An Updated Assessment of the Near-Term Potential for Improving Automotive Fuel Economy

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SUMMARY

Improving the fuel economy of cars and light trucks is the largest step that the United States can take to reduce petroleum use and its adverse economic and environmental impacts. The fuel economy of cars and light trucks (light vehicles) rose dramatically after 1973, peaking in 1987-88. Oil prices plunged in 1986, squelching market interest in fuel economy. Corporate Average Fuel Economy (CAFE) standards helped drive the increase in fuel economy, but standards have not been meaningfully raised since the mid-1980s. By 1993 most older, less efficient vehicles had essentially been replaced, particularly in terms of annual usage. Because fuel economy improvement has ceased, light vehicle fuel use is again growing at the same rate as the amount of driving, which is expected to increase 50% over the next two decades. The United States has sent more than a trillion dollars overseas for oil imports, equal to 70% of the cumulative trade deficit over the past two decades. Light vehicle fuel use accounts for 21% of U.S. carbon dioxide emissions. A major portion of hydrocarbon emissions is also directly related to gasoline use. These problems will continue to grow unless new vehicle fuel economy is substantially improved.

An understanding of the opportunities for cost-effectively improving new car fuel economy underpins the development of balanced policies for controlling light vehicle fuel use. A number of recent studies address this question. Estimates of the potential fuel economy of the new automobile fleet for the year 2001 range from 28 mpg (essentially no improvement over recent levels) to 45 mpg. Disagreements can be traced to divergent assumptions about the benefits, costs, applicability, and marketability of the technologies considered. Published estimates for improvements over the near-term (roughly 10 years) are limited in that only existing technologies are considered. The primary assessments are the studies by Energy and Environmental Analysis, Inc. (EEA), sponsored by federal agencies, and studies by auto industry consultants such as SRI. The National Research Council (NRC) study of 1992 drew mainly on these sources. The technologies included in these data bases are now already five or more years old; newer technologies and further refinements of the existing ones are not fully included.

This analysis considers more widespread use of technologies already in production plus the introduction of emerging technologies. Our review is organized as a menu of options, grouped under major headings representing the engine, transmission, and tractive load aspects of vehicle design. While this discrete approach is convenient for analysis, in reality engineers take a much more integrated approach to design. In fact, the creativity of engineers and designers continually refines and expands the menu of options which can be used to increase vehicles' efficiency and improve them in other ways as well. To both capture the integrated nature of technology refinement and check our results, we also apply an engineering model to perform an integrated analysis of efficiency improvements to a typical vehicle.

We base our assessment on the technology status of the new car fleet in 1990, which is taken as the base year for the analysis. We consider technology improvements that will improve fuel economy while maintaining the same average vehicle size and performance as in 1990. Available cost information is reviewed and technologies are screened according to cost-effectiveness, considering the fuel savings to all consumers over an average vehicle lifetime. We examine contemporary auto industry product cycles, development times, and rates of technology change, obtaining an estimate that 8-11 years of lead time are needed to achieve full penetration of the efficiency improvements. Given the late 1993 timing of this report (model year 1994 has started), this implies that the industry can achieve the estimated degree of fuel economy improvement by model years 2002-2005. There have undoubtedly

been increases in the use of some of the technologies since the 1990 base year assumed here. However, these technology improvements have not been directed toward fleetwide fuel economy improvement. Thus, achieving the vehicle efficiency increases estimated here could involve not only incorporation of new technology but also a redirection of existing technology applications. This suggests that the feasible improvements could actually happen more quickly or at lower cost than estimated here.

The resulting estimates of potential fuel economy improvement are presented in Box S1 (next page). Reflecting the uncertainties surrounding new applications of technology, we present our results at three levels of technical certainty:

> Level 1 includes technologies already in use in at least one mass market vehicle worldwide and which have no technical risk in that they are fully demonstrated and available;
>
> Level 2 incorporates measures which are ready for commercialization and for which there are no engineering constraints (such as emissions control considerations) which inhibit their use in production vehicles but which entail risk in that some "debugging" may be needed because of limited production experience;
>
> Level 3 technologies are those in advanced stages of development but which may face some technical constraints before they can be used in production vehicles.

In this context, technical risk is interpreted as the risk that a technology cannot be put into widespread use within the time horizon identified here at acceptably low cost (full production scale average cost). Allowing more time would lower the risk, but we are unable to say how much longer would be needed before such technologies could be counted on for widespread use at low cost. For options better characterized by degree of design refinement, such as aerodynamic improvements or weight reduction, the certainty levels are interpreted to be successively less conservative regarding the degree of improvement. Table S1 (page ix) lists the technologies through Level 2 and their estimated fuel economy benefits. Level 3 adds lean-burn and two-stroke engines, which must overcome nitrogen oxide emissions limitations before they can see widespread use throughout the fleet. Level 3 also includes further degrees of improvement in tractive load reduction.

In order of increasing technical uncertainty, the resulting estimates of achievable new car fleet average fuel economy are 40 mpg, 46 mpg, and 51 mpg. These values correspond to improvements of 43%, 65%, and 85%, respectively, over the 1990 base year average of 28 mpg. We also performed sensitivity analyses to investigate assumptions regarding fleet average acceleration performance and technology penetration. Increasing performance to the 1993 average lowers projected fuel economy by about 1 mpg; decreasing performance to the 1987 average raises it by about 1.5 mpg. There is a smaller sensitivity to the degree of technology penetration within the range considered. No change in average vehicle size is needed for the technology-based fuel economy improvements analyzed here.

While much judgment is clearly involved in policy development, we believe that our Level 2 estimate--a new fleet fuel economy improvement of 65% by 2002-2005--provides a reasonable target for public policies intended to increase automotive fuel economy. More ambitious targets might be justified under our Level 3 assumptions, since policy guidance can hasten the development and application of advanced technologies which have the potential for widespread commercialization.

Box S1. Achievable New Car Fleet Average Fuel Economy in 2002-2005, Incremental Cost, and Potential Nationwide Gasoline Savings.

Technology Certainty:	Level 1	Level 2	Level 3
Achievable, Cost-Effective MPG	40	46	51
Average Added Cost per Car (1993$)	590	770	840
Average Cost of Conserved Energy ($/gal)	0.55	0.53	0.51
Potential Savings in 2000 (Mbd)	0.4	0.5	0.6
Potential Savings in 2010 (Mbd)	2.1	2.8	3.2

Fuel economy values are the EPA composite 55% city, 45% highway unadjusted test ratings; note that adjusted (vehicle sticker) MPG ratings are 15% lower on average. Potential nationwide gasoline savings are given in million barrels per day (Mbd); convert to carbon emissions reductions using 50.2 MT_C/yr per Mbd and to hydrocarbon emission reductions using 0.17 MT_{HC}/yr per Mbd.

Two types of checks corroborate the fleet-average technology penetration analysis used to obtain our summary results: simulation analysis of improvements for a typical vehicle and comparison to fuel economy levels actually achieved in a particular car.

Applying an engineering model relating fuel consumption to vehicle tractive loads and engine performance for standard driving cycles enables us to simulate the effect of technologies on a specific vehicle. Taking a 1991 Ford Taurus as an example, we analyze a set of Level 2 technologies applied to reduce vehicle loads and decrease engine friction. Figure S1 illustrates energy losses in the current vehicle (lighter bars) and the reduced losses in the improved vehicle (darker bars). The result is a 43% cut in fuel consumption per mile, implying a 75% improvement in fuel economy. Thus, applying technologies for tractive load reduction, engine specific power enhancement, and optimized transmission control raises the base vehicle's fuel economy from 27 mpg to 47 mpg, an increase just exceeding the fleet average we estimate at Level 2 certainty. Incorporating Level 3 technologies, such as lean-burn or two stroke engines and a greater degree of tractive load reduction, would permit an even greater improvement, to in excess of 50 mpg.

The 1992 Honda Civic VX provides a concrete example of fuel economy levels in the ranges we estimate. The lean-burn version has a composite unadjusted fuel economy of 60 mpg, slightly higher than the 58 mpg obtained by applying our Level 3 estimates to the 1990 subcompact fleet average of 31.5 mpg. The California version of the Civic VX has a fuel economy of 55 mpg, also higher than the 52 mpg average implied for subcompacts by our Level 2 technology estimates (without lean-burn engines). Although the Honda Civic VX is not an average car (as in the modeled Taurus example), it demonstrates substantial fuel economy improvements over a comparable Civic hatchback without reducing size or performance and using only some of the technologies reviewed here. Moreover, its improvements were already achieved, over one 4-year product cycle, while our projections allow 8-11 years of lead time for the fleet as a whole.

Accurately estimating the cost of improving fuel economy is difficult because of limitations in publicly available data and costing methodologies. Our technology cost estimates are derived largely from previously published information, such as studies by Energy and Environmental Analysis (EEA) and other sources. Costs for the Level 2 technologies are listed in Table S1. These estimates represent the incremental costs of improved vehicle technology, assuming the use of a mature technology averaged over a total production period and without premature replacement of production facilities. The resulting average per-car incremental retail price estimates are $590, $770, and $840 (1993$) for technology certainty Levels 1-3, respectively. The applicability of these cost estimates depends on assumptions regarding industry product cycles and other factors which affect the economics of motor vehicle production. In particular, costs are linked to lead time, since we estimated lead time sufficient to validate the assumption of no premature replacement of production facilities.

Given the above caveats, the estimated costs of fuel economy improvement are quite modest, in the range of 3%-5% of the average cost of a new car. These estimates are corroborated by the historical experience of past technology-driven fuel economy improvements, of which retrospective analyses have observed cost increases of roughly 5% of average new car price. While the estimates reported here are affected by industry economic factors which we are not able to address, this larger uncertainty cuts both ways: while it possible that actual costs of making the fuel economy improvements identified here could be higher than estimated, it is also possible that the costs could be lower, particularly as experience is gained and opportunities arise for finding cost savings in the course of product development.

Annual fuel costs for an average new car are roughly $500 per year at current fuel prices which, adjusted for inflation, are as low as they have ever been. Thus, although market interest in fuel economy is low, improving fuel economy is quite cost-effective to consumers, with an average payback time of less than four years. In reporting that the efficiency-related technology improvements identified here are cost-effective, we are not saying that they would necessarily be salable under today's market conditions. Much more efficient vehicles could be sold under changed conditions which might be brought about by various factors, such as national policies (fuel economy regulation, vehicle pricing incentives, or dramatically higher fuel taxes) or international events (wars, oil supply cartel decisions). Thus, policies to encourage or require efficiency improvement would change market conditions so as to lower the risk of applying technologies for efficiency improvement. In this regard, we distinguish the concerns of citizens from the concerns of consumers: citizens can collectively decide that higher fuel economy is needed to address problems of national concern and therefore support policy changes to raise fuel economy above the market level which they (and the auto industry) decide when acting as individual consumers.

The technology benefit, cost, and penetration estimates can be used to construct supply curves of potential fuel economy improvement and gasoline savings, as given in Figure S2 and Table S1. Figure S2(a) plots potential new car fleet average fuel economy against the Cost of Conserved Energy (CCE), expressed in 1993$ per gallon. The CCE is based on the ratio of incremental technology cost to fuel savings discounted with a 5% real rate over a 12-year vehicle life. It is an index of cost-effectiveness from the perspective of consumers in aggregate (all owners over the car lifetime rather than only the new car buyer). Figure S2 gives costs under our Level 2 assumptions; similar curves at other technology certainty levels are presented in Figure 7 of the report.

Each step in Figure S2 represents one of the technologies considered in our analysis, showing its incremental benefit for fuel economy improvement and its marginal cost expressed as an equivalent cost of avoided gasoline consumption. Steps are numbered by technology as listed in Table S1. For example, step 8 is variable valve control (VVC), which offers an efficiency benefit of 12% and would save 580 gallons of gasoline over an average vehicle lifetime. The cost for VVC is equivalent to having to pay only $0.46/gallon for this saved fuel, shown as the CCE level for step 8 in the figure. Technologies are cost-effective if their CCE is lower than the future price of gasoline expected over the life of the improved vehicles, which we assume to be $1.65/gallon (1993$).

The bottom part of Figure S2 shows the nationwide gasoline savings and greenhouse gas emission reductions in 2010 for each increment of new vehicle fuel economy improvement achieved by 2005. This graph assumes proportionate efficiency improvements in light trucks and expresses the CCE as a crude oil price equivalent, adjusting for the differences between oil prices and retail gasoline prices. Thus, savings of 2.8 million barrels per day (Mbd) can be obtained at a cost of just under $33 per barrel, roughly the oil price projected for 2010 by the U.S. Department of Energy. These savings would amount to a one-third cut in U.S. light vehicle fuel consumption, expected to otherwise reach 9 Mbd by 2010.

The corresponding reduction in greenhouse gas emissions would be 27 million metric tons per year (MT_C/yr) in 2000 and 140 MT_C/yr in 2010 (full fuel cycle CO_2-equivalent emissions expressed on a carbon mass basis). Achieving this level of new car fuel economy improvement would thus provide an 8% cut in U.S. CO_2 emissions otherwise expected for 2010, avoiding 38% of the projected growth in U.S. CO_2 emissions over 1990-2010. The cost of CO_2 emissions reduction is zero for fuel economy improvements having a CCE up to the avoided cost of fuel consumption ($33/bbl in 1993$, equivalent to retail gasoline at $1.65/gallon). For modest levels of fuel economy improvement lower than the fully cost-effective level, greenhouse gas emissions reductions can be achieved at net savings.

Of the gasoline consumption and CO_2 emissions reductions estimated here, 60% are from the improvements in passenger car fuel economy specifically analyzed in this report. The remainder are from proportionate improvements in light truck fuel economy, which we believe are similarly feasible and cost-effective although a detailed analysis has not been done by ACEEE.

The report also addresses the relationship between investments needed to improve fuel economy and issues such as market risks and competitive factors in the auto industry. Although not all firms are equally strong in all areas, competition induces ongoing enhancements of every firm's ability to respond to evolving market conditions. To meet changes in market conditions--be they induced by consumers, the world oil market, the government, or their competitors--a firm depends on its ability to develop quality products on a tight schedule, to retool quickly, and to execute flexible, "lean," production processes. An aspect of the advancing production efficiency includes relationships among competitors in the industry, such as joint ventures, product sharing, and outsourcing of components to competitors as well as to specialized suppliers. Thus, the issue of fuel economy improvement is largely one of how the industry's substantial, competition-driven capabilities are directed. In the absence of market signals or government policies to direct advances toward improving fuel economy, the industry's energies have recently been directed toward greater performance, luxury, and product differentiation, some of these coming at the expense of fuel economy.

We find no inherent reason why the industry's capabilities could not otherwise be channeled, with little change in risk or cost, given market signals or government policies pointing toward efficiency improvement. Given adequate lead time and balanced policies that provide equitable treatment of firms in the U.S. market, the 43%-85% improvements in conventional vehicle fuel economy identified here can be reached without added market risk and at modest per-vehicle cost, with overwhelming benefits in terms of fuel savings and avoided oil import and environmental costs over the life of the improved vehicles.

Our study shows that a number of technologies, implemented throughout the fleet to varying degrees, can yield a range of new car fuel economy levels considerably higher than those of today. There is a rich array of technological approaches for improving fuel economy, so that automakers need not count on the availability of only one circumscribed set of engineering options for reaching modest or intermediate levels of new fleet average fuel economy. The potential availability of less certain technologies, e.g., those identified here as Level 3 technologies, reduces the risk for reaching low or intermediate levels of fleet wide fuel economy improvement. Thus, there are multiple ways by which the new car fleet could evolve to reach, say, our Level 2 achievable potential of 46 mpg. Different approaches might, in fact, be taken by different manufacturers.

It is important to emphasize the conservatism of the results presented here, which rely solely on incremental improvement of vehicles based on gasoline-burning internal combustion engines, without radical changes in either design or manufacturing technique. We do not consider the potentially dramatic improvements in fuel efficiency that could be achieved through the use of hybrid drivetrains for efficient power management, net-shaping of composite body structures, along with advanced computer-aided design, manufacturing, and engine/transmission control technologies. The use of such approaches for automotive design has already reached the prototype stage, and could well be used for commercial production within a decade. Policy impetus for achieving improvements in new car fuel economy would do much to stimulate the commercialization of these more advanced technologies.

In summary, our review indicates that there is a wide array of available and near-commercial technologies which can be applied to improve automotive fuel economy over the next decade. Improving new cars to the mid-range (Level 2) estimate of 46 mpg by 2005 and improving new light trucks proportionally would cut U.S. gasoline consumption by 2.8 million barrels per day and reduce oil imports by at least 2 million barrels per day in 2010. There would be corresponding annual cuts of 140 million tons of greenhouse gas emissions and nearly 500,000 tons of hydrocarbon emissions. This degree of fuel economy improvement would add about $770 to the price of an average new vehicle. The overall annual cost increase in the new vehicle market would gradually rise to as much as $11 billion. Up-front investment costs by the auto industry will occur sooner but would be only a fraction of the overall retail cost increase. These costs are quite modest compared to annual expenditures of over $200 billion in new light vehicle purchases. Viewed as a national investment, fuel economy improvement is very cost-effective, with the gasoline cost savings reaching $70 billion per year by 2010 and continuing to rise thereafter. The enhanced economic growth from re-spending of these gasoline cost savings would increase net U.S. employment by nearly 250,000 jobs by 2010, including nearly 50,000 new jobs in the auto industry. In short, the large benefits to the nation--direct consumer savings, lower oil imports, reduced hydrocarbon and CO_2 emissions, and job creation--indicate that fuel economy improvement is one of the best investments the country can make.

Table S1. List of technologies, fuel economy benefits, and costs for mid-range (Level 2) estimates of technology certainty.

	Technology	Average MPG benefit	Est. unit cost	Fleet avg MPG increase	New Car MPG	CCE $/gal	ACE $/gal	Fleet avg cost	Savings in 2010 (Mbd)
1	Compression ratio increase	1.0%	$ 0	1%	28.2	0.00	0.00	$ 0	0.08
2	Lubrication improvements	0.5%	2	2%	28.4	0.11	0.03	2	0.13
3	Lower tire rolling resistance	4.8%	22	7%	29.8	0.12	0.10	24	0.46
4	Continuously variable trans.	6.0%	33	10%	30.6	0.15	0.12	37	0.63
5	Optimized manual transmission	11.0%	66	12%	31.3	0.18	0.13	51	0.77
6	Optimized transmission control	9.0%	66	19%	33.2	0.24	0.17	99	1.14
7	Accessory improvements	1.7%	14	21%	33.8	0.30	0.18	112	1.23
8	Variable valve control	12.0%	140	32%	36.8	0.46	0.26	232	1.71
9	Variable displacement	5.0%	70	34%	37.4	0.61	0.28	260	1.81
10	Overhead cam	3.0%	44	37%	38.0	0.64	0.29	284	1.90
11	Weight reduction	9.9%	160	47%	40.9	0.79	0.37	449	2.29
12	Friction reduction	6.0%	110	53%	42.4	0.97	0.42	536	2.47
13	Four valves per cylinder	6.6%	120	57%	43.9	1.03	0.46	621	2.64
14	Torque converter lockup	3.0%	60	58%	44.0	1.17	0.46	623	2.65
15	5-speed automatic transmission	5.0%	120	60%	44.6	1.42	0.48	667	2.72
16	Aerodynamic improvements	3.8%	100	65%	45.9	1.59	0.53	766	2.85
17	Multipoint fuel injection	3.0%	80	66%	46.2	1.73	0.53	784	2.88
18	Super-/turbo- charging	5.0%	180	70%	47.3	2.27	0.59	903	3.00
19	Idle off	6.0%	290	74%	48.3	3.19	0.67	1046	3.09

Average MPG benefit is for the technology applied to an individual car with Level 2 assumptions, as given in Table 1 of the report.

Estimated unit cost and fleet average cost increase are based on Table 4 but given in 1993$ (using a GDP inflator of 1.10 to update from 1990$ to 1993$).

Fleet average MPG increase is cumulative, based on an average of the High and Full penetration assumptions given in Table 2(b), and reflects an interpolated optimization factor to account for the multiplicative interaction of load reduction and drivetrain measures (based on Table 3).

Marginal (CCE) and average (ACE) cost of conserved energy are based on 5% real discount rate and 12-year, 10,000 mi/yr lifetime; CCE and ACE values would be 30% higher using a 10% discount rate.

Nationwide gasoline savings in million barrels per day (Mbd) in 2010 assume the given percentage MPG increase is achieved in new cars and light trucks by 2005 and are calculated relative to new fleet fuel economy frozen at the 1990 level of 25.2 mpg, using a fuel economy shortfall of 20%, a cost of driving ("rebound") elasticity of 10%, and total light duty Vehicle Miles of Travel (VMT) of 2.748 x 10^{12} miles/year in 2010.

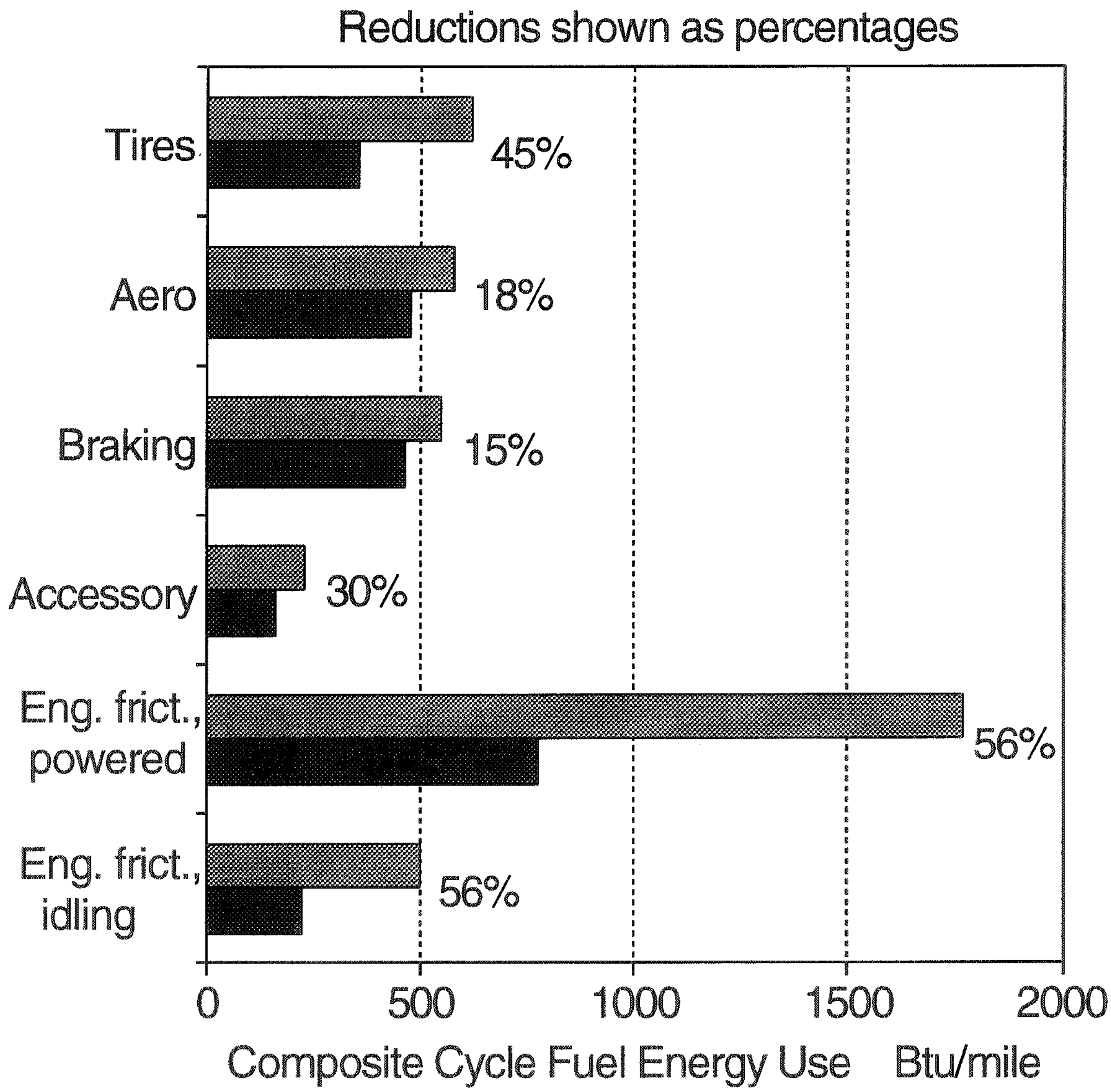

Figure S1. Potential Reductions in Fuel Energy Losses for a Typical Car

Based on application of Level 2 technologies to a 1991 Ford Taurus, resulting in an overall 43 % reduction in composite cycle energy use and a 75 % improvement in fuel economy, from 27 mpg to 47 mpg.

Tire losses reduced through lower rolling resistance and reduced vehicle weight.

Aerodynamic losses reduced through lower drag coefficient.

Braking (inertial) losses reduced through lower weight.

Accessory losses reduced by more efficient vehicle accessories.

Engine friction losses, both while under power and at idle, reduced by using a 4-valve per cylinder, variable valve timing, higher compression engine of reduced displacement with optimized transmission control.

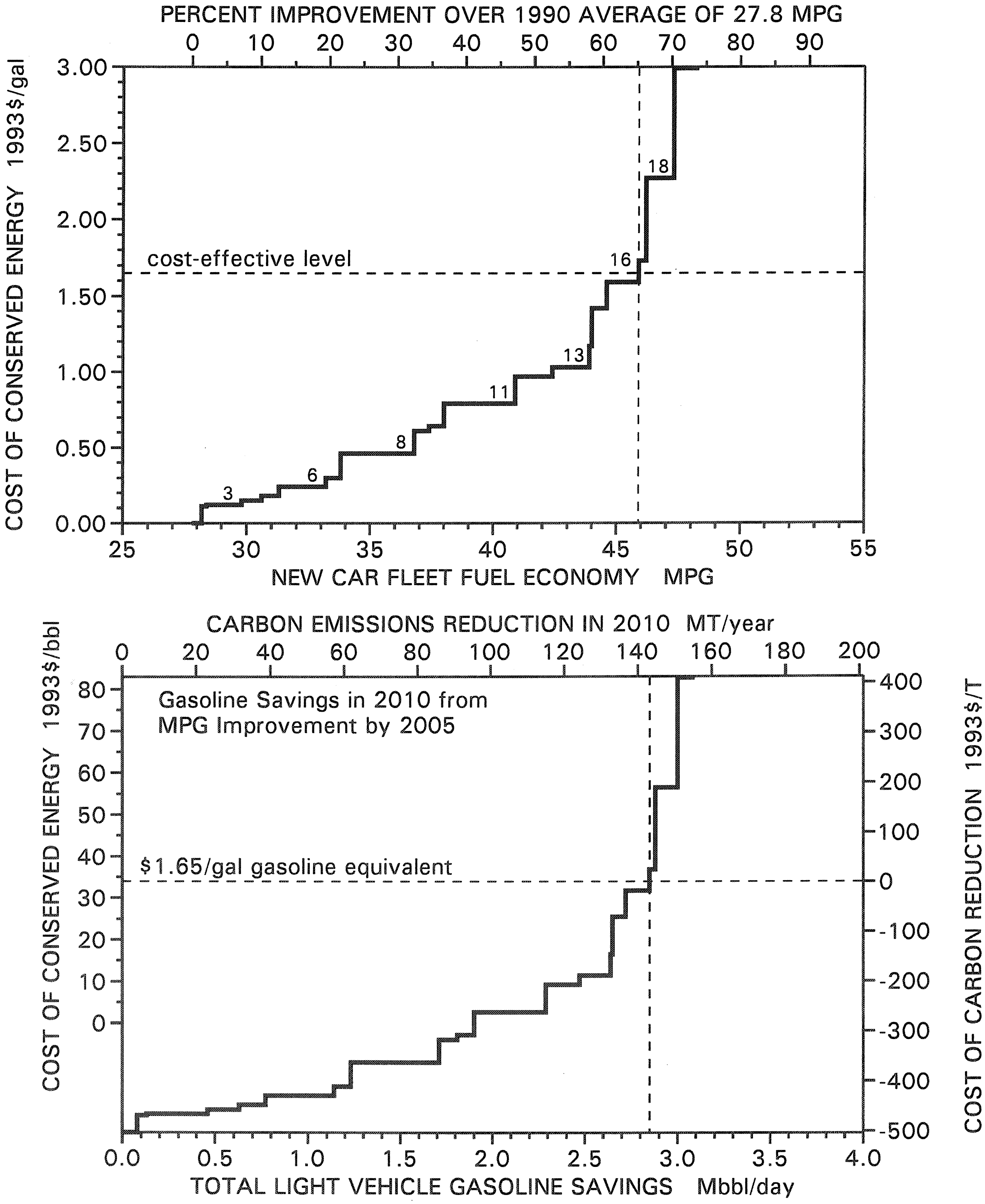

Figure S2. Cost Curves for Fuel Economy Improvement and Gasoline Savings

Results for certainty Level 2 assuming 5% discount rate and 12-year vehicle life, as in Table S1.
Steps: 1=CR inc, 2=Lube, 3=CVT, 4=Tires, 5=OptMT, 6=OptAT, 7=Access, 8=VVC, 9=Vari.D, 10=OHC, 11=Frict, 12=4-valve, 13=Wt red, 14=TCLU, 15=Boost, 16=5spAT, 17=Aero, 18=MPFI, 19=IdlOff.

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1. INTRODUCTION

Improving automotive fuel economy is a critical challenge for the United States, where cars and light trucks consume 12.3 Quads (6.4 Mbd) of petroleum fuel (98% gasoline).[1] Cars and light trucks (light duty vehicles) account for about 52% of U.S. transportation energy use and 35% of total U.S. petroleum consumption. The United States now imports over 40% of its oil, a fraction which is expected to reach 60% over the next two decades (EIA 1993). Over the past two decades, the cumulative cost of oil imports was over one trillion dollars (10^{12} 1990$) and the total economic cost to the United States is estimated at over four trillion dollars (Greene and Leiby 1993). Oil import costs equal 70% of the cumulative U.S. trade deficit since 1975, the last year in which the country had a positive trade balance (Geller et al. 1993b). While significant of itself, light vehicles' 35% direct share understates their role in overall U.S. oil consumption, since much of the remaining consumption includes by-products of the high-value transportation fuels which drive the market plus the fuel consumed to operate the fuel production and distribution system itself.

Substantial parts of U.S. hydrocarbon (HC) emissions and carbon dioxide (CO_2) emissions are directly proportional to light vehicle gasoline use. Hydrocarbon emissions are a major cause of health-threatening ozone smogs and include benzene and other compounds which are directly toxic or carcinogenic. Transportation sector fuel consumption results in seven million tons per year of HC emissions (EPA 1991), of which perhaps one-third are due to non-tailpipe emissions associated with light duty vehicles.[2] Gasoline consumption results in carbon-equivalent emissions of 25 kg/GJ (7.2 lb/gal), counting the carbon content of the fuel itself plus upstream emissions in the fuel supply system (DeLuchi 1992). Fuel use by U.S. light vehicles thus contributes 320 MT_C/yr (million metric tons per year, carbon mass basis) of greenhouse gas emissions which cause global warming.

Pushed upward by population growth, suburban sprawl, and increased numbers of working women, light duty vehicle miles of travel (VMT) nearly doubled over the past two decades, growing at an average rate of 3.4%/yr (see Figure 1, page 81). Over the next two decades, light duty VMT is projected to grow at an average annual rate of about 2%/yr.[3] The result will be a nearly 50% increase in VMT by 2010 compared to the 1990 level of 1.8 trillion (10^{12}) miles/year. Measures undertaken to control VMT, particularly in urban areas facing persistent air pollution, hold some promise for helping to control this growth. One study found that concerted nationwide efforts to reduce VMT--including aggressive transportation demand management, provision of alternative travel modes, reform of land use policy, and a $0.75/gal increase in gasoline prices--could cut 2010 VMT by 15%, leaving net growth of 26% (UCS et al. 1991). However, the political will to take such strong steps to reduce U.S. automobile dependence is just now beginning to form in a few urban areas. It is likely to take much longer for the nation as a whole.

