# Technologies and Policies for Controlling Greenhouse Gas Emissions from the U.S. Automobile and Light Truck Fleet

Steve Plotkin

Center for Transportation Research
Argonne National Laboratory

January 2000

*Argonne National Laboratory*

Argonne National Laboratory, with facilities in the states of Illinois and Idaho, is owned by the United States Government, and operated by the University of Chicago under the provisions of a contract with the Department of Energy.

This technical report is a product of Argonne's Energy Systems Division. For information on the division's scientific and engineering activities, contact:

Director, Energy Systems Division
Argonne National Laboratory
Argonne, Illinois 60439-4815
Telephone (630) 252-3724

Publishing support services were provided by Argonne's Information and Publishing Division (for more information, see IPD's home page: http://www.ipd.anl.gov/).

*Disclaimer*



Available electronically at http://www.doe.gov/bridge

Available for a processing fee to U.S. Department of Energy and its contractors, in paper, from:

U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
phone: (865) 576-8401
fax: (865) 576-5728
email: reports@adonis.osti.gov

# TECHNOLOGIES AND POLICIES FOR CONTROLLING GREENHOUSE GAS EMISSIONS FROM THE U.S. AUTOMOBILE AND LIGHT TRUCK FLEET

**Steve Plotkin**
**Center for Transportation Research**
**Argonne National Laboratory**

## INTRODUCTION

The transportation sector produces slightly more than 30% of the greenhouse gas emissions from the United States: light-duty vehicles – automobiles and light trucks – account for more than half of the sector's emissions (Davis 1998). This makes the light-duty vehicle fleet an appealing target for carbon emissions reductions undertaken in pursuit of satisfying the United States' potential obligations under the Kyoto protocol. Further, the current light-duty vehicle fleet is essentially fully dependent on petroleum for its energy supply, so reductions in greenhouse gases will yield similar reductions in U.S. oil use, an attractive proposition to those concerned about U.S. dependence on petroleum imports.

Light-duty greenhouse gas emissions and petroleum use can be reduced by increasing vehicle energy efficiency, shifting travel to more efficient modes, reducing travel overall (by increasing the price of travel, changing development patterns, or other means), changing fuels, or increasing vehicle occupancy. This paper focuses on policies and technologies for increasing vehicle energy efficiency, though policies that raise fuel prices will encourage other physical measures as well. This focus reflects the author's assignment in drafting this paper and does not reflect any belief that other measures cannot play an important role in moving the United States toward a more efficient and greenhouse-friendly personal transport system.

## BACKGROUND

The fuel economies of successive model years of U.S. new cars and light trucks have been essentially constant for the past decade – the new car and new light truck fleet fuel economies were 28.8 and 21.3 mpg in 1988 and 28.7 and 20.9 mpg in 1998 (NHTSA 1999). Further, the market share of less fuel-efficient light trucks has climbed dramatically, from about 20% in 1975 to 30% in 1988 and 40% in 1996 (NHTSA 1999) – and today, the light truck share is nearly 50%. Thus, the fuel economy of the entire (new) light-duty fleet has actually declined during the past decade.

Despite this disappointing record of stagnant and declining fuel efficiency, technologies that positively affect vehicle efficiency have continually entered the fleet during this period. These include fuel injection, 4-valve-per-cylinder engines, variable valve control, 4- (and recently 5)-speed electronically controlled automatic transmissions with lockup, growing use of lightweight materials and structural redesign for weight reduction, tires with lower rolling resistance, and improved aerodynamics. Efficiency improvements offered by these technologies have been counteracted, however, by changes that negatively affect fuel economy — increased horsepower yielding better acceleration performance and higher top speeds; weight increases due to increased body stiffness and more power and safety equipment (e.g., air bags) as well as increased interior space; and other factors. In other words, automakers and purchasers have been willing to trade fuel economy for competing vehicle amenities, such as size, power, and safety.

These trends are hardly surprising given the extraordinarily low price we pay for gasoline and the resulting consumer disinterest in fuel saving. In 1997, according to J.D. Powers surveys, only 5% of new car purchasers cited fuel economy as the most important vehicle attribute in their purchase decision; this value is down from the *42%* who cited it in 1980, when fuel prices were spiking and there were grave concerns about fuel availability as well.

While new light-duty fleet efficiency has actually declined since 1988, travel demand has been growing inexorably, with highway vehicle-miles rising by approximately 3% per year since 1970 (Davis 1998). The result is that the fuel use and greenhouse gas emissions of the light-duty highway fleet are growing at a significant rate – the 1996 fleet energy use was 10% higher than the 1990 value, for example (Davis 1998), and recent forecasts by the U.S. Department of Energy's (DOE's) Energy Information Administration (EIA) project that given current trends, year 2010 energy use will be nearly 30% higher than the 1990 level (EIA 1998). With the Kyoto goal of achieving below-1990-level greenhouse gas emission rates by 2008-2012, there is a yawning gap between hope and current reality in the transportation sector.

This history and current market conditions make it clear that achieving any significant movement toward the Kyoto goals will require a drastic change in market conditions. How can this be achieved?

## POLICIES TO IMPROVE FLEET FUEL EFFICIENCY

Policies to increase energy efficiency and reduce greenhouse gas emissions in transportation must overcome four barriers to these goals: fuel prices and transportation services that do not reflect total costs; uncertainty about the costs and benefits to consumers of increased efficiency, caused by uncertainty about future fuel prices and a lack of explicit information about the incremental costs of higher efficiency; the inability of companies to capture the full benefits of advances in the science and technology of efficiency; and the difficult trade-offs that exist between fuel efficiency and a number of important consumer amenities, such as vehicle acceleration performance. The first three barriers are market imperfections; the last is simply a characteristic of transportation technology and markets.

**Barrier 1. Underpriced fuels and transportation services.** The economic literature widely recognizes energy fuels to be underpriced, because a variety of externalities associated with fuel use and especially oil use (transportation is 95% dependent on petroleum products for fuel) are not fully taken into account. Externalities most directly tied to fuel use are air, water, and land pollution associated with discovering, extracting, processing, and distributing gasoline and other transportation fuels, including greenhouse gases, and the energy security and economic impacts associated with the uneven geographic distribution of oil resources, that is, military expenditures associated with Persian Gulf political instability; monopsony costs associated with artificially high oil prices (though monopsony costs currently are low or zero because of an oversupply – probably temporary – of oil in world markets); and the costs to the U.S. and world economies associated with occasional oil price shocks.

Transportation services are also underpriced for reasons that include but go beyond underpriced transportation fuels. Externalities more closely tied to transportation services than energy use include air pollution – excluding greenhouse gases – associated with vehicle use, environmental impacts associated with transportation infrastructure, societal costs associated with transportation accidents (especially on the highways), the costs of highway congestion, and so forth. These costs as well as the costs of petroleum use in transportation have been examined by a number of analysts, most notably Delucchi (1997). Delucchi has estimated that, for the United States, the social cost of motor vehicle usage runs into the hundreds of billions of dollars annually (Delucchi 1997).

**Barrier 2. Difficulty in making rational choices.** In making vehicle purchases, consumers and businesses experience difficulty in making rational choices about trading off the costs and benefits of different levels of energy efficiency. One cause is the substantial uncertainty associated with future fuel prices. Over the past two decades, the real price of a barrel of oil has varied by fourfold, reaching highs in the early 1980s and lows within a few years thereafter (Davis 1998). Current real oil prices are near historic lows, but energy analysts widely acknowledge that disturbances to oil markets could cause future prices to escalate rapidly to multiples of today's prices (and stay there for periods ranging from a few weeks to a few years), and there is growing controversy about the potential for oil resource shortages, coupled with higher prices, possibly beginning within the lifetime of most vehicles purchased today (Campbell and Laherrere 1998).

