Combining Vehicle Efficiency and Renewable Biofuels to Reduce Light Vehicle Oil Use and CO_2 Emissions

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SUMMARY

The continuing dependence of the U.S. transportation sector on petroleum with its accompanying economic and environmental costs motivates an ongoing search for ways to reduce gasoline consumption by light duty vehicles, which account for over half of the sector's energy use. A technology-based strategy for reducing gasoline consumption involves raising vehicle efficiency and substituting non-petroleum fuels. This paper examines two complementary approaches for pursuing this strategy: improving car and light truck fuel economy by refining conventional vehicle designs and utilizing ethanol made from cellulosic biomass with emerging low net carbon production processes. We present scenarios projecting feasible reductions in light vehicle gasoline consumption and greenhouse gas emissions by combining these approaches and discuss the types of policies needed to achieve the projected benefits over the period spanning 2005-2025. Results are given relative to a baseline projecting light vehicle greenhouse gas (GHG) emissions growth of 30% by 2005, 54% by 2015, and 78% by 2025, compared to a 1990 level of 343 million metric tons carbon-equivalent (104 billion gallons of gasoline) per year.

We find that both efficiency improvement and renewable fuels use are constrained by time lags associated with their respective investment requirements, namely, putting more efficient vehicles into production and bringing new ethanol production capacity on line. The time periods of constraint are staggered, however. Benefits of both approaches are limited by 2005. Substantial vehicle efficiency improvements can be realized by 2015, achieving up to a 40% reduction below baseline gasoline consumption. But 2015 is just when renewable ethanol could begin having significant impacts, exceeding a 5% substitution of baseline gasoline consumption. A combined approach would yield large reductions in gasoline use by 2025. A 5%/yr rate of new vehicle efficiency improvement alone could suffice to return car and light truck GHG emissions to the 1990 level by 2015. An accelerated biofuels program could provide 10 billion gallons gasoline-equivalent of very low GHG ethanol by 2015. Combining fuel economy increases of 6%/yr (1.5 mpg/yr) up to a maximum 45 mpg with accelerated biofuels production, it would be feasible to cut U.S. light vehicle gasoline consumption by 57% from baseline growth, GHG emissions to 21% below the 1990 level, and to see a 24% renewable share of fuel use in 2025.

Because strong institutional and market forces maintain the petroleum-based system that dominates personal vehicle transportation today, concerted public policy guidance is essential for transforming the system to one less reliant on petroleum. Steady research and development efforts, particularly for biofuels production, are important. But even with supportive research, market forces are unlikely to spur widespread applications of the technology advances for higher fuel economy and a mature biofuels industry that would be needed to achieve large reductions in gasoline use and GHG emissions. A final section of the paper presents a range of policies—stronger fuel economy standards, price incentives and market creation programs for efficient vehicles, commercialization subsidies for low GHG fuels, GHG-based fuel composition standards, and shifting taxes to a carbon basis—that would help advance a technology-based strategy to cut U.S. gasoline use and GHG emissions by means of higher vehicle efficiency and increasing use of renewable biofuels.

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CONTENTS

INTRODUCTION

For over two decades the United States has grappled with its dependence on foreign oil. From 1972-1991 oil imports resulted in a $\$1.2 \times 10^{12}$ (trillion) transfer of wealth to foreign oil producers and the total economic costs to the United States were estimated to be \$4.1 trillion (Greene and Leiby 1993). Imports have been steadily climbing in both absolute volume and share of consumption, reaching 8 million barrels per day (Mbd), or 46% of U.S. consumption, in 1994 (EIA 1995b). The direct cost of these imports was \$45 billion, or 30% of the U.S. merchandise trade deficit, in 1994. The country has been grappling even longer with the air pollution impacts of gasoline consumption. More recently, a longer-term environmental impact—potential climate disruption from greenhouse gas emissions—is compounding the concerns. Transportation is the most oil dependent sector and accounts for 32% of U.S. greenhouse gas emissions (EIA 1995a). Petroleum dependence and rising emissions are problems with transportation globally as well. In 1990, highway vehicles accounted for about 24% of overall fossil carbon emissions in northern industrialized (Organization for Economic Cooperation and Development) nations and an estimated 16% worldwide (OECD 1995).

There are three approaches to reducing the fuel-related impacts of motor vehicles. One is improving end-use energy efficiency, that is, improving fuel economy. Another is shifting to alternative fuels, which might be non-petroleum derived and may have lower greenhouse gas emissions per unit of energy consumed. The third is controlling the amount of travel, including greater use of modes more energy efficient than low-occupancy vehicles. Here we focus on the effects of combining the first two approaches, namely, higher vehicle efficiency with alternative, particularly renewable, fuels. For our purposes, the term "renewable" refers to fuels and fuel production processes which, ideally, can be indefinitely replenished *and* result in zero net greenhouse gas emissions. While some fuel cycles can offer greenhouse gas emissions that are a small fraction of those from fossil fuels, it may be difficult to achieve zero net greenhouse gas emissions. We treat renewability as an ideal to be approached rather than as a status that is absolutely achieved.

To quantitatively examine the potential benefits of efficiency improvement and expanded renewable fuel use, we estimate technically feasible scenarios and judge the outcomes against hypothetical sustainability targets defined for the 1995 conference. These targets, interpreted here for light duty vehicles, are:

- Reducing on-road criteria pollutant emissions to the LEV level[1] over the full life of vehicles and to lower levels in severely polluted areas.
- Reducing oil use 10% by 2005 and further thereafter.
- Returning greenhouse gas emissions to their 1990 level by 2015.
- Increasing renewable fuels to 15% of total fuel use by 2015 and further thereafter.

Since our analysis focuses on energy supply and end-use issues, we quantitatively treat only the oil use, greenhouse gas emissions, and renewable fuel use targets. We briefly comment on criteria pollutant (carbon monoxide, hydrocarbon, and nitrogen oxide) emissions, but otherwise defer to others for analyses of that topic (see German 1996; Ross and Wenzel 1996; and Ross et al. 1995).

[1] LEV refers to the California Low Emission Vehicle standard of 3.4 g/mi of carbon monoxide, 0.075 g/mi of reactive organic gases (hydrocarbons), and 0.2 g/mi of nitrogen oxides.

We estimate the feasible petroleum displacement and greenhouse gas emissions reduction from incremental refinements in conventional, internal-combustion vehicle fuel economy combined with increasing use of renewable ethanol. This fuel can be produced from woody (cellulosic) biomass using emerging, very low net carbon emitting production technologies. As production costs drop, ethanol utilization can be readily expanded without major market barriers through low level blends of gasoline with ethanol or its derivative, ethyl tertiary butyl ether (ETBE), both of which serve as oxygenates. If a nationwide distribution network is established to serve the blends market, then subsequent use of ethanol as a neat or near-neat (E85) fuel would face reduced barriers. Use of cellulosic ethanol in an internal combustion engine vehicle is a promising strategy, especially if combined with higher vehicle efficiency. This choice of topic also reflects the authors' respective areas of expertise.

Gray and Alson (1989) identified the potential benefits of using methanol in improved internal combustion powered vehicles which could have hybrid drivetrains, considering mainly fossil feedstocks for the methanol. Williams et al. (1995) examined the potential benefits of biomass-derived methanol or hydrogen as vehicle fuels, focusing on fuel cell vehicles, which offer a long-term promise for very high efficiency, rather than improved efficiency conventional vehicles. The general point worth highlighting is that substantial reductions in petroleum consumption can be attained through efficiency improvement and alternative fuel use *in combination*. Unfortunately, with a some notable exceptions (e.g., the work just mentioned and Bleviss 1989), alternative motor fuels analyses and vehicle efficiency analyses often tend to go their separate ways.

Additional synergisms of combining higher efficiency with renewable fuel use include:

- Range and utility enhancement. Ethanol, like most other alternative fuels, has a lower volumetric energy density than gasoline, so high efficiency alleviates range and on-board vehicle space trade-offs.

- Consumer cost savings. In the near term, a transition to renewable fuels will likely involve higher fuel costs, the impacts of which are reduced with more efficient vehicles, easing consumer acceptance.

- Job creation potential. Investments in both new biofuels production technologies and efficient vehicle technologies can be made domestically, so dollars directed toward such investments would create net U.S. jobs compared to dollars spent on foreign oil.

- Lower ecological impacts. Land use and habitat impacts of biofuels production will be proportional to the scale of use, which decreases with increasing end-use efficiency.

The value of a combined efficiency and renewable fuels strategy should be well known in principle. As pointed out in *Energy for a Sustainable World,* the contribution of renewable energy supplies, including biomass, can be "quite significant—as long as overall energy demand is not too large" (Goldemberg et al. 1988, 381).

Simple arithmetic can show the combined effects of efficiency improvement and fuel substitution on gasoline displacement. The fraction of gasoline displaced increases linearly with the quantity of alternative fuel supplied (on an energy-equivalent rather than volumetric basis). But the overall level of displacement depends on vehicle energy intensity (energy use per distance of travel), which is proportional to the inverse of fuel efficiency. For example, given a 50% efficiency improvement, which cuts vehicle energy requirements by one-third, a quantity of renewable fuel equivalent to one-third of the original gasoline consumption displaces one-half of the remaining fuel requirements. Thus, the combined strategy will cut the consumption level to one-third of its original value—a two-thirds reduction overall. If energy intensity is cut in half, then half as much renewable fuel is needed to achieve a 100% gasoline displacement. This simple relationship does not account for how long it takes for new vehicle and fuel supply technologies to be put into place. Neither does it account for interactions, such as the increase in driving that might result from lower driving costs or efficiency changes (negative or positive) for vehicles using an alternative fuel relative to otherwise comparable gasoline vehicles. Nevertheless, it illustrates the basic power of combining these two approaches to address problems related to transportation petroleum use. The rest of this paper provides more detailed scenarios of how and when such benefits might be achieved.

Background

Cars and light trucks account for the largest share (58%) of U.S. transportation energy consumption and 98% of their fuel use is gasoline (including gasohol and other oxygenated blends; Davis 1994). Although gasoline is primarily a petroleum product, components of gasoline itself now represent the largest portion of "alternative" (non-petroleum) fuel use in the United States. On a volumetric basis, ethanol in gasohol accounts for 1.2% of delivered motor gasoline; natural gas liquids comprise 3.1% of refinery inputs; and other oxygenates, mainly MTBE, comprise another 1.1% (EIA 1994, 1995c). Thus, while it is difficult to allocate shares of various refinery inputs to particular outputs such as gasoline, over 5% of U.S. gasoline consumption is already non-petroleum based. DOE (1995a) estimates that a 10% displacement of petroleum in light duty vehicles is feasible by 2000, based mainly on greater use of non-petroleum refinery inputs and without market-induced sales of alternatively fueled vehicles. Nevertheless, there are limits to how much alternative fuel can be introduced through the conventional gasoline supply system.

Choosing an alternative fuel involves numerous considerations and the subject has been extensively studied (see Sperling 1989, DOE 1990 et seq., and EIA 1994, among others). DeLuchi (1991) ranked vehicle and fuel choices according to their likely full fuel cycle greenhouse gas (GHG) emissions impacts relative to those of today's gasoline-powered vehicles. Table 1 summarizes results from an updated version of that analysis (Delucchi 1994). The effect of the primary energy resource dominates that of the particular energy carrier (fuel) or drivetrain. Fuels derived from solar energy, even indirectly through biomass, will have substantially lower GHG emissions than those derived from fossil sources, no matter what particular carrier or vehicle design is used.