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[1] Authors' 1993 estimate for cars and personal light trucks, derived from 1990 statistics of Davis and Strang (1993) using estimated VMT growth and stock MPG improvement rates.

[2] Actual non-tailpipe HC emissions linked to light vehicle use are highly uncertain but known to be substantial. Mid-range estimates of DeLuchi et al. (1992) imply 11 g/gal for light vehicle fuel cycle HC emissions, not counting the tailpipe component and presuming tighter pollution controls than are presently in place; this provides a lower-bound estimate of 1.2 million tons/year (Mt/yr) for HC emissions proportional to gasoline consumption. Ross et al. (1991) estimated 2 Mt/yr based on air pollution model emissions factors, but NRC (1991) noted that existing mobile source emissions factors may low by a factor of two or more.

[3] UCS et al. (1991) estimates average light duty VMT growth of 2.0%/yr for 1990-2010; EIA (1990) estimates 1.9%/yr. Underlying assumptions in both cases are 2.6%/yr average real GNP growth, 1.8%/yr increase in real gasoline prices, and no major changes in transportation infrastructure and land use.

Alternative fuels--natural gas, alcohols, electricity, and hydrogen--offer hope for lessening transportation oil use. Presently, these are also mainly motivated by clean air concerns. Major investments in new vehicle technologies as well as new fuel supply infrastructure are needed before alternative fuels can hope to displace as much as 0.5 Quads (1 Mbd) of vehicle fuel use (DOE 1990). Vehicle efficiency improvements are also needed to make alternative fuels workable (Bleviss 1989; DeCicco 1992a). Because most alternative fuels have a lower energy density than gasoline, high efficiency will be essential for adequate travel range. The majority of the technologies for improving the fuel economy of conventional vehicles are also applicable to alternatively fueled vehicles. Applying such technologies in conventional vehicles as soon as they are developed will provide valuable experience and is likely to reduce costs for application in alternatively fueled vehicles. Finally, the extent of motor vehicle use is enormous. The 200 million motor vehicles in the U.S. are driven over 2 trillion (10^{12}) miles per year. The world vehicle population is 600 million worldwide and growing rapidly (MVMA 1992). At such a scale, inefficient use of any alternative fuel is not likely to be ecologically sustainable, no matter how "renewable" the fuel might be. For example, the scale of land-use impacts for biomass fuel production is inversely proportional to the efficiency of fuel end-use and even a biofuel produced with no net CO_2 emissions can still seriously threaten biodiversity (Cook et al. 1991).

In short, there is no escaping the need to greatly improve vehicle fuel economy if the United States wishes to reduce oil consumption and its adverse economic and environmental impacts.

Fortunately, the technologies available for improving automotive efficiency have been rapidly advancing. New engine technologies--such as lean-burn, two-stroke, and direct-injection turbocharged diesel--have been regularly in the news. Computerized controls for optimizing engine and transmission operations are now coming into use. New materials and structural designs offer a variety of benefits including reduced weight, better performance, improved crashworthiness, durability, and ease of assembly. Aerodynamic advances enhance styling, performance, and fuel economy. Advances in components--engine hardware and accessories, tires, lubricants, climate control, and even "nuts and bolts" (new fastening and bonding techniques)--each provide benefits that can sum up to further efficiency gains. There is also a latent ability to improve fuel economy by trading off the large gains in power performance realized through technology improvements since the mid-1980s.

New vehicle fuel economy improvement has come to a standstill. The rated fuel economy of new light duty vehicles peaked in 1988 at an overall average of 25.9 mpg. New fleet fuel economy has been stable or showed slight declines since then. Estimated averages in 1993 are 28.0 mpg for new cars, 20.8 mpg for new light trucks, and 25.0 mpg for the new light duty fleet (Murrell et al. 1993). The fuel economy of the vehicle stock (all vehicles, new and old) lags that of new vehicles, since vehicle lifetimes are 10 years or longer (however, vehicles are driven more miles in their early years of life). Because there has been no improvement in new vehicle fuel economy for six years now, stock turnover will yield a further increase of only about 0.2 mpg. Thus, the overall U.S. light vehicle stock will reach 25 mpg in 1995 and, absent improvements in the new fleet, the stock will not improve further. Thus, there is essentially no benefit to overall fuel economy to be had by early retirement (scrappage) of older vehicles. (By contrast, modest air pollution reductions can be obtained from vehicle scrappage, since average emission rates are higher for older vehicles than they are for newer vehicles; see OTA 1992. Fuel consumption per mile does not increase with age or poor maintenance nearly as much as emissions increase.)

Unless otherwise noted, the mpg values discussed in this report refer to EPA rated (test) fuel economy, unadjusted for actual on-road driving. A source of confusion regarding automotive fuel economy is the difference ("shortfall") of at least 15% between rated (EPA test) fuel economy, based on driving cycles as used for compliance with fuel economy standards, and the on-road fuel economy experienced by vehicles as actually driven. EPA adjusts fuel economy ratings downward by an average of 15% for publishing the Gas Mileage Guide and printing on vehicle stickers. However, recent work by Mintz et al. (1993) places the average shortfall closer to 20%, noting that it may be worse for some light trucks. For the U.S. light vehicle stock, the average on-road fuel economy in 1990 was 19.4 mpg (Davis and Strang 1993). The age-weighted average EPA test fuel economy of the light vehicle stock in 1990 was 24.3 mpg, also suggesting a shortfall of 20%. Thus, given the slight improvement from stock turnover through 1993, a good estimate of overall U.S. light vehicle fuel economy is an on-road average of 20 mpg. This corresponds to a fuel consumption rate of 12 liters per 100 km and a full fuel cycle CO_2-equivalent emissions rate of 600 g(CO_2)/mi (373 g/km). A large part of shortfall is due to driving under congested conditions; some is also due to increased highway speeds in recent years (Westbrook and Patterson 1989). An and Ross (1993) provide a detailed analysis of the effect of driving patterns on fuel economy.

In-use fuel economy can be improved by better vehicle maintenance and careful driving behavior. Some vendors offer aftermarket engine devices claimed to improve fuel economy; however, we are unaware of any which provide verified improvements. Proper tire inflation and tune-ups are estimated to improve fuel economy by 5%-10% over typical maintenance habits (Makower 1992). We suspect that the lower end of this range is more reflective of current vehicles, since fuel injection and electronic ignition controls are displacing carburetors and conventional ignition and timing systems, which were more susceptible to degraded fuel economy from being out-of-tune. Replacement (aftermarket) tires have an average rolling resistance about 20% higher than new vehicle tires, which are specified by automakers to help meet vehicle fuel economy ratings (Farber 1993). An effective labeling, incentive, or standards program for aftermarket tires could potentially add about 2% to stock fuel economy. Changing driving behavior can also increase fuel economy; preliminary results from a forthcoming analysis suggest fuel savings of about 5% (An et al. 1993). Therefore, if effectively established and maintained, improvements to vehicle operation and maintenance could yield a 10% or greater improvement in overall fuel economy.

No substantial ongoing improvement in stock fuel economy is possible without a steady improvement in new vehicle fuel economy, which is the focus of this report.

1.1 Previous Studies

Estimating the potential for automotive fuel economy improvement has been a contentious topic for policy analysis since the issue was first addressed following the 1973 oil embargo. Estimates made during deliberations leading to the 1975 Energy Policy and Conservation Act (EPCA) lead to the establishment of Corporate Average Fuel Economy (CAFE) standards, which mandated a new car fleet average of 27.5 mpg by 1985. A new round of deliberation followed the 1979 Iranian revolution and resultant oil price shock. Estimates of potential new car fuel economy in 1995 and later ranged from 37 mpg with then-existing technology to over 100 mpg with major technology changes and a smaller vehicle size mix (U.S. Senate, 1980). Studies by the Department of Energy found technically feasible levels of 43-50 mpg by 1995 (DOE 1980).

More recent deliberations have been precipitated by concerns about global warming, petroleum security, and the economic costs of inefficient oil use. Bleviss (1988) provided a broad overview of the needs, opportunities, and policy options for improving automotive fuel economy. A survey of auto industry supplier firms indicated that the U.S. fleet could reach 41 mpg by 2000 (Chappell 1989). Murrell et al. (1993) present a "best in class" analysis and also compare the various approaches that have been used to estimate potential fuel economy improvements. Other studies providing specific estimates of the near-term potential for improvement include: Difiglio et al. (1989); EEA (1991a); OTA (1991); SRI (1991); Ross et al. (1991); Greene and Duleep (1992); and NRC (1992). These reports and papers have figured in the ongoing debate about increasing CAFE standards. Because of the burdens that might be placed on the automotive industry, such increases have been an extremely contentious issue.

A variety of assumptions can be made which determine the outcome of a technological assessment of the potential for increasing fuel economy. Estimates of the potential fuel economy of the new automobile fleet for the year 2001 range from 28.7 mpg (no improvement over 1988 level) to 44.2 mpg (55% higher than the 1988 level); reviews are given by OTA (1991) and NRC (1992). Disagreements can be traced to divergent assumptions about the benefits, costs, applicability, and marketability of the technologies considered. Critiques of the NRC (1992) study are given by DeCicco (1992b) and Plotkin (1993).

Many of the published near-term quantitative estimates (those that put a number on the potential fuel economy level in 10-12 years) are limited in that only technologies already in production are considered. Longer-term estimates, projecting potential fuel economy levels for 2010, were provided by EEA (1991a). Books such as Bleviss (1988) and Seiffert and Walzer (1991) discuss many advanced technologies and prototype vehicles, but did not distill the information into specific estimates of feasible fuel economy levels. The assessments that have provided quantitative estimates of feasible fuel economy levels work primarily from the technology data base built up by EEA (1985 and 1991b), which underpin the recent studies by federal agencies (DOE, EPA, and OTA). A similar data base has been prepared by auto industry consultants (SRI 1991). The technologies included in these data bases are now already five or more years old; newer technologies and further refinements of the existing ones are not fully included.

1.2 Overview and Methodology

This report updates the existing assessments of the potential for automobile fuel economy improvement by considering technological developments not included in previous studies. Another objective is to present a range of estimates, thereby reflecting the variety of ways which a particular level of fuel economy might be achieved and the greater improvements possible with refined and emerging technologies. A similar approach was taken in the EEA (1991a) study for a year 2010 time horizon, which identified three levels (45 mpg, 54 mpg, and 74 mpg) according to increasing technological uncertainty.

In our assessment we first examine the feasibility of increasing vehicle efficiency by analyzing technology options (Section 2) and then integrate the options into estimates of the technical potential for fuel economy improvement on a fleet average basis (Section 3). We check the results of the fleet average analysis by applying an engineering model of vehicle fuel consumption to evaluate potential changes to a typical car. Next, we incorporate technology cost information in order to estimate the cost-effective potential (Section 4.1). Finally, we discuss product cycle and market considerations as well as performance, emissions, and safety, leading to specific estimates of the potential fuel economy improvements achievable by a certain date (Section 4.3). A final section discusses other issues related to fuel economy improvement, including market risks, competitive factors, and broader economic impacts. Ultimately, judgements about appropriate assumptions regarding what is cost-effective and practically achievable rest with policy makers. Therefore, such judgements should not be imposed *a priori* in the first-stage analyses of technical potential, as done to varying degrees in some previous studies, notably OTA (1991), SRI (1991), and NRC (1992).

For our purposes, we adopt fuel economy as a practical measure of motor vehicle energy efficiency. Fuel economy refers to the distance traveled per unit amount of fuel consumed. More generally, fuel economy is the inverse of energy consumption per distance of travel (e.g., Btu/mile or J/m). Energy efficiency, in most engineering usages, refers to the fraction of an energy input that is effectively converted to a useful output. Physical energy efficiency is therefore dimensionless. Many practical energy end-uses, including motor vehicles, have no inherent level of output which can be used as the basis for a pure efficiency rating. Efficiency does make sense for some key vehicle components, however. A fundamental parameter is overall engine efficiency, which is the ratio of the brake energy output to the chemical potential energy contained in the fuel input. (Brake energy is that delivered through the flywheel and which is available for supplying motive energy through the remainder of a vehicle's driveline.) Transmission efficiency is the ratio of the energy delivered to the wheels net of frictional losses in the transmission (including clutch or torque converter), relative to the input from the engine at the flywheel.

End-use energy efficiency for an automobile can be defined as the average energy delivered to the wheels divided by the energy content of the fuel used. The end-use efficiency of today's average cars is only about 15% (An and Ross 1993). Thermodynamic principles and materials limitations constrain internal combustion engine efficiency to the 40% range (approaching 50% for diesel engines). Practically speaking only about 80% of this theoretical limit could ever be achieved, because of engine and drivetrain frictional losses (Ross et al. 1991). Nevertheless, the implication remains that overall efficiency might be doubled, to 30% or so, before exhausting the limits of vehicle technology based on conventional internal combustion engine designs. Moreover, because vehicle loads can also be reduced, there is an even greater potential for fuel economy improvement.

A different concept of efficiency can be described in terms of the end-use service provided rather than in absolute physical terms. For example, moving one person a certain distance is a unit of output service. Given the energy required to do this, a metric such as passenger miles per million Btu can be considered a measure of efficiency. Vehicle size can also be an index of end-use service level or output, motivating concepts such as Volume-Average Fuel Economy ("VAFE," see, e.g., McNutt and Patterson 1986; Heavenrich et al. 1991; OTA 1991). Thus, vehicle size divided by fuel use is a type of efficiency measure (e.g., ft^3mile/Btu). Ways to reduce the energy consumed to provide a given level of transportation service are thus ways to improve efficiency in this more generalized usage of the term. An example would be improvements in vehicle aerodynamics, which lower the overall energy requirements for moving a vehicle. Better aerodynamics can thus improve end-use efficiency without a change in the engineering efficiencies associated with a vehicle's driveline components (engine, transmission, driveshaft, etc.).

Increasing the efficiency of a vehicle component will result in an increase in fuel economy. Making a smaller vehicle, without any efficiency improvements in its components, will also increase fuel economy. For example, "econobox" vehicles targeted for the low end of the market may have relatively inefficient engines and mediocre aerodynamics. However, their small size and lack of amenities results in high fuel economy. Although our motivating topic is fuel economy improvement, we generally refer here to efficiency improvement, ruling out a shift to smaller vehicles as part of our analysis.

We assume new car power performance (maximum acceleration and top speed capability) equivalent to the 1990 average of a 12.1 s 0-60 mph time. This assumption is critical, since in recent years many technology improvements have been directed toward enhancing performance rather than fuel economy. The "ACCEL" curve in Figure 2 illustrates the past decade's steady improvement in acceleration ability (as measured by the inverse of 0-60 mph time). Acceleration ability is primarily a function of a vehicle's maximum power to weight ratio. The performance increases occurred during the fuel economy improvements of the mid 1980s and have persisted even through the upturn in average vehicle weight over the past five years. New car fleet average 0-60 mph fell from 13.8 s in 1984 to 11.5 s in 1993 and average fuel economy would be 2 mpg higher (30 mpg rather than 28 mpg) if acceleration performance had remained unchanged (Murrell et al. 1993). For all light duty vehicles, the performance increase in the past five years (1988-1993) represents a 4% increase in per-mile fuel consumption and CO_2 emissions. Even without further performance enhancements, this implies increased nationwide gasoline consumption of 300,000 bbl/day and increased CO_2 emissions of 15 MT_C/yr by 2000.

The method used here to estimate fuel economy improvement is similar to that used by Difiglio, Duleep, and Greene (1990), Ross et al. (1991), OTA (1991), Greene and Duleep (1992), among others. Linearized, new-fleet average estimates of fuel economy benefit (as percent improvement) are estimated for each type of technology change. As stated above, we assume that the average size and performance (acceleration ability) of the new fleet remain unchanged from the 1990 average. A scaling analysis is used to examine the effect of higher and lower average performance levels on fuel economy. In all cases, however, average vehicle size (as measured by interior volume) remains unchanged.

Time and resource limitations have restricted our detailed analysis to passenger cars even though light trucks now account for a third of the overall light duty fleet. Light truck fuel economy has been more leniently regulated than that of cars and the new light truck fleet has lower penetrations of efficient technologies. At least 80% of light truck usage is strictly for personal transportation (Bureau of the Census 1990) and the principle source of inefficiency, namely poor part load efficiency, is at least as pronounced for light trucks as it is for passenger cars. Therefore, in projecting potential future fuel savings, we assume that light truck fuel economy can be increased proportionately to that of cars. NRC (1992) also estimated potential light truck fuel economy increases proportionate to those of cars.

Because of uncertainties regarding the commercialization of various technologies or the degree of fuel economy benefit that may be obtained, the analysis is presented for three levels of technical certainty, defined in Box 1. The most certain technologies are assigned to Level 1. The least certain technologies, which may face some technical constraint on commercialization, are grouped in Level 3. In this context, technical risk is interpreted as the risk that a technology cannot be put into widespread use within the time horizon identified here at acceptably low cost (full production scale average cost).

Box 1.	Certainty Levels of Near-Term Technologies for Improving Fuel Economy
Level	Technology Characteristics
1.	Technologies currently in production in at least one mass market vehicle worldwide and which have no technical risk in the sense that they are fully demonstrated and are available to all manufacturers through either direct production or licensing. Level 1 improvements are therefore available for production use within one product cycle.
2.	Technologies ready for commercialization and for which there are no engineering constraints (such as emissions control considerations) which would inhibit their use in production vehicles. Technologies assessed at Level 2 are considered to have low technical risk in the sense that some "debugging" effort may be required because of a lack of on-road experience.
3.	Technologies in advanced stages of development but which may face some technical constraints before they can be used in production vehicles. Because Level 3 technologies bear some uncertainty as to when they will be fully available for use in production, it is not possible to presently establish with certainty that they are available for incorporation into new vehicles over the course of a complete product cycle.

Allowing more time would lower the risk, but we are unable to say how much longer would be needed before such technologies could be counted on for widespread use at low cost. For options better characterized by degree of design refinement, such as aerodynamic improvements or weight reduction, the certainty levels are interpreted to be successively less conservative regarding the degree of progress in design refinement. Although assuming the use of all Level 3 technologies would involve technical risk, there is less risk in assuming the use of at least one or a few of such technologies, particularly if there is pressure (regulatory or market changes) to favor more rapid development and commercialization. For all levels, the issue of "market" (as opposed to technical) risk is addressed later (Section 5).

Based on the discussion in Section 4 of industry product cycles, 8 to 11 years is needed for full penetration of the new technologies. Assuming that automakers start to plan for directing their product development efforts for higher fuel economy in 1993, this would imply that the full potential at any level of technical certainty could be reached by 2002 to 2005. Clearly, if one were to extend the time frame to allow more time for development, it would lower the technical risk for the technologies at any Level, as well as increase the likelihood that options not considered here (e.g., power management technologies such as electric hybrid drivetrains) might become be available for production. The fleetwide impacts of some such advanced options were estimated by EEA (1991a).

2. TECHNOLOGIES FOR EFFICIENCY IMPROVEMENT

The technological approaches for increasing vehicle efficiency can be thought of as a menu of options which automotive engineers and designers can apply to develop an improved vehicle. We organize the menu under three headings: engine improvements, transmission improvements, and load reduction. The engine is a key component, which we isolate to examine technologies and designs which can improve its efficiency. Transmission design and control has a major effect on the efficiency which any engine achieves in operation. Load reduction refers to decreasing the amount of energy that needs to be delivered by the engine and transmission (the "drivetrain") during the course of vehicle operation. Ways to cut aerodynamic drag, vehicle weight, and rolling resistance are examples of load reduction. Load is also reduced by making a vehicle smaller, but, as noted in the introduction, this approach is not considered here.

The separate treatment of engine, transmission, and load is done mainly for convenience, since in reality, these aspects of design are closely interrelated. The discrete analysis applied here is needed to provide quantitative estimates of the potential for fuel economy improvement. However, such an analysis does not capture the integrated nature of vehicle design. Design for efficiency is perhaps best thought of as part of an evolutionary process, with fuel economy being but one of many factors that designers consider together to develop a vehicle that is both elegant and efficient in a very broad sense of the word (MacCready 1992). Thus, engineers do not improve vehicle fuel economy by just discretely selecting items from a technological menu like that reviewed here. To better capture the integrated nature of design and the interactions of the options from the "menu," we also apply an engineering model to synthesize a refined design for a typical vehicle. That analysis also serves as an check on the estimates of potential fuel economy obtained from the discrete analysis.

The estimates of technology-based efficiency benefits reviewed here are listed in Table 1 (detailed tables are at the end of the report).

2.1 Engine Technologies

A number of new engine technologies have reached production and near-commercial status over the past decade. Most of these have been discussed in previous fuel economy assessments mentioned earlier. Many have been applied for increasing vehicle performance as well as efficiency, with greater gains in performance in recent years. The effects of new engine technologies are clearly revealed in Figure 2, which shows trends in various vehicle attributes from 1975 to 1993. There has been a strongly rising trend of engine specific power, shown in the figure as HP/CID (ratio of horsepower to cubic inch displacement), which permits reducing engine displacement while maintaining a given level of vehicle performance. Generally, each 1% decrease in displacement yields a 0.6% increase in fuel economy at constant performance (Murrell 1990; An and Ross 1993). A smaller engine implies lower total friction as well as a reduction of weight, both of the engine itself and indirectly from lower structural support requirements for the smaller engine, as well as a potential aerodynamic improvement from a lower hoodline. In other words, engine refinements which enable displacement reduction permit a "ripple effect" of efficiency improvements if performance is held constant. This is likewise a major attraction of two-stroke engines, which are also discussed below.

Variable Valve Control

"The future belongs to variable engine control" states a section heading in Seiffert and Walzer (1991). The multiple benefits of Variable Valve Control (VVC) have been long known to automotive engineers. In conventional engines, the timing and lift (extent of opening) of intake and exhausts valves are fixed functions of crank angle, so that the same timing and lift are used at all engine speeds and loads. VVC mechanisms permit valve positions to be controlled depending on operating conditions, thereby permitting a more optimal management of induction and exhaust processes. The benefits of VVC include improved low-end torque (i.e., torque at low engine speeds) and better driveability, reduced emissions, reduced pumping losses, and lower idle speed, yielding improved fuel economy.[4] In the past, the challenge of developing a VVC mechanism that could be cost-effectively implemented on production models inhibited much use of this technology. Widespread application is now possible in light of ongoing advances in design and electronic control capabilities, along with realization that there are VVC mechanisms which, while not fully variable, capture a large part of the potential benefit.

OTA (1991) cites a 6% fuel improvement from a variable timing and lift control form of Early Intake Valve Closing (EIVC) when the engine is downsized to provide equal performance; however, this reflects only the high RPM power boost application, without simultaneous application for low speed pumping loss reduction. Ross et al. (1991) analyzed the use of EIVC as a replacement for throttling. This provides a way to lower the engine's power output to match low loads without incurring the pumping losses associated with use of a throttle valve. The Ross et al. analysis showed a 7% MPG improvement from EIVC. However, they note that substantial further improvements if VVC were optimized to boost power at higher engine speeds, enabling engine downsizing at constant power. OTA (1991, p. 30) notes that "without the lean-burn feature, it appears that a 10- to 15-percent benefit may still be possible with VTEC [VVC] technology while maintaining all other vehicle attributes constant" and notes that such an engine could meet future federal NO_x standards. NRC (1992, p. 206) estimates a potential "gain of 16 percent for variable valve control and the changes in axle and gear ratios it permits."

Elrod and Nelson (1986) describe tests of a VVC mechanism implementing Late Intake Valve Closing (LIVC), also used as a throttle replacement strategy. Their reports claim up to a 20% fuel economy improvement from use of the VVC mechanism; however, sufficient technical information was not provided regarding the baseline engine or driving cycle context for such a large benefit. Ma (1988) performed simulation studies for LIVC on a base dual intake valve engine, suggesting the potential to simultaneously improve European driving cycle fuel economy by 11% and 0-100 km/h acceleration performance by 8% through the use of LIVC.

Honda employs VVC in its "VTEC" (variable valve timing and lift control) systems. The VTEC system is electronically controlled and capable of controlling lift and timing of both intake and exhaust valves. It can be applied in various configurations, allowing improvements in fuel economy, power, or both, depending on the design objectives. The VTEC system was first introduced on a U.S. model in the 1991 Acura NSX, for performance optimization at high RPM in its 3.0*l* V6 engine. As applied in the "VTEC-E" configuration for the Civic VX, Honda (1991) reports a 5% fuel economy benefit from VTEC employed with exhaust gas recirculation (EGR, for NO_x control) and a 15% benefit when

[4] See, for example, Gray (1988); Dresner and Barkan (1989); Amann (1989); Mendler (1991); Demmelbauer-Ebner et al. (1991); Horie et al. (1992).

employed with lean burn (discussed later). Honda has also applied VTEC in the Civic Si model since 1992 and has announced it use in the 1994 Accord; in both instances, the benefits of VVC are directed toward performance enhancement and to a lesser degree fuel economy improvement.

The Civic VX configuration, designed for fuel economy, delivers 61 hp/*l* (@5500 RPM), compared to the 90 hp/*l* (@5300 RPM) delivered by the Acura NSX (Consumer Guide 1991; Honda 1991). The best available comparison for similar applications with and without VVC is the Honda Civic Si model. The 1991 Si with 1.6*l* engine delivers 108 hp (@6000 RPM) without VVC; the 1992 model's 1.6*l* engine delivers 125 hp, incorporating VTEC for intake valve control only. This represents a 16% increase in power performance as well as a slight increase in fuel economy (other modifications of lesser significance were also involved). Downsizing the engine to 1.4*l* would deliver the same power as the 1991 version and yield a 12% fuel economy benefit.[5] Such proportionate downsizing is possible with VVC because it allows maintenance of relatively high torque at low RPM (in contrast to adding valves, which provides a power boost with high-end peak torque but has relatively less torque at low RPM--see, e.g., Horie et al. 1992). We use 12% as the estimated fuel economy benefit of VVC and classify it at Level 1 certainty. This is consistent with the range of potential benefits reported by OTA (1991) and NRC (1992).

Variable Displacement

Variable displacement is another form of variable engine control. A variable displacement engine deactivates some of its cylinders at low loads, reserving them for high load conditions. The result can be a considerable improvement in part-load efficiency and overall fuel economy. Mitsubishi introduced a variable displacement engine in Japan in 1982 and a number of other automakers have also explored this option (Bleviss 1988). In 1981, GM introduced a variable displacement engine for some Cadillac models. This was the "V8-6-4" engine, 6.0*l* with eight cylinders, delivering 140 HP @3800 RPM (GM 1981); however, this engine suffered reliability problems and was discontinued in 1984. There have been significant advances in engine control technology since then. In fact, implementation of variable displacement by deactivating the valves on the cylinders to be cut out can be thought of as an ultimate extension of variable valve control.

More recently, Mitsubishi announced a new 1.6*l* variable displacement engine, called the MIVEC, for use in Japanese Mirage models and under consideration for the U.S. market (Maskery 1992; Johnson 1992b). The MIVEC engine incorporates many advanced technologies, including four valves per cylinder plus variable valve timing and lift control. It shuts down two of its four cylinders by disengaging their valve cams at low loads below 3400 RPM, which includes cruising conditions at up to 65 mph on the model tested. The 1.6*l* MIVEC engine is rated at 175 hp, or a whopping 109 hp/liter. By contrast, the 1.6*l*, 16-valve engine used in the 1992 U.S. market Mirage delivers 77 hp/liter, which is itself a quite respectable level of performance. A variable 2-4 cylinder engine may present vibration problems; however, 3-6, 4-6, or 4-6-8 versions are likely to be acceptable and would be particularly applicable for larger cars and many light trucks.

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[5] Calculation based on model of Ross, Ledbetter, and An (1991), assuming friction coefficient of 0.25 kJ/*l**rev, indicated efficiency coefficient of 1/40%, and torque rating of 136 N*m (100 ft*lbf) at 5000 RPM.

A comparison of Mitsubishi MIVEC engine with a base 1.6*l*, DOHC, 16-valve engine from which it is derived indicates a 16% fuel economy improvement on a Japanese test cycle (Birch et al. 1993). The reported fuel economy of a MIVEC-equipped Mirage is over 50% higher than the 29 mpg rating of the 1992 U.S. market version of the Mirage (Maskery 1992). Neither of these reports provide sufficient information to make a fully adjusted comparison. Cutting off a cylinder will eliminate the pumping loss and a portion of the valve train and ring friction associated with that cylinder. Pumping losses account for about one-third of total engine friction over periods when variable displacement would be used; including the other effects, we estimate a 40% friction reduction per cylinder for a valve-control based system. Assuming cut-off of one-half of an engine's cylinders over one-half of a composite driving cycle would thus imply a 10% reduction in total engine friction. This implies a 5% fuel economy benefit.

Our estimate for variable displacement is thus much lower than the 20% efficiency improvement reported for some earlier work by Porsche, as cited in Bleviss (1988). However, we can only count the additional benefit obtained when variable displacement is used in combination with other technologies considered here. Since we estimate a 12% benefit for VVC, a 5% benefit for variable displacement is roughly consistent with the 16% improvement over the non-VVC base engine cited by Birch et al. (1993). We consider the new generation of variable displacement engines, e.g., as implemented by Mitsubishi, to be available at technology certainty Levels 2 and 3.

Variable displacement is a promising complement to the various technologies which allow net displacement reduction. By providing a part-load efficiency improvement without necessitating further overall engine downsizing, it avoids the driveability constraints that inhibit downsizing because of the need to maintain adequate low-end torque. Furthermore, it achieves the improvements without the NO_x emissions constraints faced by lean-burn (including two-stroke) engines. It is therefore applicable to all size classes and would be particularly beneficial for improving the fuel economy in the light truck classes. We estimate the potential penetration of variable displacement engines at 40%, which complements the 60% penetration limit imposed for lean burn (discussed below). This is consistent with the EEA (1991a) view that the benefits of variable displacement could be largely duplicated by other technologies including lean burn. However, we may be conservative in not considering use of a combined lean-burn variable displacement engine. The efficiency benefits for combining lean burn with variable displacement would not be fully additive, but there could still be a net additional improvement which is omitted here.

Boosting

Boosting refers to the use of a turbocharger or supercharger to pressurize cylinder intake air. A turbocharger is an intake air compressor driven by a turbine which extracts power from the exhaust stream. A supercharger is a compressor driven by other mechanical or electrical power. Boosting may also be achieved by a pressure wave ("Comprex") approach, using tuned flows in the manifolds to synchronize compression waves with intake flows. Heywood (1988), Stone (1985), and other basic automotive engineering books give general principles and examples of boosting devices. In short, the forced induction process increases intake mass flow, allowing more fuel to be burned and greater power to be delivered by an engine of a given displacement.

Because boosting can increase charge temperature, it can limit compression ratio and create an efficiency penalty. An added penalty may be increased parasitic losses for operating the boosting device. Modern supercharger and turbocharger system designs overcome most of the efficiency penalties associated with conventional designs (Bleviss 1988). Adding a turbocharger can create an emissions control problem because it comes between the exhaust manifold and the catalyst, cooling the exhaust and lengthening the time for the catalyst to reach its operating temperature (German 1993). This could be remedied by catalyst pre-heating, which adds costs, or perhaps by careful design. Superchargers would not have this problem but may not be as efficient as turbochargers because they do not recover exhaust energy.

Boosting is typically applied for the purpose of enhancing power performance. However, boosting can increase fuel economy if engine displacement is reduced while maintaining fixed vehicle performance. SRI (1992) notes that "optimal redesigns of downsized gas engine with such forced induction systems can demonstrate potential [fuel economy] gains up to 8% over comparable larger, naturally aspirated engines." EEA (1988) estimates a 5%-8% fuel economy gain for various boosting techniques applied to gasoline engines at constant performance. Our analysis using the An and Ross (1993) model indicates a potential 7% fuel economy benefit from turbocharging when adjusting other vehicle parameters for constant performance.