Another cause for uncertainty in vehicle purchases is difficulty in determining the true costs of higher efficiency. Despite required labels on new autos and light trucks specifying their fuel economy and average annual fuel costs, vehicle purchasers are rarely given explicit choices in efficiency coupled with explicit price differences associated with these choices. Instead, efficiency differences are buried in base prices or in the price of complete subsystems such as engines, and efficiency differences are always coupled with substantive differences in other critical consumer attributes, such as acceleration performance, level of luxury, vehicle handling, and so forth. Further, vehicle manufacturers' accounting systems are sufficiently arcane that clear economic choices tied to actual cost differences would be difficult for the companies to provide even if they wanted to. Additionally, properly trading off fuel savings versus changes in vehicle price involves trading off the time-discounted value of the fuel savings against the present cost of the vehicle – a calculation that many vehicle purchasers are not familiar with. Note, however, that if consumers were extremely concerned about energy savings and determined to base their purchasing decisions on them, automakers and dealers would have a strong incentive to provide them with the information that is now lacking in the marketplace, as well as with vehicle choices that provided clearer trade-offs. It can be argued that the lack of such information and choices is simply the consequence of consumer disinterest in improved fuel economy in the context of low fuel prices.

It is also worth noting that new car purchasers – who have a dominant influence on the design decisions of automakers – are not representative of the driving public, many of whom purchase their vehicles secondhand. In particular, new car purchasers are substantially wealthier than average drivers, which undoubtedly skews their purchase preferences away from considerations of fuel use and towards considerations of ride quality, power, and other vehicle qualities.

**Barrier 3. Difficulty in capturing the market benefits of technology advances.** Another barrier to advances in efficiency technology is the likelihood that the developers cannot take full advantage of such advances. By this we mean that increases in knowledge of new designs and technology are easily transferred to other industry entities without necessarily benefiting the individuals or company that provided the investment that lead to the increases; further, companies that absorb the market risk of introducing new technology generally will not reap the full benefits of trailblazing new markets. Both attributes tend to yield underinvestment in technology development and reluctance to introduce new technologies in areas where markets are not well established.

**Barrier 4. Trade-off between fuel efficiency and competing vehicle attributes.** The final barrier to increased efficiency is the set of trade-offs that exist between higher efficiency and other competing consumer attributes. In highway vehicles, for example, vehicle designers always must choose between higher fuel efficiency and increases in important attributes, such as acceleration performance and top speed, vehicle size, body rigidity (obtained by adding weight or removing less of it than might otherwise be possible), and so forth. For example, auto manufacturers have used supercomputers to redesign the body structures of new vehicles, allowing them to greatly increase body rigidity without weight gain; an alternative would have been to reduce vehicle weight at constant, or at least smaller gain in rigidity, but manufacturers typically have not chosen this path. They do so because, at current fuel prices, consumers value body rigidity, and the other competing attributes, more highly than fuel efficiency. Vehicle manufacturers have responded by emphasizing improvement of these attributes in every succeeding generation of new vehicles. In contrast, energy costs are a comparatively small part of the total costs of operating many transportation vehicles – highway vehicles in particular. The net result is that manufacturers have downplayed efficiency improvements in their vehicle design decisions, and consumers have downplayed such improvements in their vehicle purchases. Were a vehicle manufacturer to unilaterally emphasize fuel economy at the cost of power, handling, and other attributes that "compete" with fuel economy, they would risk losing market share to their competitors.

At the most basic level, fleet fuel economy will improve when any or all of the following occurs:

- Vehicle purchasers value fuel economy more than they do today and value less those features that compete with fuel economy – acceleration performance, vehicle size and weight, efficiency-robbing features such as four-wheel drive, and so forth.

- Manufacturers recognize a shift in consumer desires and change their market offerings to reflect a higher value for fuel economy.

- The cost and availability of efficiency technology improves through research and product development, allowing manufacturers to improve fuel economy with less technical and financial risk, and less need to trade fuel economy against competing consumer values.

- Manufacturers are forced to improve their fleet fuel economy through regulatory means.

A number of ways have been suggested to accomplish one or more of these four market shifts, from educational campaigns to new fuel or carbon taxes to increases in existing fuel economy standards to increased government research and development (R&D). Many of these measures have received extensive analysis and debate; frankly, many of the analyses are nonobjective, resembling lawyer's briefs rather than neutral evaluations. In many cases, the analyses' conclusions are determined almost entirely by the boundaries drawn or the assumptions adopted by the analysts. For example, two key analyses of the employment impacts of new fuel economy standards proposed in the early 1990s ranged in their projections from job losses of a few hundred thousand to job gains of a few hundred thousand. The Office of Technology Assessment (OTA) determined that these contradictory outcomes arose because one organization began its analysis with the assumption that automakers could easily meet the proposed standards without negatively impacting car sales, and found job gains from a nationwide shift of jobs from gasoline use (declining) to gains in the overall economy (from the spending of savings from fuel use reductions); and the other organization began its analysis by assuming that the industry could not meet the standards using advanced technology and would thus have to find a way to force people into smaller cars – with subsequent job losses in the auto industry primarily because of lost sales and because the factories that make smaller cars are more labor-efficient than average (U.S. Congress 1994).

The following discussion presents brief and limited evaluations of the pros and cons of some of the major policy options.

**Expanding R&D funding.** The federal government already has substantial investments in light-duty vehicle R&D, particularly in the Partnership for a New Generation of Vehicles (PNGV). However, reviews of this program by the National Research Council

(NRC 1997) and the Office of Technology Assessment (OTA 1995) identified important gaps in the program, with NRC concluding that the program was seriously underfunded. Areas where OTA identified gaps include vehicle safety, analysis of infrastructure for manufacturing, refueling, servicing and recycling, and development of composite structures. OTA was also concerned that the program was underutilizing small business expertise and innovative capacity.

There is little doubt that PNGV and related programs could easily absorb a few hundred million dollars in annual R&D funding, and possibly they would benefit from a great deal more. However, the following should be recognized:

- The outcome of increased R&D funding is essentially not subject to definitive analysis, except possibly in those areas where the only remaining task is engineering. Where breakthroughs in cost and/or performance are necessary, the likely outcome of increased funding can only be postulated.

- There remains some argument about the extent to which government funding of R&D may stifle independent commercial R&D, either by misdirecting it away from areas not favored by government program managers or by providing an outright negative incentive for R&D sponsors to fund private R&D. Where the market provides little incentive for this research – actually somewhat true today, but presumably this could change because of external market changes or changes in other government policies – this argument may be irrelevant, of course.

**Educational programs.** One basis for believing that better educating the public about automotive fuel efficiency will lead to efficiency gains is that, despite the presence on new vehicles of fuel efficiency labels, the actual cost of higher fuel economy is buried in the base price of the vehicle or in the price of an option such as an engine or transmission (Plotkin and Greene, 1997) – in other words, consumers currently don't have a good basis for calculating the costs of higher fuel economy, and presumably would make better choices if they could do so. The problems with this argument are severalfold:

- The annual fuel costs of the average light-duty vehicle are one-fifth or less of total operating costs, so that most consumers won't give a high priority to fuel efficiency trade-offs even if they understand them. Further, the benefits of higher fuel economy depend on fuel prices over the next 10 years, which few consumers would be willing to guess at, given the dramatic price fluctuations that have occurred over the past few decades.

- The purchase of a new car or light truck is a complex decision, with many of the crucial factors having virtually nothing to do with operating costs.

- Even the experts disagree about the actual costs of fuel economy savings.

Clearly, anything that makes fuel costs more important to the consumer (e.g., a hefty increase in fuel prices) will raise the value of educational programs that allow consumers to intelligently factor fuel efficiency into their purchase decisions. Without a market change that boosts the value of fuel savings to the consumer, however, educational programs of this type are likely to have little benefit.