The cellulosic ethanol fuel cycle analyzed by DeLuchi (1991) involves wood feedstocks and current conversion technologies; it would have GHG emissions roughly 2% of those of gasoline. The sensitivity of emissions to technological maturity is explored by Lynd (1996). Cellulosic ethanol also offers commercially attractive near-term applications, the potential for large research-driven cost reductions, and compatibility with existing distribution infrastructure greater than that of electricity or gaseous fuels. Predicting market acceptance for alternative fuel faces many uncertainties. Issues include the future price of gasoline and gasoline additives, regulations on fuel composition and performance, as well as the magnitude, sustained direction, and effectiveness of research and development (R&D).

Lynd et al. (1995) addressed the question: "What are the likely features and cost of a cellulosic ethanol technology at a level of maturity comparable to that of a petroleum refinery?" Considering improvements in biological conversion and pre-treatment but not other process steps, they projected the selling price for ethanol produced from a dedicated energy crop using mature technology to be $0.50 per gallon (1994$). This ethanol price corresponds to $0.69-$0.76 per gallon of gasoline energy equivalent (gge), with the higher price for low-ethanol blends and lower price for dedicated ethanol vehicles, reflecting a 10% engine efficiency benefit. The Lynd (1996) also provides further details on process and feedstock parameters supporting this price estimate.

Turning back to vehicle efficiency, relatively little attention has been paid to analyzing energy end-use in alternatively fueled internal combustion vehicles (ICVs). DeLuchi (1991, Table 11) did show sensitivities relative to baseline vehicle fuel economy using scaling relationships. He estimated alternatively fueled vehicle efficiencies relative to a baseline gasoline vehicle, drawing mainly on vehicle and component test data and reviewing estimates about the likely evolution of new technologies (batteries, traction motors and controllers, etc.) for which little commercial experience exists. Aside from relatively minor, fuel-specific refinements (e.g., higher compression ratios), no attention was paid to specific engineering opportunities for improving ICV efficiency. For light duty vehicles, DeLuchi's base case was a spark-ignition ICV rated at 30 mpg running on reformulated gasoline. This efficiency level is but 7% higher than the 28 mpg average of today's passenger cars. In contrast, published assessments of potential conventional ICV efficiency improvements range up to 55 mpg (the "Risk Level II" estimate of EEA 1991), or just about double today's new car average.

Methodology

Our approach combines scenarios of vehicle efficiency improvement and biofuel supply expansion, defined on the basis of likely technical feasibility, to project energy use and environmental impacts. Reductions in gasoline use are estimated relative to a baseline scenario that assumes no new vehicle efficiency increases over the period examined and little overall use of alternative fuels, particularly fuels derived from non-fossil sources. We compare our projections to the sustainability targets identified above. Later we suggest the policies needed to realize such scenarios.

A stock turnover model is used to compute changes in efficiency as improved vehicles replace older ones on the road and to project total light vehicle energy requirements (through 2030). We allocate this energy demand among gasoline (derived from petroleum or other non-biofuel feedstocks), gasohol, and neat or near-neat ethanol fuel. Alternative fuels other than ethanol are not treated explicitly, so the results here reflect only changes due to efficiency improvement and use of cellulosic ethanol. At initial stages of biofuel availability, all biofuel is assumed to be used in gasohol or as an oxygenate. Such use expands until 10% by volume of the gasoline market is reached (contemporary gasoline vehicles are already certified to run on up to 10% ethanol). Beyond an overall 10% level, additional ethanol production is consumed in dedicated alcohol vehicles. Our model includes efficiency adjustment factors to represent the effects of blending (zero efficiency change assumed) and dedicated alcohol use (10% higher efficiency assumed) relative to gasoline vehicle energy efficiency.

Vehicle stock energy intensity and fuel use apportioning calculations are done on an energy intensity basis, using projected fuel consumption rates (Btu/mile) and vehicle miles of travel (VMT, mi/yr) to compute fuel energy requirements (Btu/yr). Volumetric fuel requirements (gal/yr) are calculated using standard fuel energy content values. Estimating direct, first-order oil savings is then straightforward. Greenhouse gas emissions are calculated using full fuel cycle emissions factors (including effects of methane, nitrous oxide, and other gases as well as CO_2) for gasoline and biofuel, expressed in terms of CO_2-equivalence per unit of energy delivered to the vehicle (e.g., gCO_2/Btu). A full modeling of fuel market impacts is beyond the scope of this analysis. The U.S. Department of Energy's study on petroleum displacement (the "502b Study," DOE 1995a) shows generally how market effects would reduce the net savings from pursuing alternative fuels strategies, since lower transportation demand for oil would depress oil prices, stimulating demand for oil in other sectors. Thus, net oil savings and GHG reductions are likely to be lower than the first-order estimates made here.

Although GHG emissions are largely proportional to the vehicle fuel consumption rate (inverse fuel economy), the relationship is complicated by upstream emissions and non-CO_2 tailpipe emissions. For example, some tailpipe pollutants (including greenhouse gases) have emissions rates that are highly uncertain because of the poor relationship between real-world emissions and those estimated from certification testing. Nevertheless, the largest part of gasoline vehicle GHG emissions is CO_2, including the carbon in the fuel itself plus the petroleum fuels used in extraction, transportation, refining, and distribution. Fuel carbon content alone accounts for 74% of the full fuel cycle GHG emissions associated with the use of reformulated gasoline (DeLuchi 1991, Table 7). Moreover, emissions of CO_2 and other greenhouse gases from the upstream processes are largely proportional to the amount of fuel delivered. All of these major CO_2 sources plus average values of the trace gases are accounted for in the full fuel cycle GHG emissions factors estimated by DeLuchi, which are adopted here.

TECHNOLOGY ASSESSMENTS

Since our objective is to analyze the combined effects of vehicle efficiency and renewable ethanol, we start by reviewing previous analyses of these respective technological approaches.

Vehicle Efficiency

Estimating the degree of vehicle efficiency improvement possible using conventional technologies that can be phased into the fleet has been a controversial subject. Recent studies of the near-term (roughly 10-year) potential have identified new car fleet averages ranging from 28 mpg (no improvement over recent levels) to 51 mpg (OTA 1991; NRC 1992; DeCicco and Ross 1993). Key assessments include federally sponsored studies based on work by Energy and Environmental Analysis (EEA), such as Greene and Duleep (1993), and studies by auto industry consultants, such as SRI (1991). The National Research Council study (NRC 1992) drew mainly on the EEA and industry work. Disagreements are rooted in differing assumptions about the benefits, costs, applicability, and marketability of the technologies considered. EEA (1991) estimated higher levels given a longer time horizon, but did not provide cost estimates. These EEA estimates for 2010 were given at three "risk" levels: (1) 45 mpg, (2) 55 mpg, and (3) 74 mpg. EEA's Level 3 estimate goes beyond conventional gasoline vehicle technologies, requiring use of either hybrid drivetrains permitting energy storage or advanced, turbocharged diesels. Even higher potential fuel economy levels have been identified as research targets (PNGV 1994; McCarthy 1995), through the use of more advanced technologies (Duleep 1996), and as possibilities achievable through radical redesign (Lovins 1995). This paper draws on DeCicco and Ross (1993), who re-analyzed information considered by the EEA and NRC studies and supplemented it with additional information in order to provide up-to-date estimates of potential automobile efficiency improvements based only on refinements to conventional gasoline-powered designs.

Incremental improvements in car and light truck fuel economy can be obtained through more widespread use of technologies already in production plus the introduction of newer refinements of conventional technologies. DeCicco and Ross (1993) projected the potential for fleetwide fuel economy improvement, building on the status of the new car fleet in a base year (1990) for which average vehicle size and performance are maintained. The analysis was corroborated by applying an engineering model to analyze improvements for a typical mid-size passenger car and by comparisons to the 1992 Honda Civic VX, which demonstrated a 56%-85% fuel economy improvement over a DX model of similar size and performance. An examination of auto industry product cycles, development times, and rates of technology change yielded an estimate that 8-11 years are needed to achieve the efficiency improvements identified.

The conventional vehicle efficiency analysis was developed at three levels of technical certainty, reflecting the uncertainties surrounding new applications of technology:

- Level 1 technologies are already in production in at least one mass market vehicle worldwide and face no technical risk in that they are fully demonstrated and available.
- Level 2 technologies are ready for commercialization and face no technical constraints which might inhibit their use in production vehicles, but entail some risk because of limited production experience.
- Level 3 technologies are in advanced stages of development but may face some technical constraints (such as emissions control considerations) before widespread application.

In this context, technical risk is interpreted as the risk that a technology cannot be put into widespread use within a given time horizon at acceptably low cost (full production scale average cost). For options better characterized by degree of design refinement, such as aerodynamic improvements or weight reduction, the certainty levels are interpreted as being successively less conservative regarding the degree of improvement. Table 2 summarizes estimates of the potential for improving conventional vehicle fuel economy using a combination of load reduction measures and drivetrain improvements. A list of individual technologies, their efficiency benefits, and their estimated costs is given by DeCicco and Ross (1993).

Accurately estimating the cost of improving fuel economy is difficult because of limitations in publicly available data and costing methodologies. The Table 2 estimates were based on a review of previously published technology-specific information to determine an estimated average added cost per car, including only technologies that are cost effective in terms of fuel saved over the life of a car. These estimates represent the incremental retail costs of improved, mature technology averaged over a total period of production. A cost-effectiveness index is the Cost of Conserved Energy (CCE), derived from the ratio of incremental technology cost to fuel savings over the life of an improved vehicle. It is an index of cost-effectiveness from the perspective of all consumers (all owners over the car lifetime rather than only the new car buyer). A level of technically feasible fuel economy is cost-effective if its marginal CCE is less than the future cost of gasoline expected over the life of the improved vehicles. As summarized in Table 2, DeCicco and Ross (1993) estimated cost-effective new car fleet averages of 39 mpg, 45 mpg, and 51 mpg (41%, 60%, and 82% higher than the 1990 average), at certainty Levels 1, 2, and 3, respectively. The average cost of achieving Level 3 is $820 per car. The marginal CCE is $1.62/gal, based on discounting the fuel savings at a 5% real rate over a 12-year vehicle life.

The DeCicco and Ross (1993) analysis was done only for passenger cars, not for light trucks, which now account for 40% of new light vehicle sales. NRC (1992) also estimated potential light truck fuel economy increases proportionate to those for cars. Greene and Duleep (1993) estimated potential light truck fuel economy increases slightly less than proportionate to those for cars. At least 80% of light truck usage is strictly for personal transportation (Bureau of the Census 1990). Light truck fuel economy has been more leniently regulated than that of cars; the main sources of inefficiency are the same as in cars; and the new light truck fleet has lower utilization rates for efficient technologies. Therefore, in projecting potential future overall efficiency potential, we assume that light truck fuel economy can be increased proportionately to that of cars at similar incremental cost.

Using the above assumptions and the recent overall (car plus light truck) new fleet average of 25 mpg as a base yields potential new light duty average fuel economies of 32 mpg, 40 mpg, and 45 mpg, corresponding to certainly Levels 1, 2, and 3, respectively. To examine the role of efficiency improvement, we develop scenarios of fuel economy increase starting in 1998 and continuing linearly up to a maximum of 45 mpg (new fleet average for both cars and light trucks). At 45 mpg, incremental improvements are assumed to be exhausted and new fleet fuel economy is the held flat for the rest of the period (through 2030).