Because efficiency-oriented use of boosting has seen limited application to date, there is little information regarding the extent of achieved fuel economy improvement, particularly when boosting is applied in combination with the other engine efficiency measures discussed here. Kanamaru et al. (1992) examined the use of turbocharging in combination with variable valve timing and found decreases in specific fuel consumption of 5%-10% over typical engine speeds, but they did not report net test cycle-averaged fuel economy benefits. Considering the very large power increases regularly achieved even in advanced engines from the use of supercharging, a 5%-8% range of fuel economy improvement from adding boosting while maintaining performance seems to be a reasonable estimate. We thus assume that boosting offers a 5% fuel economy benefit at certainty Levels 1-2 and, because of the potentially greater emissions control challenge, assume an 8% benefit only at Level 3.

General Refinements

A number of refinements to the conventional four-stroke gasoline engine have shown steadily increasing application over the past decade. These include use of fuel injection, overhead camshafts, roller cam followers, and other friction reduction techniques. The potential fuel economy benefits of these technologies are well understood and have been documented by EEA (1985-1991b). The fuel economy benefits of these engine refinements are discussed here only insofar as they differ from previously published estimates, which should be referenced for further information.

Use of **Four Valves per Cylinder** permits a 4- or 6-cylinder engine to replace a 6- or 8-cylinder engine of equivalent performance (EEA 1985). The greater flow area and faster response provided by multivalve engines improves volumetric efficiency and allows higher engine speeds. On average, four-valve engines have peak power output levels about 40% higher than two-valve engines of a given displacement (Murrell et al. 1993). Power needs can thus be met with an engine of smaller displacement, which also lowers total engine friction, particularly at part load. The average fuel economy benefit from the resulting engine downsizing is 6.6%, based on a 1990 fleet weighted average of the EEA estimates as reported in OTA (1991). The use of four valve per cylinder engines (and three valves per cylinder, which provides an intermediate level of performance) has been increasing, but the applications have often been largely for performance enhancement. For example, there has been upsizing and performance enhancement of some compact models using powerful 24-valve, 6-cylinder engines. As is the case in general, this market trend away from fuel economy improvement does not imply a lessening of the technical potential for improvement if the technology applications were redirected.

Overhead Camshaft designs have fewer moving parts and less intertial mass than older pushrod (overhead valve) engine designs. Overhead cams are also more compatible with refinements such as four-valve heads and variable valve control. Conversion of a pushrod engine to overhead valves helps to increase volumetric efficiency and allows higher engine speeds, permitting downsizing at constant performance for an average fuel economy benefit of 3% (EEA 1991b).

Fuel Injection offers benefits not only for fuel economy, but also for performance, reliability, and emissions control. Carburetors have thus all but disappeared from the light vehicle fleet over the past several years. In 1990, the base year for this assessment, 98% of the light duty fleet was fuel injected, with 75% using multipoint (cylinder port) rather than single point (throttle body) injection. Based on a 3.0% per vehicle improvement (OTA 1991), the remaining potential fleet fuel economy improvement is 0.2 mpg from conversion of the remaining 25% of the fleet to multipoint injection.

Engine **Friction Reduction** involves a number of incremental improvements which can collectively yield a substantial fuel economy improvement. Here, we focus only on the rubbing friction that occurs among the various moving parts of the engine itself. Three current technologies for reducing rubbing friction are low friction piston/ring designs, roller cam followers, and what EEA refers to as "advanced" friction reduction.[6] Each provides an approximate 10% reduction in engine friction and so yields a 2% fuel economy benefit (NRC 1992). The sum of these improvements would be 6%, but a total of only 4% appears to be used for the maximum technology estimates in OTA (1991); the exact values assumed are unclear because intermediate baseline levels are not listed in the OTA report. The EEA estimates reported in NRC (1992) assume a 10% friction reduction from a 1987 base, with penetration of the lower friction refinements at 21.2% of the 1990 new car fleet. The friction reduction estimates identified in SRI (1991) give a range of 2% to 4.3% potential benefit. Ross et al. (1991) estimate a 6% benefit for friction reduction excluding roller cam followers, which are separately itemized as offering a 1.5% benefit, implying a total estimated benefit of 7.5% from various friction reduction techniques.

In general, measuring engine friction is difficult (Heywood 1988) and there are relatively little published data. As Ross et al. note, "a definitive estimate of the practical [friction] reduction potential isn't possible." We assume a 6% total potential benefit, which appears to be the middle range of previous estimates and corresponds to the sum of benefits listed in OTA (1991). This 6% benefit corresponds to a net 30% reduction in rubbing friction as could be achieved by incorporating low-tension rings, lighter weight and improved materials in various components such as valves, springs, pistons, and connecting rods, and roller cam followers into a base engine lacking any such refinements.

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[6] See discussion on pp. 27-28 and Tables 7-7, 7-8, 7-12, and 7-13 of OTA (1991); also, Thur, Paterson, and Reilly (1988). "Advanced" friction reduction includes use of lighter weight and better materials in various components such as valves, springs, pistons, and connecting rods.

Increasing engine **compression ratio** leads to an improvement in thermodynamic efficiency but is limited by the need to avoid knock (Heywood 1988; Stone 1989). Compression ratio can be readily increased as part of engine redesign; "the price of increasing compression ratio is essentially zero" (EEA 1985, p. 2-5). The average compression ratio of gasoline-powered new cars was 9.1 in 1990. An increase to about 10 is generally accomplished in the course of redesign with other engine refinements discussed here and is already reflected in the fuel economy benefits estimates for 4-valve engines (EEA 1991b). Ongoing ancillary refinements (cylinder head design, charge flow control, electronic control of timing and injection, knock sensors) which are integral to state-of-the-art engine technology permit further compression ratio increases without any change in fuel octane requirements.

We project a potential additional half-unit increase, to a fleet average compression ratio of 10.5. In this range, a 1-unit compression ratio increase yields an indicated efficiency benefit of about 1% (Heywood 1988, p. 842). The thermal efficiency benefit of compression ratio increase applies across an engine's load range. Assuming an average part-load efficiency of about 50%, a thermal efficiency increase of 0.5 percentage points thus implies a 1.0% fuel economy benefit. EEA (1991a) projected an increase in compression ratio to an average of 11.0 by 2010, but assumes a lower benefit, not adjusting for the equal benefit across the engine's load range. Further thermal efficiency benefit may come from the use of variable compression ratio (EEA 1991a; Seiffert and Walzer 1991). However, variable compression ratio mechanisms are fairly complex and cost estimates are not available, so they are excluded from this assessment.

Most of the engine refinements discussed here have seen increased application throughout the fleet each successive model year. There have been significant penetration increases since 1987-88, when new fleet fuel economy peaked. However, further fleet average fuel economy improvement has not occurred. In fact, since 1988, average engine displacements have increased while the technology refinements have progressed. This trend in itself indicates that the improved engine technologies are being applied contrary to fuel economy improvement, which would have enabled displacement reduction at constant performance. Instead, there have been ongoing increases in both vehicle weight and power performance. While our principal results are based on 1990 performance levels, somewhat greater fuel economy benefits from engine refinements could be realized with a relaxation of the record-high fleet average performance levels of the most recent model years. These are examined in a sensitivity analysis discussed later in the report.

Idle Off

Idle off, or engine "stop-start," allows the engine to be turned off when no power is demanded, for example, when a vehicle is stopped, braking, or coasting. This technology has been demonstrated by Volkswagen and is discussed in Bleviss (1988), Seiffert and Walzer (1991), and Ross et al. (1991). Seiffert and Walzer report potential fuel savings of 20%-30%, but did not specify the baseline. Ross et al. analyzed the fuel savings from use of idle-off over EPA driving cycles relative to a specified baseline vehicle and in combination with other technologies for improving part-load efficiency, including variable valve control and aggressive transmission management. Assuming that the engine is not turned off during one-third of the times when power is not demanded (allowing for accessory loads, etc.), the estimated fuel economy benefit is 11% for the EPA composite cycle (Ross et al. 1991). Based on re-analysis, we reduce this to 6% so as to not duplicate the benefits of other engine technologies that aggressively cut part-load losses, such as optimized VVC and variable displacement. Given that idle-off entails a greater change in engine operation than the other engine technologies discussed here and has seen only very limited application to date, further testing and refinement are needed prior to extensive use in production vehicles. We therefore list idle-off at certainty Levels 2 and 3.

Lean Burn

Most contemporary gasoline engines are designed to operate normally with a *stoichiometric* mixture of fuel and air. That is, the amount of air supplied contains precisely the amount of oxygen needed for complete combustion. For gasoline, the stoichiometric mass air-to-fuel ratio is 14.6, or roughly 15 parts of air to 1 part of fuel (Heywood 1988, Table D.4). *Lean burn* refers to techniques for using mixtures containing excess air, i.e., with air:fuel ratios greater than 15:1. Diesel engines inherently operate with lean mixtures, as do advanced two-stroke spark ignition engines. These engine types are discussed separately below; we focus here on lean burn in a four-stroke spark ignition engine. Advantages of lean burn are reduced pumping loss, an improvement in thermal efficiency, and potentially reduced emissions of hydrocarbons (HC) and carbon monoxide (CO). A disadvantage of lean burn is the difficulty in achieving catalytic reduction of nitrogen oxides (NO_x) under lean conditions and therefore a potential inability to meet NO_x emissions standards. As of this writing, lean-burn vehicles have not been certified to the 0.4 g/mi NO_x level being phased-in as the new U.S. standard over 1994-96.

The main technical challenge in achieving lean burn is overcoming combustion instability, which can lead to rough running and increased HC and CO emissions. Approaches to insuring reliable combustion of lean mixtures include use of a highly stratified charge, which ignites readily and then spreads throughout the rest of the mixture, or an ignition system which delivers higher spark energy or distributes the discharge more broadly than a single standard spark plug (Heywood 1988). The stratified charge approach may incur some charge induction friction penalty and face NO_x limitations, since there is a single flame front with a high temperature; however, it has been proven workable in practice (e.g., as demonstrated on the Honda VX). The distributed/high energy ignition approach avoids these two problems but has yet to be demonstrated in a production engine. Low engine-out NO_x (0.2 g/mi or less) can be achieved with very lean mixtures (air:fuel ratios of 25:1 or more), e.g., as have been reported by Ward (1992). Japanese automakers are simultaneously pursuing both approaches.

Toyota introduced lean-burn engines to Japan in 1984 and to Europe in 1988 (Harada et al. 1993). Lean burn was not widely considered to be a near-term option for the U.S. market until Honda's introduction of a lean-burn version of their VTEC engine in the 1992 Civic VX. Lean burn was not included in the estimates of OTA (1991) and was characterized as "most difficult to achieve" in the EEA (1991a) assessment for the year 2010. Subsequently, however, extensive efforts toward commercialization of lean-burn technologies have been reported (Johnson 1993). Honda applied a stratified charge ignition approach; describing the design, Horie et al. (1992) state that the "stratified charge ... stabilizes ignition by enriching the air-fuel ratio around the spark plug." Mitsubishi has also developed lean-burn engines based on a stratified charge ignition approach. Nissan has also announced development of a lean-burn engine. Higher energy discharge approaches to lean burn are under development by Mazda (Birch et al. 1992c; Johnson 1993) and Ward (1989, 1992). Toyota's most recent lean-burn design uses a pressure transducer for mixture control, but it is unknown whether the NO_x emissions are low enough to meet a 0.4 g/mi standard. Toyota also demonstrated a prototype lean (NO_x reduction) catalyst in the AXV-III concept car during October 1991 Tokyo motor show.

However, no manufacturers besides Honda have announced a lean-burn engine for the U.S. market. Mitsubishi is reported to be considering eventual use of their lean-burn (MVV) engine in the U.S.; they are focusing on a 2.0*l* engine (25% larger than Honda's 1.6*l* version) and view lean burn as being potentially applicable through a range of displacement requirements (Johnson 1992b).

Bleviss (1988) reviewed the development efforts of several manufacturers, which suggested potential fuel economy improvements of up to 20%. In practice and in combination with other engine technologies, the average benefit from lean burn is likely to be lower. EEA (1991b) estimated only a 6% benefit for lean burn by itself; however, reported test results are generally higher than that. Toyota's 1.6*l* lean-burn engine as applied in a Japan-only Carina (a 4-door Corona spin-off) has shown a 9%-10% fuel economy increase, achieving over 40 mpg (Johnson 1992a). More recently, Harada et al. (1993) report improvements showing a 9%-11% fuel economy while reducing NO_x emissions, but as noted earlier, it is not known whether this engine or a refinement thereof can meet the new U.S. NO_x standard. The 49-state and California versions of the Honda Civic VX have fuel economies 44% and 34% higher, respectively, than a comparable Civic without VVC, with the lean-burn model reaching an unadjusted composite rating of 60 mpg (EPA/TCL 1992). The contribution of lean burn to the overall fuel economy improvement demonstrated in the Civic VX is about 10%, consistent with the Toyota results and thus suggesting a 10% benefit from the implementation of lean burn alone.[7] We include lean burn only in assessment Level 3 because of the uncertainty regarding NO_x emissions.

Research on lean catalysts has been underway since the early 1980s. Recent focus has been on copper-zeolite catalysts; however, a system suitable for production vehicles is yet to be demonstrated (Farrauto et al. 1992). The main problem is achieving sufficient catalyst durability. The efforts to develop a lean catalyst appear to be extensive, particularly among Japanese automakers who are cooperating in a government-sponsored consortium but also have extensive private efforts. According to one researcher, "the possibility of making such a catalyst is almost 100 percent ... the only issue is when ... it will take at least five years ... we never know when the big invention will come."[8]

Without a demonstrated lean catalyst for NO_x control or demonstration of sufficiently low engine-out NO_x emissions, the potential penetration of lean burn in the U.S. market is likely to be limited to vehicles with peak engine power requirements of less than 100 hp (the 1.5 liter Honda VTEC-E engine is rated at 92 hp). Lean burn is therefore applicable throughout the compact and smaller car classes, which comprise 60% of the automobile fleet.[9] This potential penetration level is conservative in light of Mitsubishi's reported development work (Johnson 1992b) and because it reflects the tractive power requirements of the current fleet. Peak power requirements will fall across all vehicle classes because of the significant load reduction potential, discussed below in Section 2.3.

Two Stroke

Since the 1989 announcement by Orbital Engine Company of an advanced two-stroke engine that could potentially meet stringent emissions standards, there has been a renewed interest in the

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[7] Personal communication, American Honda Motor Company, August 1991; OTA (1991), p. 30; Horie et al. (1992) report fuel economy improvements of 8% and 12% on city and highway test cycles, respectively.

[8] K. Sasaki of Nissan Motor Co., as quoted in Automotive News (Johnson 1993, p. 30).

[9] Heavenrich et al. (1991). While lean burn might not be used in some of the more performance-oriented compact models or two-seaters, it could be used in some of the less performance-oriented mid-size models, so the 60% potential penetration estimate would still hold.

potential for two-stroke engines in automotive applications. The advantage of a two-stroke is that power from a cylinder is delivered on every revolution of the crankshaft, in contrast to once every two revolutions for a four-stroke engine. The resulting higher specific power output, along with better low-end torque, allow a smaller two-stroke engine to be substituted for a four-stroke at a given power requirement (EEA 1991a; Hellman et al. 1992). This substantial engine downsizing potential is one source of fuel economy gains. Modern two-strokes are an inherently lean-burn technology, allowing pumping loss reduction and substantial part-load efficiency improvement, which compound the fuel savings due to higher specific power. Some two-stroke engines do not require a valve train, resulting in further friction reduction and fuel economy improvement as well as cost savings. On the other hand, the high pressure air scavenging and reduced thermal efficiency of a two-stroke result in some offsetting efficiency losses (EEA 1991a).

Older two-stroke engines, as used in small equipment and relatively crude cars such as the former East German Trabant, had inherently high emissions, barring them from use in the U.S. market since the late 1960s. In contrast, advanced two-stroke engines, using fuel injection, forced scavenging, electronic control, and an oxidizing catalyst, have shown test results that meet the more stringent emissions standards now required (Fisher 1990; Schlunke 1991; Hellman et al. 1992). Most major automakers have expressed strong interest in the new two-strokes and Orbital is opening an engine plant in Michigan, although specific production vehicle applications have not been announced (Barkholz 1991). Other reports on the heightened interest in two-strokes include: Chrysler's work with Mercury-Marine Corp. targeting 1994-95 production of a 1.5*l* two-stroke engine; Ford's plans for using Orbital 1.2*l* engines in a test fleet of 100 Fiestas in Europe; and GM's development work on 3.0*l* V-6 two-stroke engine and use of a two-stroke methanol (M85) engine as a possible powerplant for the Ultralite prototype. Honda has also worked with Orbital on possible two-stroke applications. Toyota has been developing its own advanced two-stroke engine, using supercharger scavenging and overhead valves in contrast to Orbital's crankcase scavenging, direct-injection, cylinder-wall valve approach.

A technical challenge for two-stroke engines is meeting emissions requirements, particularly lower NO_x standards. Since advanced two-stroke engines are inherently lean burn, their application may be restricted by the present lack of a lean-operation, NO_x-reducing catalyst. As noted above, however, there have been promising developments regarding lean catalysts. Chrysler has demonstrated a lean catalyst in conjunction with its two-stroke work, reporting that the remaining hurdle is catalyst durability, as needed to meet 10-year, 100,000-mile requirements of the new standards (Keebler 1992b). Moreover, tests have suggested that two-stroke engines may be able to meet tighter standards without a lean catalyst, at least in some engine sizes. EPA has reported low-mileage NO_x emissions of 0.2-0.3 g/mi and one vehicle tested with a two-stroke engine approached the California ULEV emission levels (Hellman et al. 1991).

The EPA tests of 1990 small cars (Honda CRX-HF, Ford Festiva) retrofitted with two-stroke engines and meeting 1993 California emissions standards showed composite EPA fuel economy improvements of 5% or more (Hellman et al. 1991). However, these retrofits did not take advantage of the engine downsizing and other vehicle optimizations that would be available when using a two-stroke engine. EEA estimates the two-stroke's net fuel economy benefits at a range of 11% to 18% depending on design (EEA 1991a). Some of these benefits overlap with those achievable in an advanced multivalve four-stroke engine with VVC and lean burn. However, the two-stroke will offer these benefits at lower cost (as evidenced by the very active two-stroke development work underway by a number of major automakers). In any case, the fleetwide efficiency benefits of two-stroke engines would not be fully additive with the benefits of lean burn. Therefore, we list an estimated 10% benefit, the same as that for lean burn, which is also assumed to be additive to the engine refinements other than lean burn incorporated into our analysis. Thus, we treat two-stoke engines as an alternative and potentially lower cost approach to achieving the efficiency improvement levels of the most advanced four-stroke engines.

Diesel

Diesel (compression ignition) engines offer a significant potential for improvement over gasoline powered spark ignition engines because of their much higher compression ratios, high part-load efficiency, inherently lean operation, and amenability to turbocharging. European automakers have continued to advance the diesel engine and many of the diesel's traditional disadvantages relative to spark ignition engines, such as noise, smoke, poor acceleration, and cold start problems, have largely been overcome. Presently, the main technical hurdle for extensive use in the U.S. light duty vehicle market is the difficulty of meeting upcoming NO_x standards of 0.4 g/mi or lower while simultaneously meeting low particulate standards. California has been phasing-in its 0.4 g/mi NO_x standard over 1989-1994 and no light duty diesels have been certified in California since 1988 (CARB 1993).

Advanced direct-injection turbocharged diesels provide fuel economy benefit of 35%-40% over a gasoline engine for vehicles of similar weight (OTA 1991). It is difficult to make direct fuel economy comparisons between gasoline and diesel vehicles and the benefits appear to be somewhat lower at constant performance. However, fuel economy shortfall is generally lower in diesel vehicles compared to gasoline-powered vehicles (Bleviss 1988). Accounting for the incorporation of turbocharging and lean burn in our assessment of gasoline vehicles, the net additional benefit of such diesels would be 15%-20%.

The availability of a lean catalyst could remove the emissions barrier to new use of diesels (although the specific lean catalyst design would probably have to be different than that for lean-burn gasoline engines, since the fuels and their combustion products are so different). Radical load reduction or a hybrid electric design may also allow engine-out diesel emissions to meet stringent NO_x standards. However, only a lean catalyst is likely to permit major reductions in diesel NO_x emissions in non-hybrid vehicles (Calvert et al. 1993). Meanwhile, the potential need for additional control of particulate emissions coupled with the generally higher cost of diesel engines may remain as additional barriers to their use in the United States. Since we have not found research results that would support the use of petroleum-fueled diesel engines in non-hybrid vehicles, we exclude diesels from our estimates of potential fuel economy improvement, even at certainty Level 3. As noted above, however, the very active European efforts to pursue diesel technology through advanced direct injection designs and emissions controls with low-sulfur fuel suggest that diesels may re-emerge as a promising option for the U.S. market.

The U.S. EPA has been conducting research on methanol-fueled, glowplug-assisted diesel engines, which show great promise of achieving low emissions without either a lean catalyst or particle traps. Such compression ignition engines could thus play an important role in alternatively fueled vehicles. Diesels are also likely to be useful in hybrid vehicles which combine an engine with some type of energy or peak power storage device; the opportunities for efficiency improvement and emissions reduction with such designs appear to be quite large. Technologies for alternative fuels and hybrid vehicles are both beyond the scope of this work, but are important areas to investigate for the next level of fuel economy improvement beyond that discussed here.

2.2 Transmission Improvements

As pointed out above, an engine's efficiency drops off when it is operated away from the ideal throttle setting, which is near wide open throttle. Many of the engine technologies described above reduce this loss in mechanical efficiency. To maximize the amount of time an engine operates near its peak efficiency, however, requires an optimal synchronization of the transmission with the engine. The trade-off involved is largely one of driveability, referring to the response of a car to changes in power requirements. For example, suppose acceleration is needed while driving with a manual transmission in high gear. Pressing the gas pedal without shifting yields moderate acceleration. A driver can accelerate more quickly by downshifting, thereby moving the engine to a higher revolutions per minute (RPM). With an automatic transmission, there is a similar experience: moderate accelerations are accomplished without a gear change, but attempting a hard acceleration results in an automatic downshift and revving of the engine, so as to obtain greater power. There will be a more frequent need to downshift if engine displacement is reduced so as to take full advantage of the potential engine efficiency improvements identified above.

The situation is illustrated in Figure 3, which shows power curves and gear shifting options in terms of power output versus engine speed. Two power curves are shown: the upper curve represents a larger displacement pushrod engine and the lower curve represents a smaller displacement, overhead cam, 4-valve engine. There is a 4-speed transmission in both cases. Both engines have the same maximum power but the smaller engine achieves it at higher RPM. Consider a driving situation where an increase in power is needed for acceleration. The initial condition is denoted by point A on the figure, at about 15 hp, in 4th gear at just under 2000 RPM. The required power is 55 hp, which is below the maximum (wide open throttle) output of the larger engine at 2000 RPM but higher than the wide open throttle output of the smaller engine at this engine speed. With the larger engine, the higher power level is immediately obtained by simply pressing the accelerator, opening the throttle to the required level: this is denoted by the dashed line movement from point A to point B. With the smaller engine, 55 hp can only be obtained at higher RPM in a lower gear. Thus, acceleration requires downshifting from point A to point A', which revs the engine, and then opening the throttle to move to point B', at which the required power is delivered. The requirement for a downshift introduces a slight delay which is avoided with the larger engine.

The situation represented in Figure 3 suggests the driveability implications associated with reaping efficiency benefits through engine downsizing, even when maximum engine power output is preserved. Mechanical efficiency is higher for the smaller engine than for the larger engine at point A, which delivers adequate power for typical cruise or low load driving conditions. With the smaller engine, friction is reduced both because the engine is physically smaller and because the throttle is more open on average, reducing throttling losses.

Two aspects of transmission design are most relevant here. One is the number of gears, their ratios, and power bearing capabilities--i.e., the mechanical design parameters of a vehicle's transmission (and differential or transaxle, as applicable). A key parameter is the "N/v" ratio, expressed in RPM per mph, which corresponds to the number of engine revolutions per distance travelled in top gear. The fewer engine revolutions needed to move the vehicle a given distance, the less total engine friction, which is energy wasted. The other aspect of transmission design is to determine the best possible shift schedule for a particular mechanical transmission design along with a given engine and a specified set of driveability requirements. All of these factors are interrelated, of course, and the designer must manipulate them together in order to achieve the desired balance of performance, driveability, and efficiency.

Basic refinements

Two standard approaches for transmission improvement are **adding gears** in either manual or automatic transmissions, and **torque converter lockup** in automatics. Torque converter lockup reduces hydraulic frictional losses under many driving conditions. Adding gears allows a transmission to operate in an efficient regime with adequate driveability, effectively lowering the average number of engine revolutions per distance driven. Both of these technologies are included in the EEA assessments and we adopt the fuel economy benefits of 3% for torque converter lockup and 5% (net of adjustments for pumping loss reduction overlap with VVC) for increasing to five gears, as reported by OTA (1991). The torque converter lockup estimate is probably conservative, as it pertains to use of lockup in top gear only whereas newer mechanisms can provide lockup in lower gears as well, for a total potential benefit of up to 5% (EEA 1991b).

CVT

Continuously Variable Transmissions (CVTs) of various designs have been under development for some time and are in production on models such as the Subaru Justy. The fuel economy benefits of CVT have been extensively discussed in most of the fuel economy assessments cited earlier. A CVT allows an engine to operate at the lowest possible RPM under a given load and rev the engine up when more power is needed. Referring back to Figure 3, a CVT would allow a continuous transition of both throttle opening and overall gear ratio, following a smooth curve between point A and point B' (not shown). The delay associated with downshifting might be largely eliminated, thereby avoiding some of the driveability trade-offs that might occur when using a more aggressive shift schedule with discrete gearing. A CVT can have a friction penalty relative to discretely geared transmissions, such as manuals or automatics with lockup. Electronic control is needed for an optimally functioning CVT and "drive-by-wire" control would further enhance a CVT's ability to provide high efficiency along with good driveability (see Optimal Control, below).

The first generation of production CVTs are belt-driven and have been limited to smaller vehicles, with lower power (torque transmitting) requirements (e.g., the Justy weighs less than 2000 lbs and has a 66 hp engine). A number of automakers have been exploring CVT designs that would work at higher power levels. For example, Nissan has a non-belt-driven "toroidal" CVT under development which can work on larger vehicles, but is not projecting commercial availability before 2000 (Johnson 1991; Birch et al. 1992a). Based on EEA (1991b), we adopt the estimate of 6% higher fuel economy than a 3-speed automatic, which includes a 2% downward adjustment to account for overlap with VVC but excludes the potential effects of optimized transmission control, which is discussed separately below. CVTs would be used in place of 5-speed automatics in vehicles where their application results in manufacturing cost savings. Reported CVT cost estimates range from an incremental cost of $110 down to a savings of $50 (see Table 4). We adopt a mid-range cost of $30 under the assumption that CVTs will only be applied when they are more economical than an advanced multispeed automatic transmission.

Optimal Transmission Control

From an efficiency point of view, an optimal transmission shift schedule keeps the engine operating at as low an RPM as possible subject to smoothness and driveability constraints. A transmission control strategy for accomplishing this, termed Aggressive Transmission Management (ATM), is discussed in detail by Ross et al. (1991). The estimated fuel economy benefit in addition to that achieved by adding a gear (for a 5-speed automatic transmission) is 9%. Transmission optimization is implemented through electronic control, including sensing and control of throttle position and other engine parameters as needed to optimally synchronize the transmission with the engine and smooth the shifting over the load range. A more sophisticated version of electronic transmission control can be obtained through "drive-by-wire" control (Ganoung 1990). In this case, the accelerator pedal sends a signal to an electronic control system, which then actuates the throttle and possibly other engine and transmission settings as well. A drive-by-wire control system would contain knowledge of an engine's performance and fuel consumption map and select the throttle position which will deliver the needed power most efficiently.

The Level 1 transmission optimization benefit is a small, 0.5% improvement from the use of electronic control with standard shift schedules (OTA 1991). We project fully optimized transmission control as a Level 2 technology since it has not yet been put into production vehicles. It can be implemented with electronic control hardware similar to that already in use; only the shift schedule is controlled much more aggressively, so that shifts occur more frequently. Once a transmission has electronic control, it can be reprogrammed to meet different goals, such as performance or fuel economy (Frame 1990). We do not estimate a specific fuel economy benefit for drive-by-wire, which is likely to be helpful in realizing optimized multispeed automatic transmissions as well as optimized CVTs, but for which we have no definitive estimates available. The potential penetration of optimized transmission control is over all automatic transmissions, or 80% of the new car fleet, including vehicles can use CVTs.

Optimized Manual Transmissions

As with automatic transmissions, the number of gears and the shift schedule of a manual transmission determine how well the transmission and engine work together to maximize the amount of time the engine operates efficiently. Neither the OTA (1991) nor NRC (1992) assessments considered manual transmission optimizations. Honda has attributed a 20% fuel economy benefit from the transmission and gearing changes applied in the 1992 Civic VX. These changes were enabled in part by the use of VVC to increase low end torque. Practically speaking, it is difficult to allocate the improvement between engine and transmission changes. However, the fuel economy benefits estimated for VVC presume only gearing and axle ratio changes needed to take advantage of engine downsizing, without moving to a more fundamentally efficient shift schedule (as described above for optimized transmission control). Therefore, there is a potential benefit for manual transmission shift schedule changes over and above the benefits enabled by engine improvements and adding gears alone.

The penetration of 5-speed manuals in the 1990 new car fleet was 16%, representing a majority of cars with manual transmissions (Greene 1993). Manual transmission use has been shrinking as more "import" models are moving to automatic transmissions and, as noted earlier, manuals were used in only 20% of new cars by 1991, down from 30% in 1981. About 25% of light trucks have manual transmissions, and that share has also declined. For this analysis, we assume a fixed 20% share of new cars with manual transmissions. We project that the remaining 3- and 4-speeds will be replaced by 5-speeds over the time horizon examined here. EEA estimates an average fuel economy benefit of 8% for a 5-speed manual over a 3-speed (Greene 1993), but this does not include any shift schedule optimizations. We assume half this benefit for improving from a 4- to 5-speed; there were hardly any 3-speeds left in the fleet by 1990. Some additional improvement (at additional cost) could come from moving to a 6-speed, but we do not have an estimate for this and so exclude it here. For convenience, rather than separately itemizing the estimated 4% benefit for increasing the number of gears from four to five, we apportion it as a 1% benefit over all cars with manual transmissions.

With a manual transmission, the shift schedule is largely left up to the driver. A shift indicator light, which signals the driver to upshift, is a way to help a driver follow a more efficient shift schedule. A specific shift schedule is followed on the EPA test procedure driving cycles, so that rated fuel economy is increased for cars with a shift indicator light by an average of 7% above that of models identically equipped except for the indicator.[10] Certain mechanical designs can also favor following a better shift schedule. "Tall gear ratios," that is, gears that are more spread out in certain ranges, can lead the driver to spend more time in higher gears (and therefore at lower RPM), thereby improving fuel economy. This is one of the strategies used on the Honda Civic VX (and earlier on the Honda CRX-HF), which also includes a shift indicator light.

A cautionary note is in order here: the fuel economy gains we estimate for improved manual transmissions are those that would be realized when following the EPA test procedure shift schedule, which is not how most car owners drive. Real-world shifting is likely to be much less careful from an efficiency point of view, implying that this measure will have relatively large shortfall. However, since it is unadjusted test fuel economy that we estimate here, we do not make an adjustment to our estimates of technical potential (in any case, data to do so are not available). By contrast, engine measures that reduce friction and pumping losses are likely to have lower than average shortfall, which we also do not attempt to take into account in making our estimates.

Though the Honda example suggests a larger benefit, we estimate that manual transmission optimization yields a fuel economy benefit of 10%, from conversion to taller gearing and including any use of shift indicator lights in the vehicles (i.e., we assume the 7% average benefit for shift indicator lights is included in the 10%). Note that this is closely consistent with the 9% benefit estimated for optimization of automatic transmissions. We assume full conversion to 5-speed manual transmissions as needed to enable optimized gear ratios; the use of 6-speeds could help further. Adding the apportioned 1% benefit for increased gears to the 10% benefit for optimization yields the 11% benefit listed in Table 1. Our cost estimate for this technology reflects the cost of adding gears, as noted in Table 4.