Aside from helping consumers factor fuel savings into their purchase decisions, educational programs could be designed to transform the market itself, by encouraging consumers to place a higher value on environment-friendly technologies, that is, on "green" technologies. This would move the government's educational role from one of providing information to one of advocating a change in basic societal goals. This is not a unique role for government outreach programs, but it is certainly a more controversial one.

**Fuel or carbon taxes.** Fuel taxation is attractive to economists because it can simultaneously increase energy efficiency – higher fuel prices provide incentives for consumers to purchase and manufacturers to produce more efficient vehicles – and reduce transportation demand. Further, many economists believe that fuel prices are too low, because they do not reflect the externalities associated with fuel use, e.g. air pollution, congestion, societal costs of automobile accidents, and so forth. A recent comprehensive review of the social cost of motor vehicle travel (Delucchi 1997) found that motor-vehicle travel annually costs society $13-49 billion for monetary accident costs not paid by the responsible party; $34-136 billion in congestion costs; $19-284 billion dollars in mortality and morbidity from air pollution (primarily from particulates) caused by vehicle emissions; and a variety of other costs – adding up to about $100-900 billion in annual externality costs. Of course, the conclusion that fuel prices, and transportation services in general are underpriced is not universally accepted. Areas of controversy associated with Delucchi's and other analyses include the appropriate monetary value of premature deaths, the evidence associated with very high fatality estimates for transportation-related fine particulate emissions, the failure to include transportation benefits in analyses of this type, and a variety of other issues.

Three critical issues associated with a decision about the usefulness of fuel or carbon taxes are their effect on fuel use (and, thus, on greenhouse gas emissions), their overall economic efficiency, and their net impact on GNP.

- *Impact on fuel use***.** Studies done in the 1970s and early 1980s of fuel price effects on fuel demand (Dahl 1986) found that fuel demand was very responsive to fuel price over the long term – that a 10% increase in price would cause a drop in fuel use of approximately the same percentage, with half the drop coming from improved vehicle efficiency and half from reduced travel. More recent estimates, discussed in Plotkin and Greene (1997) project only about a 5-6% decrease in fuel use from a 10% price increase. Thus, a $0.50/gallon gasoline tax (added to a baseline $1.25/gallon) might be expected to reduce gasoline use by perhaps 20%

over the long run. The latter values are less affected by the turmoil in gasoline markets of the OPEC embargo/Iranian crisis era and should be more credible.

- *Economic efficiency.* Although fuel taxes or carbon taxes should be more efficient than fuel economy standards, their economic efficiency suffers from the fact that most of the externalities of motor vehicle travel – which fuel or carbon taxes would seek to "internalize" – do not vary directly with fuel use. Health damages from emissions of fine particulates may even vary somewhat inversely with fuel use, since fuel-efficient diesels emit more particulate matter than less-efficient gasoline engines.

- *Impact on GNP*. Opposition to raising fuel taxes, or instituting carbon taxes, often is based on the assumption that increased taxes will negatively affect GNP. Actually, the impact on GNP is affected strongly by what is done with the collected tax receipts. If, for example, the tax change is revenue neutral with receipts used to reduce other taxes, the net economic impact will depend on the relative efficiencies of the new and displaced taxes. It is theoretically possible, if the displaced tax is particularly inefficient and distorting, that the overall long-term impact of the new tax on GNP could be positive, though the regressive aspects of fuel and carbon taxes will yield negative distributive effects on economically-vulnerable populations if the tax revenues are not used to compensate for such effects. Further, short-term GNP impacts can be moderated by introducing tax increases gradually over a number of years – though consumer acclimatization to a gradual tax increase conceivably might reduce the tax's effect on travel behavior and vehicle purchases, yielding lower benefits in reduced oil use and greenhouse gas emissions.

Any decision to support new fuel or carbon taxes is made more difficult because all the available historical evidence is that politicians and much of the public hate such taxes; President Clinton found this out early in his first term when he met a firestorm of protest against a tax of approximately $0.05/gallon – and it is quite clear that taxes on the order of five or ten times as much – or higher—would be necessary to make a significant dent in fuel use. Nevertheless, there is good evidence that highway transportation is underpriced – and further evidence of global warming would only make this clearer. Further, as noted earlier, *revenue-neutral* fuel or carbon taxes may be constructed to have little long-term cost to the national economy, though short-term adjustment costs are inevitable. Policymakers ought to consider carefully the use of such taxes, *as well as other charges designed to efficiently capture externality costs*, as an important component of any strategy to reduce greenhouse emissions.

**Fuel economy standards.** Fuel economy standards represent perhaps the most contentious way of reducing fuel use – the major domestic auto companies appear unalterably opposed to them, as does a Congress that has consistently renewed the budget of the agency (the National Highway Traffic Safety Administration) responsible for adjusting standards with strict instructions not to spend a penny on such activity. Despite protests to the contrary, however, it is clear that the CAFE (Corporate Average Fuel Economy) standards imposed by the federal government in 1975 worked well and were responsible for a large part of the doubling of fuel economy the new car fleet achieved by the middle 1980s (Greene 1989). Although it often is argued that the standards "failed" because they did not achieve their original purpose – to actually *reduce* automotive fuel use – the standards *did* save huge amounts of oil over *what would have been used* had they never come into existence.

Many opponents of higher CAFE standards focus primarily on the conflict between government-dictated levels of fuel economy and the opposition of the marketplace, which clearly places little value on higher fuel economy. The primary feature of this argument is as follows: Automakers rely on consumer perceptions that new cars are markedly superior to older ones to maintain high sales of new vehicles. Most purchasers of new cars can choose to keep their older ones, at least for a time, if they aren't impressed with their potential replacements. Requirements for markedly higher fuel economy will force automakers to trade off fuel economy with other features that consumers find more desirable (e.g., low cost, size, power, body stiffness, and so forth). This will make new cars less desirable to potential purchasers, depressing sales and costing industry jobs (and, incidentally, slowing the turnover of new cars for old that is the responsible for improving the overall fuel efficiency of the fleet).

Of course, the same argument applies to all attempts to "internalize" externalities; the market plainly does not "value" reductions in air pollution, in that consumers are unlikely to pay more for a less-polluting car if given the choice, yet consumers appear to have accepted the significant costs associated with requiring *all* cars to meet the same emissions standard. Similarly, consumers might accept the costs associated with increased fuel economy if they perceive both that the costs are widely shared and that the goal – reduced U.S. oil use and greenhouse gas emissions – is one worth sacrificing for. Presumably, it makes little sense to pursue such standards unless the public accepts the premise that the goal is worthwhile and important. And, of course, the cost must not be too high.

One further point: Even if U.S. consumers came to accept the argument that higher fuel economy and lower greenhouse emissions are important for society, these same consumers might still retain their taste for the features that conflict with such goals. Standards might then prove to be the only mechanism that would insulate automakers from at least some of the market risk associated with making design trade-offs that favored fuel economy – because all companies would be forced to make the same trade-offs.

Even with acceptance of the goal of reducing oil use and greenhouse emissions, are new CAFÉ standards a reasonable method of attaining the goal? This is likely to remain a contentious issue, but perhaps the main deciding points are the following:

- Can standards be structured in a way that avoids severe market distortions?

- Can a reasonable technology level (e.g., one that avoids large technological and market risks) be defined?

Since the advent of the original 27.5-mpg standards, the domestic industry has complained bitterly about the severe market distortions that have accompanied the standards. Among the worst of these have been price distortions, whereby companies sold smaller, more efficient cars at a loss to balance the sales of less efficient larger cars and maintain adequate levels of fleet fuel economy, and the shifting of cars between "import" and "export" fleets – with movement of jobs from domestic to overseas, or vice versa – to allow the more efficient import fleets to "donate" their most efficient models or to "absorb" the least efficient domestic models. These market distortions are not a necessary product of fuel economy standards but are instead the product of the specific form of standard adopted. The degree of distortion caused by new standards could be minimized by

- Making no distinction between import and domestic fleets
- Allowing trading of fuel economy "credits" among companies
- Combining autos and light trucks into one fleet
- Avoiding a "one size fits all" uniform standard and instead designing a standard that takes account of the technological potential associated with each fleet based on some measure of vehicle size (perhaps embodied in interior volume), carrying capacity, and function (This would allow light trucks a more lenient standard than autos but insist on a relatively equal level of *technical* efficiency as embodied by vehicle technology and design.)