Renewable Ethanol

While ethanol production from crops such as corn is an established industry in the United States, this product is neither economic at current oil prices nor renewable according to the working definition adopted here. However, a growing literature points to the potential for a competitive industry producing renewable ethanol from cellulosic biomass (Lynd et al. 1991; DOE 1993). Further analysis regarding the potential emergence of such a cellulosic ethanol industry is presented by Lynd (1996) and in greater detail by Lynd et al. (1995). In general, the rate at which ethanol might enter the fuels market depends on the relative prices of ethanol and gasoline as well as on the rate at which a biomass ethanol industry could expand given favorable economics. These are considered separately below.

Relative Price. Primary factors influencing the future cost of producing ethanol from cellulosic biomass are: feedstock cost, plant scale, level of technological maturity, and cost of capital. Production volume (annual gallons produced nationwide) is a key determinant of three of these factors:

- the cost of biomass feedstocks, because higher cost feedstocks will be needed at higher production volumes;
- plant scale, because larger plants can be expected as the technology matures and as production shifts from wastes to energy crops; and
- the cost of capital, because the technical and business risk will decrease as the ethanol market expands.

Production volume depends on time, ethanol price, gasoline price, R&D, and policies that impact the relative price of gasoline and ethanol. R&D is a key determinant of future decreases in the cost of producing ethanol from energy crops, and future decreases in the cost of conversion technology. Factors influencing the impact of R&D are its level of effort (determined by policy), the extent of success, and time.

Corn ethanol now sells for about $1.20/gal ($1.80/gge) and current technology cellulosic production would probably sell for a similar price (DOE 1993). Our analysis assumes that the cost of producing ethanol progressively declines to $0.50/gal, the likely production cost for mature technology estimated by Lynd et al. (1995). ("Production cost" here refers to a price based on recovery of operating costs and return on capital investments; the actual selling price would be dictated by market conditions.) We represent the pace of progress by two cases summarized in Table 3. Case A involves a continuation of the current R&D effort; Case B involves an accelerated effort. We assume that the research-driven cost decreases are underway and continue until the mature technology level is reached.

In Case A the production cost (independent of feedstock and at constant scale) is assumed to decrease by 3% per year, so that the ethanol price drops to $0.88/gal by 2005 and reaches the $0.50/gal level by 2025. In Case B, accelerated R&D results in a mature biomass ethanol conversion technology being available for incorporation into production facilities in 2005. The industry-average production cost then decreases over 2005-2010 as average plant size increases, new technology displaces older less efficient plant technology (via both new construction and retrofit), and the cost of energy crops decreases (also driven by R&D). Thus, in Case B, we assume a very rapid price drop of 6%/yr, so that the $0.50/gal level is reached by 2010. Case B achieves mature, "advanced technology" production status roughly 15 years sooner than Case A. These prices represent plant sales; the $0.50 per gallon of ethanol corresponds to $0.76/gge (lower heating value equivalence, without adjusting for the efficiency boost available if used in a dedicated vehicle; properly comparable to the wholesale price of gasoline, which averaged $0.60/gal in 1995). Assuming a $0.14/gal distribution cost, similar to that for today's gasoline, brings the pre-tax end-user cost to $0.90/gge (vs. $0.74/gal for gasoline in 1995). If used in dedicated (near-neat) ethanol vehicles, the 10% efficiency benefit would lower the effective cost to $0.83/gge.

Replacing gasoline with alternative fuels involves transition barriers and costs arising from immature technology, supplier and consumer unfamiliarity, new operational complexities and training needs, higher costs of capital, less realization of economies of scale, lack of available infrastructure, and other factors (see, e.g., Singh and Mintz 1996). Cellulosic ethanol has a number of attributes serving to reduce such transition costs relative to most other alternative fuels. Low-cost waste feedstocks may be utilized during early stages of market expansion. The gasohol and oxygenates markets provide a higher base of established distribution infrastructure compared to other alternative fuels. Also, the costs of incrementally expanding this infrastructure would be predictable and relatively low. While we expect that a transition to ethanol could be less costly than that for most other alternative fuels, further analysis is needed to estimate the transition costs for scenarios such as those outlined here.

Expansion rate. Even given strong economic or regulatory incentives, other factors would still constrain the rate at which cellulosic ethanol production capacity could be expanded. Such constraints include: the expansion rate of feedstock development, the availability of capital, the availability of expertise (e.g. to design and build plants), and limits in fuel distribution and vehicle infrastructure. A detailed study of likely ethanol market penetration for scenarios of cellulosic ethanol becoming cost competitive with gasoline on a energy content basis is a worthy subject for future analysis.

Approximately 1 billion gallons of corn ethanol capacity were developed between the late 1970s and late 1980s. A higher growth rate should be possible for cellulosic ethanol; such an expansion can build on the foundation provided by an existing fuel ethanol industry, whereas this was not the case for corn ethanol. By 2005, therefore, we use an annual capacity estimate of 2 billion gallons for cellulosic ethanol under Case B (accelerated R&D) and adopt a lower estimate of 0.7 billion gallons for Case A (current R&D).

Accelerated R&D is expected to permit commercial plants to incorporate technology offering large R&D-driven cost reductions by 2005. The resulting lower ethanol selling price would then allow substantially higher production capacity growth. We assume a 22% compounded rate of growth from 2 billion gallons to 15 billion gallons of annual ethanol capacity over a 10-year period from 2005 to 2015. This 7.5-fold increase over a decade would correspond to tripling the number of plants together with a 2.5-fold increase in the average capacity of new plants. This compounding growth cannot continue indefinitely and so for capacities above 15 billion gallons, we assume a constant expansion rate of 2.5 billion gallons per year, resulting in 40 billion gallons of annual capacity by 2025 in Case B.

For Case A, we assume a compound capacity growth rate of 10% per year after 2005, consistent with fewer R&D driven improvements than for Case B. In defining policies to accelerate cellulosic ethanol production, we specify R&D expenditures of approximately $800 million over an 8-year period (discussed later). It would take a considerable amount of time for an R&D effort of this magnitude to be mounted based on the ethanol sales in Case A. For example, assuming an average ethanol selling price of $1.00/gal, a profit margin of 10%, and a 20% re-investment into R&D (each one of these three values is probably high) beginning in 2005, it would take about 12 years before the cumulative R&D investment reached $500 million. The 10% growth rate is assumed until 2010; then the growth rate increases by 1% per year, up to 22% in 2022. As with the Case B, annual capacity increases are capped at 2.5 billion gallons. Table 3 summarizes the projected availability of ethanol derived from cellulosic conversion technologies for the two cases outlined here.

In terms of greenhouse gas emissions, cellulosic ethanol offers very substantial reductions over current corn ethanol production. DeLuchi (1991) estimates full fuel cycle greenhouse gas emissions for corn ethanol of 3.1 kgC/gal (kg of carbon-mass equivalent per gallon) but only 0.16 kgC/gal for cellulosic ethanol. Our scenarios assume that corn ethanol is replaced as soon as cellulosic conversion technology becomes available, since the latter will be much more cost competitive. Thus, the lower emission factor is realized by 2010 in Case A and by 2005 in Case B.

Combining advanced ethanol production technology with electric power cogeneration promises further net economic and environmental benefits beyond those identified here. For example, combined cycle gas turbines would utilize biomass feedstock residues to generate process heat and electricity plus substantial net electricity for export to the grid. The resulting plant could simultaneously displace petroleum motor fuels and fossil-based electricity, providing exceptionally low GHG performance overall. Our analysis does not assume the higher total process efficiency attainable through such an approach, which would yield even better economics and a lower (potentially negative in the context of this one sector) greenhouse gas emissions factor than assumed here.

Technical Compatibility and Criteria Emissions Issues

The vehicle efficiency technologies considered here are compatible with dedicated ethanol fuel use, although not all have been demonstrated with this fuel. Achieving more reliable cold-start performance had been considered a technical concern for use of ethanol in conventional vehicles. However, this problem is not a fundamental barrier but rather something that can be worked out given adequate engineering. Cold-start problems have already been solved for E85 in some vehicle applications, but not yet for E100 (Lynd et al. 1991). Extensive ethanol vehicle development work has been done for the Brazilian market, where neat ethanol has long seen widespread use as a motor fuel. However, the Brazilian experience does not apply very well to the current and future U.S. situation because of the much more stringent emissions standards in the United States.

As is generally the case with respect to criteria pollutant emissions, data on real-world, in-use emissions over vehicle lifetimes are woefully limited, a knowledge gap that is only recently beginning to be remedied. As noted earlier, other chapters in this volume discuss real-world emissions from ICVs. Standardized emissions tests of ethanol vehicles have produced mixed results. As for oxygenates generally, ethanol is expected to help reduce carbon monoxide emissions. However, gasohol can have increased volatility, potentially aggravating evaporative emissions; such volatility problems do not occur if ethanol is converted to ETBE for use as an oxygenate (EIA 1994). In any case, many of the most important issues in real-world emissions control, such as off-cycle and malfunction emissions, are likely to be similar for any hydrocarbon fuel. Qualitatively speaking, it is unlikely that a given level of ICV emissions control would be more difficult to achieve with ethanol than with gasoline, and in dedicated vehicles, ethanol may facilitate emissions control.

Although our focus is on conventional ICVs, ethanol could be readily used in hybrid vehicles and may also be usable in fuel cell vehicles, either of which may offer large criteria pollution emissions control benefits as well as greater energy efficiency. Reckoning from the point of delivery to a fuel cell drivetrain, pure hydrogen offers the highest efficiency; methanol has the next highest; and ethanol would have a somewhat lower efficiency because it requires use of a partial oxidation convertor (Williams et al. 1995). However, fuel distribution and storage advantages, offering lower transition barriers, may counterbalance ethanol's efficiency penalty for fuel cell vehicles. Thus, expanded use of renewable ethanol is unlikely to be a dead-end strategy and it could augment the efficiency-driven energy consumption and emissions reductions associated with leap-forward technologies of the future. Questions of ethanol's criteria emissions impacts and its potential applicability in fuel cell vehicles—including research on more efficient reforming methods—are worthy topics for future study.

ANALYSIS

Our analysis covers the period from 1995 through 2030, with particular attention to results for 2005 and 2015. Motor vehicle energy consumption is determined by VMT and vehicle energy efficiency; greenhouse gas emissions are determined by energy consumption and the full fuel cycle

GHG emissions associated with the fuels used. We first establish a baseline projection of the growth of light vehicle fuel use and greenhouse gas emissions based on assumptions about VMT growth and vehicle efficiency in the absence of policy change or dramatic technology breakthroughs entering the market. Light duty vehicles are taken to include passenger cars and 2-axle, 4-tire light trucks as reported in the Federal Highway Administration's *Highway Statistics* (FHWA 1992). We use a stock turnover model to account for vehicle replacement and retirement, assuming that vehicle sales and the size of the stock grow in proportion to VMT (equivalent to assuming constant average vehicle lifetime and usage rate). Our stock model does not explicitly provide vehicle counts, although these could be derived; further details on the vehicle stock modeling are given in DeCicco (1995).

Light duty VMT was 1.989×10^{12} mi/yr in 1990 (FHWA 1992). We forecast VMT growth using the model of Greene et al. (1995) and an assumed 1%/yr real fuel price increase over 1995-2030, essentially an extension of the EIA (1995a) reference fuel price projection. The result is quite similar to a VMT forecast developed for "Car Talk."[2] Figure 1 illustrates this baseline VMT forecast, showing the steady growth in travel demand that must be offset by improved technology absent drastic increases in the price of driving. Baseline new light vehicle fuel economy is assumed to be constant at 25 mpg (EPA unadjusted composite city/highway average for cars and light trucks), which has been the average within ± 0.9 mpg from 1982-1994 (Murrell et al. 1993). A frozen efficiency assumption is consistent with low gasoline price growth and CAFE standards being currently binding and not raised further. Given market imperfections, this assumption does not contradict the estimates of the potential for cost-effective efficiency improvements given in Table 2. Past achievements of policy-driven energy efficiency improvements at relatively low cost refute the notion of a well-functioning market for vehicle efficiency. Such evidence for market failure has been observed in markets for a number of energy-using products (Levine et al. 1994).