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[10] The average benefit from a comparison of matched pairs of cars from the EPA 1990 Test Car List with and without the shift indicator light is 6.8 ($\pm$0.4)% (authors' analysis).

2.3 Load Reduction

All of the technologies covered so far pertain to a vehicle's drivetrain and are related to the efficiency with which energy is delivered to a vehicle's wheels. The amount of energy which the drivetrain is required to deliver is called the vehicle's "load." Load includes air and tire resistance, inertia and braking (related to vehicle mass), plus accessories such as heating, air conditioning, lighting, and power steering. Reducing load reduces the engine's power-producing requirements and the transmission's power-transmitting requirements. This has a ripple effect on fuel economy, since with lower power requirements, the drivetrain components can be made smaller, resulting in lower loads from the mass and size of the engine and transmission themselves. Load reduction is the most crucial strategy for obtaining substantial automotive efficiency gains in the long run; the dramatic improvements that can be obtained through radical redesign of vehicles for ultra-low tractive loads are outlined by Lovins et al. (1993). Here, however, we examine only the more modest degrees of load reduction that can be obtained by moving the fleet toward the best available practice in conventional vehicle design.

Box 2. Energy Sinks over Driving Cycles for a 1991 Ford Taurus

EPA driving cycles:	City		Highway		Composite	
ENERGY SINK	kJ/mi	%	kJ/mi	%	kJ/mi	%
Tire rolling resistance	668	12.4	633	18.9	652	14.6
Aerodynamic drag	397	7.3	868	25.9	609	13.6
Braking	907	16.8	178	5.3	579	12.9
Accessories	331	6.1	134	4.0	242	5.4
Vehicle Load Subtotal	2303	42.6	1813	54.1	2082	46.5
Engine friction, powered	2198	40.7	1458	43.6	1865	41.6
Engine friction, idling	903	16.7	77	2.3	531	11.9
Engine friction Subtotal	3101	57.4	1535	45.9	2396	53.5
TOTAL	5403	100.0	3347	100.0	4478	100.0
FUEL ECONOMY (MPG)	22.3		36.0		26.9	

Based on analysis of a Ford Taurus as listed in EPA/TCL (1991) using the model of An and Ross (1993). Relevant parameters are: test weight 1588 kg (3500 lbs); 3.0 liter (183 in^3) engine with maximum power of 104 kW (140 hp); specific engine friction 0.25 kJ/l*rev; thermal efficiency 0.42 (listed compression ratio is 9.2); idle speed 750 RPM; accessory load 0.75 kW (1 hp); 4-speed automatic lockup transmission with assumed efficiencies of 0.90 city, 0.95 highway; N/v ratio 31.9 rpm/mph; v_{gear} 55 mph; drag coefficient (C_D) 0.33 and frontal area 2.1 m^2; tire rolling resistance (C_R) 0.01; passenger plus cargo volume 117 ft^3 (mid-size). Interior volume and engine power are not used for the analysis; see An and Ross (1993) for definitions and model equations.
Fuel economy is computed as 120,600 kJ/gal (lower heating value of test fuel) divided by total energy use per mile. Composite results are for a weighted average of 55% city and 45% highway driving.
For comparison, the Test Car List ratings are 22.2 mpg city, 37.5 mpg highway, and 27.2 mpg composite.

Box 2 shows how energy is utilized over the standard driving cycles for a typical vehicle. We use a 1991 Ford Taurus as our example; it is a mid-sized vehicle with a fuel economy close to the new car fleet average in both 1990 and 1991. The first four lines list the contribution of vehicle loads to fuel energy use, which is given in kilojoules per mile (kJ/mi) and as a percentage of the total for each driving cycle.[11] Also listed is the energy dissipated in engine friction, shown separately for the portions of the cycles when the engine is under power and when the engine is idling (including non-powered deceleration). In this context, engine friction includes rubbing friction plus pumping losses and engine accessories. Engine accessories include the alternator, water pump, radiator fan, etc., as opposed to vehicle accessories such as power steering, lighting, and air conditioning--these are counted under vehicle loads. In contrast to breakdowns which distribute all engine losses over the vehicle loads, we find it useful to show engine friction as an energy sink, since reducing engine friction is a major opportunity for efficiency improvement. Thermodynamic losses of fuel combustion are not broken out here, but distributed through all frictional and load energy sinks.

On average (for the EPA composite cycle), the major portion of the tractive load is nearly equally divided between tire rolling resistance, aerodynamic drag, and braking. Braking (inertial) losses dominate in urban driving, with its greater number of stops and starts. In today's cars (which lack regenerative braking), braking dissipates (as heat) the portion of a vehicle's energy of motion not lost to other sinks. Aerodynamic losses dominate in highway driving, since the drag force increases at higher speeds. Tire rolling resistance per mile is essentially constant across the speed range and is close to aerodynamic drag over a composite cycle. Vehicle accessories use about 5% of the energy. Based on Ross et al. (1991), we estimate a 30% reduction in accessory loads, implying a 1.7% fuel economy benefit, and a 0.5% benefit from improved lubricants. The discussion below focuses on the major sources of load reduction, lower tire rolling resistance, lower drag, and lower weight.

Tires

The force and vibration absorbing abilities of tires, as well as some of their road-holding abilities, result in an energy dissipation which implies a resistance to a vehicle's rolling motion. The ratio of a tire's rolling resistance (e.g., expressed in pounds of force against rolling motion) to its load (the weight borne by the tire) is termed the coefficient of rolling resistance, C_R (Stone 1989). C_R can thus be expressed as a percentage; for example, a rolling resistance of 1% means 1 pound-force of resistance for each 100 pounds of tire load. EEA (1991a) reports an average C_R of 1.1% as a current baseline value for new automobiles (1990-91). Rolling resistance can be decreased by a variety of tire design and construction features and ongoing improvements have been made over the years. EEA (1991a) projects a decrease in average C_R to 0.85% by 2001. This C_R estimate is also used in OTA (1991) and is consistent with values reported in Schellenbarger et al. (1991). However, the most efficient tire in an EPA survey from the early 1980s already had a rolling resistance of 0.87% (Engler 1984).

[11] A kilojoule is a metric unit of energy, approximately equal to a British Thermal Unit (1 kJ = 0.948 Btu) and the energy available in about 0.001 ounce of gasoline; thus, the 4478 kJ/mi shown for the composite driving cycle indicates that about 4½ ounces of fuel are burned to go one mile (this is approximate since the standard test fuel contains somewhat less energy than typical gasoline).

Recent announcements by some tire manufacturers suggest achieved C_R values lower than 0.85%. Michelin recently announced new tires claiming a 35% lower rolling resistance (from an unspecified baseline) and with a increase in width, so that there is no compromise of traction and handling (Michelin 1993). The Goodyear Invicta GFE series tires claim a 4% fuel economy benefit from a 20% cut in rolling resistance, but again, the baseline is not given. Goodyear noted that the rolling resistance decrease was obtained through rubber compounding improvements without any tradeoff in traction or treadwear (Goodyear 1991). It is estimated that these tires have rolling resistances in the 0.6%-0.7% range (Mendler 1992). EEA (1991a) projects that an average C_R of 0.75% could be achieved by 2010, citing communication from Dunlop that this C_R level is "possible without significant loss in traction in handling" (EEA 1991a, p. 4-12). Additional improvements can result from new materials, such as plastic injection molded tires, which could have a rolling resistance of 0.6% (EEA 1991a, p. 4-12); the potential for plastic tires is also discussed by Bleviss (1988) and Ross et al. (1991). The 65 psi tires developed by Goodyear for the GM Impact electric vehicle have a 0.48% C_R (GM 1990), but GM hedges on whether and when such a level might be broadly applicable throughout the fleet.

The sensitivity of fuel consumption to rolling resistance depends on the contribution of tire resistance to overall vehicle energy requirements, which depends on both vehicle characteristics and the driving cycle under which fuel economy is evaluated. Calculations using the An and Ross (1993) model suggest a sensitivity of 0.15 over the EPA composite test cycle assuming typical 1990 car characteristics. EEA (1991a) estimates the sensitivity as 0.24, e.g., a 10% decrease in rolling resistance yields a 2.4% decrease in fuel consumption. Vera and Simpson (1992) give a range of 0.14 to 0.20; Thompson and Reineman (1980) estimate 0.18. Bleviss estimates a sensitivity of 0.3 to 0.4, but uses a higher baseline value of C_R at 1.5%. Noting the uncertainty implied by the range of estimates reviewed here, we assume an average sensitivity of 0.15 for the purpose of projecting the fuel economy benefit.

As with many other automotive design features, there is a trade-off between performance ability and fuel economy. Recent trends towards high performance tires (mostly wider) that improve handling under extreme driving conditions have resulted in increased rolling resistance (EEA 1991a). Original equipment tires, specified by automakers to conform to vehicle requirements including CAFE compliance needs, often have lower C_R than aftermarket tires, which are sold directly to consumers and are more likely to emphasize performance and handling abilities. A sample of high performance tires from the early 1980s had an average rolling resistance about 20% higher than a sample of efficient tires (Engler 1984), but some have suggested that the differences in C_R may be as much as 50% (Vera 1992). Allowing for some trade-off against performance (or at least the appearance of "performance"), this variability and current market trend away from low rolling resistance does not constrain what would be technically achievable under different market conditions.

Given the range of variability and the significant improvements that have already been demonstrated in prototypes, we estimate a new fleet average C_R range of 0.85% down to 0.65%. Relative to a 1.1% C_R baseline these values represent rolling resistance decreases of 23% to 41%, respectively. We assign the range over our three levels of certainty, so that C_R decreases of 23%, 32%, and 41% correspond to certainty Levels 1, 2, and 3, respectively. Using a sensitivity coefficient of 0.15, the resulting fuel economy benefits for the three levels of reduced average rolling resistance are 3.4%, 4.8%, and 6.1%, respectively, as listed in Table 1.

The potential fleetwide fuel economy benefit from tire improvements estimated here are higher than those reported by EEA, e.g., in OTA (1991) or as used in NRC (1992). For example, OTA (1991) reports a cumulative 1% fuel economy benefit potential for tire improvements relative to a 1988 baseline. Although the EEA tabulations (e.g., Tables 7-7 to 7-12 in OTA 1991) list 100% penetration increases for tire improvements, it appears that what EEA meant was 100% of applicable segments of the fleet. EEA assumed that improvements would not be applicable to the economy car segment, which already has lower rolling resistance tires, and the sports and luxury segments, where marketing considerations might render more efficient tires to be inappropriate. Consistent with our assumptions regarding technical (as opposed to marketing) feasibility, we do not apply such restrictions here. The economy segment of the market could continue to advance the state-of-the-art for tire efficiency, so that tires used on economy cars would have rolling resistances below the fleet average. Conversely, for our higher improvement level, the sports and luxury segments of the market would utilize tires with C_R higher than average, but deviating less than they might under less fuel efficient fleetwide assumptions.

Aerodynamics

Aerodynamic drag wastes energy, contributing to an average 14% share of energy consumption for a typical car over the composite city/highway driving cycle (Box 2). Aerodynamic losses are much higher at highway speeds, since the drag force increases with the square of speed. Drag is directly proportional to the frontal area of a vehicle and to a *drag coefficient* (C_D), which depends on the shape of the vehicle. Improved aerodynamics concentrates on streamlining, e.g., more rounded, gently tapered contours and sloped windshields, in order to reduce the C_D. Recent discussions of C_D reductions that can be obtained through various body styling changes are given by Seiffert and Walzer (1991, p. 29) and by Ito and Hoshino (1992).

The 1987 average new automobile C_D was about 0.38 (OTA 1991) and in 1990 the estimated average C_D was 0.352 ($\pm$0.037), with 25% of models having a C_D of 0.33 or less.[12] The EEA projections for 2001 estimate a fleet average C_D of 0.30, or a 15% reduction below the 1990 average. At least 13 models with C_D below 0.30 have been in mass production since 1987 (Ito and Hoshino 1992). Currently, the most streamlined production model is the GM Opel Calibra, with a C_D of 0.26 since 1990. Much lower C_D values have been achieved in many prototypes; the GM's Impact and Ultralite prototypes have a C_D of 0.19 and a Ford research prototype has achieved a C_D as low as 0.14. EEA (1991a) projects a new fleet C_D average of about 0.23 as attainable by 2010. We estimate potential new car C_D values ranging from 0.28 for certainty Level 1 to 0.26 for Level 3, based on the current best production C_D value as well as interpolation toward EEA's 2010 estimate. Based on the composite cycle energy share, each 10% reduction in C_D yields a 1.57% improvement in fuel economy. Thus, the estimated fleetwide fuel economy benefits from drag reduction range from 3.3% for Level 1 to 4.3% for Level 3.

Frontal area is related to the width and height of a vehicle and so only limited reductions are possible under an assumption of constant interior space, as made here. EEA (1991a) estimates that a 5% frontal area reduction would be possible through improved packaging, mainly among the larger vehicle classes. Although EEA's projection is for 2010, we see no reason why this cannot be

[12] ACEEE analysis of data from Duleep (1993a); C_D values were available for 290 of the 511 car models in the data base, covering 60% of sales.

accomplished over one major redesign cycle and be applicable to about one-third of the fleet. Frontal area reduction is not explicitly included here, but the potential for an added net 1%-2% reduction in drag from frontal area reduction provides a degree of conservatism to the drag reductions estimated here.

Weight reduction

Reducing vehicle mass (weight) is a key approach for fuel economy improvement. This is particularly true for urban driving, where frequent braking dissipates much of a vehicle's kinetic energy, which is proportional to mass. With engine power held constant, a 1% reduction in mass (curb weight) implies an approximately 0.3% improvement in the EPA composite fuel economy of average cars (Murrell 1990; An and Ross 1993). However, reducing mass at fixed engine power also boosts performance as measured by acceleration ability. If instead, a car's engine is downsized to maintain constant performance, then mass reduction implies a much larger fuel economy improvement. EEA (1991b) estimates that, accounting for driveability constraints, a 1% reduction in mass yields a 0.66% improvement in fuel economy for average 1990 vehicles when holding acceleration ability constant.

Vehicle downsizing is an obvious way to reduce mass (as well as drag), but as noted earlier, this analysis excludes changes in vehicle size which reduce the passenger or load carrying capability of a vehicle. This means that interior volume, as used to define EPA vehicle classes,[13] is assumed to be fixed, although exterior dimensions, such as overall height, length, and width, or wheelbase and track width, may change. In the past, weight reduction was partly accomplished by shrinking exterior dimensions, as indicated by the vehicle attribute trends shown in Figure 2. For example, average passenger car wheelbase dropped 7% while weight dropped 21% between 1975 and 1991. Overall length and width have shown larger drops.

There are clearly limits to shrinking exterior dimensions while preserving interior volume. However, future weight reduction does not imply shrinkage of vehicle dimensions. This is illustrated in Figure 4, which presents one automaker's view of trends in vehicle design. Overall length may change little while wheelbase grows, preserving or increasing interior volume while allowing greater streamlining. The bottom profile shown in the figure is similar to that of the GM Ultralite prototype, for example, which represents an advanced application of weight reduction techniques for improvement of both performance and fuel economy (GM 1992). The Ultralite has an interior volume comparable to that of today's Chevy Corsica or Pontiac Grand Am (105-106 ft^3 combined passenger plus cargo space--just below the 108 ft^3 average of 1990 cars) and a longer wheelbase, but weighs only one-half as much as these contemporary models. In assessing GM's Ultralite project, Lovins et al. (1993) identify an "Ultralite" strategy, involving radical reductions in vehicle mass achieved through the use of advanced composite materials. This approach could have profound implications on the future of automobiles, transforming the whole design and manufacturing process as well as resulting in vehicles of dramatically improved efficiency.

[13] For passenger cars, the EPA classes are defined by standard measures of passenger and cargo interior volume--see EPA/GMG (1993), for example.

Less radical is Ford's Synthesis 2010 prototype, which is based on the Taurus platform but emphasizes aluminum use, resulting in 28% less weight while having the same passenger and cargo space as today's Taurus. In discussing the Synthesis 2010, a Ford manager remarked that "in the future, the guy with the biggest, lightest cars wins ... weight will be of strategic importance to Ford and all makers" (quoted in Keebler 1993a). The many benefits of weight reduction, as well as the fact that it is often a side benefit of other design advances, are clear to anyone who regularly browses the automotive trade press.

Major weight reduction during the 1980s was achieved through conversion from rear- to front-wheel drive and the use of unit-body (as opposed to body-on-chassis) construction. EEA has estimated a total fuel economy benefit of 10% from conversion to front wheel drive, including the direct weight savings from front wheel drive plus conversion to unit body and driveline efficiency improvement. As of 1990, about 88% of the passenger car fleet had been converted to front wheel drive (Greene and Duleep 1993). Although some further conversion is possible, we do not count further fuel economy gains from front-wheel drive conversion for this analysis. New car weight reached its minimum in the late 1980's, with test weight averaging 3040 lbs in 1986-88. Weight has since risen by about 5% and in the 1990 base year used for this analysis new car test weight averaged 3180 lbs (Heavenrich et al. 1991). Since the late 1980's, there have been some further increases in front wheel drive and there have presumably been ongoing substitutions of lighter weight materials where they provide advantages. As with engine technology in recent years, manufacturers have generally been using new materials for goals other than higher fuel economy.

The technical potential for future weight reduction will come mainly from substitution of materials as well as improved design and manufacturing techniques. Bleviss (1988) surveyed a number materials substitution possibilities, including plastics, high-strength steel, aluminum, and magnesium, many of which have been demonstrated in prototype vehicles developed in the early 1980s. EEA has reviewed a number of studies regarding the potential for materials substitution and reports an estimate of 10% weight reduction, or about 300 lbs (138 kg) relative to the 1987 fleet, as possible by 2001 (EEA 1991b). This estimate is very robust in that it is confirmed with part-by-part analyses itemizing the particular sources of weight savings as well as being in line with other studies reviewed. EEA (1991a) estimates a total of about 20% weight reduction (relative to 1987 cars) as being very likely by 2010, largely through further progress with materials substitution. However, our examination of the size and weight makeup of the current fleet, plus reports in automotive literature, suggest that the near-term opportunities for weight reduction are likely to be much greater than 10%.

Figure 5 plots curb weight against interior volume for model year 1990 passenger cars. There is a trend of increasing weight with increasing size, but there is enormous variation of weight for vehicles of a given size.[14] A best-in-class type of analysis can be used to quantify the scope for mass reduction without changing passenger or cargo space. The points in Figure 5 are plotted by EPA size class. In Figure 6 the data are plotted separately for the (a) subcompact, (b) compact, (c) midsize, and (d) large car classes, which together comprised 94% of 1990 sales. The essentially vertical scatter in these break-outs makes it clear that most of weight variation in the fleet is within, rather than among, the volume-based car classes. This is also apparent from an inspection of the class points in Figure 5. The points in Figure 6 are plotted to indicate front (F), rear (R) and four (4) wheel drive;

[14] Less than one-fourth of the variation in weight is related to the variation in volume ($r^2 = 0.225$).

the weight reduction associated with front wheel drive is apparent. It is also notable that the four wheel drive models are not the heaviest and generally fall in the middle to upper-middle range of each car class.

Box 3 shows weight variation statistics for the dominant classes, and an estimation of the potential for weight reduction based on one-half the difference in weight between the heaviest and lightest cars in the class, excluding rear-wheel drive models. The resulting average potential reduction in curb weight is 19%. A very similar estimate of 21% potential reduction is obtained from the residuals to a fit of curb weight to interior volume for the overall fleet (i.e., taking one-half of the scatter around a line through the points in Figure 5). Thus, we infer a potential curb weight reduction of approximately 20% based on evolution of the fleet toward the better half of current achievement in terms of weight vs. interior volume. Little of the existing weight vs. volume variability on which this analysis is based comes from differences in material use among the 1990 models. Therefore, the preceding projection of 20% weight reduction does not reflect much of the potential 10% reduction from material substitution noted earlier.

Box 3. Potential for weight reduction based on variations of the 1990 new car fleet within volume-based size classes.

Vehicle Class	Market share	No. of models	Median curb weight (lbs)	One-half of weight range (lbs)	Weight reduction
Subcompact (3)	22%	158	2400	800	33%
Compact (4)	33%	140	2750	550	20%
Midsize (5)	25%	86	3150	450	14%
Large (6)	14%	19	3300	300	9%
Average (3-6)	94%	403	2850	542	19%

Authors' analysis of data from Greene (1993), not including rear-wheel drive models.

A limitation of this type of analyses is the lack of accounting for engine and drivetrain differences among similarly sized vehicles. For example, the smaller car classes do include many sports and luxury models, which tend to have larger engines, higher performance, and higher weight than average for their class. On the other hand, the exclusion of rear-wheel drive conversion is an element of conservatism in the analysis. Inclusion of rear-wheel drive models in the estimation would mainly impact the large cars, increasing the large car median weight from 3300 to 3700 pounds and their weight reduction potential from 9% to 19%.

The need to improve fuel economy is not the only factor driving weight reduction. The multiple considerations involved in materials use and design are particularly important when it comes to estimating the cost of weight reduction. EEA estimates the cost of weight reduction at $0.50 per pound, assuming engine downsizing as needed to maintain constant performance (Duleep 1992). This estimate appears to reflect an aluminum substitution strategy, as exemplified in Table 3.3 of EEA (1991b), which is a relatively high cost strategy. Approaches using high strength steel and engineering plastics can yield some or all of the assumed levels of weight reduction with a net cost savings. For example, Lindgren and Jones (1990) compared use of high strength steel, aluminum, and plastics in weight reduction. They found a 6% weight reduction relative to a baseline 1990 Ford Taurus to be achievable at negative cost, i.e., a manufacturing cost savings of $0.25 per pound, using a plastics-based strategy. They estimated that aluminum substitution would provide less weight reduction and cost $0.74 per pound of reduction. Clearly, whether a particular material substitution can be had at net cost or savings depends on the particular part or structural application. It also depends on manufacturing techniques, and more broadly, integrated approaches to design.

Aluminum is a good case in point. Although the material cost for aluminum is three to five times higher than for steel, automakers are actively exploring greater aluminum use because of potentially large manufacturing cost savings and other benefits, such as high scrap value, corrosion resistance, and "high-tech" marketing appeal (Keebler 1993b). Aluminum spaceframes, made of multi-cell, interlocking, extruded channels or tubes, offer greater design flexibility, potentially better crashworthiness, reductions in parts counts, simplified assembly, implying lower costs for tooling, facilities, and labor (Fleming 1992). Spaceframe construction is beneficial with steel as well, and is also compatible with use of lightweight structural composites. As mentioned earlier, Ford has developed an aluminum prototype dubbed the Synthesis 2010 based on the Taurus. What is significant about this effort is that, rather than just building a concept model, the Synthesis 2010 project developed "soft tooling," flexible prototype tooling for testing high-volume production using aluminum. This allows them to develop not just a vehicle, but an integrated design/manufacturing process, reflective of the lean production approach discussed later in this report under "Product Cycles." Ford is said to be spending $25 million on this aluminum-based lightweight vehicle development effort and many other automakers have similar efforts underway (Keebler 1993a,b). Audi has been active in exploring aluminum use (Seiffert and Walzer 1991) and Volvo (1992) also recently revealed an aluminum prototype, the ECC (Environmental Concept Car), which also features an electric hybrid drive train with a gas turbine for range extension.[15]

New manufacturing techniques offer weight reduction opportunities even with conventional materials, like iron and steel. For example, metallurgical advances in cast iron formulation could cut cast iron component weights by as much as one-third (Wall Street Journal 1991). Vacuum casting for steel parts allows better placement of material in just the locations and quantities needed, compared to techniques conventionally used (Warren 1992). This allows designers to create structurally optimized castings with much less material, achieving strength-to-weight ratios which were long known to be possible from engineering analysis but which were previously too difficult to manufacture. Jost (1992) reported on a variety of advances in manufacturing techniques, all of which offer multiple benefits. Cost savings are paramount, but weight savings are frequently a by-product of such advances. For example, the use of lasers for cutting and welding steps can cut as much as $100 from the cost of a car body. At the same time, the laser welding permits the width of weld flanges to be reduced by one-third, cutting material use throughout a body and reducing weight by up to 88 lbs (F. DiPietro of LASE, Inc., as cited by Jost 1992). One can also expect broad benefits from the increasing use of computer aided structural analysis, design, and manufacturing techniques, which greatly enhance engineers' ability to improve strength and dynamic characteristics while reducing weight and cost.

[15] Volvo claims a 12% weight reduction relative to an unspecified baseline; the traction batteries would complicate comparisons to conventional vehicles. Detailed vehicle and component weight data for the Volvo ECC were unavailable at time of writing.

The prominence of weight reduction as a selling point for automotive parts suppliers is apparent in publications such as *Automotive Engineering* magazine. Looking back through the 1992 issues, a reader sees numerous advertisements such as: Arco's foams for lower weight side-impact protection, Exxon's polymers for interior applications, Dow's "moldable, woven-glass reinforced polymer" bumpers (citing savings of 33 lbs for some large cars), Hüls' plastics for carpet backing (citing 12 lbs weight savings). Engineering plastics and composites for body panels are offered by Ashland, Rockwell, General Electric, and others. BASF's composite manifolds cite engine performance benefits and manufacturing cost savings as well as weight savings. Spicer offers composite drive shafts and other drive train components that save weight while providing better dynamic characteristics and reductions in noise, vibration, and harshness of ride. Aluminum manufacturers (Alcoa, Alcan, Kaiser, and others)--who are involved in the vehicle prototype mentioned above--offer a variety of products for body parts and engines, including aluminum composites tailored for various applications. Among the components for which suppliers also advertise weight savings are radiators, filters, rotors, instrument panels, seats, interior and exterior features, insulation, liners, and many others. Supplier firms clearly see business opportunities in new approaches for weight reduction--most of which yield multiple benefits. This is consistent with the views expressed in the 1989 Kearney survey, which found a suppliers' consensus that 41 mpg new car fleet average could be achieved by the year 2000 and that weight reduction would make an important contribution (Chappell 1989).

It is not possible within an analysis of this scope to synthesize the wide variety of advances in automotive manufacturing and materials engineering into specific weight reduction techniques for a given vehicle--that is a task for the design engineers. It does seem clear that EEA's estimate of 10% weight reduction potential is overly conservative. We take this as our Level 1 estimate. We estimate a 30% potential curb weight reduction at certainty Level 3, based on our analysis of variations within classes in the 1990 fleet plus the reductions possible through materials substitution. This is well within the range of the 21%-40% weight reduction estimated by EEA (1991a). Although EEA made these estimates for a 2010 time horizon, our review of product cycles later in this paper leaves little doubt that substantial progress in weight reduction is feasible much sooner than that, based on the variations in design already reflected in the fleet and material substitution possibilities already identified. An intermediate value of 20% curb weight reduction is assumed for Level 2.

These percentage reductions are assumed to apply to curb (as opposed to test) weight. Before applying them in our integrated analysis, we make an upward adjustment of 100 lbs to account for effects of safety and emissions standards. The resulting estimates are detailed in Table 1 and imply fuel economy benefits of 4% to 16% for technical certainty Levels 1 to 3. As noted earlier, the average 1986-88 new car test weight was 3040 lbs, 5% lower than the 3180 lbs average of 1990. The trend of increasing weight has continued through 1993, when average test weight reached 3234 lbs, the highest value since 1979 (Murrell et al. 1993). As with performance-boosting engine technologies, engineering advances are apparently being applied for vehicle amenities other than fuel economy. Redirecting new design capabilities and materials use toward achieving average weight reduction can contribute to fuel economy improvement assuming appropriate policy changes.

Regarding cost, EEA estimates a 10% potential weight reduction is achievable at an average cost of $0.50 per pound. However, the preceding survey, as well as the studies of product development and production reviewed below under "Product Cycles," suggests that weight savings are likely to be realized at zero cost and even net savings. This is particularly true since there are multiple benefits, not just fuel economy. Nevertheless, for conservatism we use an average cost of $150 per vehicle based on the EEA estimate. However, we apply this as a fixed cost for all three Levels, implying not only a greater benefit, but also a greater benefit/cost ratio, at the increasing Levels of technical progress.

The reported weight reductions achievable through materials substitution are based on component-level analyses, which is an inherently limited, piecemeal view of design. An integrated approach would take advantage of the specific properties of new materials and the greater manufacturing flexibilities they can offer. The vehicle body would have a fundamentally different structure (although the general appearance need not change), using manufacturing techniques optimized for new materials. Vehicle design would move in the direction of the "Ultralite" strategy, demonstrated by General Motors and articulated by Lovins et al. (1993), resulting in potential weight reductions of 50% compared to current automobiles. The reasonableness of such a radical approach is apparent by considering a basic paradox of current designs, with 3000 pound vehicles carrying average loads of 300 pounds or less. Although we cannot explore the implications of this potentially profound transformation of automotive design within the incrementalist cost/benefit approach followed here, we believe that our estimates of 10% to 30% potential curb weight reduction are conservative in light of late 20^{th} century technological capabilities.

3. PROJECTIONS OF TECHNICAL POTENTIAL

This section combines the efficiency benefits of each technology into projections of the new fleet average fuel economy for automobiles. The results are developed at the three certainty levels previously defined in Box 1. We first establish the base year fleet characteristics and discuss the expected evolution of fuel economy through market forces alone.

3.1 Base Year Technology Usage

The method adopted here works from a characterization of the new car fleet in a specified base year and posits changes in technology in order to project the potential fuel economy level achievable in the future. Base years of 1987 for domestic cars and 1987/88 for imported cars were used by recent U.S. government-sponsored assessments of potential improvements in new car fuel economy (Difiglio et al. 1990; OTA 1991; Greene and Duleep 1992) and by ACEEE's previous analysis (Ross et al. 1991). The SRI (1991) and NRC (1992) studies used a 1990 base year, which is also adopted here. Model year 1990 is the most recent year for which substantially complete statistics on technology usage in new cars are available. We draw mainly on Duleep (1993a), Greene (1993), and Murrell et al. (1993), plus trade publications such as the *Automotive News Market Data Book*, for base year information. For purposes of the analysis, we take 27.8 mpg as the 1990 base year new car fleet average fuel economy, referencing Heavenrich et al. (1991), which was used to compile technology penetration statistics. The estimated 1990 average was revised to 27.7 mpg in Murrell et al. (1993) but this small difference is of little consequence to the results, for which we claim no more than ± 2 mpg accuracy for any point estimate.

As discussed in Section 1, the fuel economy benefit of a technology is specified with respect to some base technology. For example, the 5% benefit estimated for a 5-speed automatic transmission is the improvement relative to a 3-speed automatic, assuming that both transmissions have torque converter lockup. The 4-speed automatic transmission is an intermediate level, yielding a 2.5% benefit over a 3-speed. Our projections are made for increases in the penetration of the most efficient available technology relative to a base year fleet containing a mixture of technological levels. For example, starting from a base transmission mix of 20% manual, 28% 3-speed automatic, and 52% 4-speed automatic and projecting the greatest possible penetration for 5-speed automatic transmissions would imply that 80% of the new car fleet (i.e., manuals excluded) improves by the weighted average of the benefits of a 5-speed over 3- and 4-speed transmissions.

3.2 Market-Driven Fuel Economy Expectations

We foresee little or no near-term improvement in new fleet fuel economies in the absence of policy changes that specifically promote increased fuel economy. Our reference projection, as used for comparison to potential improvements, is for average new car rated fuel economy to remain at 28 mpg and that for the light duty fleet as a whole to remain at an average of 25 mpg, essentially the same as it has been in 1990-1993. Historical new car fuel economy levels are shown in Figure 2 and also in Figure 9 along with our scenarios of projected improvements. The justification for a frozen rated fuel economy reference projection is as follows.

The 1990-91 Middle East crisis had a relatively small and temporary impact on oil prices. There appears to be no market expectation of major oil supply disruption. Price rises are expected to be very modest; DOE (1993) projects average retail gasoline prices of $1.30/gallon in 2000 and $1.51/gallon in 2010 (constant 1991$), or an average escalation rate of only 1%/yr. New car rated fuel economy has been essentially flat at 28 mpg in spite of ongoing technology advances, which have been largely directed toward increases in power performance and other amenities. Murrell et al. (1993) report falling 0-60 mph acceleration times and increases in estimated top speed ability, reaching 121 mph in 1993 (average performance increase rate of 2.2%/yr since 1982), even while average weight increased since 1987. Weight increases can be interpreted as adding luxury or other amenities that are difficult to measure but which generally increase vehicle weight.

