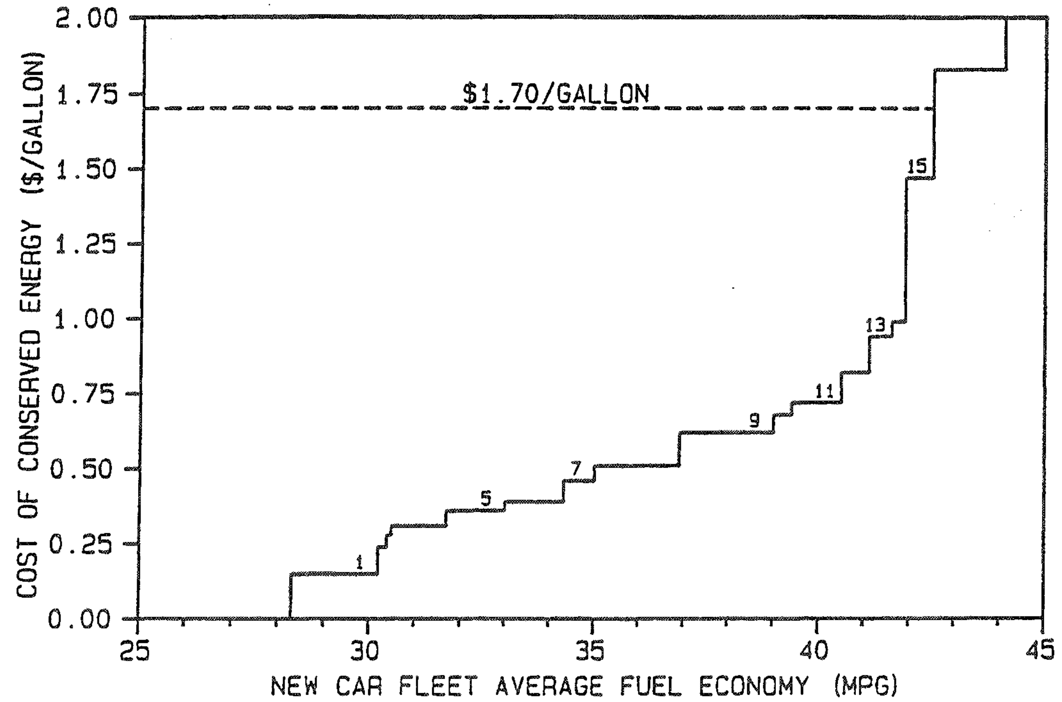


Figure 1. **Past and projected CO_2 emissions per mile from new light duty vehicles in the United States.**

Solid curve: historical emissions and projections, assuming no strengthening of CAFE standards and a continuing erosion of on-road efficiency due to increasing congestion and higher highway speeds.

Dashed curve: projection assuming new CAFE standards and other policy support as needed to achieve 40% improvement in rated fuel economy by 2001, with a continuing advance to an 80% improvement by 2010.

Figure 2. Cost of fuel economy improvement for automobiles



TECHNOLOGY LIST plus cost/benefit assumptions	Indiv. New car MPG inc. (%)	Retail Price Inc. ($)	Market Share Inc. (%)	AvgCum Consumer Cost ($)	Fleet EPA MPG	Cost of Consv. Energy ($/gal)	Cum Avg CCE ($/gal)
Baseline: 1987 new fleet					28.3		
1 Transmission mgmt	9.0	60	75	45	30.2	0.15	0.15
2 Roller cam followers	1.5	15	37	51	30.4	0.24	0.15
3 Torque conv. lockup	3.0	35	16	56	30.5	0.28	0.16
4 Overhead cam	6.0	74	69	107	31.7	0.31	0.21
5 Adv friction reduction	6.0	80	80	171	33.0	0.36	0.25
6 Intake valve control	6.0	80	75	231	34.3	0.39	0.27
7 Front wheel drive	10.0	150	23	266	35.0	0.46	0.29
8 4 valves / cylinder	6.8	105	100	371	36.9	0.51	0.33
9 Idle off	15.0	250	50	496	39.0	0.62	0.37
10 Accessory improve	1.7	29	80	519	39.4	0.68	0.38
11 Aerodynamic, Cd 0.30	4.6	80	85	587	40.5	0.72	0.40
12 Multi-point fuel inj	3.5	67	56	624	41.1	0.82	0.42
13 Continuous vary trans	4.7	100	45	669	41.6	0.94	0.43
14 Lube & tire improve	1.0	22	100	691	41.9	0.99	0.44
15 5sp auto OD trans	4.7	150	40	751	42.5	1.47	0.47
16 Weight reduction	6.6	250	85	964	44.1	1.83	0.56
17 Advanced tires	0.5	20	100	984	44.2	2.01	0.57

Based on Ross *et al.* (1991), assuming a 3% discount rate and 10 year term.