The model's 1990 levels are fuel energy consumption of 13 Quads (10^{15} Btu) or 104.4×10^9 gge (billion gallons of gasoline equivalent) and greenhouse gas emissions of 343 MTc (million metric tonnes of carbon equivalent; all energy and volume levels are annual values). The fuel consumption includes 1.1×10^9 gal (0.73×10^9 gge) of ethanol from corn, which is blended with some of the gasoline to provide gasohol, and 103.7×10^9 gal of gasoline from petroleum and other feedstocks. We assume the baseline value of corn ethanol to be constant at 1.1×10^9 gal, the 1992 level reported by EIA (1994, Table 14). In our analysis for blends, each gallon of ethanol available for blending displaces 0.66 gallons of gasoline, based on the ratio of lower heating values as given by EIA (1994). With a 10% volumetric blend (typical of gasohol) the volumetric fuel economy of a vehicle is 3.4% lower than when operating on pure gasoline.

Although ethanol in principle can be blended up to 15% without detracting from gasoline vehicle performance (other than the lower volumetric fuel economy), we hold the blend level to 10% in our analysis. Thus, we first apply cellulosic ethanol to back out corn ethanol in blends; once the baseline volume of ethanol for gasohol is reached, remaining ethanol production is used to expand the low-level blend pool, either in the form of gasohol or as ETBE oxygenated gasoline. Finally, once a 10% level

[2] "Car Talk" was a colloquial name for the "Policy Dialog Advisory Committee to Assist in the Development of Measures to Significantly Reduce Greenhouse Gas Emissions from Personal Motor Vehicles," which met from September 1994 to September 1995; see Resolve (1995) and Majority Report (1995).

is reached nationwide, additional capacity is assumed to go to dedicated or flexible fuel vehicles. If ethanol use in low-level blends is considered to be a too limited approach for criteria pollution control, an earlier transition to dedicated fuel vehicles could be pursued.

Our analysis does not attempt to explicitly treat alternative or replacement fuels (including oxygenates) other than ethanol. Other analyses (such as DOE 1995a and EIA 1995a) indicate that, while some increases in alternative fuels will occur in the absence of new policies, the effects on overall gasoline use and greenhouse gas emissions are relatively minor, especially compared to the substantial effects needed for the sustainability targets addressed in this paper. Although our baseline is not fully accurate because it excludes impacts from these other fuels, it suffices for our more limited objective of examining the effects of only two factors, efficiency improvement and ethanol substitution, and serves to adequately elucidate their interaction without the complications of other alternative fuels.

The model, basically an accounting framework, constructed for this analysis, allows us to vary assumptions regarding policy-driven vehicle efficiency improvements and ethanol production capacity expansions. New fleet fuel economy improvements are assumed to start in 1998 and continue linearly at various assumed rates up to 6%/yr. Over a 10 year period, highest rate would imply a 60% improvement in new car and light truck fuel economy, reaching Level 2 as given in Table 2. We continue improvements up to a maximum new light fleet (combined car and light truck) fuel economy level of 45 mpg. This vehicle efficiency cap corresponds to an 80% improvement over the 1990 new fleet average, reflecting Level 3 as given in Table 2. Thus, vehicle efficiency improvements are constrained to those achievable through incremental refinements of existing ICV technology. Renewable fuel use is analyzed using the two cases given in Table 3, for lower and higher (accelerated) rates of capacity expansion for cellulosic ethanol production. Renewable fuels utilization is thus limited according to projected fuel supply capacity constraints.

We did not estimate the numbers of alcohol vehicles needed, although vehicle numbers could be inferred from the fuel use projections. DOE (1995a) applied vehicle choice modeling to examine how varying assumptions about the availability and costs of alternative fuels and vehicles would effect market equilibrium, leaving aside transition issues. The study found that vehicles fueled by alcohols and liquified petroleum gases (LPG) could sustain significant market shares (15% - 20% of the light duty stock) in 2010, with the fuel mix being quite sensitive to the relative pricing of fuels. Ethanol would have a significant share if its current tax subsidy were retained. Since, as shown below, our projected fuel use shares by 2010 are lower than those estimated by DOE (1995a), we infer that, given competitive fuel pricing, vehicle choice considerations would not limit ethanol use at the production capacity-constrained levels examined here.

Results

Our model's baseline forecast is for light vehicle fuel use rising to 136×10^9 gge by 2005 and 161×10^9 gge by 2015, increases of 30% and 54%, respectively, over the 1990 level. Baseline GHG emissions show a similar rise, to 444 MTc by 2005 and 526 MTc by 2015, compared to a 1990 level of 343 MTc. Figure 2 shows the results of attempting to control GHG emissions using efficiency improvement only. Shown is the percent change in light vehicle GHG emissions from the 1990 level as a function of the new fleet fuel economy improvement rate, with the dashed curve for 2005 and the solid curve for 2015. Fuel efficiency improvement is modeled linearly, indicated as a percentage of the 1990 average (25 mpg); for example, a 4%/yr improvement implies a 1 mpg/yr increase in the new fleet average, starting in 1998. Fuel economy levels are capped at 45 mpg, which, for example, would be reached in 20 years (by 2018) with a 4%/yr improvement rate. Stock turnover limitations constrain the reductions achievable within one decade. At the rates considered here (up to 6%/yr), efficiency improvement alone cannot return light vehicle GHG emissions to the 1990 level by 2005. As shown in Figure 2, however, another ten years makes a big difference, since about 90% of the vehicle stock is replaced over the course of a decade. Thus, an efficiency improvement rate of roughly 5%/yr will suffice to return light vehicle GHG emissions to the 1990 level by 2015.

Combining vehicle efficiency improvement with renewable ethanol use increases the gasoline savings and GHG reductions. Table 4 summarizes scenarios using three rates of fuel economy improvement (0%/yr, 3%/yr, and 6%/yr) with lower (Case A) and higher (Case B) ethanol production levels. Figure 3 plots the resulting changes in year 2015 GHG emissions compared to the 1990 level as a function of efficiency improvement rate. The two curves correspond to the lower and higher (accelerated) biofuels production cases. In 2015, Case A is little different than the efficiency-only case of Figure 2, since only 2.7 billion gallons of ethanol (1.1% of 2015 baseline fuel consumption on an energy-equivalent basis) are available. The accelerated biofuels case provides 15 billion gallons of ethanol by 2015, or 6% of the baseline energy requirement, allowing return of emissions to the 1990 level with an efficiency improvement rate of just under 4%/yr. In other words, the difference between the lower and higher renewable ethanol cases shaves roughly 1%/yr from the vehicle efficiency improvement rate needed for a 2015 GHG emissions return target.

Table 4 shows that projected 2005 gasoline use is 9% lower than the baseline for the 0.75 mpg/yr (3%/yr) efficiency increase rate for either ethanol production case. Meeting a targeted 10% reduction in light vehicle oil use by 2005 would require a slightly faster efficiency improvement, since even the higher ethanol production case only contributes $1.3x10^9$ gge toward the requisite $13.6x10^9$ gge reduction. (This assessment ignores the role of other alternative fuels, including non-petroleum inputs used in gasoline production.) Improving new fleet fuel economy 6%/yr would cut 15% from 2005 light vehicle gasoline use compared to the baseline projection of $136x10^9$ gge.

Figure 4 shows the share of 2015 light vehicle fuel consumption that can be met by renewable ethanol for the lower and higher production cases. The renewable share increases as a function of the underlying vehicle efficiency improvement. Year 2015 production capacity is small in Case A, amounting to less than 2% of light vehicle energy needs even with a 6%/yr efficiency improvement. In Case B, the $15x10^9$ gallons ($9.6x10^9$ gge) of ethanol available by 2015 imply a 6% renewable share even without efficiency improvement. With the 6%/yr new fleet efficiency improvement working to reduce the overall fuel energy requirements, the Case B provides just over 9% of the market—a significant portion, but still shy of a 15% renewable share in 2015.

Just as lags in stock turnover make a big difference in what efficiency improvement can accomplish by 2005 vs. 2015, constraints in ethanol capacity expansion make a big difference in the impacts of fuel substitution between 2015 and later years. Figure 5 shows, for the scenario of lower ethanol production (Case A) and no vehicle efficiency increase, shares of the overall U.S. light vehicle fuel use for: ethanol in blends (gasohol or oxygenate), renewable ethanol (low-carbon emissions cellulosic as opposed to corn-based), and ethanol use in dedicated vehicles. The same items are shown in Figure 6 for the scenario of higher ethanol production (Case B) and a 6%/yr vehicle efficiency increase (note that the vertical scale in Figure 6 is three times that in Figure 5). In Figure 5, the renewable energy share is only 1.1% by 2015, when cellulosic ethanol capacity expansion is just beginning to take off, and a 10% share is not reached until 2030. The fuels market is not saturated with blended ethanol until nearly 2025, after which dedicated vehicles would be needed to utilize the ethanol production capacity. In contrast, Figure 6 shows how rapid efficiency improvement coupled with accelerated biofuel production capacity expansion would yield a renewable share of nearly 10% by 2015 and a substantial share in later years, nearly 30% by 2030. Even in this more ambitious scenario, the renewable share is just starting to rapidly climb in 2010 and widespread use of dedicated vehicles only begins in 2013. The blended ethanol share falls once dedicated vehicles come into play, since the gasoline fuel market in which blends can be used is then shrinking.

Our principal results are summarized in Figure 7, which shows projected baseline light vehicle GHG emissions plus an ethanol-only scenario (Case B), an efficiency-only scenario (6%/yr improvement), and a scenario combining these two approaches. Note that our scenarios do not allow for a progressive decline in gasoline consumption or GHG emissions, since vehicle efficiency improvement is capped at 45 mpg. Ongoing efficiency improvements, most likely requiring advanced technology, would be able to sustain a declining trend, especially if combined with an increasing availability of renewable fuel. Results are also, of course, sensitive to VMT growth and the success of efforts to control it.

In any scenario, once the assumed 10% volumetric blending limit is reached, use in flexible fuel or dedicated vehicles would have to rapidly rise in order to keep pace with growth in renewable ethanol production capacity expansion. Although flexible fuel vehicles are one way to ease the transition, addressing issues confronting greatly expanded use of ethanol in high-level blends is beyond the scope of our work. Our analysis shows that ethanol production capacity is the binding constraint for the next two decades or longer (depending on the degree of vehicle efficiency improvement). Subsequently, expansion could be constrained by vehicle and fuel availability barriers to non-gasoline fuel use. However, by that time, an extensive nationwide bulk ethanol distribution network would have been put into place for serving the blended fuel market. Thus, one major barrier would be greatly reduced, easing the way toward dedicated ethanol fuel use.

A Comment on Costs

Although a full cost-benefit analysis is beyond the scope of this paper, the technology assessments reviewed above do provide cost estimates for improving fuel economy and supplying cellulosic ethanol. These estimates can be compared the gasoline price plus its indirect and externality costs associated with energy security and greenhouse gas emissions.