Note that the first three attributes of a new standard are precisely specified, and the last is not. The precise form this attribute takes will be of critical importance to the industry, since the specification of this attribute will inevitably provide some market advantage or disadvantage to each company. The language of this specification will undoubtedly be a lightning rod for controversy. Determining this specification will thus be the most difficult part of implementing a new standard and would best be undertaken in a cooperative effort with all segments of the industry.

Choosing an appropriate target level for a new CAFE standard is difficult because achieving improvements to fuel economy is likely to demand the acceptance of both technological risk and the market risk associated with forcing automakers to choose high fuel economy over other competing automotive values (e.g., vehicle price, size and interior volume, acceleration and grade climbing ability, vehicle stiffness) and a host of other values that might have to be downplayed if fuel economy performance becomes too important. Most analyses have examined the costs and fuel economy effects of changes in vehicle drivetrains and other characteristics *while holding competing vehicle characteristics constant.* This has the advantage of dealing with vehicles whose characteristics have already been accepted by the marketplace – rather than examining vehicles with compromised characteristics (e.g., less acceleration power or smaller interior volume).[1] The problem with assuming constant fleet characteristics is, however, that by the time the target year is reached, in all likelihood the market will have shifted – if current trends are indicative, toward higher power engines, more interior space, increased crash protection, stiffer bodies for improved handling, and so forth. These changes will yield a less efficient fleet than was projected under the "no change" assumption, but if higher fuel economy is purchased at the cost of foregoing these changes, the fleet may be less attractive to consumers.

In other words, the selection of an appropriate fuel economy standard for the U.S. light-duty fleet involves careful technical analysis, but it is also inherently a political decision. Should the industry be required to improve its fleet fuel economy to a level that disregards ongoing market trends that oppose efficiency improvements? Should a level be chosen that supposes a vehicle price increase but allows continued increases in power and other amenities? Should a level be chosen that explicitly recognizes an externality value of carbon reductions and oil savings? These are decisions for politicians, not technical analysts.

To provide some initial guidance at selecting an appropriate standard, I will briefly discuss the fuel economy levels that could be achieved by *introductory* vehicles – midsize family cars – if their basic attributes remain unchanged from today's. Please remember that market trends will likely reduce these fuel economy levels by the time the cars could enter the market. Also, note that it would be unrealistic to expect this level of technology to be instantly introduced to all models.

By 2005 or 2006, *if automakers were to decide (or be required) to design for maximum fuel economy and hold off on the ongoing horsepower race (and other "races" [e.g. for increasing body stiffness]*), they should be able to produce family cars attaining 39-42 mpg (EPA test values[2]) using ultra-lightweight steel bodies, significant improvements in aerodynamic design, low-rolling-resistance tires, advanced engines and transmissions, and more efficient accessories (Plotkin and Greene 1997). By 2015, 50-55 mpg should be achievable *without* moving to nonconventional drivetrains, by shifting to optimized aluminum structures, direct-injection (DI) engines (preferably diesel, but emissions problems may favor gasoline), with incremental aerodynamic and tire improvements (rolling resistance coefficient approaching 0.005, aero drag coefficient approaching 0.22).

---

1 This generally is the case with analyses that examine "best in class" vehicles, which have better fuel economy than their counterparts but often have other characteristics that make them less popular in the marketplace.

2 CAFE ratings, based on 55%city/45% highway driving cycles. On-road fuel economy will be somewhat lower; EPA uses a 10% reduction on the city cycle, 22% on the highway cycle.

The use of hybrid electric drivetrains – combining an internal combustion engine (ICE) with a battery, generator, and electric motor – would allow higher values of fuel economy to be achieved. Until recently, I would have projected that hybrid electric vehicles (HEVs) would not enter the U.S. market in large numbers before 2007 or 2008, though I would have expected to see a few small-scale entries before that time. The recent launch of the Toyota Prius in Japan (and the projected year 2000 launch of a version designed for the U.S. market), with its 66-mpg fuel economy on the Japanese cycle and 50+ mpg on the EPA test (EPA 1998), has changed drastically the prospects for having large numbers of HEVs enter the U.S. fleet by 2005 or perhaps a bit earlier.

However, there remain important concerns about the likelihood that automakers can reduce the costs of hybrid drivetrains enough to make them commercially viable. Further, we should be cautious about what shifting to HEVs will mean for fuel economy. The Prius design appears to increase fuel economy by nearly 60% on the EPA test (and double it on the Japanese cycle) over the comparable-in-size Toyota Corona. However, Prius is a relatively underpowered (by U.S. standards) vehicle with 0-60 mpg times of about 14 seconds vs. 11 seconds or less for comparable American autos (EPA 1998). Also, its engine is a sophisticated Atkinson cycle design with variable valve timing, and it has low rolling resistance tires. These features explain a substantial part of the Prius's fuel economy gain over comparably sized autos; the hybridization of the drivetrain probably only contributes about a 20 or 30% gain on the EPA test. In other words, were the "39-42 mpg" and "50-55 mpg" autos described above designed as HEVs, their fuel economy would likely be about 50-55 mpg and 60-70 mpg, respectively.

Accounting for the normal process of staggered introduction of new models or major model redesigns, it might be feasible for the industry to attain a fleet CAFE of 40 mpg (30 mpg light trucks) by 2010, and perhaps 55 mpg (40 mpg light trucks) by 2020 – *if* the regulatory standard were designed well enough to force all competing automakers to attain approximately the same level of technology, and if the public were convinced that the social benefits of reduced greenhouse gases and oil dependency were valuable enough to society to support a CAFE standard at this level. The 2020 fuel economy level in particular depends on successful continued development of new automotive technologies. I make no claim, though, that these fuel economy levels are in any sense optimal or even desirable – such judgments are too subjective.

**Feebates.** Feebate plans award rebates to purchasers of new vehicles that attain fuel economy above a target level, and charge fees to purchasers of vehicles with fuel economy below the target. If the target is the fleet average fuel economy, the program will be approximately revenue neutral and will tend to offer a permanent incentive for purchasers to buy more efficient vehicles and manufacturers to raise the fuel economy of their offerings. Such programs have never been tried in the United States, but a several countries (e.g., Austria, Denmark, Germany, and Sweden) have offered economic incentives and disincentives designed to improve fuel economy (U.S. Congress 1994).

An analyst at Lawrence Berkeley Laboratory has estimated the impact of a variety of feebate programs, examining both consumer and manufacturer responses (Davis 1993). He concluded that a program that awarded $500 for the difference between 20 and 25 mpg could achieve a 15% improvement in new car fleet fuel economy over expected levels within about 15 years, with most of the improvement coming from manufacturers' building more efficient vehicles rather than consumers changing their purchasing decisions. In other words, he expected that most automakers would upgrade their vehicles in much the same manner, so that customers who still wanted to buy vehicles in the same size and performance class wouldn't be presented with great changes in the relative value of competing vehicles…and they also expected customers *not* to switch in large numbers to vehicles with significantly different size and performance characteristics.