Most recent announcements in the automotive trade suggest a continuation of these trends for at least the next few model years. Even if these trends saturate, allowing an increase in fuel economy in the late 1990s, it appears that market-driven fuel economy levels might at best return to the 1988 average by 2000. Frozen rated fuel economy thus appears to be a reasonable reference scenario for projecting stock average fuel economy and estimating reductions in light duty vehicle fuel consumption caused by policy changes to encourage efficiency improvement.

The recent plateau of fuel economy improvement also indicates a degree of flexibility in manufacturer product offering with respect to fuel economy. Many models offered in the late 1980s and recently were planned prior to 1986, under different market conditions. DOE projections based on mid-1980s trends showed ongoing increases in fuel economy due to increased use of technologies (most of those discussed here) for efficiency improvement. Usage of improved technology has in fact increased, but the technology improvements have been largely applied for performance gain, contributing to the recent stagnation of fuel economy improvement.

3.3 Technically Feasible MPG Levels

Table 1 summarizes the technology benefit estimates reviewed earlier in Section 2. Potential benefits are presented at the three technology certainty levels defined in Box 1. Also shown for comparison are recent EEA estimates from Greene and Duleep (1992). The values shown in Table 1 represent the improvement obtained by using a technology on an individual vehicle to which it is applicable. To estimate the improvement to the new car fleet as a whole, one must multiply these individual vehicle benefit estimates by the potential increase in technology use (penetration) throughout the fleet, which are given in Table 2.

Table 2 has two parts: (a) lists the technology penetration (utilization) rates in the base year (1990) new car fleet; (b) lists estimates of the potential increases in penetration. Table 2(a) is based on Greene (1993) and lists the base technologies relative to which improvements are made, as discussed in EEA (1991b). The EEA technology list is more disaggregated than our list in Table 1. We therefore aggregated and summed over car classes to obtain the "Actual 1990" penetration estimates listed in the first column of Table 2(b).

Two levels of increased penetration are given: a "High" level, as estimated by EEA (for technologies included by EEA), and a "Full" level, which represents our projections of the most widespread possible utilization in the fleet. The High levels shown in Table 2(b) generally correspond to the so-called "maximum technology" penetration levels of OTA (1991). As noted earlier, we draw a distinction between what is technically possible and what some might think practical for marketability reasons. Therefore, we also examine Full penetration rates based on what is technically possible in the fleet and which yield greater projected fuel economy levels. Readers may choose the penetration assumptions most in line with their judgements regarding appropriate degrees of market intervention. The question of when such increased penetration rates might be achieved is taken up below in Section 4.

All estimates are adjusted to reflect interactions and potential overlaps among the technologies, either by adjusting benefits estimates in Table 1 to avoid double counting or by setting penetration limits in Table 2 to avoid overlapping applications. The fuel economy benefit estimates for some technologies were derated because of their order on the list, reflecting our judgement of which technology is likely to be applied sooner because of better cost-effectiveness or recent technology trends. For example, we gave variable valve control (VVC) priority over variable displacement and idle-off. The latter two would have higher benefits if implemented without VVC, but we presume that VVC is more likely to be implemented first. The fuel economy benefit for some transmission technologies is reduced by 2% to account for synergism with engine measures that also derive their benefits from improving part load efficiency. Also, penetration limits on CVTs and 5-speed automatic transmissions were chosen to sum to 80%, representing the fact that only one of the pair would be used on a given vehicle. These and other adjustments were discussed on a case-by-case basis as the technologies were reviewed in Section 2. In any event, such adjustments do not affect the total estimated technical potential, although they do affect the ranking of technologies in the cost/benefit (supply curve) analysis described in Section 4. The adequacy of our procedures for avoiding double counting was verified by simulation analyses of representative vehicles, as reported by Ross et al. (1991) and presented below in Section 3.4.

Table 3 summarizes our estimation of the cumulative fleetwide fuel economy potential obtained by using the technologies identified here. The entries in Table 3 are obtained by multiplying the individual vehicle benefits from Table 1 by the appropriate penetration increases from Table 2(b). Combining the three technical certainty levels of Table 1 with the two penetration increase levels of Table 2 yield the six combinations given in Table 3 (in addition to the EEA column, shown first for comparison). Each entry in the table represents the percentage improvement in the new fleet average fuel economy for a given technology improvement under the specified technical certainty and penetration assumptions. The total technical potential is found by adding up the incremental improvements due to each item. The summed percentages are shown in the bottom part of Table 3, with subtotals by the major categories of improvement (engine, transmission, and load reduction).

Simulation analyses, as described in Ross et al. (1991) and illustrated below in Section 3.4, show that the engine and transmission improvements can be accurately combined in an additive fashion, once interactions have been taken into account for the individual benefits estimates. The load reduction measures combine with the drivetrain improvements in a multiplicative fashion. Thus, our final estimates of technical potential, shown as the "Optimal Total" at the bottom of Table 3, are formed by multiplying the summed load reduction benefits by the summed drivetrain (engine and transmission) benefits. Reports such as OTA (1991) and Greene and Duleep (1992) based on EEA work use a strictly additive calculation, which understates the combined potential when combining drivetrain and load reduction improvements. EEA (1991a) makes note of the conservatism and readjusts its 2001 estimates upward using an engineering analysis with a model similar to that used here.

By way of example, consider the High penetration, Level 2 estimates shown in Table 3. The sum of engine (27.5%) and transmission (12.3%) improvements gives a drivetrain improvement factor of 1.398 (1 + 39.8%). The load reductions give a factor of 1.204. Multiplying these two factors gives 1.683, or a potential fuel economy improvement of 68.3% (corresponding to a fuel consumption reduction of 40.6%). Applying this to the 1990 fleet average of 27.8 mpg yields a potential average fuel economy of 46.8 MPG for the new car fleet. Estimates for the various technical certainty and penetration assumptions are summarized in Box 4.

Box 4. Estimated Technical Potential for Improving New Car Fuel Economy

New Fleet Average EPA Composite Unadjusted MPG (from Table 3)

Penetration Increase (see Table 2)	Technical Certainty (see Box 1) Level 1	Level 2	Level 3
High	40.4	46.8	52.6
Full	42.9	49.8	56.0

These technical potential estimates range from 40 mpg to 56 mpg, or a 40% to 100% improvement over the 27.8 mpg base, depending on assumptions. The larger differences in improvement are due to differences in technology between certainty levels rather than differences in penetration of technologies in common among certainty levels. Level 3 is 44% higher (relative to the 27.8 MPG base) than Level 1 under the High penetration assumptions. The Full penetration cases are about 10% higher than the corresponding High penetration cases. Specific differences may be seen by examining the incremental contributions for each technology, certainty level, and penetration level in Table 3. The jump from Level 1 to Level 2 is due to improvements in all three categories (engine, transmission, load). The jump from Level 2 to Level 3 is due to further engine improvements and load reduction. Generally, about half of the net improvement potential level is from engine technology, about three-tenths is from load reduction, and the remainder is from transmission improvement.

For comparison purposes, Table 3 also lists estimates made according to the EEA assumptions. Although the technologies are aggregated differently in our tables, the results are essentially the same as those of the "maximum technology" scenarios of OTA (1991) and Greene and Duleep (1992). For example, the "max tech" fleet fuel economy estimates of OTA (1991, p. 57) imply an unadjusted fleet average of 37.9 mpg, or a 35% improvement over the 1987 new fleet average. This is closely matches than the 33% improvement calculated here (the EEA column in Table 3) using similar assumptions. Successive columns in Table 3 list the greater degrees of improvement made possible by adding technologies or refinements of technologies not included in the EEA analysis. For example, comparing our Level 2, High penetration estimate (46.8 mpg) to the EEA estimate, engine improvements such as variable valve control, variable displacement, and other refinements account for about 12% of the difference (all percentages are given relative to the 27.8 mpg base). Transmission measures, mainly efficiency optimized shift schedules for both automatics and manuals, account for another 7% of the difference. Moving to Level 3, the inclusion of lean-burn or two-stroke engines contributes another 6% to the fleet average technical potential. Our Level 1 load reduction assumptions are similar to those of EEA; each successive Level adds about 8% further improvement.

An implication of this analysis is that many technologies implemented to varying degrees provide a large range of potential fuel economy improvement. Higher levels involve greater uncertainty, but at an intermediate level, uncertainties are reduced because there are multiple options. Thus, there are multiple ways by which the fleet could evolve to reach mid-range levels, e.g., a 45 mpg to 50 mpg fleet average, given adequate lead time. While the application of any one technology might involve uncertainty, a similar degree of efficiency improvement can be achieved through other technologies. Different approaches might, in fact, be taken by different manufacturers. The cost/benefit analysis addressed in the next section will restrict the potential fuel economy levels somewhat. Nevertheless, a key conclusion from this review is that there is a rich array of technological options for improving fuel economy. Policy makers need not count on the availability of only one circumscribed set of automotive engineering options for reaching a new fleet average fuel economy in the intermediate range identified here. Such results are even more conservative in light of the potential for further innovations and advances likely to occur as time goes on.

3.4 Efficiency Improvement of an Example Car

The foregoing estimates were developed through an aggregate analysis for the new car fleet, using average technology benefits applied to average fleet characteristics. We have a very high degree of confidence in this approach (it is similar to that used by EEA, OTA, and NRC) and it is the most tractable method for developing estimates of the fleetwide potential for improving fuel economy. Nevertheless, it is reasonable to ask how the technologies reviewed might be applied to improve the fuel economy of a particular contemporary car. This can be done through a simulation analysis using the engineering model of engine fuel consumption and vehicle loads (Ross and An 1993; An and Ross 1993), taking the known characteristics of an example vehicle and then changing the characteristics according to the effect of technology improvements reviewed here. This complementary approach to the analysis of Tables 1-3 is valuable for addressing concerns related to the use of several technologies to improve part-load efficiency. Modeling analysis allows us to verify that there are indeed such potential gains in efficiency and also to insure that we are not double counting the benefits of the multiple technologies which impact the same source of energy waste.

As an example, we take the 1991 Ford Taurus analyzed to provide the breakdown of energy use over driving cycles shown earlier in Box 2. The Taurus is very close to average in terms of size and fuel economy and has been one of the top selling vehicles in recent years. This car has a 3.0 liter, overhead valve V-6 engine, two valves per cylinder, port (multipoint) fuel injection, and a four-speed lockup automatic transmission, for a composite EPA-rated fuel economy of 27.2 mpg. The engine specific power is 47 hp/liter, which is typical for contemporary overhead valve ("advanced pushrod") engines (it is just under the average of similar engines in the sub-4 liter sizes listed in General Motors 1993). Our simulation model generally fits Test Car List fuel economy values to within ±5% using publicly available data on vehicle characteristics (An and Ross 1993). As shown in Box 2, the fit happens to be quite good for the Taurus, for which the modeled composite fuel economy is within 1% of the measured test value.

In detailed form, the simulation model has eight parameters representing physical characteristics of a vehicle and seven parameters representing characteristics of a driving cycle. For purposes of this discussion, we use the following representation of the model:

$$P_f = kV\langle N\rangle + \frac{1}{\eta}\langle P_b\rangle \qquad (1)$$

This equation represents the average rate of fuel use P_f (e.g., in kilowatts, analogous to gallons of fuel use per minute) in terms of engine speed, N (e.g., in rev/sec) and brake power output, P_b (power available at the flywheel for moving the vehicle). The key engine parameters are k, representing engine friction per revolution and unit displacement; V, representing engine displacement; and η, representing thermal efficiency. To apply the model for projecting potential fuel economy improvements, one must estimate the effect of each technology improvement on the model's parameters.

The two main means of raising fuel economy are load reduction, which reduces brake power requirements, and mechanical efficiency improvement, corresponding to decreases in overall engine friction. Load reduction decreases the required brake power P_b (in the second term of Eqtn. 1). Mechanical efficiency improvement involves reduction of total engine friction, decreasing the $kV\langle N\rangle$ product (the first term of Eqtn. 1). A substantial source of mechanical efficiency gain is engine downsizing enabled by technologies that enhance specific power (P_{max}/V, e.g., kW/liter) while making compensating changes in the transmission/driveline and shift schedule in order to make higher power available when it is needed while maintaining low average engine speeds.

To estimate parameter changes, we first consider the effect of technologies for enhancing specific power: 4-valves per cylinder, overhead cams, compression ratio increase, and multipoint fuel injection. Compared to two-valve per cylinder, overhead-valve engines such as that in the 1991 Taurus example, four-valve overhead cam engines generally give specific power improvements of 45% [Table D-1 of Murrell et al. (1993) indicates 45%; a comparison of engines from General Motors (1993) indicates 48%]. However, torque at a given engine speed is only 3%-4% higher in 4-valve engines, so with a downsized engine, downshifting is needed to access power (as illustrated in Figure 3). Improved engines can also have compression ratios about 10% higher, implying a 2.5% increase in η.

We assume that, other things being equal, these enhancements would be balanced by a 3% increase in specific friction, k. This is consistent with the lack of fuel economy improvement observed when comparing similar vehicles with and without higher specific power engines in the absence of displacement reduction (i.e., when the specific power enhancing technologies are applied mainly for performance increase). Thus, we model these engine enhancements so as to imply no fuel economy benefit without reductions in displacement or engine speed (average engine speed could be reduced by changing transmission and gearing ratios). However, engine friction reduction techniques as discussed in the text permit a decrease in k; we estimate 10% decrease, corresponding to 5.7% increase in fuel economy if these techniques were applied in isolation.

We next consider transmission changes, namely, adding gears and applying optimal electronic control. These technologies allow maintenance of low average engine speeds while taking advantage of the sharp engine downsizing made possible by the technologies that boost specific power. Maintaining driveability implies an increase in N/v (engine revs per mph), which we estimate at 10%, but transmission management (optimized shift schedule) reduces average engine speed. On balance, therefore, the base value of average engine speed $\langle N\rangle$ is maintained. This could also be accomplished by using an electronically controlled continuously variable transmission (CVT).

Variable valve control (VVC) permits substantial improvement of the engine torque across the RPM range. This permits reduction of both displacement and average engine speed, yielding an estimated fuel economy benefit of 12%, as discussed in Section 3.1. The effect of VVC can thus be represented as an adjustment factor, c, to the $kV<N>$ product in Eqtn. (1):

$$ckV<N> \ + \ \frac{1}{\eta}<P_b> \ = \ \frac{1}{1+12\%} \qquad (2)$$

Solving to match the estimated fuel economy benefit, using composite driving cycle energy shares of 54% and 46% (Box 2) for the two terms of the equation, gives an estimated friction term reduction of c = 0.80 for VVC. We assume that this reduction factors roughly equally as a 90% multiplier for k (pumping loss reduction) and a 90% multiplier for V (enabled by the torque improvement yielding higher output at wide open throttle).

Next, we consider the effects of load reduction. Modeling these effects is straightforward, since they translate directly into proportionate reductions of the load terms listed in Box 2. Corresponding to the technical certainty Level 2 estimates as described in Section 2.3, we reduce tire rolling resistance by 32%, aerodynamic drag by 18%, braking losses by 15% (through weight reduction), and accessory loads by 30%. The vehicle weight reduction compounds the reduction in tire losses, since they are equal to the product of C_R and vehicle mass. We conservatively assume that the 15% vehicle weight reduction includes the benefits of the smaller engine, which we specify below. A smaller engine also facilitates aerodynamic improvements.

To summarize the effects of drivetrain improvements on the engine, we multiply out the reduction factors implied by each item:

Specific friction (k) reduction equals (1.03 from 4-valve, etc.) times (0.90 from friction reducing technologies) times (0.90 from VVC), yielding 0.83.

Displacement (V) reduction equals (0.85 from weight reduction) times (0.69 from 4-valve heads, etc.) times (0.90 from VVC), yielding 0.53.

Average running engine speed (N) is assumed to be unchanged, given an added gear and optimized electronic transmission control.

Thus, the improved Taurus would have an engine of roughly half the current displacement: a 4-cylinder, 1.6 liter, 16-valve, variable-valve control, overhead cam engine, with reduced friction, coupled to a 5-speed automatic transmission (or CVT) with an optimized shift schedule under electronic control.

Box 5 summarizes the effects of the improvements over a composite driving cycle (see also Figure S1 in the report summary). The 1991 model's energy losses (from Box 2) are reduced by the factors above and listed in the middle column of the table, yielding the losses for the improved vehicle shown in the third column. These results are also illustrated in the report summary (Figure S1). The compression ratio increase obtained with the more advanced engine implies a 2.5% thermal efficiency improvement (relative, not absolute), which is applied to the subtotal of vehicle loads which the engine must meet. The 53% displacement reduction and 83% specific friction reduction yield a combined engine friction loss reduction factor of 0.44 (shown in brackets). Vehicle loads are reduced by 26% (the 0.74 reduction factor shown in brackets). The total reduction of energy consumption is 1925 kJ/mi,

Box 5.	**Effect of Technology Improvements on Composite Cycle Energy Sinks and Rated Fuel Economy for a Ford Taurus**				
	1991 model		Reduction	New model	
ENERGY SINK	kJ/mi	%	factor	kJ/mi	%
Tire rolling resistance	652	15	(0.68)(0.85)	377	15
Aerodynamic drag	609	14	(0.82)	499	19
Braking	579	13	(0.85)	492	19
Accessories	242	5	(0.70)	169	7
Vehicle Load Subtotal	2082	46	[0.74]	1538	
effect of 2.5% CR increase:			(0.975)	1499	59
Engine friction, powered	1865	42	(0.53)(0.83)	820	32
Engine friction, idling	531	12	(0.53)(0.83)	234	9
Engine Friction Subtotal	2396	54	[0.44]	1054	41
TOTAL	4478	100	[0.57]	2553	100
FUEL ECONOMY (MPG)	26.9		[1.75]	47.2	

breaking down as 544 kJ/mi (28%) from load reduction and 1381 kJ/mi (72%) from engine and transportation improvements that improve part-load efficiency. The improved "Taurus" thus has a composite fuel economy of 47 mpg, a 75% increase above the 27 mpg rating of the 1991 model.

There are a number of issues that come up in considering what this improved Taurus would be like to drive. Outward appearances would be little changed: the vehicle would be the same size (no change in interior volume and no need to shrink wheelbase) but more aerodynamic, with a drop from 0.33 to 0.27 in drag coefficient (C_D). Average running engine speed is the same as with the 1991 model, but with a four rather than six cylinder engine, this could raise vibration concerns at lower speeds. However, the estimated average engine speed is 1755 RPM, which does not present problems for driving with today's four-cylinder engines. When downshifting to access more power, which will happen more frequently in the improved car, engine speeds are likely to increase by about 33% (based on comparisons of power curves to determine engine speeds at which the needed peak power is available). Compared to the 1755 RPM average, this would only push the speed up to 2335 RPM. To cruise at 70 mph in the improved car, the power needed is about 15 kW (20 hp); with the 1.6 liter engine, about 42 kW (56 hp) would be available at 3000 RPM, so it appears that the engine operating conditions will not entail excessive noise and vibration. In any case, these effects can be addressed by careful design.

More noticeable might be the downshift delays, which are typically one-half second or less. These are a common experience in some 4-cylinder vehicles with automatic transmissions and would become more common in the improved Taurus, which would use a downshift strategy to access power with the smaller engine (as illustrated in Figure 3). Thus, the "feel" of driving will be different in the improved car, although shift transitions can be smoothed out using the electronic controls. We do not suggest that these modifications to improve fuel economy and changes in the "feel" of driving would be well suited to sell cars under today's market conditions. We do suggest that such cars could be sold under changed conditions, such as might be brought about by a policy consensus that higher fleet average fuel economy is needed to address problems of national concern.

This vehicle-specific analysis verifies the inherent conservatism of the aggregate analysis presented in Tables 1-3. Using only Level 2 technologies, this example indicates a 75% fuel economy improvement in a very typical car, compared to the fleet average technical potential improvement of 68% estimated in Table 3. The higher estimate from the modeling analysis is largely due to the strong positive interactions which are difficult to capture in the aggregate analysis. Moreover, the example does not use a number of the technologies discussed, even at certainty Level 2, such as variable displacement, turbocharging, or idle-off. The cost of improvements will be modest, roughly $765 based on the costs discussed in the next section (see Table 4). This would be a 5% increase over the $14,700 list price of the base 1991 Taurus. The cost could be lower if a CVT were used rather than a 5-speed automatic and lower still if a two-stroke engine were used. The load reductions will make it easier meet emissions standards with a two-stroke engine. Thus, although we do not develop an analysis for the Taurus using technologies listed at technical certainty Level 3, they provide a possibility of improving to more than 50 mpg, most likely at lower cost.

Note that, with the substantial improvement in mechanical efficiency (reflecting reduced engine friction), vehicle loads will account for proportionately more of the relative energy losses in the vehicle. The ratio of tractive loads to engine friction for the 1991 Taurus is 46:54; for the improved Taurus, it is 59:41. Thus load reduction becomes ever more important as we push the limit of conventional drivetrain efficiency improvement. This underscores the importance of the "Ultralite" strategy identified by Lovins et al. (1993), which, it turns out, will become even more important for unconventional drivetrain technologies (such as hybrid electric vehicles) which are likely to involve storage devices having energy- and power-to-weight ratios much poorer than that of an internal combustion engine and its fuel tank.

Finally, the example of the Honda Civic VX illustrates the degree of fuel economy improvement that can be obtained when technologies are optimally applied for fuel economy. Introduced in 1992, the Civic VX demonstrated a fuel economy improvement of 56% over a comparable previous model (the 1991 Civic DX hatchback) without changing size or performance. The fuel economy improvement in the VX over the course of one 4-year model cycle resulted in a fuel economy level that exceeded the higher NRC (1992) estimate of what is achievable for subcompact cars in 2006, even after adjusting for differences between the Civic VX and the average subcompact (Plotkin 1992). The 1990 subcompact class average was 31.5 mpg (Murrell et al. 1993); our Level 3 projected improvement of 85% would thus imply 58 mpg for average subcompacts, just under the 60 mpg EPA/TCL (1992) rating of the Civic VX (technology Level 3 is the appropriate comparison since the Civic VX uses a lean-burn engine). The California version of the Civic VX has a fuel economy of 55 mpg, also higher than the 52 mpg average implied for subcompacts by our Level 2 technology estimates (without lean-burn engines). While one cannot necessarily make inferences from a single model to the whole fleet unless the model has been chosen to have representative characteristics (as in the Taurus example), the fact that fuel economy observed in the Civic VX is similar to that estimated from our analysis is another corroboration of our results.

4. COSTS AND ACHIEVABLE FUEL ECONOMY IMPROVEMENT

There are costs associated with the technology changes identified above and, in principle, the same direct costs are incurred no matter what forces drive the changes. Gasoline prices could rise, oil supplies could be curtailed, or policies could be instituted to motivate or require fuel economy improvement--and it is the feasibility of such policies which concerns us here. The cost of changing automobile technology is related to three factors: inherent technology costs, timing of investments, and market risk. This section addresses the first two of these factors in order to develop estimates of cost-effective levels of fuel economy improvement and when they might be achieved. The issue of market risk is taken up later, in Section 5.

If technology improvements are made during the course of normal product cycles, then the only added costs are those inherent in the changed technology itself. As reported here at the retail level, the incremental cost covers research, development, tooling and other capital expenses, labor and other variable costs, and distribution costs. The incremental capital expenses are critical, because they become sunk costs that must be recovered through adequate sales. For example, there is likely to be a cost associated with the greater complexity of a five-speed automatic transmission over a four-speed. Provided the tooling costs for building the four-speed transmissions already in production have been recovered, then the basic retooling for production of the five-speed transmissions represents no additional cost burden. Given sufficient time, the only additional cost is that which is inherent to the improved technology (e.g., due to the greater complexity of the five-speed transmission). Costs may be higher early on, when a technology is new, but then drop as it comes into widespread use. Our analysis assumes that the technology is mature, so the cost estimates represent average values over the entire period of production.

Even the inherent cost of a given technology can be ambiguous when the technology has benefits in addition to fuel economy. For example, electronic transmission control can provide better shift smoothness and reliability as well as higher fuel economy. Similarly, multipoint fuel injection can improve engine smoothness, ease starting, and facilitate emissions control as well as improve fuel economy. We noted earlier that materials and design changes resulting in weight reduction can provide many benefits, including reduced manufacturing costs. We have not attempted to resolve such allocation issues here, but believe that they add a degree of conservatism to our results regarding the cost-effectiveness of fuel economy improvement.

Regarding the timing of investments, we are not in a position to estimate either excess costs arising from a lack of sufficient time to recover existing sunk costs or the development and tooling costs for new technologies. Therefore, we estimate the requisite lead time and allow such time when stating the year when we believe the technical potential can be realized; this validates the assumption that the only added cost is the average cost increment for the new technology at full production levels. In other words, our costs assume that the time allowed for technology change is long enough to avoid premature replacement of existing capital investments. What is meant by "premature" is a key question. It is related to rates of product evolution in the industry, which we take up below in Section 4.2. Because questions of cost are intimately linked to rates of product change and marketing considerations, one must not overstate the certainty of cost-effectiveness evaluations, even though quantitative "point" estimates are made. The approach used here is the best that can be done with publicly available information and, in spite of the limitations and uncertainties, we believe it provides a fair guide to the economic practicality of improving fleet average fuel economy by increased use of the technologies reviewed here.

4.1 Determining Cost-Effectiveness

The starting point for the cost figures used here is set of estimates developed by EEA and as reported in OTA (1991) and Greene and Duleep (1992). These estimates, given at the retail price equivalent (MSRP) level, are based mainly on comparisons of production vehicles which are similar except for the use of a particular technology (EEA 1988). EEA also draws some information from analyses by L. Lindgren, and we also supplement our information with estimates from Lindgren and Jones (1990). Table 4 lists the EEA cost estimates along with our estimates if they differ or pertain to technologies not included in the EEA assessment. Our assumptions and reasons for differences from the EEA estimates are explained in the detailed notes to the table. For technologies that improve engine specific power (kW/liter), the cost estimates reflect adjustment for the savings from engine downsizing, as described in the table notes. Technology-specific costs are listed in Table 4 in 1990$ for consistency with our data base and to facilitate comparison to previously published sources (such as NRC 1992). We update our fleet average cost and cost-effectiveness results (as given in the report Summary) to current (1993) dollars using a GDP price inflator of 1.10.

Although we are not able to provide estimates of the uncertainty of the cost figures, it is important to point out how dependent they are on assumptions regarding the timing and nature of tooling investments and that costs can vary among manufacturers. The wide range behind some particular estimates is revealed in our notes to Table 4. For example, the estimates of the cost of converting to overhead cams range from zero (or even a savings) to many times the value we choose. Greatly higher values for technology cost have been given by industry sources such as SRI (1992), where costs for technologies in common with the EEA estimates average three times as high (based on a penetration-weighted comparison of estimates given in Table B-2 of NRC 1992). However, the assumptions behind such numbers are very dubious. The overhead cam example is a case in point: the SRI (1992) estimate is $400, but it is difficult to see how this engine improvement could have achieved its 20% penetration in the new car fleet by 1990 at such a cost. We have carefully examined the available cost data and selected estimates which have a credible basis and are appropriate for the assumptions noted above. The values should be interpreted in that regard and taken as a general guide for assessing cost-effectiveness. Although any particular number may be rather uncertain, it is less likely that estimates are greatly uncertain in aggregate; this is the appropriate view, since the technologies changes would be applied in aggregate. Moreover, it is just as likely that actual costs would be lower than the numbers used here as it is that they would be higher.

One measure of cost-effectiveness is the simple payback period, defined as the cost increment divided by annual fuel cost savings. This is shown in the last column of Table 4. Simple payback does not depend on assumptions regarding discount rate or vehicle lifetime; it depends on fuel price, which we assume to be $1.20 per gallon for calculating payback. Of the 21 measures identified here, all but two have a payback times of less than 5½ years, which is the average time new buyers expect to keep their cars (MVMA 1992). The longest payback period is that for idle off, at 8½ years (less if used alone, see table notes) and the next longest is for super- or turbocharging. That all payback times are shorter than the 12-year lifetime of the average vehicle suggests that fuel economy improvement is beneficial from an aggregate consumer perspective, even without considering the broader benefits of avoiding the external costs of fuel consumption.

Another view of cost-effectiveness is obtained by lifecycle cost analysis. One can compare the discounted present value of fuel savings to the cost of the technology (effectively amortizing the technology cost over the vehicle lifetime) to calculate the Cost of Conserved Energy (CCE). We evaluate CCE at a 5% real discount rate and 10,000 miles of annual driving over a 12 year vehicle life. It is important to recognize the value of fuel savings over the full life of a vehicle rather than to the first owner alone. An improvement is considered to be cost-effective as long as its CCE is no greater than the comparison price ("avoided cost") of fuel. An appropriate comparison price is the expected price of gasoline levelized over the life of new vehicles at the time they become available. We use a comparison price of $1.50/gal (1990$), based on the DOE (1993) gasoline price projection for 2010, about midway through the life of vehicles sold as new cars in 2005.

Tables 5(a)-(c) list, for High penetration of technologies at certainty Levels 1-3, respectively, the marginal (CCE) and average (ACE) costs of conserved energy for each technology in order of increasing CCE, as well as the average per-vehicle incremental cost to reach a given level of fleet average fuel economy. Under the Level 2 technology assumptions, for example, the estimated cost-effective new car fleet average is 44.8 mpg, reached at a marginal CCE of $1.49/gal. The corresponding ACE is $0.47/gal and the average per-vehicle incremental cost to improve the fleet from 27.8 to 44.8 mpg is $663 (1990$). Using a 10% instead of 5% real discount rate would increase the CCE and ACE estimates by roughly 30% at each level. In computing the cumulative fleet average fuel economy improvements as shown in Table 5, we applied an optimization factor to account for the multiplicative interaction of load reduction and drivetrain measures. This factor was interpolated from zero at the base fleet level to its maximum value at the last technology, so that the bottom line of each table matches the corresponding technical potential given in Table 3.

A graphical representation of the cost-effectiveness calculations is given in Figure 7, which shows conservation supply curves for fuel economy improvement. Figure 7(a) plots CCE against new car fleet fuel economy, so that the CCE at each step represents the marginal cost, expressed as a gasoline price equivalent, of each increment of fuel economy improvement. Curves L1-L3 are for our Level 1-3 technology certainty assumptions; also shown for comparison is a curve using EEA technology assumptions (based on Greene and Duleep 1992). The CCE calculations of Table 5 and Figure 7 are based on our High technology penetration assumptions. Similar results based on the Full penetration assumptions are not listed but were averaged with the High penetration results to calculate the summary results. These are presented later (Box 6, in Section 4.3) and indicate cost-effective new car fleet averages of 40 mpg, 46 mpg, and 51 mpg for Levels 1, 2, and 3, respectively.

Figure 7(b) is nationwide end-use energy conservation supply curve corresponding to the fuel economy cost curve in part (a) of the figure. One barrel (42 gal) of end-use gasoline savings results in more than one barrel of primary oil savings. Just accounting for the energy used in extraction, refining, and distribution implies oil savings roughly 20% higher than end-use gasoline savings (DeLuchi 1991); however, not all of this "upstream" energy use occurs in the United States. Accounting for the fact that gasoline is a high-value commodity that drives the U.S. petroleum products market would imply an even larger ratio of oil savings to end-use gasoline savings. However, we do not attempt such adjustments here, so nationwide oil savings are larger than the gasoline savings shown in our tables and figures.