For reference, the current pre-tax price of gasoline is \$0.74/gal, including roughly \$0.14/gal for distribution and marketing costs (EIA 1995b). OTA (1994, 127-128) summarized estimates of the economic and military costs associated with oil imports, which range \$0.26 - \$0.63 per gallon (updated to 1995\$). OTA's estimates of the greenhouse gas emissions externality ranged \$0.03 - \$0.32 per gallon. The upper end of this range essentially matches that implied by a carbon tax of \$92 per ton (carbon mass basis), which was the value adopted by UCS et al. (1991) as appropriate for a cross-sectoral U.S. carbon emissions control scenario. This value falls in the middle of the very wide range of estimates based on carbon sequestration through forest plantings, which Pace University (1990, 165-185) reviewed as ranging from \$2/ton for projects in Central America up to \$200/ton for forest plantations in North America. Including the mid-range value of \$0.44/gal for oil import economic and military costs plus \$0.32/gal for greenhouse gas emissions yields \$0.76/gal as an externality for gasoline. Thus, including these social costs essentially doubles the current pre-tax price of gasoline in the United States, bringing the current avoidable cost to $1.50/gal. EIA (1995a) gives a 2010 reference case gasoline price projection of $1.46/gal (1995$) including taxes; deducting the $0.44 of taxes implies an underlying price of $1.02/gal. Including social costs of $0.76/gal brings the estimated 2010 avoidable cost of gasoline to $1.78/gal (1995$), providing a point of comparison for the costs of fuel conservation and renewable fuel supply.

The cost estimates for vehicle efficiency and cellulosic ethanol supply, summarized in Tables 2 and 3, respectively, provide some of the inputs that would be needed for a cost-benefit analysis. Basic cost comparisons do suggest the likely cost-effectiveness of the scenarios presented here. The estimated marginal cost of energy saved through vehicle efficiency improvements is $1.62/gal. The estimated end-user cost of mature cellulosic ethanol is $0.83 - $0.90 per gallon of gasoline energy equivalent (including distribution costs). Both of these compare favorably to a projected 2010 gasoline cost of $1.78/gal including energy security and global warming externalities. Note that our renewable ethanol cost is premised on research-driven technology advances; by contrast, our vehicle efficiency cost assumes use of technology that is already largely available. Since efficiency R&D initiatives like PNGV are underway, we expect a drop in the future cost of achieving a given level of efficiency improvement. On the other hand, the current level of R&D commitment to cellulosic ethanol appears low compared to the potential of this technology; timely realization its benefits would require an expanded development program, such as that premised by Case B.

POLICY NEEDS

Strong institutional and market forces sustain the petroleum-fueled internal combustion engine design of current personal transportation vehicles in the United States and throughout the world. Strong public policy guidance is most likely necessary to bring about changes such as those envisioned here, as for any changes toward a system substantially less resource consumptive and environmentally damaging.

Whatever approach is taken to addressing transportation energy issues, strong, coordinated, and sustained public and private research and development programs are important. The Partnership for a New Generation of Vehicles (PNGV) has recently provided greater prominence to R&D for advancing fuel economy. The PNGV Goal 3 of tripling fuel economy transcends the incremental confines of the vehicle efficiency assessments on which we based our analysis. However, PNGV Goal 1, advancing competitive manufacturing capabilities, and Goal 2, developing technologies useful for near-term efficiency and emissions control improvements, support, at least in principle, efficiency improvements of the timing and magnitude illustrated here. On the fuels side, current R&D efforts are smaller and less concerted than those of the PNGV. An expanded R&D effort targeting low GHG fuels is, therefore, part of a strategy needed to realize scenarios such as those illustrated here. Cellulosic ethanol is a promising option for a low GHG renewable fuel; other promising options include biomass derived methanol and hydrogen (particularly suitable for fuel cell vehicles). A strong R&D program should address all promising options.

R&D is intended to make new technology available; the extent to which new technology is adopted depends on the market, which currently does not value reductions in either greenhouse gas or transportation petroleum use. Policies that cause the market to value these and other "intangible" or external benefits are likely to be necessary to motivate significant adoption of new technologies in ways that achieve such benefits. Moreover, the "technology pull" exerted by a policy-guided market can greatly enhance the success of R&D. Consistent with this perspective, we do not expect the scenarios sketched here to be realized without supportive market intervention.

For advancing vehicle efficiency, fuel economy standards have demonstrated their effectiveness (including substantial net economic savings) and they are likely to be effective again. Indeed, fuel economy standards drew improved conventional vehicle technologies—products of private sector R&D—into the market, contributing to the 47% improvement in on-road car and light truck efficiency achieved between 1975 and 1993 (DOE 1995). The general historical experience with standards is most encouraging, for motor vehicles as well as other energy-using products (Geller and Nadel 1994). Ramping standards up to levels identified as being technically feasible and cost effective would reliably yield vehicle efficiency improvements along with predictable gasoline savings and GHG emissions reductions. DeCicco (1995) analyzed a range of fuel economy standards scenarios similar to those presented here. Various complicating factors exist, but none were found to substantially detract from the effectiveness of standards. The main obstacles are political, given the waxing influence of anti-regulatory rhetoric and continuing auto industry objections to stronger standards. The "Car Talk" experience suggests unwavering auto industry opposition to efficiency standards, even with reforming of the regulatory structure and packaging with market-oriented policies (any of which also face serious political obstacles).

Policies complementary to standards include fees and rebates ("feebates") linked to vehicle efficiency, market creation programs for efficient vehicles, and higher gasoline taxes (which can be designed with offsets to reduce other taxes). These mechanisms can be structured to motivate both vehicle efficiency and renewable fuels use. For example, full fuel cycle greenhouse gas emissions per mile could be used as a basis for vehicle-oriented policies. Higher gasoline taxes could be carbon-based. Any of these approaches can be designed for revenue neutrality, so as to avoid a net increase in taxation. Nevertheless, given the limited experience with market mechanisms and the large uncertainties in response to pricing changes, only fuel economy standards, or equivalent approaches such as a regulatory cap on greenhouse gas emissions, are likely to provide the certainty needed to reach particular sustainability targets such as those examined here. A set of policies that would work together to induce vehicle efficiency improvements includes:

- Strengthening fuel economy standards, proportionately for cars and light trucks, to target a 6%/yr increase in new fleet average MPG.
- Extending the gas guzzler tax to a system of largely revenue-neutral fees and rebates covering all light duty vehicles. Such "feebates" could be enacted at both federal and state levels.
- Establishing a voluntary market encouragement and market creation programs for efficient vehicles, involving coordinated purchase commitments of "best-in-class" vehicles in the near term and "next-generation" vehicles when they approach commercial viability.

A similar policy package for improving vehicle efficiency is among the recommendations of the "Car Talk" Majority Report (1995), which both authors endorsed.

Higher fuel prices can also help motivate vehicle efficiency improvement. However, in the U.S. context, the leverage offered by fuel pricing is far too weak to achieve the efficiency levels identified here without a drastic change in fiscal policies (DeCicco and Gordon 1995). On the other hand, fuel pricing policies would be valuable for orienting the market and can provide important leverage over fuel choices. As suggested below, modest fuel taxation changes linked to appropriate renewable fuel subsidies could help swing the market toward low-carbon fuels.

As noted earlier, the fuel economy horizon for refinements of conventional ICVs probably falls short of doubled fuel economy. The 6%/yr increase scenario would reach this horizon in about 16 years. While beyond the scope of this paper, ongoing efficiency improvements would be possible if R&D efforts such as the PNGV pay off. The success of R&D efforts, in terms of providing marketable technologies, is likely to be enhanced through steady regulatory and incentive pressure for higher fuel economy along with market creation programs designed to overcome barriers to newer, leap-forward technologies.

Price is the main barrier to expansion of cellulosic ethanol production capacity. Policy remedies include targeting R&D to decrease the cost of production and providing subsidies or incentives to make ethanol cost-competitive with gasoline. The "Car Talk" Committee considered policies to accelerate deployment of cellulosic ethanol among the alternative fuel options for reducing light vehicle GHG emissions. The Majority Report (1995) recommended supporting liquid biofuels R&D, particularly for cellulosic ethanol, by ramping federal biofuels R&D support from the recent level of $25 million per year up to $100 million per year by 1999 and sustaining that level through 2005.

The existing federal ethanol subsidy is $0.54/gal, or $0.82/gal on a gasoline energy-equivalency basis, and currently costs about $650 million per year. This annual figure is very nearly equal to the cumulative increase in R&D effort suggested here. Successful R&D would lower the cost of producing ethanol, motivating current producers to adopt improved processes and begin using cellulosic feedstocks (which could initially be provided from waste materials). Nevertheless, if ethanol is valued at its energy content and gasoline prices rise no higher than the EIA 1995a projections (roughly a 1%/yr increase), even our accelerated R&D scenario (Case B in Table 3) indicates that a subsidy would be needed through 2018 (unless a carbon tax, GHG-based fuel composition standards, or similar measures were instituted to make the market better account for environmental costs). The Majority Report (1995) outlined a low-GHG fuels incentive program having the following elements:

- Subsidies proportional to a fuel's full cycle GHG emission factor, based on plant-by-plant auditing, available to all liquid and gaseous fuels; the subsidies (which could be either direct payments or tax waivers) would be capped at $180/MTc (carbon equivalent) reduction compared to gasoline.

- Straight-line phase-out over 2000-2010 of the current ethanol subsidy, which would be capped at $650 million per year.

- An overall cap such that the combined expenditures for the fuel GHG reduction subsidy and the current ethanol tax incentive do not exceed $1.1 billion; this subsidy pool would be phased out over 2015-2025.

This proposed low GHG subsidy is applicable to any fuel, in contrast to the current tax incentive, which subsidizes ethanol no matter how it is produced and irrespective of its embodied fossil fuel use and GHG emissions. Subsidies would need to discriminate fuel deliveries according to their "pedigree" with respect to full fuel cycle GHG emissions. Production plant audits according to fossil energy inputs and other emissions could be part of a fuel producer's environmental accounting requirements. Such rating is feasible because of the generally large scale of production; for example, 75% of current ethanol production comes from four plants. Corn ethanol producers should not be permitted to double-dip during periods of overlapping subsidies for ethanol itself and low-GHG fuels generally. Producers could obtain the larger, but not both, of the non-greenhouse linked ethanol subsidy and the greenhouse-linked subsidy in any given year.

We have not attempted an economic analysis to estimate a market response to the proposed renewable fuels incentives. For vehicle efficiency, stronger fuel economy standards would, if established, have a very high likelihood of yielding the targeted efficiency levels. In contrast, the impact of incentives is much more difficult to predict, particularly when there is little empirical evidence to guide the analysis. (A similar situation is encountered when trying the predict the vehicle efficiency response to incentives alone.) Also, unlike fuel economy increases which rely mainly on technology already in production, achievement of the ethanol capacity levels requires R&D progress plus commercialization of new production processes, which are inherently difficult to predict. Thus, while we cannot claim a quantitative link, we believe that a concerted and sustained program of R&D plus low-GHG fuel incentives would plausibly support achievement of the renewable fuels utilization levels presented here.

This renewable fuel policy package is designed as a commercialization incentive to help build new motor fuels industries which, it is hoped, would eventually become economically competitive with petroleum refining even when only considering private market costs. While incentives such as these are needed to begin moving markets toward renewable fuels, they may not suffice for an ongoing and substantial transition of the U.S. transportation energy system. The long-term establishment of a low-carbon, more environmentally benign fuels will probably require additional policy guidance. For example, achieving the substantial oil savings suggested by the combined efficiency and renewable fuels scenarios identified here would depress the world oil price, particularly if the new technologies also diffused to global markets. While clearly an economic boon to oil importing countries like the United States, a lower oil price would make it even more difficult for new technologies to compete.