As with most analyses of this sort, caution should be used in interpreting the results. Davis assumes that consumer and manufacturer's decision-making processes are much simpler than they actually are. For example, the analysis assumes that manufacturers will add any technology that is cost-effective based on the technology cost, size of the feebate, and fuel savings that would be accomplished – ignoring the trade-off between fuel savings and competing attributes such as acceleration performance. Also, there are inherent uncertainties in the technology cost and performance values used, especially for technologies that are not yet commercial. Nevertheless, the analysis indicates that feebates should be considered a viable candidate for helping to realize the Kyoto goals for the light-duty fleet. And they are particularly attractive because they can provide a *continuing* incentive to improve fleet fuel economy – as the average fleet fuel economy increases, the program will continue to reward vehicles that achieve still higher fuel economy levels.

## TECHNOLOGIES TO IMPROVE VEHICLE FUEL EFFICIENCY

There is wide agreement that new efficiency technologies will continue to enter the fleet and that technologies recently entered will gain market share. The most important of these technologies, from the standpoint of their potential impact on fleet fuel efficiency during the next few decades, are described briefly below.

**Material Substitution.** Weight reduction has been a key factor in the U.S. automobile fleet's fuel economy improvement since the early 1970s, and will likely play an important role in future improvements. Past weight reductions involved a combination of a widespread conversion to front-wheel drive, which eliminated the drive shaft and rear axle and allowed important packaging gains; a significant downsizing of the fleet, made possible by changing consumer demands; the shift in automobiles to unit body construction from a chassis on frame structure; and material substitution, largely from plain carbon steel to high-strength low-alloy steels, but also including shifts to plastic parts and some aluminum as well. Recently, structural redesign using supercomputers has allowed significant weight savings. However, much of these savings have been taken back by increases in body rigidity, which enhances ride quality and safety, as well as the addition of safety and power equipment. Accordingly, the average weight of the fleet has been increasing steadily for over a decade (Heavenrich and Hellman 1996).

Despite past improvements, there remain substantive possibilities for large weight reductions without sacrificing vehicle interior space or safety. OTA (OTA 1995)[3] identified an array of weight-reduction scenarios ranging from a "clean sheet" design using advanced steel alloys that might achieve greater than a 10% weight reduction in a mid-sized auto, to all-aluminum vehicles using successively more optimized designs achieving up to a 30% reduction, to a technically optimistic design using polymer composites achieving a 35-40% reduction (OTA considered this last scenario to be quite uncertain from a commercial standpoint because it requires breakthroughs in manufacturing technology).

**Aerodynamic Drag Reduction.** Improvements in vehicle aerodynamics have been an important part of the overall fuel economy improvement of the U.S. light-duty vehicle fleet, with average drag coefficients ($C_d$) being reduced from 0.45-0.50 in 1979-1980 to 0.30-0.35 today, with some models in the 0.27-0.29 range. These reductions are important to vehicle fuel economy because a 10% reduction in $C_d$ typically will yield a 2.0-2.5% increase in fuel economy at constant performance. Improvement in vehicle aerodynamics is particularly important at highway speeds, because drag forces increase with the square of velocity; the energy/mile needed to overcome aerodynamic forces at 60 mph is nine times that needed at 20 mph.

Prototypes with extraordinarily low $C_d$s (e.g., 0.18 for the Chevrolet Citation IV and 0.15 for the Ford Probe IV ("Going with the Wind" 1984) have been shown, and the General Motors EV1 electric car attains a $C_d$ of 0.19. There is a strong consensus among automakers, however, that mass market vehicles will likely be limited to a $C_d$ of about 0.25 because of limits on the practical slope of windshields, need for cargo space (a low $C_d$ requires a tapered rear end), and other factors, including customer design preferences. Further, reductions in the $C_d$ of light trucks are limited by factors such as need for high ground clearance and large tires, open beds in pickup trucks, and so forth. Also, the short length of subcompact autos limits the degree to which their $C_d$ can be reduced.

In our view, significant market pressure on fuel economy could reduce $C_d$ values a bit further than projected by the automakers. Some existing vehicle designs that have attained lower $C_d$s without some of the design compromises of the prototypes noted above indicate that a $C_d$ of 0.22 should be practical for a mid-size car without requiring wheel skirts or a sharply tapered rear end.[4]

---

3 This is a summary report. The full report, which presents this material, was not published due to OTA's closure, but it is now available as part of a three-CD set that contains all of OTA's reports since its inception. U.S. Congress, Office of Technology Assessment, *OTA Legacy: 1972 through 1995,* U.S. Government Printing Office, Washington, DC, Stock no. 052-003-01457-2, $23.00 U.S.

4 The Toyota AXV5, with a $C_d$ of 0.20, appears to avoid sacrifices in interior and cargo space. Removing its wheel skirts, which might inhibit maintenance and restrict the vehicle's turning circle, would likely raise its $C_d$ to about 0.22. Because the vehicle's underbody cover adds weight, the net positive effect on fuel economy will be reduced somewhat (OTA 1995).

**Improved Automatic Transmissions.** A range of potential improvements to automatic transmissions can offer fuel economy benefits of up to about 6% in automobiles. Key areas of improvement are design changes that reduce hydraulic losses in the torque converter and transmissions with added numbers of gears, with continually variable transmissions possible.

Five-speed automatic transmissions were introduced in Japan and Europe a few years ago and have recently been introduced to the United States in a few luxury models. Nissan and Mercedes have experienced fuel economy gains over a four-speed automatic in the 2-3 mpg range (Hattori et al. 1990). A number of continuously variable transmissions (CVTs) have been tested with widely varying results, and Honda sells a small car (the Civic HX) with a CVT in the U.S. market. OTA estimated that a CVT should be capable of achieving approximately a 6% fuel economy increase over a four-speed automatic.

Electronic transmission control of both conventional automatic transmissions and CVTs will add some benefits over the older mechanical controls. First generation controls selected only the shift points and provided about 0.5% benefit in fuel economy, and such controls were in most transmissions by 1995. More advanced second-generation controls have appeared, and they interact with the engine control to optimally select torque converter lock-up and shift points while also determining engine calibration. Such controls provide a 1.5% benefit over mechanical controls.

**Engine Friction Reduction.** Reducing mechanical friction is an ongoing process in engine development, and steady reductions in friction have occurred as engine designers continually modify existing engines and introduce new engine families. There is substantial potential for fuel economy gains as existing friction-reduction improvements are rolled into the fleet. Primary areas for further improvement are:

- Piston and connecting rod weight reduction using lightweight materials
- Lightweight valves and valve springs
- Use of two rings instead of three
- Improved oil pumps
- Improved lubricants
- Low-friction crankcase seals
- Roller cam followers

Only roller cam followers and two-ring pistons are discrete technologies, with specific benefits of 2% in fuel economy, while other benefits are based on design evolution.
Fuel economy improvements of as much as 4.5% (compared with current engines) should be available by using the full range of existing technologies

**Variable Valve Timing.** In conventional engines, the timing and extent of opening of the intake and exhaust valves are fixed, with settings that are compromises between the very different needs of high and low power operation. Variable valve control allows substantial efficiency improvement, for example, closing the intake valves early can substitute for throttling to reduce air intake, thus reducing pumping losses at low load. Also, variable valve control boosts average engine power and "flattens" the torque curve (allowing higher torque at low engine rpm), allowing engine downsizing while maintaining performance.

Honda uses a system called VTEC that controls both lift and timing of intake and exhaust valves. VTEC is not a fully variable system, offering only two settings for valve timing and lift, but it still obtains an 8% fuel economy improvement at constant performance. It has been used in the U.S. market both for boosting power (Acura NSX, Prelude VTEC) and improving fuel economy (Civic HX).

Although variable valve timing was introduced to the U.S. market in 1991 (in the NSX), neither VTEC nor competing systems (Mitsubishi uses the MIIVEC system, which combines valve control with cylinder shutdown at low loads) have gained significant market share since then. The major concerns are cost and complexity. Recently, however, such systems are being introduced more widely into luxury models (e.g., BMW 3 series and higher, Mercedes, Toyota, Volvo, etc.).