In Figure 7(b), the CCE for gasoline savings is shown as crude oil price equivalent, derived from the relationship between world oil price and retail gasoline price given in DOE (1993).[16] The bottom axis represents the gasoline savings in 2010 for fuel economy improvements achieved in the new fleet by 2005. We assume that the entire light duty fleet (cars and light trucks) improves by the same percentage and at the same relative cost as given by our analysis for cars alone. Achieved fuel economy is frozen after 2005 and the baseline fuel economy frozen at the current new light duty fleet average of 25 mpg. Other pertinent assumptions are constant fuel economy shortfall of 20%, a VMT rebound effect of 10%, an average VMT growth rate of 2%/yr over 1990-2010. Using our mid-range, Level 2 assumptions and recalling that oil savings exceed gasoline savings, we see that nationwide oil savings of 2.8 million barrels per day (Mbd) can be obtained at a cost of just under $30 per barrel, which is the oil price projected for 2010 by DOE (1993).

Since CO_2 emissions from motor vehicle use are directly proportional to fuel consumption, the curves of Figure 7(b) also represent potential cuts in CO_2 emissions. This is indicated by the scale along the top of the graph, using an emissions factor of 50.2 million metric tons per year of carbon mass-equivalent emissions (MT_C/yr) for each Mbd of gasoline consumption (corresponds to full fuel cycle CO_2-equivalent emissions of 12 $kgCO_2$/gal, based on DeLuchi 1991). The right axis of Figure 7(b) shows the cost per ton of carbon emissions reduction, net of the fuel cost savings. CO_2 reduction costs are negative through the cost-effective level of fuel economy, since they are based on the difference between the avoided gasoline cost and the cost of conserved gasoline. Since the cost curve developed here rises so sharply beyond the cost-effective level, we see that a CO_2 emissions reduction value of $100/ton is not sufficient to warrant much further fuel economy improvement. Through the cost-effective level, however, greenhouse gas emissions reductions are obtained at net savings.

In using an aggregate consumer perspective for judging cost-effectiveness, we consider the fuel cost savings to all owners of a vehicle over its lifetime (original owner as well as those who will the vehicle as a used car). Thus, the appropriate fuel price is the retail price of gasoline, including taxes, paid by consumers (rising from a recent level of about $1.20/gal to $1.50/gal by 2010). A societal perspective would exclude taxes, implying a lower fuel price. However, it would then be appropriate to include externalities, such as petroleum security costs and fuel-related environmental costs, and use a societal discount rate, which would be lower or perhaps zero (since impacts on future generations become a valid concern). Such an approach is likely to improve the cost-effectiveness at each fuel economy level depending on the externality values chosen. Greene and Duleep (1992) give a discounted present value analysis of various costs and benefits, showing that, even with fairly conservative assumptions about externalities, there are net positive benefits beyond the direct technology costs and fuel savings.

The cumulative incremental retail cost of the technology improvements identified up to the cost-effective potential is $540-$760 for Levels 1-3. The fuel economy improvements will thus add less than 5% to the average new car price. Nevertheless, the industry's investment requirements for these improvements are substantial. Assuming a proportional degree of fuel economy improvement for the whole light duty fleet (cars and light trucks) and sales of 15 million new vehicles annually, the nationwide cost to new car buyers would be up to $11 billion per year at the full level of fuel

[16] The relationship is: (Gasoline Price) = $28.52 + 1.144(Oil Price), in 1991$/bbl, based on a fit to the oil price scenarios of DOE (1993).

economy improvement. By way of context, annual new vehicle retail sales amount to more than $200 billion and annual gasoline sales now exceed $100 billion. Assuming that incremental up-front investment costs are approximately 10% of the incremental retail price, the implication is that about $1 billion of additional annual investments for product development and retooling might be required of the industry as a whole for fuel economy improvement. From 1987-1991, annual U.S. motor vehicle output averaged about $200 billion while expenditures on motor vehicle industry plant and equipment averaged $11 billion (MVMA 1992), so the 10% estimate for investment costs as a fraction of incremental sales price is probably generous.

The complete supply curve of Figure 7 shows the technical potential for fuel economy improvement for the technologies, benefits, and costs identified here. Selecting technologies having a CCE up to the avoided fuel cost implies the cost-effective level of fuel economy improvement. We have not yet addressed the issue of when such levels might be achieved; that is the next topic. (The years used in constructing Figure 7(b) are based on the discussion that follows.) Estimating the achievable potential for improvement will also require considering trade-offs, such as performance, safety, and emissions, related to vehicle fuel economy.

4.2 Estimating Lead Time

To estimate how long it will take to make the efficiency improvements identified here, we examined auto industry product cycles, development times, and rates of technology evolution. The product cycle--how long a vehicle design stays in production--is determined by balancing the need to sustain high sales volumes by having a "fresh" product with the need to recover the substantial fixed costs of product development and tooling (Burke 1992). Product development time refers to how long it take to develop new models (or major components, such as engines and transmissions) up to the commencement of mass production (Clark and Fujimoto 1991). Long product development times generally imply higher product development costs and therefore the need for a longer product cycle to recover these costs. Finally, one can observe rates of technology evolution over the industry as a whole (rather than tracking individual model projects) to provide an empirical estimate of how long it might take improved technologies to penetrate.

In this section, we examine all of these factors and end up relying on observed technology penetration rates to estimate lead time requirements. The lead time estimated on this basis is much longer than typical product development times and yields a time horizon no shorter the longest contemporary product cycles. While most technologies can reach their full potential penetration levels (Table 2b) within the time frame estimated, we do constrain some penetration levels (e.g., for VVC) so as to not require a faster rate of penetration than would be achievable within the estimated lead time. In this case, allowing more time would allow the improved technology greater penetration and result in higher fleet average fuel economy; however, we do not pursue such an analysis here.

Allowing time for recovery of investments is clearly a critical aspect of the cost issue; on the other hand, market share can drop off if a model stays in production too long. The competitive advantage of fresh designs depends on market segment--we will examine this shortly--but it is clear that, on average, there has been an increased importance of product innovation for capturing market share. Success depends on anticipating and creating the direction of buyers' tastes, and this cannot be done with static or only superficially changed product designs. Reviewing Chrysler's weakness in major car segments in the 1980s and the importance of the new LH-models for Chrysler (just introduced), Connelly (1991) noted that "saddled with outmoded car models, the company has had to address future possibilities rather than current realities." Taub (1991) emphasizes the importance of innovation and even what appeared to be "radical" new design for the success of the Ford Taurus. Ford clearly saw that, by the 1980s, there was much greater risk in merely being a follower of other's products rather than the risks involved in serious product innovation.

Product turnover is constrained by the need for profitable cost recovery, which depends in turn on product development performance. Initial engineering design for the Taurus/Sable project began in early 1980 and the vehicle was launched in December 1985 (model year 1986). The Taurus was significantly updated in 1992, 6 years after introduction, with a "reskinning" (new body and interior) plus assorted mechanical improvements, but major engine and powertrain components were not fundamentally changed. Ford's planners project that the 6-year, $3 billion development program for the Taurus implies a 10-12 year time before complete redesign, slated for model year 1996-1998 (Taub 1991; Jackson 1991). According to Taub, however, such a long cycle is perceived to give "Japanese competitors a further wedge into the increasingly competitive family-car market." A look backward at some of the U.S. producer's past cycles does indeed imply times between major redesign of 12-15 years, which form the basis of the timing assumptions adopted by NRC (1992), for example.

However, extensive research at Harvard and MIT has clearly documented that such long cycles are likely to doom any producer in the marketplace of the 1990s. Clark and Fujimoto (1991) conclude that the ability to quickly move new concepts from R&D to design and on into production is "a hallmark of success" and "a key source of competitive advantage." They identify lead-time along with development productivity and product quality as key parameters of market performance. Average lead times range from 4 years for Japanese auto firms to about 5 years for U.S. and European firms. Shorter lead times imply lower development costs, enabling a shorter product cycle to be profitable, which is compatible with maintaining a competitive degree of product newness. Womack et al. (1990) document how an integrated design, development, parts supply, and production process emphasizing continuous improvement--"lean production" as pioneered by Japanese firms--has slashed investment costs, manufacturing costs, and lead-times in the auto industry. Firms that have mastered lean production can more effectively track, as well as define to their own advantage, evolving market conditions, thereby gaining market share.

In summer 1991, *Automotive News* ran a series entitled "Future Product" which examined how the major automakers currently develop new products for the U.S. market. Estimates from these sources are summarized here in Box 6, which lists the likely product cycles by market segment. Frame (June 1991) outlined GM's "Four Phase Process" for product development using the H-body large cars, which were newly redesigned for model year 1992. Development of these vehicles--the Buick LeSabre, Oldsmobile 88, and Pontiac Bonneville--began with a concept initiation step in "Phase Zero," which occurred in June 1987. The final phase of actual production began in April 1991, illustrating a 4-year development process. Frame reported that the H-cars are slated for replacement in 1998, suggesting a 6-year production cycle for these large cars. Connelly (1991) reported that Chrysler plans model replacement cycles of 4, 6, and 8 years for cars, minivans, and trucks, respectively. Reports on the Chrysler Neon project, which saw a new vehicle including a new engine and transmission developed in well under four years (Woodruff and Miller 1993), suggest success in making this transformation. Moreover, Chrysler is now supplying engines to Mitsubishi. Thus, the conclusions of Harvard and MIT researchers appear to be well validated in reports by the trade press and industry analysts.

Box 6. Light vehicle product cycles

Vehicle Class	Market Share	Product Cycles (years) Faster	Slower
Subcompact, etc.	17.1%	4	5
Compact	23.9%	4	5
Midsize	18.5%	4	10
Large car	10.5%	4	10
Small Van/Utility	11.6%	6	7
Large Van/Utility	3.7%	8	12
Small Pickup	4.1%	8	12
Large Pickup	10.6%	8	12
OVERALL	100.0%	5	8

Vehicle Classes: Subcompact includes two-seaters and minicompacts; Compact, Midsize, and Large cars include Small, Medium, and Large station wagons, respectively.
Market Shares: 1990 values from Heavenrich et al. (1991).
Product Cycle: estimates based on reports of Connelly (1991), Frame (1991a,b), and (Jackson 1991). The best cycles are also consistent with product development times identified by Clark and Fujimoto (1991).

Weighting the shortest and longest estimates by market share yields a range of 5 to 8 years for light vehicles on average. Although some segments are slower than average for financially viable redesign, other segments will be transformed faster, and so the use of such averages are appropriate for an aggregate fuel economy improvement assessment as presented here. The upper end of the range identified in Box 6, namely, 8 years, thus gives a cautious estimate of the time needed for major model redesign. However, while these cycles apply to vehicle models, engines and transmissions follow their own cycles, which have generally remained longer than the product cycles.

As noted in the first section, engine improvement is the largest source of technical potential for fuel economy improvement. Engines, as well as transmissions, have major production cycles and associated investment requirements of their own. These are related to the cycles of particular models, among which major drivetrain components can be shared. Ford, for example, has a modular engine program, which "allows the company to manufacture a variety of engine configurations on a flexible line" (Jackson 1991), substantially reducing costs for a given engine requirement. The tooling investments for engine manufacturing are substantial and on a par with those for a major product line. Ford is reported to have spent $2 billion over four years to develop its "Zeta" engine, a family of 4-cylinder, 16-valve, DOHC, fuel-injected engines slated for use in a variety of products, initially in Europe, but also for North American and Pacific markets (Birch et al. 1992b). According to this same report, by the end of the century Ford expects to replace all of its European car engines that were in production in 1991.

Published information specific to engine development cycles is less readily available. Some engines lines have remained in production for many years. Engine blocks, for example, require very large tooling investments. As with vehicle models, however, competitive pressures have resulted in reduced development costs and lead times similar to those for vehicle models. Doi (1992) showed that the best performing firms had engine development programs compatible with short product cycles and which reflected steady refinements through a hierarchy of the major aspects of engine design: displacement changes, new fuel systems, new cylinder heads (valves and camshafts), and new blocks. Firms that gained market share had the highest rates of engine technology change. Also, recent new model projects have included new engine development on the same rapid schedule as the vehicle project, as noted earlier for the case of the Chrylser Neon (Woodruff and Miller 1993).

According to Doi (1992), changing the cylinder bore and stroke for a given block can yield displacement changes of up to about 20% (0.5 liter; average car engine displacement in 1990 was 2.7 liters), without major retooling. This is significant, because it implies that only low costs would be involved for some of the engine downsizing changes needed to re-optimize vehicles for better fuel economy at constant performance. Changes in fuel delivery (e.g., fuel injection) and valve arrangement (multivalve heads, overhead camshafts, variable valve control) can also be accomplished short of major engine line retooling. In some circumstances, automakers can obtain these parts from outside suppliers (including other automakers), more quickly and at lower cost than wholly developing them by themselves. Thus, many of the engine technologies needed for fuel economy improvement (or performance enhancement, depending on application) can be introduced without a complete redesign of engine production.

Doi (1992) identified rates of engine refinement between 1978-1990 and showed that, averaged over all firms, there were penetration increase rates of up to 6.5% per year for multivalve heads, 5.8% per year for fuel injection, and 3.5% per year for overhead cams. There was, of course, significant variation among firms, with the best performing firms consistently showing above average rates of new technology penetration. Murrell et al. (1993) document average penetration increase rates of 4.9%/yr for 4-valve heads, 5.9%/yr for front-wheel drive, and 8.6%/yr for fuel injection. These rates are consistent with the generic technology introduction profiles of EEA (1991a), which indicate penetration increase rates of up to 9% per year during the "broad adoption" phase of a given technology. EEA suggests allowing 50% longer for engine technologies, implying a penetration increase rate of 6% per year. These rates may be conservatively low since they are based on historical trends not reflective of the recent advances in productivity.

For most of the major engine changes analyzed here, we estimate penetration increases of up to 67%. This implies a lead time range of 7½ to 11 years, corresponding to faster (9%/yr) and slower (6%/yr) penetration rates, respectively. Although we see a potential 100% penetration increase for variable valve control (VVC), we held our penetration increase estimate for VVC to 67% for the purpose of estimating the achievable potential within the time bounds implied by other major engine refinements.

In general, the shortening of vehicle product cycles reflects a diffusion of lean production to American firms (Womack et al. 1990). In Chrysler's case, this was aided by their joint ventures and other collaborations with Mitsubishi plus management commitment and determination to go forward with aggressive plans for developing new models that would be competitive in all major car segments (witnessed by the recent releases of the "LH" and Neon models). GM has been attempting to do the same, by means of successful joint ventures, such as NUMMI with Toyota and CAMI with Suzuki, and through their own Saturn program. Some U.S. firms' transitional efforts, such as GM's Saturn and Ford's Taurus programs, have taken longer and cost more than Japanese producers product development (Keller 1989; Taub 1991), saddling these lines with longer cost recovery times. According to industry analysts, these relatively high-cost, long-lead-time projects are a poor guide to what will work in the 1990s. Reviewing GM's Ultralite project, Lovins et al. (1993) note that the prototype went from the concept stage to road test in just 8 months at a cost of less than $6 million, illustrating the "lithe and agile tactics that underpin a winning industrial strategy." The Ultralite effort did not include tooling for volume production, of course, and so does not represent a realistic estimate of product development time.

Thus, market demands for newness and a quicker, lower-cost development process have both driven a shortening of product cycles. Clearly, lead times cannot shrink without limit; there is a need to avoid premature introduction of new technology, which could compromise quality and reliability. But these two critical product attributes are best assured by the better integration product development and manufacturing that also characterizes lean production. As Womack et al. (1990) point out, the maxims "faster is dearer" and "quality costs more" belong on "the junk heap of ideas left over from the age of mass production." According to Clark and Fujimoto (1991), assurance of quality and reliability when introducing new technologies might raise development time from 4 up to 5 or 6 years, depending on market segment.

Based on the previously mentioned range of penetration rates for engine technologies, we estimate a range of 8 to 11 years for accomplishing the technology improvements identified here for increasing average fuel economy. Note that this allows for at least two full 4-year model cycles under state-of-the art product development rates that have come to characterize the major, competitive segments of the market. Projection of the ability to achieve the full fuel economy improvement potential within 11 years, or model year 2005, is generous, time-wise, since the use of some of the engine technologies which most constrain the analysis has probably already increased since 1990.

4.3 Achievable Potential

Vehicle fuel economy is affected by changes in other vehicle attributes, including those associated with power performance, emissions control, safety, and luxury. Vehicle size is also related to fuel economy as well as some of these other attributes, but this analysis maintains an assumption that average vehicle size remains fixed. Here we examine the effect of changes in these other attributes on fuel economy in order to adjust the estimated cost-effective fuel economy levels as needed to determine the achievable potential for improvement.

Performance

Many of the technologies discussed here can improve either power performance (acceleration and top speed ability) or fuel economy. They have largely been applied for performance improvement in recent years. If engine displacement is unchanged, fuel injection, multivalve heads, overhead cams, higher compression ratio, variable valve control, and boosting all enhance performance, often substantially and sometimes with a modest fuel economy benefit. Applying these technologies at constant performance offers the large fuel economy benefits listed in Table 1, mainly because they enable displacement reduction. Reducing engine displacement provides a direct, proportionate reduction in engine friction which, as shown in Box 2, accounts for more than half of the energy loss over a driving cycle.

Both performance and fuel economy are also enhanced by load reduction. Even if engine power is unchanged, all of the load reduction technologies provide a fuel economy benefit. Reducing tire rolling resistance will then improve both acceleration and top speed. Reducing air drag provides some acceleration benefit (mostly at higher speeds) and raises top speed capability. Reducing weight provides a great benefit for acceleration ability at any speed. As with the engine technologies, capturing the full fuel economy benefit of load reduction involves holding performance constant by reducing engine displacement and making appropriate changes in gearing.

The fuel economy improvement estimates made above are based on the 1990 fleet and so assume constant performance at a 1990 level. The averages for 1990 new cars are a 0-60 mph time of 12.1 s and an estimated top speed of 117 mph, which are all-time highs for both measures of performance. Performance increases have continued since then, with average new car fleet 0-60 mph acceleration time dropping to 11.5 s by 1993 (Murrell et al. 1993). The trade-off between performance and fuel economy can be examined by varying the assumed acceleration time, which is closely correlated with a vehicle's power-to-weight ratio. Each 1% increase in 0-60 mph acceleration time implies a 0.44% improvement in fuel economy on a fleet average basis (Murrell 1990). (A stronger sensitivity of about 0.6% is implied by physical modeling of peak power-to-weight ratio vs. fuel consumption, but this does not consider torque constraints at lower engine speeds.)

To examine the trade-off, we consider performance changes from the 1990 base to fleet average acceleration times ranging from 11 s (even quicker than the 1993 average) to 14 s (the 1983 average). Figure 8 shows fleet average acceleration vs. fuel economy trade-off curves for the three technical certainty levels. At the slower performance, using a sensitivity coefficient of 0.44 implies an average fuel economy improvement of 6.6%. Conversely, an faster performance lowers the potential fuel economy by 2.2%. For technology certainty Level 2 and the average of High and Full penetration assumptions as depicted in Figure 8, the 1983 to 1993 performance range thus implies a +3 mpg to -1 mpg range around the projected average of 46 mpg.

Emissions

Vehicle emissions of criteria pollutants--carbon monoxide (CO), hydrocarbons (HC), and nitrogen oxides (NO_x)--are largely a function of emissions control technologies. Three-way catalytic converters can reduce engine-out emissions of the criteria pollutants by 80% or more (Heywood 1988). Since emissions standards are specified on a per-mile basis for all cars, rated emissions have little meaningful correlation to fuel economy. Actual emissions are strongly related to how well emissions control systems are maintained as well as how well they cover conditions experienced in real-world driving, as opposed to the test cycles used for compliance with emissions standards. While older vehicles are more likely to be high polluters than newer cars, excessive emissions occur in vehicles of all ages and average in-use emissions are many times the test cycle emissions (Calvert et al. 1993). Ongoing studies by the U.S. EPA and the California Air Resources Board have revealed enormous increases in emissions during situations such as cold starts, high speed driving, and hard accelerations. Some controls needed to address these problems, such as electrically heated catalysts, can add weight to a vehicle, creating a fuel economy trade-off. We noted earlier that tighter test-cycle NO_x standards may constrain some efficient technologies, such as lean-burn engines, unless improved systems or new controls are developed.

Meeting the 1990 Clean Air Act Amendments Tier I-II emissions standards (see EPA 1990) is expected to add 5-15 pounds, respectively, to average vehicle weight (Duleep 1993b). Combined with weight additions from safety standards discussed below, we applied this as an adjustment to the potential vehicle weight reductions estimated in Section 2.3. No additional adjustment is needed for possible NO_x emission constraints, which are accounted for in the assumptions regarding technical certainty (NO_x-constrained technologies are confined to Level 3). While emissions are dominated by the quality and effectiveness of control technology, reducing vehicle loads generally reduces fuel/air mass throughput and can reduce the cost of control at a given per-mile emissions standard. Thus, load reduction is generally seen by automakers as a way to help compliance with stronger emissions standards.

Fuel economy improvement provides definite reductions in hydrocarbon (HC, VOC) emissions at service stations, refineries, and throughout the gasoline production and distribution system. Comparing this benefit to other costs of HC control could justify a fuel economy 1-2 mpg higher than that determined to be cost-effective on the basis of fuel savings alone (DeLuchi et al. 1992). We discuss the potential nationwide HC emission reductions in Section 5 but do not adjust our estimates of achievable fuel economy on this basis. Accounting for such externalities generally yields higher estimates of the cost-effective fuel economy level.

Safety

Because fuel economy improvement entails significant changes in vehicles, particularly changes in weight, there is an issue of possible impacts on highway safety. The question is how the changes made to improve fuel economy will impact overall traffic fatalities and injuries, considering the mix of all vehicles on the road and including impacts on other road users such as children, pedestrians, and bikers. No studies to date have been comprehensive enough to answer this question.

Opponents of fuel economy regulation often assert an adverse safety effect by using examples of a larger, heavier car crashing into smaller, lighter car (e.g., advertisements by the Coalition for Vehicle Choice, a lobbying group created by the auto industry). This is an unbalanced and misleading approach to the issue, since it neglects the greater risks imposed on other road users by the larger vehicle and the lesser risks to others by the smaller vehicle. Safety advocates, by contrast, find no conflict between improved fuel economy and safety, pointing out that vehicle crashworthiness is primarily a function of design (Ditlow 1991; Freidman et al. 1991). For many externalities, such as air pollution, costs may be highly uncertain. Nevertheless, there is strong evidence that they are significantly greater than zero and therefore a bias will result from ignoring them. Particularly since our projected increases in fuel economy rely on technology improvement rather than vehicle downsizing, the available evidence is far from sufficient to show that the safety impacts of improving fuel economy are greater than zero.

While some studies have purported to show an adverse safety impact associated with fuel economy improvement (e.g., Crandall and Graham 1989), reviews have shown these results to be incomplete, highly sensitive to methodological biases, and ultimately inconclusive (Ledbetter 1989; Khazzoom 1991; OTA 1991; NRC 1992). NRC (1992) noted the ambiguous effect of vehicle weight in two-car collisions, since, while a heavier vehicle may be relatively protective of its occupants, it is more damaging to the occupants of other vehicles. NRC emphasized that there are no conclusive answers to the question of safety vs. fuel economy, that further study should be undertaken, and that meanwhile, "concern for safety should not be allowed to paralyze the debate" on increasing light vehicle fuel economy. Greene and Duleep (1992) used worst-case estimates of an adverse safety impact and found that the resulting costs are small in aggregate and do not substantially change the outcome of a fuel economy cost/benefit analysis.

Achievable Fuel Economy Targets

Box 7 summarizes our estimates of the achievable potential for improving new car fuel economy. The earlier review of product cycles implied allowing 8-11 years of lead time. Given the timing of this report in late-1993 (beginning of model year 1994), the implication is that the assumed technology penetrations can be reached by model year 2002-2005. The first line summarizes the technical potential estimates from Table 3. At each Technology Certainty Level (Box 1) we show the range corresponding to High vs. Full penetration assumptions (Table 2b). Averaging over the penetration range and adjusting for cost-effectiveness yield estimates of 40 mpg, 46 mpg, and 51 mpg, for Levels 1, 2, and 3, respectively, corresponding to improvements of 43%, 65%, and 85% over the 1990 base year level of 27.8 mpg. We take these as our summary estimates of achievable, cost-effective targets for new car fleet average EPA-rated fuel economy given roughly 10-years of lead time. Cost estimates are obtained from the supply curves as shown in Table 5 and Figure 7. Averaging over the penetration ranges and updating from 1990$ to 1993$ using a GDP inflator of 1.10 yield the average per-car incremental cost estimates of $590, $770, and $840 shown in Box 7.

Regarding the likely accuracy of the fleet average fuel economy projections, the methodology used here is similar to that of EEA, which has a certainty level of within $\pm 5\%$ for a specified set of technology assumptions (EEA 1991a), implying general uncertainty of about ± 2 mpg for any "point" estimate. Reckoning percentages relative to 28 mpg, assumptions regarding technology certainty give a variation of roughly $\pm 20\%$, which dominates the variations of roughly $\pm 10\%$ due to power performance assumptions (11 s to 14 s 0-60 mph times) and $\pm 5\%$ due to technology penetration assumptions (High to Full). Thus, the most important assumptions behind our results are those regarding the availability and effectiveness of the technology measures.

Clearly, much judgement is involved in making assumptions appropriate for specifying public policies such as regulatory standards or targets of market mechanisms. We believe that our Level 2 assumptions are conservative in that they assume only use of available technologies for which there are no known technical constraints that must be overcome before widespread adoption throughout the fleet. More ambitious targets can be justified under the Level 3 assumptions, since public policy can hasten the development and widespread application of advances such as two-stroke or lean-burn engines and more aggressive efforts at load reduction. Moreover, there have already been increases in the use of some of the technologies since the 1990 base year assumed here, although not toward fuel economy improvement, at least on average. Thus, achieving fuel economy improvement could also involve the redirection of existing technology applications.

Box 7. New Car Fleet Average Fuel Economy Achievable by 2002-2005 and Potential Nationwide Gasoline Savings in 2000-2010.			
Technology Certainty:	Level 1	Level 2	Level 3
Technical Potential MPG	40-43	47-50	53-56
Cost-Effective Potential MPG	40	46	51
Potential Savings in 2000 (Mbd)	0.4	0.5	0.6
Potential Savings in 2005 (Mbd)	1.3	1.7	2.0
Potential Savings in 2010 (Mbd)	2.1	2.8	3.2

Fuel economy values are the EPA composite 55% city, 45% highway unadjusted test ratings. Potential gasoline savings in million barrels per day (Mbd) are estimated as in Figure 9.

Figure 9(a) illustrates a linear ramp-up to the three levels of potential new car fleet average fuel economy estimated here. Historical statistics from 1970-1993 are also shown. To compute the fuel savings estimates for 2010, we assume that the fuel economy improvements level off after 2005, as shown in the figure. This does not mean to imply that further improvements are infeasible in that later period; indeed, ongoing technological progress may make much greater increases feasible. For example, EEA (1991a) estimated potential 2010 new car fuel economy levels ranging up to 75 mpg. Beginning to pursue the design strategy outlined by Lovins et al. (1993) would imply dramatically greater gains in fuel efficiency.

Part (b) of Figure 9 shows the nationwide gasoline consumption implications of the fuel economy improvement scenarios shown in part (a). These consumption projections are based on a model of vehicle stock turnover as described by DeCicco (1992d) and account for the shortfall between EPA-rated and on-road fuel economy (assumed to be constant at 20%) and the so-called rebound effect (assumed to be 10%). The projections assume that the targeted levels of Figure 9(a) are actually achieved as new fleet averages and do not address the details of any particular regulatory or market mechanisms which might be needed to effect a given degree of fleet average fuel economy improvement. Differences between regulatory targets and achieved fuel economy can arise from details such as spacing of targets multiple years apart, administrative adjustments, carry-forward credits, alternative fuel vehicle credits, percentage increase caps, etc.; see OTA (1991) and DeCicco (1992d) for discussion of these complications.

As justified in Section 1, our scenarios of projected fuel consumption--in Figure 9(b), Figure 7(b), and Table 5, for example--assume proportionate fuel economy improvements for light trucks. If light trucks maintain a 33% share of the light duty market, have an average fuel economy 25% lower than that of cars (as at present), and are driven the same average distances with the same shortfall as cars, then light trucks will account for 40% of overall light duty fuel consumption. Thus, light trucks account for 40% of our projected fuel consumption and savings estimates (i.e., the estimates for cars alone are 60% of the consumption and savings values).

Our reference case (baseline) for analyzing nationwide gasoline savings is shown as the dashed-line projection in Figure 9. With a baseline of frozen new light vehicle fuel economy and average VMT growth of 2%/yr over 1990-2010 (Figure 1), U.S. light vehicle fuel consumption would grow to approximately 9 Mbd by 2010. Fuel economy improvement will reduce growth in gasoline consumption, with reductions of the order 0.5 Mbd by 2000 and increasing steadily in the following years. Full improvement levels are reached by 2005; five more years is sufficient time for fully improved vehicles to account for 60% of light duty VMT. Thus, substantial gasoline savings of 2-3 Mbd are obtained by 2010 depending on the degree of improvement (Box 7, Figure 9b). As noted above, nationwide oil savings would be roughly 20% larger. DOE (1993) projects that 60% of U.S. oil needs will be imported by 2010. Assuming that imports are avoided only in proportion to their average share and that oil savings are 20% higher than end-use gasoline savings implies that the 2.8 Mbd gasoline savings in 2010 for Level 2 yield an estimated oil import reduction of 2 Mbd in 2010. The import savings would be greater if reduced domestic oil consumption results in a disproportionate reduction of oil imports.

As shown on the right axis of Figure 9(b), greenhouse gas emissions from light vehicles would grow from 320 MTc/yr in 1990 to 370 MTc/yr by 2000 and 450 MTc/yr by 2010 (17% and 41%, respectively, above the 1990 level).[2] Achieving the potential fuel economy levels identified here would result in substantially reduced growth in light vehicle CO_2 emissions, as shown by the curves for Levels 1-3 in Figure 9(b). Thus, reaching even Level 1 fleet average efficiencies over the next decade or so would be sufficient to stabilize U.S. light vehicle fuel consumption and CO_2 emissions. The higher Levels would initiate downward trends. Of course, ongoing fuel economy improvements, requiring technology advances beyond those examined here, would be needed to continue the energy consumption reductions as long as VMT continues to grow.

4.4 Comparison to Previous Analyses

As noted in the introduction, this study builds on and goes beyond the series of studies done in recent years to assess the potential for fuel economy improvement. A number of points of comparison were noted in our preceding sections as we discussed our selection of assumptions and estimates. This section highlights the resulting differences between the analyses of this report and others.

Recent studies providing cost/benefit analysis of the near-term potential for automotive fuel economy improvement include industry sponsored efforts such as Berger et al. (1990) and SRI (1991); government-sponsored efforts based on the work of EEA, such as OTA (1991) and Greene and Duleep (1992); and ACEEE's previous studies, such as Ross et al. (1991). The NRC (1992) study drew largely on the SRI and EEA work; although the specifics of the methodology were vague and poorly documented, the NRC's higher estimate of technical potential (about 37 mpg for passenger cars by 2006) closely matches to the EEA results. The NRC's lower estimate of 34 mpg by 2006 is between the EEA estimate and SRI's estimate of about 30 mpg. All of these studies, and our own present

[2] Our projections differ from those of the U.S. Department of Energy (DOE), which assumes market-driven increases in new light vehicle fuel economy of roughly 1%/yr (DOE 1993, Table A14; similar assumptions appear to have been used in the recently released Climate Action Plan). Combined with DOE's somewhat slower VMT growth rates, the result is notably lower growth in light vehicle fuel consumption and CO_2 emissions (13% by 2000 and 22% by 2010 above the 1990 level). As discussed in Section 3.2, we believe that a frozen average fuel economy projection is better supported by the available data and observed trends.

study, take an incremental approach, based hypothetically applying various refinements to vehicles having the same fundamental design as today's vehicles. All yield estimates that are short of a doubling of new car fuel economy, relative to recent (1990-93) average of 28 mpg. Higher levels were estimated by EEA (1991a) for 2010, up to the 75 mpg "Risk Level III" case, which incorporates substantial design evolution and either advanced diesel engines or hybrid drivetrains; however, costs estimates were not provided. More recently, Lovins et al. (1993) presented a new analysis based on fundamental redesign of both vehicle structure and drivetrain, yielding fuel economy estimates of 150 mpg and higher; specific costs estimates were not given in this case either.