Such countervailing market forces, as well as general market barriers and imperfections, could be overcome by broad-based interventions including fuel composition standards and a shift toward environmental taxation. Specifying such policies is beyond the scope of this paper; however, we can indicate possibilities. Motor fuels have long been subject to composition standards, from privately developed quality standards to environmentally motivated standards such as the phase-out of lead and more recent reformulation standards addressing volatility, oxygenation, and lower sulfur content. This approach can be extended to standards specifying a maximum full fuel cycle GHG factor (e.g., in grams of carbon-equivalent per joule of energy content), which could be implemented as an average cap on the national motor fuel pool. As in the case of vehicle efficiency, a regulatory approach has the advantage of predictability for achieving environmental goals; it would have the disadvantage of incrementalism, since standard-setting is a conservative process in practice. Environmental taxation could entail carbon-based fuels taxes, as well as more general externalities taxes (such as national security costs associated with oil imports). Since even a relatively small transportation fuel tax involves substantial sums on a nationwide basis, environmental taxation is best pursued as part of a tax shifting or tax reform strategy. Further analyses of all such options are needed.

CONCLUSION

Examining scenarios that combine vehicle efficiency improvements with increased use of a renewable fuel, specifically ethanol produced from woody biomass, shows that likely near- to medium-term national goals for oil displacement and greenhouse gas emissions reductions are achievable without resorting to radical changes in vehicle technology. While targets of 10% oil savings by 2005 and returning light vehicle sector greenhouse gas emissions to their 1990 level by 2015 are in reach, a target of 15% renewable share by 2015 was not reached in any of the scenarios we presented. Criteria pollution emissions effects were not analyzed, however, we believe that expanded ethanol use would not prevent achievement of lower vehicle emissions targets. Although a cost-benefit analysis was not performed, the estimated current costs of fuel economy improvement and projected future costs of cellulosic ethanol supply appear to compare favorably to the cost of gasoline when considering environmental and energy import externalities. The limitations of our analysis in both of these areas—criteria emissions and economic analysis—point out subjects of needed future investigation.

Technology-based improvements in vehicle efficiency and increases in renewable fuel use are complementary strategies. Higher vehicle efficiency can partially alleviate some of the concerns associated with cellulosic ethanol use by reducing the land area needed for a given gasoline displacement and by reducing the overall pollutant emissions during fuel production, distribution, and use. Both efficiency improvement and renewable fuels use are constrained by time lags associated with their investment requirements, namely, putting efficient vehicle technologies into production and onto the road, and bringing new ethanol production capacity on line. The time periods of their respective constraints are staggered, however. Benefits of both approaches are limited by 2005. Substantial vehicle efficiency improvements can be realized by 2015, but 2015 is just when ethanol capacity expansions would start to have significant impacts. The picture changes dramatically between 2015 and 2025. By 2025, an accelerated ethanol capacity program could provide up to 26×10^9 gge (3.3 Quads) of very low GHG fuel; fuel economy increases of 6% (1.5 mpg) per year (up to a maximum 45 mpg) would cut fuel use by 41% (9.5 Quads) relative to the baseline. Combining the two approaches, U.S. light vehicle gasoline consumption in 2025 would be cut by 57% from baseline growth, GHG emissions would be 21% below the 1990 level, and the renewable fuels share would be 24%.

In terms of moving toward a more sustainable light duty vehicle transportation system in the United States, we identified technology improvements that would suffice to meet near-term goals of reduced petroleum consumption and greenhouse gas emissions. However, market forces alone are unlikely to spur sufficient applications of these technology advances—for higher fuel economy and a mature biofuels industry—even if supportive R&D efforts are pursued. A range of public policies, including sustained R&D, particularly for biofuels, plus a set of regulatory and incentive mechanisms for advancing both vehicle efficiency and renewable fuels in the marketplace, are needed to achieve progress such as that envisioned in the scenarios presented here.

Table 1. Relative Greenhouse Gas Emissions Ranking of Automotive Fuel Options by Type of Drivetrain, Energy Carrier, and Energy Resource

VEHICLE & FUEL DIST.			PRIMARY ENERGY RESOURCE					
Drivetrain	Energy Carrier	(a)	Solar	Biomass	Nuclear	Nat.Gas	Oil	Coal
Battery	Electricity	1	*					
Combustion	Ethanol	2		*				
Fuel Cell	Hydrogen	2	*					
Combustion	Hydrogen	6	*					
Battery	Electricity	7			*			
Fuel Cell	Hydrides	15			*			
Fuel Cell	Methanol	15		*				
Combustion	Methanol	25		*				
Combustion	Methane	29		*				
Combustion	Hydrides	33			*			
Fuel Cell	Methanol	56				*		
Battery	Electricity	66				*		
Combustion	LPG	74				*	*	
Combustion	Nat.Gas	76				*		
Combustion	Hydrogen	82			*			
Combustion	Diesel	85					*	
Combustion	Methanol	95				*		
Battery	Electricity (marginal mix)	98			*	*	*	*
Combustion	Gasoline	100					*	
Fuel Cell	Methanol	102						*
Battery	Electricity	107						*
Combustion	Ethanol (from corn)	112		*				*
Combustion	Methanol	167						*

(a) Relative full fuel cycle greenhouse gas emissions (gasoline internal combustion = 100).

Source: Adapted from a similar table in Majority Report (1995, 34), based on a presentation by Mark Delucchi to the "Car Talk" Committee.

Table 2. Potential New Car Fleet Average Fuel Economy and Cost Estimates

Technology Certainty:	Level 1	Level 2	Level 3
Achievable fuel economy (MPG)	39	45	51
Improvement over 1990 new fleet	41%	60%	82%
Average added cost per car (1995$)	560	690	820
Average Cost of Conserved Energy ($/gal)	0.51	0.50	0.50
Marginal Cost of Conserved Energy ($/gal)	1.46	1.48	1.62

Source: DeCicco & Ross (1993), updated to 1995$ using 4% cumulative inflation.

Fuel economy values are the EPA composite 55% city, 45% highway unadjusted test ratings.

Cost-effectiveness estimates are based on a 5% real discount rate and 12-year, 10,000 miles/year vehicle life.

Table 3. Projected Price and Production Quantity for Cases of Cellulosic Ethanol Industry Expansion.

Price in 1995$/gal, Quantity in 10^9 gallons/year

Year	Case A (current R&D) Price	Case A (current R&D) Quantity	Case B (accelerated R&D) Price	Case B (accelerated R&D) Quantity
2005	0.88	0.7	0.65	2.0
2010	0.76	1.3	0.50	4.2
2015	0.65	2.7	0.50	15
2020	0.56	7.4	0.50	27
2025	0.50	19	0.50	40
2030	0.50	31	0.50	53

For price, starting from a current value of $1.20/gal, Case A assumes a 3%/yr decline and Case B assumes a 6%/yr decline until reaching the $0.50/gal estimate of Lynd et al. (1995). For quantities, projections were made as described in the text.

Table 4. **Summary Results from Scenarios of Fuel Economy Improvement and Increased Use of Cellulosic Ethanol in U.S. Light Duty Vehicles**

Baseline Projections	**1990**	**2005**	**2015**	**2025**
Gasoline consumption (10^9 gal/yr)	104	136	161	186
GHG emissions (MTc/yr)	343	444	526	608

Projected changes in gasoline use, greenhouse gas emissions, and renewable fuel share:

(A) Lower Ethanol Capacity Case	**2005**	**2015**	**2025**
Ethanol production (10^9gal/yr)	*0.7*	*2.7*	*19*
No fuel economy improvement			
Gasoline consumption vs. baseline	-0.3%	-1.1%	-6.8%
GHG emissions vs. 1990 level	30%	52%	66%
Renewable fuel share	0.3%	1.1%	6.8%
3% (0.75 mpg) per year improvement			
Gasoline consumption vs. baseline	-9%	-26%	-44%
GHG emissions vs. 1990 level	19%	14%	0%
Renewable fuel share	0.4%	1.5%	10.7%
6% (1.5 mpg) per year improvement			
Gasoline consumption vs. baseline	-15%	-38%	-48%
GHG emissions vs. 1990 level	11%	-5%	-7%
Renewable fuel share	0.4%	1.8%	11.4%

(B) Higher Ethanol Capacity Case	**2005**	**2015**	**2025**
Ethanol production (10^9gal/yr)	*2*	*15*	*40*
No fuel economy improvement			
Gasoline consumption vs. baseline	-1.0%	-6.0%	-15.2%
GHG emissions vs. 1990 level	30%	45%	53%
Renewable fuel share	1%	6%	14%
3% (0.75 mpg) per year improvement			
Gasoline consumption vs. baseline	-9%	-31%	-52%
GHG emissions vs. 1990 level	19%	7%	-14%
Renewable fuel share	1%	8%	23%
6% (1.5 mpg) per year improvement			
Gasoline consumption vs. baseline	-15%	-43%	-57%
GHG emissions vs. 1990 level	11%	-12%	-21%
Renewable fuel share	1%	9%	24%

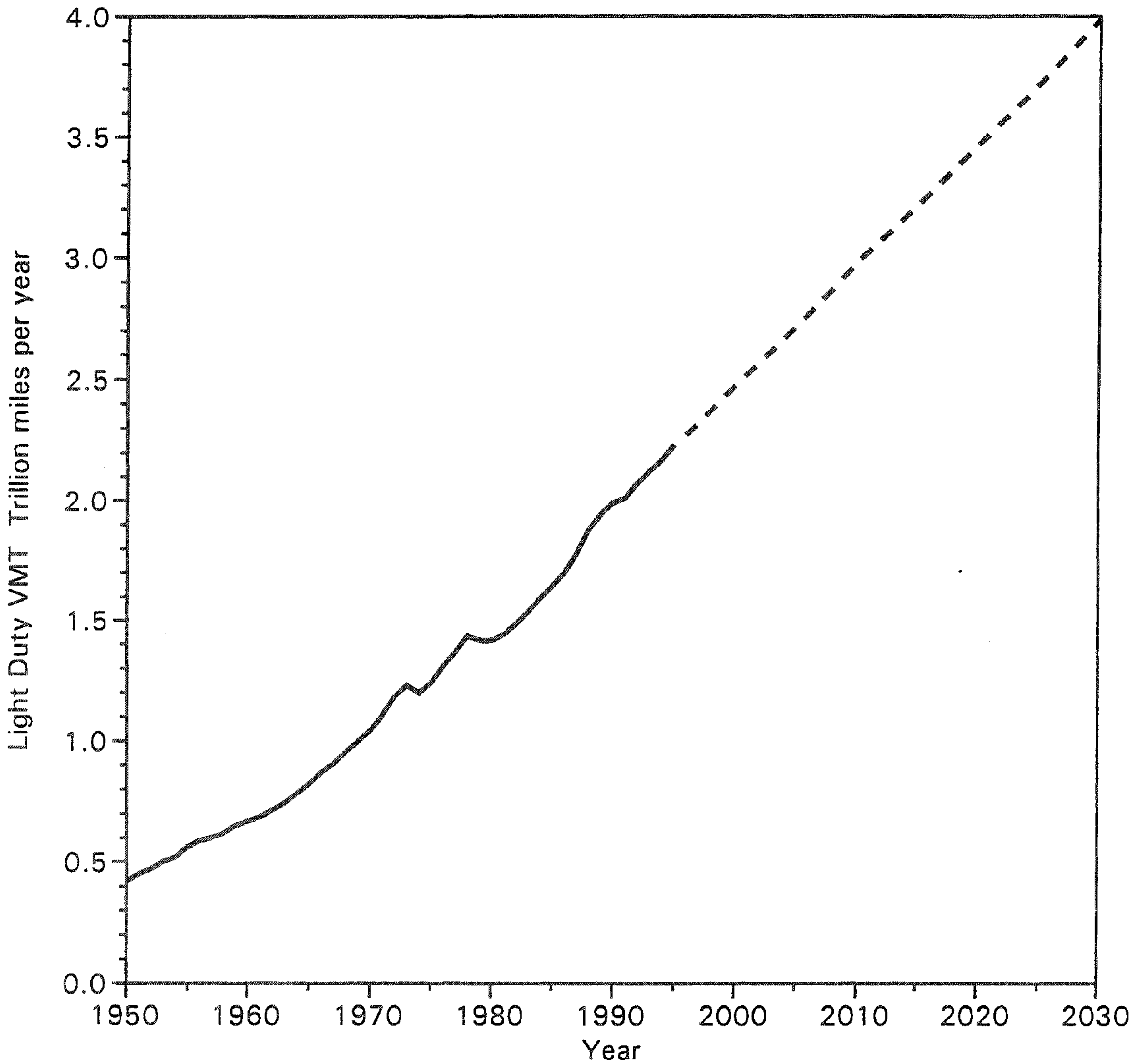

Figure 1. **Past and Projected Light Duty Vehicle Miles of Travel (VMT) in the United States, 1950-2030.**

Source: Through 1995, from FHWA (1992, 1995); 1996-2030, authors' projections as described in the text.