Second-generation variable valve timing systems that offer wider control of lift and timing are expected to increase fuel economy benefits at constant performance to 10%.

**Direct Injection Stratified Charge (DISC) Gasoline Engines.** Conventional spark ignition (gasoline) engines are inefficient at part load in large part because they reduce power by throttling back on their air supply as fuel flow is reduced, creating large drag losses (so-called "pumping losses") in the stream of intake air. They do this to maintain a constant air/fuel ratio at or below a level, called "stoichiometric," (about 14.6:1) where there is just enough air to fully combust the fuel. This air/fuel ratio allows stable combustion and prevents the exhaust from containing excess oxygen that would prevent the $NO_X$ catalyst from working properly.

Direct injection stratified charge engines do not throttle intake air; instead, they reduce only fuel flow at part load, operating at fuel/air ratios as low as 1:50. They manage this by injecting fuel directly into each cylinder at high pressures (700 psi or higher compared with 50 psi in a conventional fuel injection system (Markus 1997) in such a way that the fuel/air mixture is stratified (thus, "stratified charge"), with high fuel concentrations near the spark plug so as to maintain stable combustion. The combination of zero throttling losses, low fuel use at light loads because of the very lean fuel mixture, and some added benefits of DI – particularly, more precise control of combustion and fewer problems such as fuel condensation on intake-port walls – yields substantial fuel efficiency improvements rivaling those of DI diesels.

Concerns with DISC engines include problems with increased $NO_X$ emissions because normal reduction catalysts will not operate in the oxygen-rich exhaust environment of a lean-burn engine; the expense and durability of the fuel injectors, which have to operate at very high pressures ranging up to 2000 psi; the potential for increased fine particulate emissions; and the need for extremely precise control of combustion to maintain smooth performance from the engine as it shifts back and forth between lean to stoichiometric operation.

Both Toyota and Mitsubishi have introduced DISC engines into their fleets in Japan, Mitsubishi with a 1.8-liter, 148-hp engine in its Galant sedan and Legnum wagon, Toyota with a 2.0-liter, 143-hp engine in its Carina sedan (Markus 1997). Both companies use catalysts to reduce $NO_X$ emissions: Mitsubishi's is a true lean-$NO_X$ catalyst that reacts hydrocarbons with $NO_X$ to form nitrogen, oxygen, water, and carbon dioxide; Toyota's system stores $NO_X$ and reduces it to nitrogen during high power operation when the engine uses a stoichiometric (no excess air) air/fuel mixture (Markus 1997). Neither system is believed ready to meet U.S. emissions requirements, especially for catalyst longevity. The Toyota system would likely experience difficulties with high levels of sulfur in U.S. fuels, which can poison the catalyst material.

Available data suggests that Toyota's DISC engine provides a 25% fuel economy benefit in the Japanese 10-mode cycle, which could translate to an 18% benefit in the U.S. FTP (the "city" part of the CAFE test) if emissions problems are solved. However, the DISC engine addresses some of the same engine losses as variable valve technology, so that the fuel economy benefit of the two working together would not be strictly additive.

**Turbocharged DI Diesel Engines.** Until recently, all diesel powertrains used in light-duty vehicles in the United States were indirect injection diesels (IDI). In an IDI diesel, fuel is sprayed into a prechamber, mixed with air, and partially burned before the charge is passed into a main combustion chamber where the combustion continues. This design was desirable for automobiles because it yields smoother combustion with less noise and lower $NO_X$ emissions than DI designs. These advantages are purchased at the expense of some efficiency losses from heat transfer from the prechamber and pressure losses as the partially burned gases flow through the passages between the prechamber and main combustion chamber.

Advances in fuel injection technology and combustion chamber design, coupled with turbocharging and intercooling, have allowed DI diesels to attain smoothness and noise levels comparable with those of IDI diesels, with low $NO_X$ emissions and with specific power (power/weight) levels approaching those of naturally aspirated four-valve-per-cylinder gasoline engines. The best four-valve turbocharged DI diesels can attain mpg improvements of 40% or more over current two-valve-per-cylinder engines, though conversion to gasoline equivalent fuel economy yields closer to a 30% gain (diesel fuel is a more energy-dense fuel than gasoline). Successful widespread use in the U.S. requires that lean-$NO_X$ catalysts be successfully adapted to diesels to meet $NO_X$ standards. Catalyst researchers generally are considerably less optimistic about success for diesels than they are for gasoline-fueled vehicles. The recent decision by the California Air Resources Board to require diesels to meet the same stringent $NO_X$ emissions standard as gasoline vehicles may further complicate the future viability of advanced diesels.

As noted above, Volkswagen has introduced DI diesels into the U.S. fleet in its Golf, Jetta, and Passat models. These engines are 1.9 liter and produce 105 hp. Audi produces a larger 2.5-liter engine for its European models, and Mazda offers a 2.0-liter engine in Japan and Europe.

**Advanced Tires.** Rolling resistance accounts for approximately a third of the loads on an automobile during the EPA test procedure, not counting accessory losses. The magnitude of this resistance is approximately linearly related to the rolling resistance coefficient of the vehicle's tires, though part of the total rolling resistance of the vehicle occurs in the brakes and bearings. Reducing the rolling resistance coefficient through changes in tread design, tire materials, and tire structure will thus have a significant positive impact on fuel economy.

Tire design and materials have improved steadily throughout the years, with the switch to radials from bias-ply tires beginning in the late 1970s, then the shift to second generation radials beginning in the mid-1980s each achieving about a 20-25% reduction in rolling resistance.

Additional improvements have recently been introduced by Michelin and other companies and are beginning to penetrate the fleet. Use of these and other, further-improved designs can yield about a 25% reduction in rolling resistance by 2005, with 5% improvement in fuel economy resulting; an additional 3% fuel economy improvement may be possible by 2015 (Hattori et al. 1990). Some of these gains are likely to be offset by manufacturer design decisions that increase tire traction and durability, so that only about half the potential fuel economy gains are likely to be realized.

**Hybrid Electric Powertrains.** Hybrid electric powertrains combine two energy sources with an electric drivetrain, with one or both sources providing electricity to the electric motor. Although many configurations are possible, all have some form of energy storage (battery, flywheel, ultracapacitor, etc.). Hybrids offer a theoretical efficiency advantage over conventional ICE drivetrains because

- They offer the potential to recapture some of the vehicle's potential energy that is normally lost (as heat) when the vehicle is braked. In an HEV, the electric drive motor can be operated in generator mode to brake the vehicle, which allows the electric energy produced to be stored in the battery or other storage device.

- The hybrid drivetrain allows the vehicle powerplant to be smaller and to operate more efficiently than the powerplant in a conventional drivetrain. In a conventional drivetrain, the engine is sized for the maximum load (usually short-term rapid acceleration) and can produce many times the power it uses during the great majority of its operation. For example, during idle, low-speed cruise, or deceleration, the powerplant may be operating below 10% of its maximum power capability, and most engines – especially gasoline engines – are very inefficient at such lower power levels. Because the storage device can absorb any excess power (over that needed to operate the vehicle) produced by the engine, the engine can be operated at an efficient power level (or can be shut off if the storage device is full) even when the vehicle loads are low. Also, in a HEV, the storage device can provide part of the power for maximum acceleration, which allows its powerplant to be smaller than in a conventional vehicle – sized either for average power or for the power needed to operate where the battery can't help (e.g. for sustained hill-climbing).

The net energy gains from the regenerative braking, smaller and lighter powerplant, and improved powerplant cycle efficiency are counteracted by losses in the electrical components (storage device, generator, motor/controller) and their added weight (in particular, weight of the storage device and electric motor). The wide variety of hybrid configurations and component designs, the relatively early stage of development of hybrid powertrain systems, and the ongoing redesign of hybrid powertrain components to satisfy the unique requirements of hybrid operation has yielded a wide range of estimates of the potential efficiency benefits of shifting to hybrid drivetrains. Further, ongoing changes in engine design for conventional drivetrains shift the relative value of hybridization. For example, reduction in pumping losses achieved by variable valve control reduces the benefit of hybridization because these are the among the losses hybridization is designed to counter.