Fuel Economy Benefit Estimates

Regarding fuel economy benefit estimates based on an incremental approach, which makes cost analysis tractable, our results are higher than others because (a) we assume technology applications optimized for fuel economy; (b) we consider a greater degree of refinement in existing technologies; and (c) we include technologies excluded from other assessments. Specific, item-by-item comparisons of how our analysis differ from that of EEA (e.g., as given by Greene and Duleep 1992) can be obtained by inspecting Tables 1, 2, and 3. Here we summarize the differences in estimated technical potential for fuel economy improvement according to the three major reasons noted.

The issue of optimization for fuel economy was noted throughout the technology review section of this report. Nearly all technologies can meet multiple objectives. For example, engine refinements such as 4-valves per cylinder, overhead cams, and variable valve timing, when applied to an engine of a given size, will yield a substantial power boost. As these technologies are introduced, manufacturers often apply them for power enhancement, in line with their marketing strategies which interact with consumer tastes during recent years of low gasoline prices and little concern about supply disruptions.

Estimates of the potential fuel economy benefit derived from typical market-driven technology applications will be smaller than the technical potential based on applications optimized for fuel economy. For engine technologies such as fuel injection, 4-valves per cylinder, and overhead cams, and for continuously variable transmissions, such optimizations are partly considered in the EEA estimates and apparently in the higher NRC estimates, but not in the SRI estimates and apparently not in the lower NRC estimates. While SRI claims its estimates are optimized for fuel economy with performance neutral, their fuel economy benefit estimates are not consistent with known engineering characteristics of the technologies involved.

For example, EEA's estimates imply a 6.6% fuel economy benefit from increasing from 2- to 4-valves per cylinder (based on a weighted average of engine sizes to which this technology is applicable; this is the estimate we adopt here). Many recent market applications of 4-valve engines have been for the higher performance versions of a vehicle. Ford offers the Taurus with a 3.0 liter, V-6 engine in 12- and 24-valve versions, with 140 hp and 220 hp, respectively. The latter, "SHO" model has lower fuel economy but is a much "hotter" car. Current applications of turbocharging are similarly performance oriented. The Dodge Stealth 3.0 liter, V-6 engine has 12- and 24-valve versions, with the latter also offered in a turbocharged version. The respective power ratings are 164 hp, 220 hp, and 300 hp (turbocharged). Thus, these 4-valve engines were not downsized to reap a fuel economy benefit. A moderate degree of downsizing can yield both performance enhancement and some degree of fuel economy benefit--this is presumably the case behind an estimate such as SRI's, which lists a 3% benefit for 4-valve engines compared to 2-valve engines. A greater degree of engine downsizing along with drivetrain reoptimization can yield a larger fuel economy benefit, as assumed here.

Transmission improvements are another important example of differences in outcome based on the assumed degree of optimization for efficiency. EEA, SRI, and NRC give a 0.5% benefit for electronic transmission control; SRI also lists "advanced automatic transmission" as providing an additional 2% benefit. However, neither of these reflect the ability to electronically control the shift schedule so that it is better synchronized with the engine map for optimizing fuel economy (as shown in Figure 3). To fully address the sharp drop-off in mechanical efficiency at part-load requires a combination of engine measures and optimal transmission control (which will entail more frequent shifting) to maximize the amount of operation at mostly open throttle positions with compensating gearing and shift changes to maintain driveability. The transmission "hardware" needed is no different than that considered by other analysts, but the assumed implementation is different. The result is the 9% fuel economy benefit, above that estimated for engine improvements without shift schedule change, as estimated by Ross et al. (1991) and used here for our Level 2-3 estimates. Moreover, we estimated a similar potential improvement in manual transmission shift schedule, which was neglected by EEA and NRC. Although optimized transmission control may change the "feel" of driving, it would neither impair driveability or detract from measurable vehicle performance (high power would still be available on demand). Although it is valid to raise consumer acceptance concerns with such technology, it does not imply that the greater potential is not technically achievable.

Altogether, the degree of optimization estimated here adds 5% to 18% to our results for the technically achievable fuel economy levels compared to the EEA estimates and higher estimates of NRC. (These percentage comparisons are relative to the base year fleet average of 27.8 mpg, and so correspond to increases in estimated fuel economy of 1.4 mpg to 5 mpg.) The estimated optimizations were verified by the simulation analysis discussed in Section 3.4 and account for the interaction between engine and transmission measures (a negative effect, compared to adding the idealized potential for engine and transmission improvements separately) as well as the interaction between load reduction and engine/transmission measures (a positive effect on fuel economy).

The benefits estimated for variable valve control (VVC) are a good example of an engine technology offering different degrees of refinement. The estimates used by EEA and listed in the NRC report are for a limited form of VVC, namely intake valve control for pumping loss reduction, which yields a 6% fuel economy benefit. The SRI estimate is even lower than this. However, the NRC report itself notes that the ability of VVC to boost torque across the RPM range would enable engine displacement reduction and gearing changes, yielding a greater benefit of 12%-16% (NRC 1992, p. 206). Our 12% estimate for VVC is at the lower end of this range, but was excluded from quantitative results reported by NRC as well as EEA and SRI. Weighted for potential fleetwide penetrations, the greater degree of refinement we assume for engine technologies adds another 2% to 5% to our results compared to the EEA and higher NRC results.

The assumed degree of refinement also pertains to the load reduction technologies: reduced weight, reduced tire rolling resistance, reduced aerodynamic drag, and improved accessories. Our rationales for estimating greater degrees of potential refinement were discussed for each of these in our technology review. Collectively, they account for an additional 2% to 12% of fuel economy improvement (for Levels 1 to 3, respectively) compared to the EEA and higher NRC estimates.

Technologies not included by EEA and apparently not included by NRC are variable displacement, lean-burn and two-stroke engines, turbocharging, and idle-off. The bases for our including them here (including the emissions qualifications regarding two-stroke and lean-burn engines) were discussed earlier. Weighted by potential fleetwide penetration rates, these engine technologies together account for 8% to 16% of fuel economy improvement (for Levels 1 to 3, respectively) compared to the EEA and the higher NRC estimates.

Technology Cost Estimates

There are great uncertainties about cost estimates for specific technologies and even about the methodology for estimating costs. Recall, however, that most of the technologies considered here entail only incremental changes in vehicle design, many of which have already been in production for several years. No exotic or radical approaches are involved; thus, one would not expect large cost increases (as with electric vehicles, for which adequate battery capacity comes only at very high cost). Furthermore, we reiterate the assumption that the cost estimates are to be interpreted as average incremental costs over a full period of mass production, as opposed to costs of prototypes or models in initial limited production.

Cost estimates are detailed in the notes to Table 4, which includes comparisons to some of the major sources. Most of our estimates are taken from EEA, as listed by Greene and Duleep (1992). We generally dismissed the very high costs given by industry sources, such as SRI (1991), which were among the estimates used by NRC (1992). While a few of the SRI costs are consistent with the EEA estimates, there are notable exceptions in two key areas: engine refinements that boost specific power and weight reduction.

For example, SRI estimates an incremental cost of $400 for switching to overhead cams (from a base, pushrod valve actuation design). This does not make sense, since the overhead valve actuation is mechanically simpler and more compact than a pushrod engine. In fact, NRC (1992, p. 204), states "there is little inherent reason for an OHC engine to cost more since it has fewer moving parts and does not require any exotic technologies." However, the NRC study used the EEA and the very high SRI (1991) cost estimates, even while noting that "the committee believes that both of these estimates may be too high." Lindgren and Jones (1990) reported no price difference for a single overhead cam engine relative to a standard 2-valve engine and a small difference for double overhead cams (which forms the basis for our estimate, as noted in Table 4). Similarly inflated estimates are given by SRI for important technologies such as 4-valve cylinder heads, multipoint fuel injection, friction reduction, accessories, and transmission improvements. The industry's arguments of very high costs for future fuel economy improvement are consistent with their historical record when faced with stronger standards for safety and emissions as well as fuel economy. As Plotkin (1993) points out, "in each case, the arguments turned out to be exaggerated."

SRI's high estimate of the cost of weight reduction appears to be based on an component-substitution, aluminum-intensive strategy. As discussed earlier in Section 2.3, weight reduction can be achieved through an integrated redesign strategy involving a variety of materials--including engineering plastics, high-strength steels, magnesium, and various alloys, as well as aluminum--and is often part of cost-saving manufacturing strategies. While we admit the difficulty of developing quantitative estimates of the average cost of weight reduction, all indications are that it is part of a trend serving multiple goals besides fuel economy and the issue is largely one of how the advancing materials use and design strategies will be directed, e.g., toward increasing fuel economy or toward increasing other vehicle amenities.

In its summary tables, NRC (1992) gave a range of cost estimates, although the method by which they developed the specific numbers is not documented (inadequate information is given by NRC to reproduce either the fuel economy estimates or the cost estimates presented in the summary tables of the report). It is difficult to understand NRC's presentation of cost estimates at confidence levels that seem logically opposite to their confidence levels for technology improvement; as Plotkin (1993) notes regarding the cost issue, "the committee's analysis is somewhat inexplicable and should be viewed skeptically."

5. OTHER ISSUES

There are a number of other issues related to interpretation of the results presented here. These include the way fuel economy improvement might affect the position of firms in what is a highly competitive industry, market risks of fuel economy improvement, and economic issues beyond those directly related to efficient technologies and fuel savings. These issues are similar no matter what forces might drive fuel economy improvement--be they standards, feebates and guzzler taxes, substantially higher fuel prices (tax induced or otherwise), or another oil crisis.

5.1 Competitive Equity

Our analysis of potential improvements new car fuel economy treated the industry as a whole; it did not consider differences among firms. Automakers competing in the U.S. market differ in their current Corporate Average Fuel Economy (CAFE) levels, which are shown in Table 6 for model year 1990, the base year of this analysis. Firms also differ in their competitive situations and capabilities for product development and efficient manufacturing. The Harvard studies of product development (Clark and Fujimoto 1991) and the MIT studies of manufacturing (Womack et al. 1990) suggest that firms with contemporary, "state-of-the-art" competitive performance would be easily able to meet the product change timetable identified here. But these studies also reveal the performance variability among firms. Not all firms have the same capabilities to move quickly and at low cost.

If fuel economy improvement--like any other product change required by either market forces or external factors affecting the market--becomes a basis for competition, then Table 6 shows that not all manufacturers start at the same place. Moreover, some firms' capabilities may be stronger than others. Two questions arise. First, do competitive considerations warrant lowering estimates of achievable potential by a certain year? Second, what are the implications for public policies seeking to increase fuel economy? The questions are related, because policies can be structured so as to account for the differing positions of firms and provide incentives or assistance to compensate for differing capabilities.

Examples of policy structures which attempt to account for competitive factors are: the existing separation of domestic and import fleets, the Uniform Percentage Increase (UPI) proposed in recent CAFE bills, and vehicle-based approaches to fuel economy standards, such as Volume Average Fuel Economy (VAFE). Similar considerations apply to the structuring of incentives such a gas guzzler taxes and feebates. The question of how to structure fuel economy policies has been discussed by McNutt and Patterson (1986), Heavenrich et al. (1991), Ing (1991), OTA (1991), DeCicco (1992c), DeCicco et al. (1993), among others, and at sessions on CAFE and alternative forms of regulation held at recent SAE meetings.

Given a policy structure which adequately accounts for differences among firms, we conclude that there is no need to decrease the estimates of achievable potential to be used a targets for fleetwide average fuel economy improvement. Suppose the targets were decreased to some lower common denominator based on the firms starting from a lower CAFE base or having a slower ability to change. This would not really help such firms, because the other firms that are stronger or have a head start would simply find it easier to reach the lower targets and could direct their resources to other factors of market advantage.

This view is corroborated by the way that Japanese firms are making inroads into the larger car and luxury markets. Such moves are facilitated because these firms face CAFE constraints that are relatively less binding, much like relatively low new targets would be. On the other hand, the desire to remain within CAFE constraints and avoid the Gas Guzzler Tax, keeping their reputation for efficient vehicles, has been known to prompt technical innovation by Japanese firms. For example, the Acura NSX sportscar employed an aluminum body, variable valve control, and other refinements to deliver ultra-high performance while remaining above the 22.5 mpg Gas Guzzler Tax threshold (Honda 1992).

Another example, working instead to Detroit's advantage, is the effect of fuel economy regulation during the 1979-80 oil crisis, when gasoline prices shot up dramatically. Planning to meet the increasing CAFE standards established in 1975 helped focus U.S. firms on raising the efficiency of their product lines. In the early 1980s, both Detroit management and union leaders noted that the regulations helped keep a bad situation from turning out even worse (Fraser 1980).

Thus, it is the structure of policies for motivating fuel economy improvement that is critical for addressing competitiveness concerns. Of course, the weaker the policy, the less impact it is likely to have on competitiveness. In the limit, abandonment of fuel economy policy might absolve the government of concern about policy-induced inequities. However, given the prominence of factors other than energy and environmental regulation in determining competitiveness in the automotive marketplace, it is doubtful that a *laissez-faire* approach to fuel economy would itself improve the positions of any given firm. As long as there are compelling reasons to address automotive fuel consumption, one cannot escape the need to properly craft policies for improving fuel economy simply by weakening them. In fact, Porter (1990) recommends that policy makers "enforce strict product, safety, and environmental standards," noting that competitive advantages can follow from upgraded products to meet social demands and that easing standards can be counterproductive.

5.2 Market Risks

Because automakers recover fixed costs by achieving sufficient sales, there is concern about market risk. For example, if a product planned for an average volume of at least 100,000 vehicles a year for five years only averages sales of 50,000 per year, then costs are not recovered, and the "cost" of changes made in the product will have been very high. Our estimates thus assume that, given adequate lead time for developing, testing, and incorporating known technologies, the market risks for fuel economy improvement are no different than those entailed in any product change. This presumes that all manufacturers face similar policy pressure, so that none can escape the risks (e.g., regulatory penalties) of failing to adequately direct their product planning toward fuel economy improvement. The issue of added "market" risk due to policy-driven factors then becomes moot. Otherwise put, a properly crafted policy will lower or eliminate the risks, of directing technology change towards greater efficiency, that occur under market conditions that do not favor energy efficiency. This is borne out by the historical experience of the technology-driven fuel economy improvements that occurred through the mid-1980s. The year of peak sales, 1988, coincided with peak fleet average fuel economy, even though oil prices had fallen sharply two years earlier.

It can be argued that forcing automakers to incur investment costs on a set timetable might dampen profitability. Consider a decision of whether or not to change from a four- to a five-speed automatic transmission, for example. It may well be that the market value of improving to five speeds is very small and so an automaker may find it most profitable to keep the four speed transmissions in production long after the initial fixed costs are recovered. Switching to five-speed transmissions can thus lower profits even if it does not entail premature retirement of investments. This situation is difficult to assess from a public policy perspective, because it entails judging fair or adequate profits over a period of time--a subject which is bound to be contentious even if complete information were available, which it is not. The best that can be done is to make an assessment of adequate lead time, based on contemporary, competitive product development and manufacturing performance, and treat policy-driven fuel economy improvement as just another force--among the many market forces and constraints--to which automakers must respond.

Any change in product involves market risk, however, there is also risk to not changing a product and becoming technologically out of date. This aspect of risk (and cost) varies with market segment. Some segments, such as full-sized pickup trucks, can be very conservative--buyers may be perfectly happy with their old trucks which are wearing out and want to replace them with new trucks that are little different than the ones which have served them so well. In other segments, such as sports cars and some luxury models, innovation sells--buyers look for a vehicle that is state-of-the-art in terms of styling and equipment. Such differences in what buyers expect are reflected in the natural product cycles of various market segments. There is no added risk as long as the basic functionality of a vehicle within its market segment is not adversely affected by the product evolution.

The risk of a technology is clearly related to how it is applied. As noted earlier, most of the technologies identified here can yield greater performance or greater efficiency, depending on application. Under the conditions that have characterized the market since the mid-1980s, with low oil prices and a leveling off of fuel economy standards, it would be risky for a manufacturer to apply new technologies mainly for efficiency improvement. This explains the outcome of flat or dropping fuel economy since the peak achieved in the 1987-88 model years. Market conditions can be changed by various factors, including international events (wars, oil supply cartel decisions) and national policies (fuel taxation, vehicle pricing incentives, or regulation). Policies to encourage or require efficiency improvement would change market conditions so as to lower the risk of applying technologies for efficiency improvement. In this regard, Kempton (1991) pointed out the difference between the concerns of citizens and the concerns of consumers. Citizens can collectively decide that higher fuel economy is needed to address problems of national concern and therefore support policy changes to raise fuel economy above the level that is the outcome of the market in which they participate as individual consumers.

As noted above, the position of individual firms can be greatly affected by the structure of the policies. Provided that fuel economy regulation is equitable, there need not be additional risk from applying technology for efficiency improvement in a more stringently regulated market rather applying it for performance enhancement in a leniently regulated market. Thus, like other factors which could change market conditions regarding fuel economy, carefully structured regulation can serve to reduce the risk of applying technologies to achieved improved fuel economy. OTA (1991) has also pointed out the potentially risk-reducing aspects of regulation, particularly how it can enhance the industry's preparedness for possible oil market instabilities which could result in sudden market demand for improved fuel economy. OTA's latter conclusion that the severity of the financial risk may increase if regulation is imposed in the absence of other factors favoring fuel economy improvement (such as fuel price hikes or oil supply disruptions) appears to lose sight of this crucial risk-reducing aspect of regulatory standards.

The technology changes needed to improve fuel economy without reducing size or performance may raise the price of new cars. For the levels of potential fuel economy improvement identified here, we estimated a retail price increase of 3%-5%, rising gradually over the 8-11 year time period needed to achieve penetration of the improved technologies. New car buyers may not fully value improvements made for the sake of fuel economy. On the other hand, the actual fuel savings following from the efficiency improvements will result in higher consumer spending on goods (including cars) other than gasoline. This implies a net gain in revenues for the industry (Geller et al. 1992). Therefore, the economic benefits of the substantial fuel savings will strengthen the automotive market as long as the level of fuel economy improvement is cost-effective from an aggregate consumer perspective, as are the improvements identified here.

In summary, we draw three conclusions regarding issues of cost, competition, and market risk. First, there is no reason to believe that market conditions adverse to fuel economy improvement will increase the costs of technology improvement beyond those estimated here. This is particularly true since many of the technologies identified here are already entering the fleet, often designed and introduced for reasons other than fuel economy. Thus, the issue is one of redirecting how technologies are applied rather than whether they are applied. The only market conditions that might imply higher costs are those that would affect the factors of production, e.g., if for some reason the price of components needed for efficiency improvement goes up when the price of oil goes down. We are not aware of such conditions occurring.

Second, competitive considerations and the relative positions of firms do deserve careful consideration when structuring policies to induce fuel economy improvement. However, such concerns do not warrant lowering targets for fuel economy improvement. There are better ways, such as research and development assistance, to address the special needs of particular firms, who are not likely to be helped anyway by compromising national energy conservation objectives.

Finally, for changes made on a given timetable, the costs of automotive fuel economy improvement should be the same whether the technology changes are induced by regulation, incentives, much higher fuel prices, or an expected fuel supply disruption. While specific policy recommendations are beyond the scope of this discussion, a complementary approach involving CAFE standards, vehicle price incentives (an expanded gas guzzler tax or feebates), and fuel taxation--all of which must be equitably structured for both manufacturers and consumers--appears promising.[18] For vehicle-directed policies such as CAFE standards or feebates, equitable treatment of firms is crucial. Given equitable policies, we see no reason that there will be added market risks from a redirection of technological progress toward higher fuel economy.

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[18] See, e.g., Gordon (1991); Ross et al. (1991); UCS et al. (1991); DeCicco and Gordon (1993).

5.3 Air Pollution

As noted in the introduction, two forms of light vehicle air pollution are directly correlated to the rate of fuel consumption: non-tailpipe hydrocarbons (HC) and carbon dioxide (CO_2). The other major pollutants from U.S. light vehicles, carbon monoxide (CO) and nitrogen oxides (NO_x), do not generally correlate with the rate of fuel consumption. Other things equal, reducing a vehicle's rate of fuel consumption would reduce emissions of any of these pollutants; however, such emissions reductions might not be realized in practice because of the form of U.S. emissions regulations.

Hydrocarbon emissions are precursors of ozone and also have direct adverse health effects (some components are carcinogenic). Automobile use results in high pollutant exposure levels to drivers and non-drivers alike (Jefferiss et al. 1992). DeLuchi et al. (1992) performed a detailed analysis of vehicle related HC sources, including tailpipe (exhaust) emissions, non-tailpipe vehicle emissions (leaks, evaporation, and escape of fuel before it reaches the cylinder intake), as well as "upstream" fuel cycle emissions (filling station, fuel storage and transport, refinery, petroleum extraction). It has also been found that a substantial portion of emissions occur from "gross emitters:" older vehicles without controls as well as newer vehicles with malfunctioning controls, and driving patterns that significantly deviate from the test conditions which vehicle emissions control systems are designed to address (Calvert et al. 1993). We do not know how much if any of this last category of HC emissions can be avoided by efficiency improvement. As much as 98% of tailpipe HC emissions are cleaned up by a properly functioning catalytic converter. DeLuchi et al. (1992) found some relation between test procedure measurements of tailpipe emissions and fuel economy, but the correlations are highly uncertain. On the other hand, a portion of non-tailpipe HC emissions from fuel supply, refueling, and on-board evaporative losses are directly related to the amount of fuel consumed and are therefore reduced by improved fuel economy.

Mid-range estimates of avoidable HC emissions, excluding the tailpipe component, are given in Table 7. These estimates are for a post-2000 time frame, assuming more stringent emission controls than are currently in place. The resulting mid-range estimate is 11 g/gal, i.e., grams of HC emissions per gallon of fuel consumed in light duty vehicles. As shown in Table 7, 9.1 g/gal, or 83% of the emissions, occur either at the vehicle or in its vicinity of operation (e.g., at filling stations). DeLuchi et al. (1992) also estimate a "high" case, slightly more than double the mid-range values shown here, and note that current emissions levels are much higher than even their "high" case. DeLuchi et al. conclude that the nationwide HC emissions reduction from a 40% improvement in light vehicle fuel economy would be quite substantial, 0.35-1.35 million metric tons per year, which is on a par with other methods being established for HC emissions control.

Improving light vehicle fuel economy by 65% over the 1990 levels (our Level 2 achievable potential) will reduce HC emissions by 0.21 g/mi based on the 11 g/gal estimate of avoidable non-tailpipe emissions. This is larger than the drop from 0.41 g/mi to 0.25 g/mi required by the 1990 Federal Clean Air Act Amendments Tier I standards. Nationwide, the implied reduction is 0.17 million metric tons of hydrocarbons per year (MT_{HC}/yr) per million barrels per day (Mbd) of reduced light vehicle gasoline consumption. For our Level 2 scenario, the resulting HC emissions reductions amount to 500,000 tons per year. Moreover, since the current tailpipe emissions certification procedures poorly reflect actual on-road emissions, it is likely that HC emissions reductions resulting from fuel economy improvement will be obtained with greater certainty than reductions predicted from a tightening of emissions standards under current test procedures.

Based on the carbon content of typical blends, about 19.5 lbs of CO_2 are emitted when a gallon of gasoline is burned. But the use of gasoline involves "upstream" CO_2 emissions from the production and transportation of the fuel, plus CO_2-equivalent greenhouse effects of associated nitrous oxide (N_2O) and methane (CH_4) emissions. Gasoline consumption therefore entails these fuel cycle emissions, and so the full fuel cycle greenhouse gas emissions from gasoline are about 26.5 lbs/gal (12 kg/gal, or 91 kg/GJ) on a CO_2-equivalent basis (DeLuchi 1991). Thus, each million barrels per day (Mbd) of savings in gasoline end-use results in a reduction of CO_2-equivalent greenhouse gas emissions by 50.2 million metric tons of carbon per year (MT_C/yr). This factor forms the basis of the carbon emissions reductions reported here.

The reduction in U.S. CO_2 emissions corresponding to our Level 2 fuel economy improvements would be 140 MT_C/yr relative to our baseline of frozen new car fuel economy. By way of context, DOE (1993) estimates total U.S. carbon emissions from fossil fuel use at 1340 MT_C/yr in 1990. DOE projects carbon emissions growing to 1640 MT_C/yr by 2010 but assumes a baseline new light vehicle fuel economy increase of 23% by 2010. As noted earlier, a baseline of frozen efficiency is more in line with recent history and current trends. DOE also assumes a lower value of 1.7%/yr for VMT growth from 1990-2010 than our value of 2%/yr. The result is that DOE's baseline projections of light vehicle fuel consumption and CO_2 emissions are roughly 15% lower than ours, i.e., lower by 1.4 Mbd and 70 MT_C/yr, respectively, in 2010. Making this adjustment to the DOE baseline yields estimated total U.S. carbon emissions of 1710 MT_C/yr in 2010, so that the 140 MT_C/yr reduction from our Level 2 fuel economy improvement scenario represents an 8% cut in projected 2010 emissions. Thus, cost-effective fuel economy improvement can avoid 38% of the growth in U.S. CO_2 emissions that would otherwise occur between 1990 and 2010. Compared to other near-term actions, improving light vehicle fuel economy is truly the "biggest single step" that the United States can take to reduce greenhouse gas emissions (Becker et al. 1991; Geller et al. 1993).

5.4 Economic Factors

There are broad economic benefits, particularly beneficial employment impacts, to improving automotive fuel economy. These macroeconomic issues were examined by Geller et al. (1992), who analyzed a fuel economy improvement scenario similar to our Level 2 scenario but with a continuing increase through 2010. The result was a strong positive effect on the U.S. economy, with a net increase of nearly 250,000 jobs by 2010, including increased employment of nearly 50,000 jobs in the auto industry. The direct employment impact of building more efficient vehicles is small, since the incremental vehicle cost for efficiency improvement is small. However, the indirect effect, resulting from respending of fuel savings, is quite large. Money which drivers now spend on gasoline goes mainly to the capital intensive petroleum supply industry and to overseas oil producers. Fuel cost savings largely stay in the U.S. economy and are respent in industries which are more labor intensive than the petroleum industry, stimulating demand for domestically produced goods and services, including automobiles. The resulting enhancement of vehicle sales would strengthen the automobile industry. The job creation estimate cited here assumes no change in import market share as a result of fuel economy improvement; this is a reasonable assumption given the ability to design policies which are equitable in the their treatment of firms.

New car sales volumes are almost wholly driven by the health of the economy. Past regulations to address safety, emissions, and fuel economy have entailed modest vehicle cost increases but have not driven buyers from the showrooms. "It has long been established that government has the right and the obligation, for the common good, to establish rules for the kind of motor vehicles that are sold ... Hypothetically, Congress could require that all U.S. cars be painted red, white, and blue! ... given adequate lead time ... total sales would not be affected. Market share would shift, however, to those manufacturers who were most creative and innovative in producing a range of products complying with such mandates" (Feaheny 1991). While no one is proposing mandatory car coloring, improved fuel economy is in the public interest. With oil imports accounting for $45 billion of the U.S. trade deficit, improved automotive efficiency would certainly help the economy. Customers will undoubtedly buy a fleet much more efficient than the present fleet. The recent years with the highest new vehicle sales, 1987-88, also had the highest new fleet CAFE levels.

As noted above, the capabilities of modern industrial management and production techniques apply independently of the rules of the game regarding fuel economy in the marketplace. Under a lenient or absent regulatory conditions with low and stable oil prices, the most capable producers will win at offering vehicle performance, luxury, and other features that the market will favor. If another oil supply disruption occurs, capable producers will win at adjusting to the rapidly changing market conditions. If the government changes the rules of the game, e.g., by imposing standards and incentives for higher fuel economy, capable producers will succeed in meeting those requirements as well. U.S. automakers have been strengthening their competitive abilities and as pointed out in the preceding section, it is doubtful that weak or absent policies for improving fuel economy would help U.S. automakers.

Moreover, interrelationships and cohesiveness within the industry can compensate for the differing positions and capabilities of automakers. Among U.S. firms, cooperative research and development programs such as USCAR serve to strengthen the abilities of individual firms. There are extensive interconnections among firms, partial ownership, such as joint ventures, technology sharing, supply contracts, and various cooperative relationships for assembly, distribution, and marketing, as detailed by Ward's (1992). The auto industry has very much become a global network, as generally described by Reich (1991). Thus, the industry itself is capable of making arrangements for sharing technologies and product development abilities that can go a long way toward compensating for the disadvantages individual firms might have in the evolving market, including the situation when the evolution is redirected toward efficiency improvement due to policy interventions. Also, considerable federal research support is being given to the auto industry and this support is to be increasingly channeled toward efficiency improvement under the auspices of the "Clean Car Initiative" announced by the Clinton Administration in 1993. This Initiative includes a goal of moving efficiency technologies into near-term production as well as a long-term goal of developing vehicles having a fuel economy triple that of today's vehicles.

Not just supply, but also demand for automobiles is global; in fact, there is likely to be greater growth in the market globally than in the United States, where auto ownership rates are already very high while population growth is slowing. Improving fuel economy can help U.S.-based auto manufacturers enhance their competitiveness in this global marketplace where most future growth will occur. Fuel efficiency and low emissions will be increasingly important factors in overseas markets. Countries with lax standards compared to those of the United States will be forced to confront petroleum dependency and emissions problems exacerbated by high rates of growth in motor vehicle use. Porter (1990) points out that tough regulations, anticipating standards that will spread internationally, can give domestic industry a lead in products that will become increasingly valuable in other countries. As Walsh (1993) puts it, "those companies which will be most successful in meeting that [global] market demand will be those which produce highly efficient (low CO_2) and clean (low HC, NO_x, and CO) vehicles."

6. CONCLUSION

Our review of the automotive engineering literature reveals a wide array of available and near-commercial technologies which can be applied to improve fuel economy over the next decade. Examining recent applications of new technologies and performing physical analyses of vehicle energy use (including interactions among measures), we developed estimates of the technical potential for new car fuel economy improvement. These results, presented at three levels of technical certainty, show that a new fleet average of 40 mpg to 51 mpg (43% to 85% improvement over the 1990 fleet average of 28 mpg) is achievable using near-term technologies. The broad range of estimates reflects the variety of assumptions that can be made about technology. The different technical certainty levels reflect the varying degrees of confidence with which efficient technologies can be put into widespread use over a defined time frame of 8-11 years. Allowing more time would increase the certainty with which the higher levels of fuel economy could be reached.

We also analyzed the costs of the technologies, ranking them in order of increasing cost/benefit ratio. Nearly all technologies are cost-effective according to the cost/benefit indices examined. Most have payback times of less than five years, the expected ownership period of a new car. Estimates of the cost of conserved energy for the technologies were used to build a conservation supply curve. Our estimates of the cost-effective new fleet fuel economy level were obtained by discounting fuel savings at a 5% real rate over a 12-year vehicle lifetime and selecting technologies up to an avoided cost of $1.65/gal (1993$). The average cost of conserved energy is roughly $0.53/gal for the cost-effective potential at all technology levels. The cumulative incremental retail cost of these improvements would be $590-$840, or 3%-5% of the average new car price of $17,600 (1993$). The implied additional investment requirements for the auto industry are of the order $1 billion annually for product development and retooling to reach the full level of improvement. The industry would recover these additional investment costs through the modest increases in vehicle price.

Trade-offs regarding emissions, safety, and performance were found to have relatively small effects on the outcome. Additive adjustments to projected vehicle weight were made to account for improved safety and emissions features; these yield a 2% decrement to potential fuel economy, which is accounted for in our estimates. We assume a 1990 fleet average acceleration performance (12.1 s 0-60 mph time); increasing performance to 1993 level would lower the projected fuel economy by about 1 mpg and reducing it to the 1987 level would raise it by about 1.5 mpg. No change in average vehicle size is needed for the technology-based fuel economy improvements analyzed here.

Lead time, marketability, and competitiveness issues were examined to estimate how long it would take manufacturers to implement technology-based fuel economy improvements. Our review of studies by industry analysts and reports in the trade press indicates a lead time of 8-11 years. Given the late 1993 release of this report, the implication is that substantial improvements in new car fleet average fuel economy can be achieved by 2002-2005. With policies structured to appropriately address equity among competing firms, there would be minimal risk to the industry in achieving the identified levels of new car fuel economy.