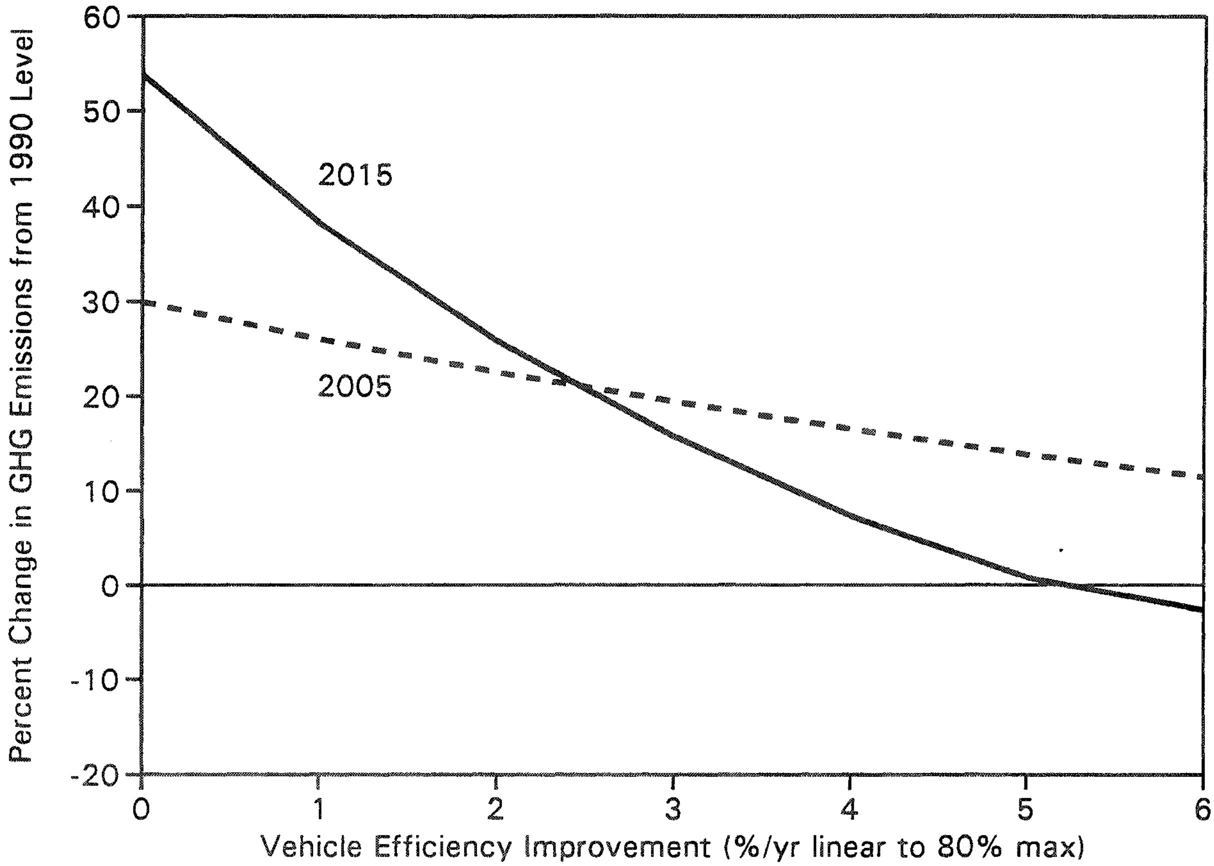

Figure 2. **Projected Change from 1990 Level of Light Vehicle Greenhouse Gas Emissions in 2005 and 2015 as Function of Fuel Efficiency Improvement Rate.**

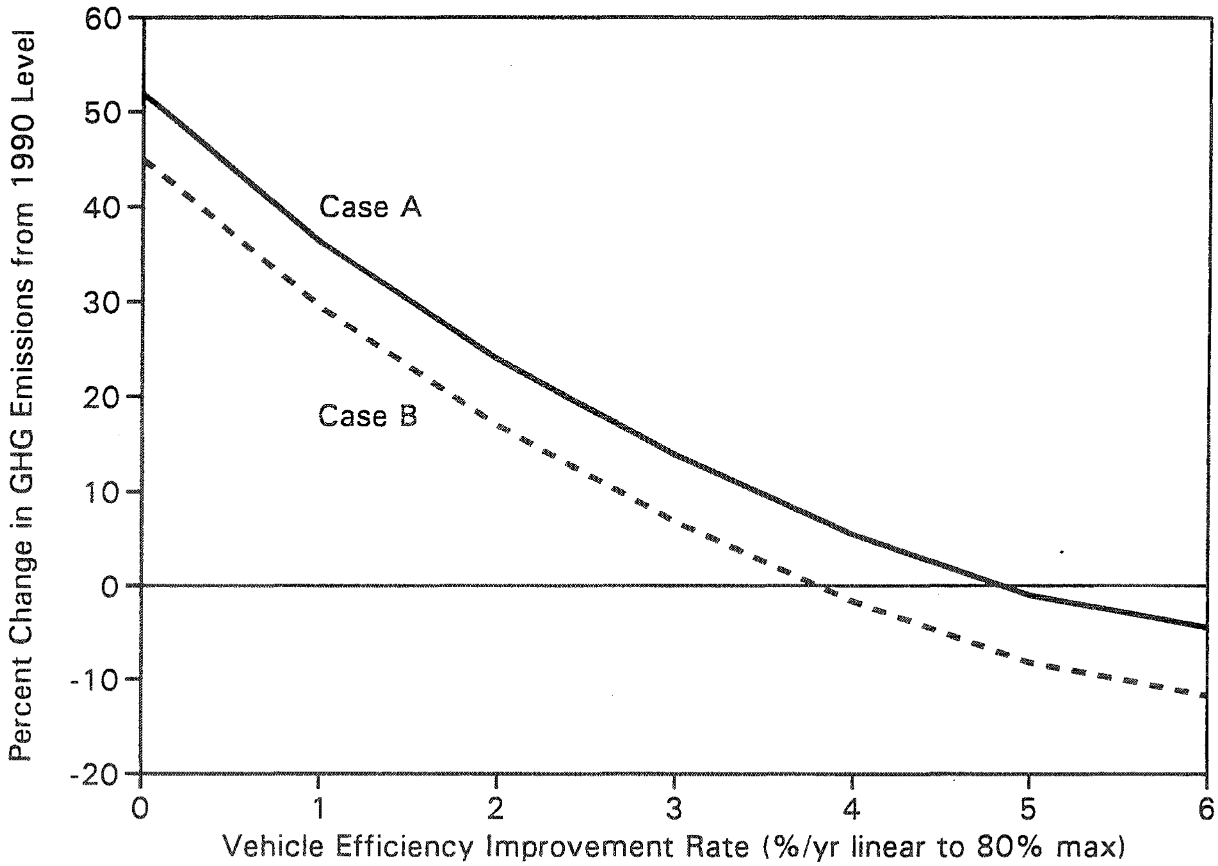

Figure 3. Projected Change from 1990 Level of Light Vehicle Greenhouse Gas Emissions in 2015 by Ethanol Production Case and Fuel Efficiency Improvement Rate.

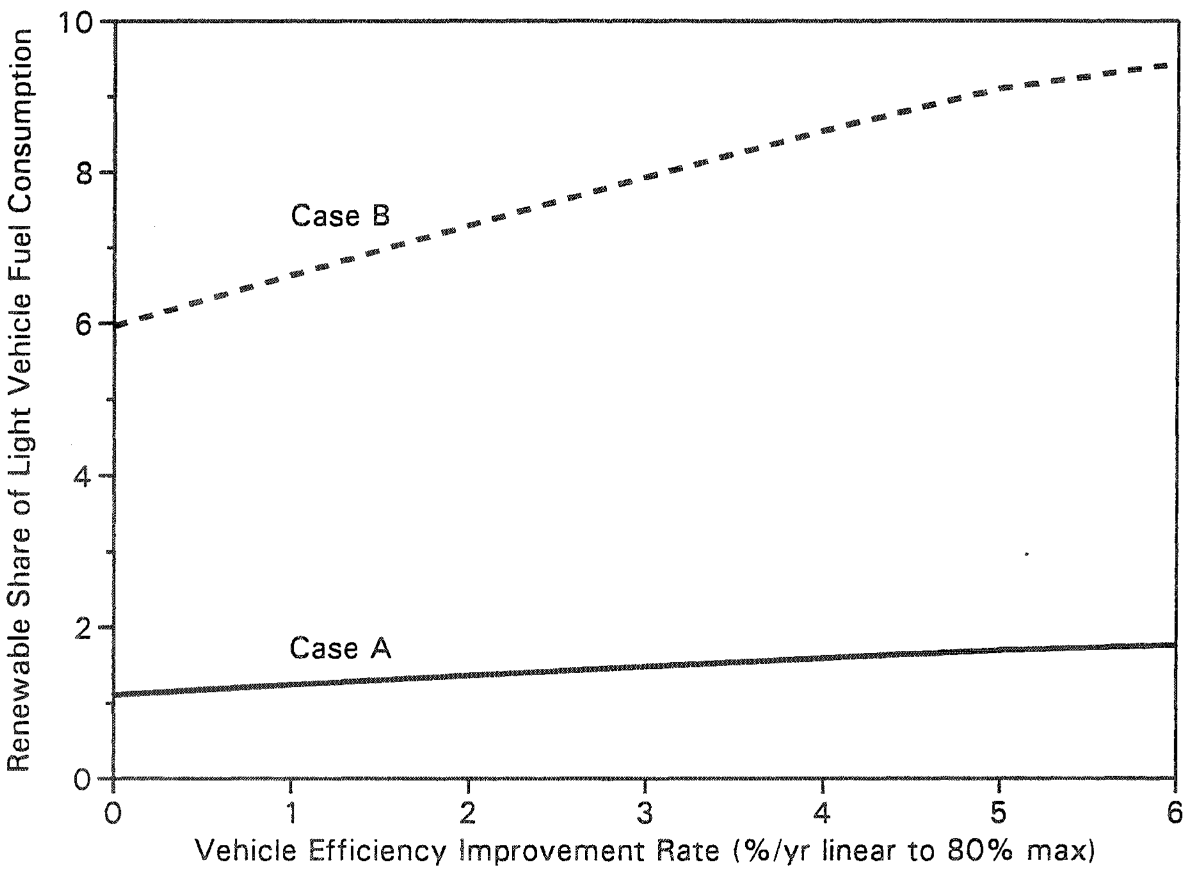

Figure 4. **Renewable Share of Light Vehicle Fuel Consumption in 2015 by Ethanol Production Case and Fuel Efficiency Improvement Rate.**