The OTA has estimated that a battery/ICE HEV can achieve about a 25-35% gain over a conventional vehicle with the same type of powerplant, assuming what it considered optimistic values for the efficiencies of the battery and electric motor (OTA 1995). The first HEV in commercial production, the Toyota Prius, appears to achieve fuel economy gains from hybridization in this range; much of its total gain in fuel economy against comparable conventional vehicles (it attains about 66 mpg on the Japanese 10-mode cycle and slightly more than 50 mpg on the CAFE test conducted on this vehicle by EPA [EPA 1998]) appears to be the result of factors other than the hybrid drivetrain (e.g., low rolling resistance tires, reduced aerodynamic drag, variable valve control, and an advanced Atkinson cycle engine). On the other hand, the DOE's goal for its hybrid drivetrain R&D program is a doubling of fuel economy, and theoretical analyses of hybrid configurations using simulation models have projected gains ranging as high as the DOE goal (Burke 1995; Ross 1996). In our view, gains this high are unlikely without sacrificing some aspects of performance or operational flexibility. On the other hand, there are active R&D efforts on hybrid components such as ultracapacitors and high efficiency electric motors that, if successful, could raise the efficiency advantage of hybridization to somewhat higher levels than OTA projected.

The primary barriers to successful commercialization of HEVs are the current high costs of electric motors, controllers, and batteries and the need for additional progress in reducing the specific power and increasing the efficiency of these electrical components. In particular, there is an urgent need for reliable high-efficiency, high-specific-power batteries. There recently has been substantial progress on such batteries, as demonstrated by the short-term success of the Prius battery.

**Proton Exchange Membrane (PEM) Fuel Cell Powertrains.** Fuel cells are electrochemical devices that convert the chemical energy in fuels to electrical energy directly, without combustion. This process avoids the thermodynamic limitations imposed by the Carnot cycle, and fuel cells theoretically can have efficiencies of 90% or greater. With hydrogen as a fuel, fuel cells have emissions only of water; with fuels such as methanol or hydrocarbons, reforming to obtain hydrogen will produce small quantities of carbon monoxide and other pollutants as byproducts and larger quantities of carbon dioxide.

For the immediate future, PEM fuel cells appear to be the clear choice among alternative fuel cell technologies for light-duty vehicle applications because they operate at moderate temperatures (20-120°C) and developers have been able to rapidly improve their power density (from 0.085 kW/L in 1989 to about 1 kW/L today) and decrease their costs (platinum loadings, a major cost factor, have been reduced from about 4 $mg/cm^2$ in 1990 to current levels of about 0.15 $mg/cm^2$) (Oei 1997).

Despite rapid progress, fuel cells must overcome major hurdles before they can succeed commercially in the light-duty market. Costs must be sharply reduced. Even with mass production, PEM fuel cells would cost at least $200/kW to manufacture with today's production technology and cell designs—nearly ten times the cost of ICE engines (Oei 1997) disregarding the additional cost of needed hydrogen storage or reformers.[5]

Key needs are development of low-cost membranes, size and cost reduction of hydrogen reformers or onboard storage, and improvement of "balance of plant." Also, there are several "engineering" issues that will have to be dealt with once stack design has gotten to the point where serious vehicle design is contemplated. Among these issues is cooling (low-temperature operation of fuel cells means that the heat being rejected is very low grade heat, requiring lots of air movement or large radiator surface areas, neither very appealing to vehicle designers [Borroni-Bird 1997]) and preventing freezing in cold weather.

Onboard fuel storage represents a significant barrier because hydrogen's energy density is very low and the easiest fuel to reform into hydrogen onboard the vehicle, methanol, has

---

5 An accurate cost comparison would have to account for differential costs of the transmission needed by the conventional drivetrain versus the electric motor and controller and reduction gear needed in the fuel cell drivetrain to convert the cell's output electricity into shaft power. Also, the fuel cell drivetrain may need a powerful battery to drive the vehicle until the cell can warm up, adding to total costs.

no significant supply infrastructure. DaimlerChrysler in partnership with DOE recently announced significant progress toward onboard production of hydrogen from gasoline, which would solve the supply infrastructure problem and allow much easier fuel storage than hydrogen. Not surprisingly, however, the selection of gasoline as the preferred "hydrogen carrier" for fuel cells is by no means an easy call. For example, gasoline's availability and easier fuel storage must be traded off against the cost and space occupied by the reformer (Jost 1997).[6] Toyota has claimed a substantial improvement in hydrogen storage technology using an advanced metal hydride adsorbent that matches the energy density of liquefied hydrogen storage with only 10 atmospheres of pressure required (Yamaguchi 1997). Presumably, however, this type of storage would be extremely heavy. Other options being pursued by various researchers include direct methanol fuel cells, which preclude the need for a reformer, and the use of ethanol in place of methanol or gasoline as a hydrogen source. The latter option is especially attractive if the ethanol can be produced from cellulosic materials, because the effect on reducing greenhouse gas emissions is particularly large for this technology.

We expect the rate of progress and probability of commercialization of fuel cell powertrains to be sensitive to the level of R&D funding and market pressures to improve overall vehicle fuel economy. Progress has in fact been rapid, as shown by the improvements in power density discussed above. Ford, General Motors, and DaimlerChrysler are all pursuing fuel cell vehicle R&D, as are Japanese and European companies, with Toyota's and Mercedes Benz's programs being the most visible. A Canadian company, Ballard, appears to be in a leading position in PEM fuel cell R&D and has supplied systems to most of the vehicle R&D programs. Given current funding levels and the market's lack of pressure on fuel economy levels as well as the large amount of development work that remains to be done, however, introduction of fuel cells into mass market vehicles appears likely to be beyond the 2010 timeframe. This, in fact, was the conclusion of the NRC's advisory panel overseeing the PNGV program (NRC 1997, table H-1). On the other hand, increased funding and market pressure and/or particularly fortuitous progress in the ongoing R&D program might move the date of introduction forward. Further, the newness of the technology and the dependence of the basic fuel cell stack costs on manufacturing design leaves open the potential that the eventual cost of the fuel cell system might be somewhat lower than competing ICE drivetrains; this depends on substantial cost reduction over a range of technologies, because the costs of hydrogen storage or reforming, the electric motor, and even the battery that is likely to be necessary for startup power, all play a significant role in total system costs.

Note that most major automakers – with the exception of Mercedes – are not projecting a pre-2010 commercial introduction of fuel cell vehicles, even assuming a high level of

6 An additional cost may be the loss in system efficiency associated with onboard reforming as well as the original refining of the gasoline. However, onboard hydrogen storage has energy costs in the form of hydrogen production (probably at a large scale, and more efficient than the onboard reformer) and pressurization if stored in high pressure tanks.

success in their development programs. The PNGV program envisions that the earliest fuel cells will use a reformer to produce hydrogen from gasoline. With optimistic assumptions about fuel cell efficiency and the efficiency of gasoline reforming, it appears that powertrains using fuel cells in conjunction with a gasoline reformer can be about 70% more efficient than current gasoline powertrains, which is only slightly more efficient than a diesel hybrid powertrain. Some recent analyses have questioned even this level of efficiency, however, concluding that a gasoline fuel cell system may be *at best* only 45% more efficient than current gasoline engine powertrains, and may be more likely to have only a small advantage over such powertrains (Thomas 1998).

## CONCLUSIONS

One message conveyed by the above discussion is that there is no shortage of technologies available to improve the fuel efficiency of the U.S. fleet of autos and light trucks. It clearly is technically feasible to improve greatly the fuel economy of the average new light-duty vehicle. Many of these technologies require trade-offs, however, that manufacturers are unwilling or (as yet) unable to make in today's market and regulatory environment. These trade-offs involve higher costs (that might be reduced substantially over time with learning and economies of scale), technical risk and added complexity, emissions concerns (especially for DI engines, and especially with respect to diesel engine technology), and customer acceptance issues. Even with current low U.S. oil prices, however, many of these technologies may find their way into the U.S. market, or increase their market share, as a consequence of their initial penetration of European and Japanese markets with their high gasoline prices. Automotive technology is "fungible," that is, it can be easily transported from one market to another. Nevertheless, it probably is unrealistic to expect substantial increases in the average fuel economy of the U.S. light-duty fleet without significant changes in the market, e.g. more stringent CAFE standards, significantly higher gasoline taxes, or gasoline price increases caused by sustained increases in world oil prices. Without such changes, the technologies that do penetrate the U.S. market are more likely to be used to increase acceleration performance or stiffen vehicle structures or enable four-wheel drive to be included in vehicles without a net mpg penalty. In other words, technology by itself is not likely to be enough to raise fleet fuel economy levels – this was the conclusion of the 1995 Asilomar Conference on Energy and Sustainable Transportation, organized by the Transportation Research Board's Committees on Energy and Alternative Fuels, and it is one I share.

In other words, I basically share the conclusion of the most recent EIA forecasts of transportation energy use, that the efficiency of the light-duty fleet will remain essentially stagnant over time in the absence of an unforeseen change in market conditions or strong new government policy measures (EIA 1998). I share this view despite PNGV, despite the introduction of the Toyota Prius HEV into the Japanese market this past year and its impending entry into the U.S. market, despite Honda's announced introduction of an HEV in the U.S. market within the year, despite better-than-expected research successes in the fuel cell development program, despite European automakers' voluntary agreement to cut new car fuel consumption by 25% within the next 10 years, and despite the probability of a Japanese agreement or standard of similar magnitude. The U.S. market will be influenced by these factors, but the basic shape of the market will be determined more by U.S. consumers' continuing disinterest in fuel economy, their high valuation of vehicle power, size, and luxury, and the U.S. Congress's strong opposition to the Kyoto treaty or any federal policy measures that appear to implement the treaty.

However, love affairs can end, and seemingly well-entrenched positions can change. *If* Congress changed its mind, either because of a change in personnel or in circumstance, and *if* the U.S. public began to believe that reducing fuel use and greenhouse emissions was as important as reducing health-related air emissions, policy tools and technology are available to make a real difference in light-duty fuel use and greenhouse emissions. Measures such as new fuel economy standards can be effective tools to accomplish this, but they must be applied with careful attention to both the fairness of their regulatory structure and the time required for automakers to adjust their plans and carefully redesign their fleets. Higher fuel taxes are another useful tool, because they change the economic signals sent by the price of gasoline to both consumers and vehicle manufacturers. In structuring a new fuel tax, Congress should pay careful attention to both its phase-in and to the use of collected taxes; appropriate reductions in other taxes can minimize negative impacts on the national economy. Finally, measures to increase research and development have the potential to pay large dividends in reduced technology costs and increased performance; the "toolbox" of potential new technologies contains a significant number that promise large gains in efficiency, with DI engines, hybrid drivetrains, and fuel cells being prominent examples.

## REFERENCES


Borroni-Bird, C., 1997. DaimlerChrysler Corp., personal communication (Mar. 14).

Burke, A.F., 1995. "Electric/Hybrid Super Car Design Using Ultracapacitors," 30th IECEC Meeting, Orlando, Florida (Aug.).

Campbell, C.J., and Laherrere, J.H., 1998. "The End of Cheap Oil," *Scientific American* (Mar.).

Dahl, C.A., 1986. "Gasoline Demand Survey," *The Energy Journal*, Vol. 7, No. 1, pp. 67-82.

Davis, S.C., 1998. *Transportation Energy Data Book: Edition 18*. ORNL-6941, Oak Ridge National Laboratory, Oak Ridge, Tenn. (Sept.).

Davis, W.B., et al., 1993. *Feebates: Estimated Impacts on Vehicle Fuel Economy, Fuel Consumption, $CO_2$ Emissions, and Consumer Surplus*, LBL-34408, Lawrence Berkeley Laboratory, Berkeley, Calif.

Lawrence Berkeley Laboratory, 1994, Draft, reported in U.S. Congress (Aug.).

Delucchi, M.A., 1997. *The Annualized Social Cost of Motor-Vehicle Use in the U.S., 1990-1991: Summary of Theory, Data, Methods, and Results*, Institute of Transportation Studies, University of California, Davis (June).

EIA, 1998. *Annual Energy Outlook 1999*, DOE/EIA-0383(99), U.S. Department of Energy, Energy Information Administration (Dec.).

EPA, 1998. *Evaluation of a Toyota Prius Hybrid System (THS)*, Hellman, K.H., Peralta, M.R., and Piotrowski, G.K., Technical Report 420-R-98-006, U.S. Environmental Protection Agency.

"Going with the Wind," 1984. *Car and Driver* (Aug.).

Greene, D.L., 1989. *CAFE or Price?: An Analysis of the Effects of Fuel Economy Regulations and Gasoline Price on New Car MPG, 1978-89*, Oak Ridge National Laboratory, Oak Ridge, Tenn. (rev. Nov. 30, 1989).

Hattori, et al., 1990. *A New 5-Speed Automatic Transmission for Passenger Cars*, SAE Paper 900551.

Heavenrich, R.M., and K.H. Hellman, 1996. *Light-Duty Automotive Technology and Fuel Economy Trends Through 1996*, EPA/AA/TDSG/96-01, U.S. Environmental Protection Agency, Office of Mobile Sources, Ann Arbor, Mich.

Jost, K., 1997. "Gasoline-Reforming Fuel Cell," *Automotive Engineering*, Vol. 105, No. 2, pp. 51-52 (Feb.).

Markus, M., 1997. "A Tale of Two-Strokes," *Car and Driver*, pp. 115-118 (Mar.).

NRC, 1997. *Review of the Research Program of the Partnership for a New Generation of Vehicles: Third Report*, National Research Council, Standing Committee to Review the Research Program of the Partnership for a New Generation of Vehicles, National Academy Press, Washington, DC.

NTHSA, 1999. Data provided by Orren Kee, National Highway Traffic Safety Administration, personal communication (Jan. 14).

Oei, D-G., 1997. "Fuel Cell Engines for Vehicles," *Automotive Engineering*, Ford Motor Company (Feb.).

OTA, 1995. *Advanced Automotive Technology: Visions of a Super-Efficient Family Car*, OTA-ETI-638 U.S. Congress, Office of Technology Assessment, U.S. Government Printing Office, Washington, DC (Sept.).

OTA, 1994. *Saving Energy in U.S. Transportation*, OTA-ETI-589 U.S. Congress, Office of Technology Assessment U.S. Government Printing Office, Washington, DC (July).

Plotkin, S.E., and D.L. Greene, 1997. "Prospects for Improving the Fuel Economy of Light-Duty Vehicles," *Energy Policy*, Vol. 25, Nos. 14-15, pp. 1179-1188.

Ross, M., et al., 1996. "A Parallel Hybrid Automobile with Less Than 0.1 kWh of Storage," Technical Paper Series, #961282, Society of Automotive Engineers, Warrendale, Penn.

Thomas, C.E., et al., 1998. *Integrated Analysis of Hydrogen Passenger Vehicle Transportation Pathways; Draft Final Report*, Directed Technologies, Inc. report to National Renewable Energy Laboratory, U.S. Department of Energy (Mar.).

Yamaguchi, J., 1997. "Toyota RAV4 EV – Today and Tomorrow," *Automotive Engineering* (Feb.).