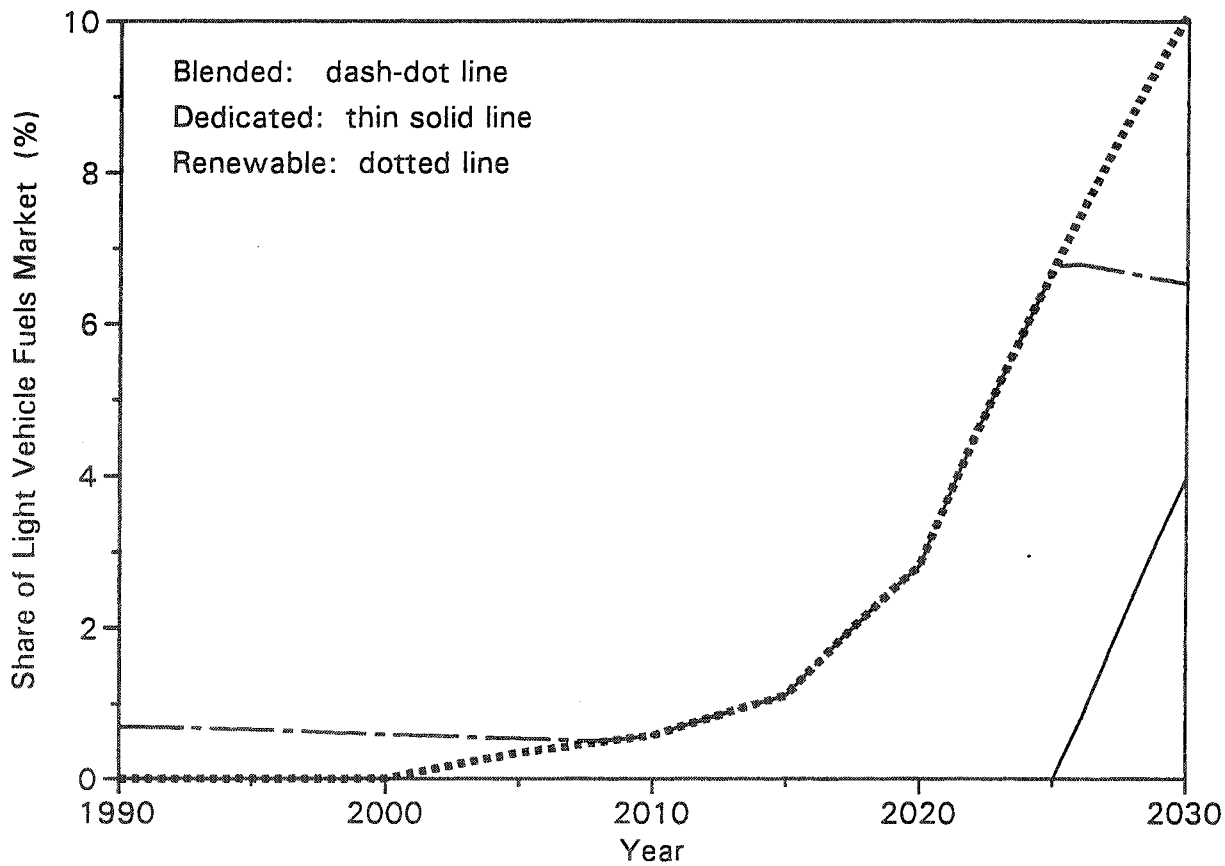

Figure 5. Future Shares of Light Vehicle Fuel Market for Case A Cellulosic Ethanol Production and No Fuel Economy Improvement.

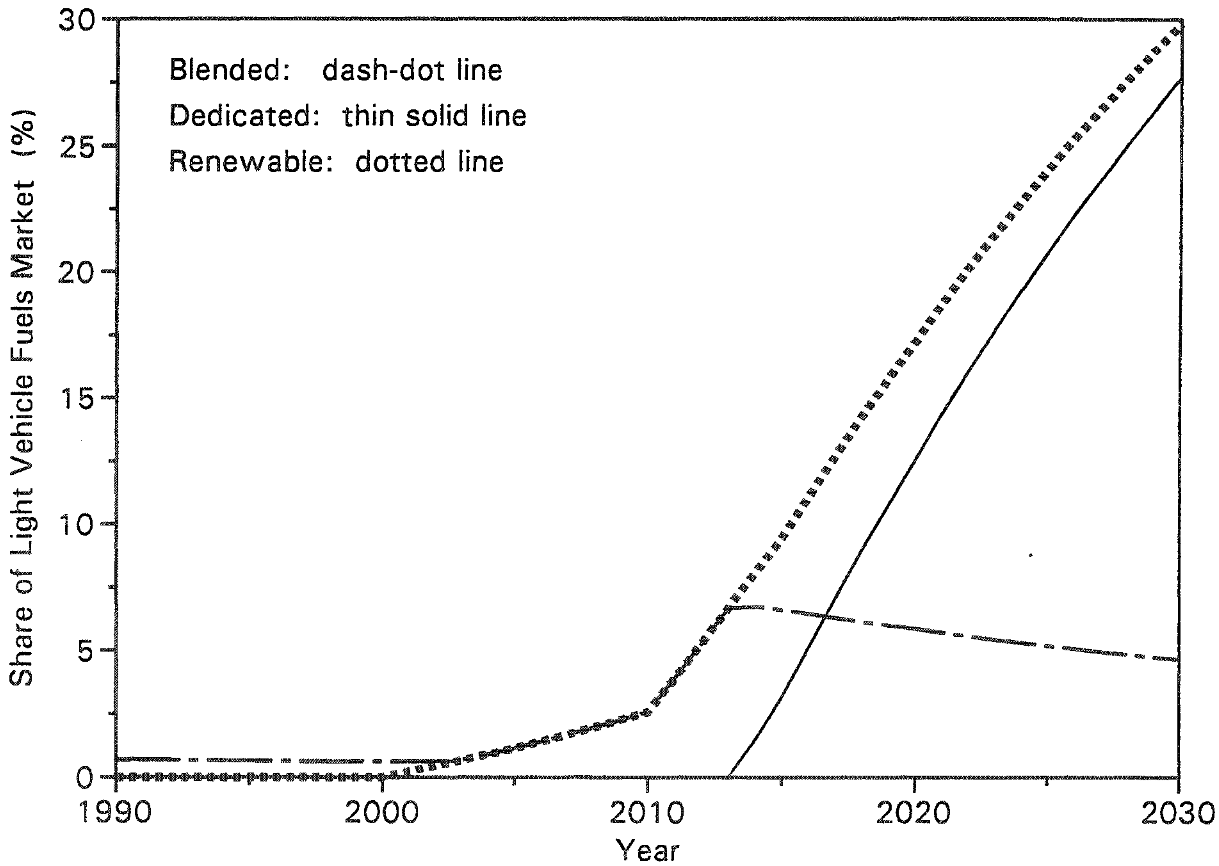

Figure 6. **Future Shares of Light Vehicle Fuel Market for Case B Cellulosic Ethanol Production and 6%/year Fuel Economy Improvement.**

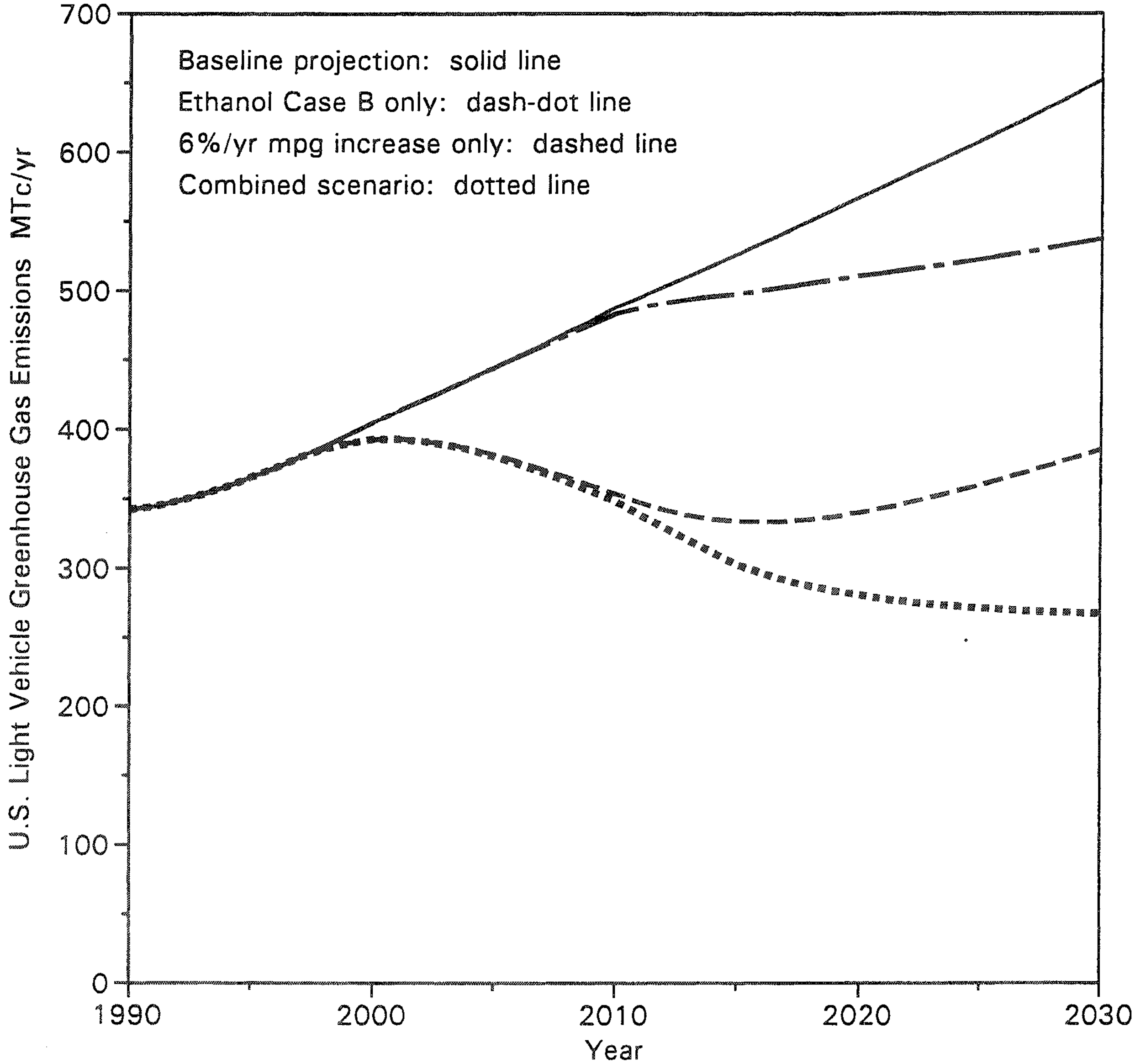

Figure 7. **Projected U.S. Light Vehicle Greenhouse Gas Emissions under Various Scenarios of Efficiency Improvement and Cellulosic Ethanol Use.**

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