Box 8 collects the key results for our mid-range estimate of cost-effective new car fuel economy improvement and the corresponding scenario of improving the new light duty fleet to this level by 2005. Projected costs, savings, and other benefits are given for 2010, allowing time for substantial penetration of improved vehicles into the on-road stock. Our mid-range (Level 2) estimate is for a new car fleet average of 46 mpg achievable at an average retail price increase of $770. While this

Box 8. Summary of Mid-Range Projections of Cost-Effective Fuel Economy Improvement Achievable by 2005 and Resulting Benefits in 2010.

New car fuel economy reached in 2005	46 mpg
Overall new light vehicle MPG improvement	65%
Average new light vehicle price increase	$770
Annual total new vehicle market cost increase	$12 billion
Gasoline savings in 2010	2.8 Mbd
Reduction of oil imports in 2010	2 Mbd
Annual consumer fuel cost savings in 2010	$71 billion
Net U.S. employment gain in 2010	250,000 jobs
Greenhouse gas emissions reduction in 2010	140 MT_C/yr
Hydrocarbon emissions reduction in 2010	500,000 T_{HC}/yr

Costs are given in 1993$ assuming a retail gasoline price of $1.65/gal in 2010.

mid-range estimate involves some technologies not yet in widespread use, it does not require the use of any technologies facing technical constraints, e.g., the emissions restrictions on lean-burn or two-stroke engines. The overall annual added retail cost of these improvements to vehicles would amount to about $12 billion (compared to a base light vehicle market of $260 billion; 1993$). If such more advanced technologies become commercially available within a few years, either a higher fleet average (51 mpg) could be reached or the 46 mpg level could be reached at lower cost.

Improving new car fuel economy to 46 mpg by 2005 with proportionate improvements in light trucks would cut U.S. oil consumption by 2.8 million barrels per day in 2010. This is 31% of the consumption otherwise projected to occur by 2010; the reduction in oil imports would be at least 2 million barrels per day. There would be corresponding annual cuts of 140 million metric tons of carbon-equivalent greenhouse gas emissions and nearly 500,000 metric tons of hydrocarbon emissions. The costs of fuel economy improvement are modest in the context of the projected $71 billion of annual consumer fuel cost savings by 2010 and annual consumer gasoline expenditures that would exceed $200 billion in the absence of fuel economy improvement. The economic benefits of the gasoline savings would yield a net increase of 250,000 U.S. jobs by 2010. In summary, the large benefits to the nation--direct consumer savings, lower oil imports, reduced hydrocarbon and CO_2 emissions, enhanced economic growth, and job creation--indicate that fuel economy improvement is one of the best investments the country can make.

Table 1. Fuel Economy Benefit Estimates by Technology

Lists percentage increase in fuel economy from application of each technology to an individual average vehicle. Estimates were derived as discussed in text, with some particulars noted below. The "Key" column is used for cross-referencing to other tables.

TECHNOLOGIES BY CATEGORY	Key	EEA(a)	CERTAINTY LEVEL (Box 1) Level 1	Level 2	Level 3
ENGINE					
Multipoint fuel injection	MPFI	3.0%	3.0%	3.0%	3.0%
Four valves per cylinder (b)	4valve	6.6%	6.6%	6.6%	6.6%
Friction reduction (c)	Frict	2.9%	6.0%	6.0%	6.0%
Overhead camshaft	OHC	3.0%	3.0%	3.0%	3.0%
Compression ratio increase	CR inc	0	1.0%	1.0%	1.0%
Variable Valve Control	VVC	6.0%	12.0%	12.0%	12.0%
Super- or Turbo-charging	Boost	0	5.0%	5.0%	8.0%
Variable displacement	Vari-D	0	0	5.0%	5.0%
Idle off	IdlOff	0	0	6.0%	6.0%
Lean burn or Two stroke	Lean	0	0	0	10.0%
TRANSMISSION					
Five-speed automatic (d)	5spAT	5.0%	5.0%	5.0%	5.0%
CVT (d)	CVT	6.5%	6.0%	6.0%	6.0%
Torque converter lockup	TCLU	3.0%	3.0%	3.0%	3.0%
Optimized transmission control	OptAT	0.5%	0.5%	9.0%	9.0%
Optimized manual transmission	OptMT	0	11.0%	11.0%	11.0%
LOAD					
Tire improvements	Tires	1.0%	3.4%	4.8%	6.1%
Aerodynamic improvements	Aero	4.6%	3.3%	3.8%	4.3%
Weight reduction (e)	Wt red	6.6%	3.9%	9.9%	15.9%
Accessory improvements (f)	Access	0.9%	1.7%	1.7%	1.7%
Lubricant improvements (f)	Lube	0.5%	0.5%	0.5%	0.5%

NOTES

(a) Estimates by Energy and Environmental Analysis, Inc. (EEA), as discussed in EEA (1991b) or Greene and Duleep (1992), relative to a 1987-88 baseline.

(b) Based on the EEA estimates of 8% benefit with and 5% benefit without reduction in number of cylinders, weighted by the 1990 fleet engine mix and 4-valve penetration levels.

(c) Includes roller cam followers, with EEA estimates adjusted for penetration differences.

(d) 5-speed automatic and CVT benefits reduced by 2% to account for interaction with VVC, as discussed in OTA (1991).

(e) Levels 1, 2, and 3 are based on decreases of 10%, 20%, and 30%, respectively, in average curb weight of 2880 lbs (the 1990 average test weight minus 300 lbs), adjusted upwards by 100 lbs for effects of emissions and safety standards. The resulting estimated reductions are 188 lbs, 476 lbs, and 764 lbs, respectively, implying net cuts of 5.9%, 15.0%, and 24.0% in average *test* weight. Applying a sensitivity coefficient of 0.66 yields the fuel economy improvements shown.

(f) As discussed in Ross et al. (1991).

Table 2. Technology Penetration Estimates

(A) Technology Utilization in the Base Year (1990)

IMPROVED TECHNOLOGY	REFERENCE TECHNOLOGY	PENETRATION LEVELS IN 1990 NEW CAR FLEET Subcomp	Compact	Midsize	Large	Average
ENGINE						
Roller cam followers	Flat followers	29.2%	41.5%	31.0%	100.0%	44.9%
Friction reduction, 10%	Base 1987	12.3%	10.3%	34.1%	37.3%	21.2%
Accessories	Conventional	0.0%	0.0%	0.0%	0.0%	0.0%
Decel fuel shut-off	None	58.0%	68.3%	85.8%	97.3%	75.0%
Compression ratio +0.5	9:1, 4-valve only	0.0%	0.0%	9.0%	0.4%	2.4%
Throttle-body FI	Carburetor	34.8%	31.7%	14.4%	0.0%	22.9%
Multipoint FI	Carburetor	58.0%	68.3%	84.7%	97.3%	74.7%
Advanced OHV	Pushrod (OHV)	1.8%	36.8%	80.3%	63.9%	44.3%
Overhead camshaft	Pushrod	43.7%	17.6%	14.9%	0.0%	20.2%
4 valves per cylinder	2 valves	36.3%	38.5%	9.0%	0.4%	24.3%
Variable valve timing	Fixed timing	0.0%	0.0%	0.0%	0.0%	0.0%
ADVANCED ENGINES						
Lean burn engine	Stoichiometric	0.0%	0.0%	0.0%	0.0%	0.0%
Two stroke engine	4 Stroke, OHC, 2V	0.0%	0.0%	0.0%	0.0%	0.0%
TRANSMISSION						
Torque converter lock-up	Open converter	45.5%	71.3%	96.1%	99.4%	76.2%
Elect. trans. control	Hydraulic	0.0%	0.0%	0.0%	0.0%	0.0%
4 speed lock-up	3 speed LU	16.8%	42.0%	68.8%	99.4%	52.1%
5 speed lock-up	3 speed LU	0.0%	0.0%	0.0%	0.0%	0.0%
CVT	3 speed LU	0.0%	0.0%	0.0%	0.0%	0.0%
5 speed Manual	3 speed LU	42.5%	16.0%	3.1%	0.1%	16.3%
LOAD REDUCTION						
Front wheel drive	Rear wheel drive	94.1%	90.2%	94.0%	65.9%	88.3%
Aerodynamics	Cd .37 to .33	18.3%	18.6%	54.5%	0.0%	25.1%
Weight reduction, 10%	Base	0.0%	0.0%	0.0%	0.0%	0.0%
Electric power steering	Conventional	0.0%	0.0%	0.0%	0.0%	0.0%
Adv. tires, 10%	Base	0.0%	0.0%	0.0%	0.0%	0.0%
Advanced lubricants	Conventional	0.0%	0.0%	0.0%	0.0%	0.0%

GENERAL STATISTICS OF BASE YEAR NEW CAR FLEET	Subcomp	Compact	Midsize	Large	Average
Engine Size					
4 cylinder	97.1%	87.9%	18.6%	0.0%	58.1%
6 cylinder	2.9%	12.1%	81.4%	69.7%	37.2%
8 cylinder	0.0%	0.0%	0.0%	30.3%	4.7%
Market share	21.8%	32.6%	24.7%	14.5%	93.6%
Normalized to add to 100%	23.3%	34.8%	26.4%	15.5%	100.0%

SOURCES:
Penetration statistics are from spreadsheets of Greene (1993).
Market share by class is from Heavenrich et al. (1991).

Table 2. Technology Penetration Estimates (continued)

(B) Potential Increases in Technology Penetration

This part of the table provides estimates for two levels of potential increase in technology utilization. The "High" level is as used for the main analysis discussed in the text, with penetration rates limited according to the analysis of EEA (e.g., OTA 1991; Greene and Duleep 1992) for technologies addressed by EEA. The "Full" level represents the maximum full penetration possible.

	Actual 1990 (a)	Maximum Use Levels (b) High	Maximum Use Levels (b) Full	Potential increases over 1987 EEA (c)	Potential increases over 1990 High	Potential increases over 1990 Full
ENGINE						
Multipoint fuel injection	74.7%	92.5%	100.0%	50.0%	17.8%	25.3%
Four valves per cylinder	24.3%	90.0%	100.0%	90.0%	65.7%	75.7%
Friction reduction (d)	21.2%	100.0%	100.0%	93.0%	78.8%	78.8%
Overhead camshaft	20.3%	49.0%	100.0%	49.0%	28.7%	79.7%
Compression ratio increase	0.0%	100.0%	100.0%	0	100.0%	100.0%
Variable Valve Control	0	67.0%	100.0%	67.0%	67.0%	100.0%
Super- or Turbo-charging	0	60.0%	75.0%	0	60.0%	75.0%
Variable displacement	0	40.0%	40.0%	0	40.0%	40.0%
Idle off	0	50.0%	50.0%	0	50.0%	50.0%
Lean burn or Two stroke	0	60.0%	60.0%	0	60.0%	60.0%
TRANSMISSION						
Five-speed automatic	0	32.0%	40.0%	32.0%	32.0%	40.0%
CVT	0	40.0%	40.0%	40.0%	40.0%	40.0%
Torque converter lockup	76.2%	80.0%	80.0%	16.0%	3.8%	3.8%
Optimized transmission control	0	67.0%	80.0%	67.0%	67.0%	80.0%
Optimized manual transmissions	0	20.0%	20.0%	0	20.0%	20.0%
LOAD						
Tire improvements	0	100.0%	100.0%	100.0%	100.0%	100.0%
Aerodynamics (e)	0	100.0%	100.0%	100.0%	100.0%	100.0%
Weight reduction (f)	0	100.0%	100.0%	97.0%	100.0%	100.0%
Accessory improvements	0	80.0%	100.0%	80.0%	80.0%	100.0%
Lubricant improvements	0	100.0%	100.0%	100.0%	100.0%	100.0%

NOTES

(a) Base year (1990) levels are from Part (A) of the table unless otherwise noted.

(b) The "High" case maximum use levels are from Greene (1993), except for measures not included in the EEA assessments, for which maximum use levels are as discussed in the text. The "Full" levels are authors' estimates.

(c) Shown to facilitate comparison to previous work are the increases over 1987 technology levels which are used for the EEA assessments (OTA 1991, Greene and Duleep 1992).

(d) Based on allocating the levels shown in Part (A) of 44.9% for roller cam followers and 21.2% for "10% reduction" as contributing 33% each.

(e) Relative to a base level drag coefficient (C_D) of 0.35, the 1990 fleet average.

(f) Using the 1990 new car fleet average weight of 3180 lbs as the base level, 100% penetration represents the full potential reduction assumed for each Level in Table 1. Note that EEA's base level was the 1987 fleet average of 3031 lbs, about 5% lighter than in 1990.

Table 3. Technical Potential for Improving New Car Fleet Average Fuel Economy

Lists the new car fleet percentage fuel economy improvement for each technology, computed by multiplying the potential penetration increases (from Table 2B, at High and Full penetration levels) times the benefits (from Table 1, given by certainty level).

Penetration Level:	High		High			Full	
Certainty Level:	EEA	L1	L2	L3	L1	L2	L3
ENGINE							
Multipoint fuel inject	1.5%	0.5%	0.5%	0.5%	0.8%	0.8%	0.8%
Four valves per cylinder	5.9%	4.3%	4.3%	4.3%	5.0%	5.0%	5.0%
Friction reduction	2.7%	4.7%	4.7%	4.7%	4.7%	4.7%	4.7%
Overhead camshaft	1.5%	0.9%	0.9%	0.9%	2.4%	2.4%	2.4%
Compression ratio increase	0	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%
Variable Valve Control	4.0%	8.0%	8.0%	8.0%	12.0%	12.0%	12.0%
Super-/turbo- charging	0	3.0%	3.0%	4.8%	3.8%	3.8%	6.0%
Variable displacement	0	0	2.0%	2.0%	0	2.0%	2.0%
Idle off	0	0	3.0%	3.0%	0	3.0%	3.0%
Lean burn or Two stroke	0	0	0	6.0%	0	0	6.0%
TRANSMISSION							
Five speed automatic	1.6%	1.6%	1.6%	1.6%	2.0%	2.0%	2.0%
CVT	2.6%	2.4%	2.4%	2.4%	2.4%	2.4%	2.4%
Torque converter lockup	0.5%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%
Optimized control	0.3%	0.3%	6.0%	6.0%	0.4%	7.2%	7.2%
Optimized manual	0	2.2%	2.2%	2.2%	2.2%	2.2%	2.2%
LOAD							
Tire improvements	1.0%	3.4%	4.8%	6.1%	3.4%	4.8%	6.1%
Aerodynamic improvements	3.7%	3.3%	3.8%	4.3%	3.3%	3.8%	4.3%
Weight reduction	6.4%	3.9%	9.9%	15.9%	3.9%	9.9%	15.9%
Accessory improvements	0.7%	1.4%	1.4%	1.4%	1.7%	1.7%	1.7%
Lubricant improvements	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%
SUMS BY CATEGORY:							
ENGINE	15.6%	22.5%	27.5%	35.3%	29.6%	34.6%	42.9%
TRANSMISSION	5.0%	6.6%	12.3%	12.3%	7.1%	13.9%	13.9%
LOAD REDUCTION	12.3%	12.5%	20.4%	28.2%	12.8%	20.7%	28.5%
TOTAL (a):	32.9%	41.6%	60.2%	75.8%	49.5%	69.2%	85.3%
OPTIMAL TOTAL (b):	**35.5%**	**45.2%**	**68.3%**	**89.2%**	**54.2%**	**79.3%**	**101.5%**
POTENTIAL MPG (c):	**37.7**	**40.4**	**46.8**	**52.6**	**42.9**	**49.8**	**56.0**
CONSUMPTION REDUCTION:	26.2%	31.1%	40.6%	47.2%	35.2%	44.2%	50.4%

NOTES

(a) The simple total is the sum of all individual percentages (subtotals are shown by category). This is a conservative estimate, since some technologies are positively synergistic (adjustments for negative synergisms were already reflected in the benefits estimates of Table 1).

(b) The optimal total fuel economy improvement is the sum of engine and transmission improvements multiplied by the load reduction improvements, since the interaction between tractive load and drivetrain is multiplicative.

(c) The technical potential fuel economy is based on the optimal total improvement over the 1990 new car fleet average of 27.8 MPG. Also shown is the reduction in fuel consumption rate (gal/mi), based on the reciprocal of the optimal total fuel economy improvement, which also represents the reduction in new fleet average CO_2 emissions.

Table 4. Technology Cost Estimates

TECHNOLOGY IMPROVEMENT	Retail price increment (1990$)[a] EEA[b]	ACEEE	Adjusted[c]	Payback (years)[d]
Engine displacement reduction[e]	(140)	same	--	--
Multipoint fuel injection[f]	75	same	75	4.8
Four valves per cylinder[g]	180	same	110	3.3
Friction reduction[h]	100	same	100	3.3
Overhead cam[i]	150	40	40	2.5
Compression ratio increase	0	same	0	0
Variable valve control[j]	180	130	130	2.2
Super- /Turbo- charger[k]	300	same	160	6.2
Variable displacement[l]	--	65	65	2.5
Idle off[m]	--	260	260	8.5
Lean burn engine[n]	--	75	75	1.5
Two stroke engine	--	0	0	0
Five-speed automatic transmission	110	same	110	4.3
Continuously variable transmission[o]	110	30	30	1.0
Torque converter lockup	55	same	55	3.5
Optimized transmission control[p]	25	60	60	1.3
Optimized manual transmission[q]	--	60	60	1.1
Lower tire rolling resistance	20	same	20	0.8
Aerodynamic improvements	90	same	90	4.6
Weight reduction[r]	150	same	150	3.1
Accessory improvements	13	same	13	1.4
Lubrication improvements	2	same	2	0.7

(a) Increase in MSRP, including manufacturer, delivery, and dealer markups above manufacturing costs.

(b) Greene and Duleep (1992), p. A-24, updated from 1988$ to 1990$ using a GDP inflator of 1.087 and rounded to two significant figures. Estimates given separately by EEA for 4, 6, or 8-cylinder engines were averaged using 1990 fleet shares of 0.57, 0.31, and 0.12, respectively, from Heavenrich *et al.* (1991).

(c) Adjusted estimates are used for our cost-effectiveness analysis. Adjustments are made to reflect average savings from engine downsizing when applicable [note (e)]. We estimate downsizing as potentially applicable to the 43% of the fleet with 6 or 8 cylinder engines plus one-half of the 56% having 4 cylinders, or 71% of the fleet.

(d) Simple payback is calculated as adjusted price increment divided by annual fuel cost savings assuming Level 2 benefits from Table 1. Annual savings is based on 10,000 miles per year, $1.20 per gallon fuel price, and a base fuel economy of 27.8 mpg with 20% shortfall.

(e) EEA lists the costs of technologies which enhance engine specific performance (e.g., hp/liter) without reflecting the savings from the engine downsizing (e.g., from six cylinders to four cylinders) involved when applying the technologies so as to maintain contant vehicle performance. EEA estimates savings of $150 for downsizing from 6 to 4 cylinders and $200 for downsizing from 8 to 6 cylinders and apply the adjustment later in their cost/benefit calculations (pers. comm., K.G. Duleep). We estimate 4 to 3 cylinder downsizing savings at $100, which combines with the preceding estimates to yield an average savings of $140.

(f) Includes $15 for conversion of cars which still had carburetors to fuel injection ($60 each for 26% of 1987 fleet baseline).

(g) The average EEA estimate is $180. Engine downsizing is required to capture the fuel economy benefits of 4-valve designs, but we take only one-half of the average downsizing credit, yielding an adjusted cost of $110, to reflect the facts that downsizing is also entailed when using supercharging and that not all displacement reduction need entail a decrease in the number of cylinders.

(h) Includes friction reduction I and II plus roller cam followers, as listed by EEA.

(i) NRC (1992), p. 204, states "there is little inherent reason for an OHC engine to cost more since it has fewer moving parts and does not require any exotic technologies." However, the NRC study used the EEA and the very high SRI (1991) cost estimates, even while noting that "the committee believes that both of these estimates may be too high." This is corroborated by Lindgren and Jones (1990), who reported no price difference for a single overhead cam engine relative to a standard 2-valve engine and a $8-$15 (depending on size) manufacturing cost difference for double overhead cams (DOHC). Earlier, EEA (1986) used an average cost of $80 (updated to 1990$) for OHC; more recent EEA work, such as OTA (1991), uses an average cost of $150. We assume a $40 average cost, based on markup over the DOHC estimate of Lindgren and Jones.

(j) SRI (1991), p. 28, estimates $100 for VVC applied to an overhead cam engine, which is the assumed base engine for this analysis. EEA estimates an average of $180, depending on engine size (OTA 1991). Lindgren and Jones estimate a manufacturing price increments of $44-$61 for 4-6 cylinder engines, implying an average retail price increment of about $130, which is adopted here.

(k) For fuel economy improvement at constant performance, supercharging would be applied to a downsized engine. We therefore subtract the $140 average cost savings [note (e)] from the average EEA (1985) estimate of $300, yielding a $160 adjusted cost estimate. Payback improves (falling to 4.0 yrs) if the higher, Level 3 benefit of 8% is used.

(l) For variable displacement implemented through valve train control, as in the Mitsubishi MIVEC engine; estimated as a 50% addition to the cost estimate for variable valve control.

(m) For idle off used in combination with other engine technologies addressing part-load efficiency, based on cost estimate by Ross *et al.* (1991). Payback would improve (falling to 4.9 yrs) if idle off is applied without technologies such as VVC and variable displacement.

(n) On the 1992 Honda Civic VX, lean burn is achieved by using the variable valve control and fuel injection hardware with a special oxygen sensor for mixture control. The retail price of this sensor is $75 higher than that of the oxygen sensor on the 1992 Honda Civic DX hatchback (pers. comm., Honda Customer Service Dept., Gaithersburg, MD). Beyond the VVC/MPFI base engine design, no other manufacturing costs have been reported. Costs may be different for lean burn implemented using the alternative approaches to lean burn being pursued by Mazda and Toyota, which are discussed in the text.

(o) The EEA estimate for a CVT over a 4-speed automatic is $100 (1988$, OTA 1991). Lindgren and Jones (1990), however, estimate a $20 manufacturing cost savings relative to a 3-speed automatic and larger savings relative to a 4-speed. Averaging these values at the MSRP level yields the $30 estimate given here.

(p) The Ross *et al.* (1991) estimate is for the more sophisticated form of transmission control discussed in the text, which optimizes the shift schedule for fuel economy.

(q) Based on Lindgren and Jones (1990) cost differential between a 5-speed and 4-speed manual transaxle.

(r) EEA estimates weight reduction at $0.50 per pound (pers. comm., K.G. Duleep); the estimate is for an average reduction of approximately 300 lbs.

Table 5. Supply Curves of Fuel Economy Improvement and Gasoline Savings

(a) Level 1 Technology, High Penetration

Gasoline consumption and savings in 2010 given new fleet MPG improvements achieved by 2005.

Tech. Key	New Cars	New LDVs	Total Stock	CCE $/gal	ACE $/gal	Cost $	Consume Mbd	Save Mbd
Base 1990	27.8	25.2	25.2	0.00	0.00	0	8.90	0.00
1 CR-inc	28.1	25.5	25.4	0.00	0.00	0	8.82	0.07
2 Lube	28.3	25.7	25.6	0.10	0.03	2	8.78	0.11
3 CVT	29.0	26.3	26.1	0.13	0.09	14	8.61	0.28
4 Opt-MT	29.7	26.9	26.6	0.15	0.11	26	8.47	0.43
5 Tires	30.7	27.8	27.4	0.17	0.13	46	8.25	0.64
6 Access	31.1	28.2	27.7	0.23	0.14	56	8.16	0.73
7 VVC	33.4	30.3	29.5	0.36	0.23	144	7.72	1.17
8 OHC	33.7	30.5	29.7	0.48	0.24	155	7.67	1.22
9 Frict	35.1	31.8	30.7	0.62	0.30	234	7.44	1.46
10 4valve	36.4	33.0	31.7	0.67	0.34	306	7.23	1.66
11 TCLU	36.4	33.0	31.8	0.76	0.34	308	7.22	1.67
12 5sp-AT	37.0	33.5	32.1	0.93	0.37	343	7.15	1.75
13 MPFI	37.2	33.7	32.3	1.07	0.38	357	7.11	1.78
14 Aero	38.2	34.6	33.0	1.21	0.44	447	6.97	1.93
15 Boost	39.1	35.4	33.7	1.48	0.50	543	6.84	2.05
16 Wt-red	40.2	36.5	34.6	1.87	0.59	693	6.69	2.20
17 Opt-AT	40.4	36.6	34.7	6.02	0.63	733	6.67	2.23

Technology abbreviations are keyed to the list given in Table 1.

Fuel economy values are unadjusted EPA composite MPG. New LDVs (all light duty vehicles) have the same percent improvement as New Cars, assuming the 1990 mix of cars and light trucks. Total Stock fuel economy is that of all light vehicles, new and used, in 2010, calculated using vintaging statistics from Davis and Strang (1993).

Cost of Conserved Energy (CCE) and Average Cost of Conserved Energy (ACE) are given in constant 1990$ based on a 5% real discount rate, 12 year vehicle life, and average driving of 10,000 miles per year, for a Capital Recovery Factor (CRF) of 0.1128. Doubling the discount rate to 10% increases the CRF to 0.1468, implying a 30% increase in CCE for each technology.

The Cost column gives the average increase in new car retail price (1990$) at each level of improvement, calculated from the High case penetration increases in Table 2(B) and the technology costs in Table 4.

Assumes that new fleet MPG levels are achieved in 2005 and then remain flat through 2010, with consumption and savings projections in million barrels per day (Mbd) for 2010. Savings projections are relative to new fleet fuel economy frozen at the base year (1990) level of 25.2 mpg for all new Light Duty Vehicles (LDVs).

Gasoline consumption projections assume a fuel economy shortfall of 20%, a cost of driving ("rebound") elasticity of 10%, and total light duty Vehicle Miles of Travel (VMT) of 2.748×10^{12} miles/year in 2010.

Table 5(b). Supply Curve for Level 2 Technology, High Penetration

Gasoline consumption and savings in 2010 given new fleet MPG improvements achieved by 2005.

Tech. Key	New Cars	New LDVs	Total Stock	CCE $/gal	ACE $/gal	Cost $	Consume Mbd	Save Mbd
Base 1990	27.8	25.2	25.2	0.00	0.00	0	8.90	0.00
1 CR-inc	28.2	25.5	25.4	0.00	0.00	0	8.81	0.08
2 Lube	28.4	25.7	25.6	0.10	0.03	2	8.77	0.13
3 Tires	29.8	27.0	26.7	0.11	0.09	22	8.44	0.46
4 CVT	30.5	27.7	27.3	0.14	0.11	34	8.28	0.62
5 Opt-MT	31.2	28.3	27.8	0.16	0.12	46	8.13	0.76
6 Opt-AT	33.0	29.9	29.2	0.22	0.15	86	7.79	1.10
7 Access	33.5	30.4	29.5	0.27	0.16	97	7.71	1.18
8 VVC	35.9	32.5	31.3	0.41	0.22	184	7.31	1.58
9 Vari-D	36.5	33.1	31.8	0.53	0.24	210	7.21	1.68
10 OHC	36.9	33.4	32.1	0.55	0.25	221	7.15	1.74
11 Wt-red	39.8	36.1	34.3	0.68	0.33	371	6.74	2.15
12 Frict	41.3	37.4	35.4	0.84	0.37	450	6.56	2.34
13 4valve	42.6	38.6	36.3	0.89	0.40	522	6.39	2.50
14 TCLU	42.8	38.8	36.4	1.01	0.40	524	6.38	2.51
15 5sp-AT	43.3	39.3	36.9	1.23	0.42	560	6.31	2.58
16 Aero	44.6	40.4	37.8	1.37	0.47	650	6.18	2.72
17 MPFI	44.8	40.6	38.0	1.49	0.47	663	6.15	2.74
18 Boost	45.8	41.5	38.7	1.95	0.52	759	6.04	2.85
19 IdlOff	46.8	42.4	39.4	2.74	0.59	889	5.94	2.95

See Table 5(a) for explanatory notes.

Table 5(c). Supply Curve for Level 3 Technology, High Penetration

Gasoline consumption and savings in 2010 given new fleet MPG improvements achieved by 2005.

Tech. Key	New Cars	New LDVs	Total Stock	CCE $/gal	ACE $/gal	Cost $	Consume Mbd	Save Mbd
Base 1990	27.8	25.2	25.2	0.00	0.00	0	8.90	0.00
1 CR-inc	28.2	25.6	25.5	0.00	0.00	0	8.81	0.09
2 Tires	30.0	27.2	26.9	0.09	0.08	20	8.39	0.50
3 Lube	30.3	27.4	27.1	0.12	0.08	22	8.34	0.55
4 CVT	31.0	28.1	27.7	0.15	0.09	34	8.17	0.72
5 Opt-MT	31.8	28.8	28.2	0.17	0.11	46	8.03	0.86
6 Opt-AT	33.6	30.5	29.6	0.22	0.14	86	7.69	1.20
7 Access	34.1	30.9	30.0	0.27	0.15	97	7.60	1.30
8 Lean	36.0	32.6	31.4	0.28	0.17	142	7.29	1.60
9 Wt-red	40.7	36.9	34.9	0.42	0.25	292	6.63	2.26
10 VVC	43.1	39.1	36.7	0.58	0.29	379	6.33	2.56
11 Vari-D	43.9	39.8	37.3	0.74	0.30	405	6.25	2.64
12 OHC	44.3	40.1	37.6	0.77	0.30	416	6.21	2.69
13 Frict	45.8	41.6	38.7	1.00	0.34	495	6.04	2.85
14 4valve	47.3	42.8	39.8	1.06	0.37	567	5.90	2.99
15 TCLU	47.5	43.0	39.9	1.20	0.37	569	5.88	3.01
16 Boost	49.1	44.5	41.1	1.35	0.42	665	5.73	3.16
17 Aero	50.5	45.8	42.1	1.49	0.46	755	5.60	3.29
18 5sp-AT	51.2	46.4	42.6	1.62	0.47	791	5.54	3.35
19 MPFI	51.5	46.7	42.8	1.87	0.48	804	5.52	3.38
20 IdlOff	52.6	47.7	43.6	3.30	0.54	934	5.43	3.47

See Table 5(a) for explanatory notes.

Table 6. Model year 1990 Light Duty Vehicle (LDV) Corporate Average Fuel Economy (CAFE) performance by manufacturer.

CAFE Rank	Manufacturer	Total 1990 LDV sales	Car CAFE	Light truck CAFE	LDV CAFE
15	General Motors	4,337,760	27.5	19.6	24.7
17	Ford	2,709,521	26.5	20.0	23.7
16	Chrysler	1,648,822	27.7	21.4	24.0
7	Toyota	975,421	30.8	21.8	28.0
5	Honda	894,186	30.8		30.8
11	Nissan	650,871	28.5	25.3	27.6
10	Mazda	370,893	30.2	24.0	27.9
8	Mitsubishi	221,388	30.4	22.4	28.4
6	Volkswagen	153,861	29.1	20.8	28.6
9	Subaru	143,450	27.8	28.9	27.9
4	Hyundai	113,817	33.3		33.3
18	Isuzu	104,056	33.5	22.2	22.5
12	Volvo	102,037	25.1		25.1
21	Mercedes	57,561	21.4		21.4
19	BMW	56,144	22.2		22.2
1	Suzuki	24,045	46.5	32.6	37.8
2	Daihatsu	19,961	41.0	27.3	34.5
20	Porche	7,013	21.7		21.7
23	Range Rover	4,862		16.3	16.3
22	Fiat	1,906	20.1		20.1
14	Sterling	1,201	24.9		24.9
3	Yugo	1,117	34.0		34.0
13	Peugeot	688	25.1		25.1
	All	12,600,581	28.0	20.7	25.3

Market shares	Car	Light Truck	LDV
All manufacturers	70%	30%	100%
D3 (GM, Ford, Chrysler)	64%	81%	69%
J5 (Toyota, Honda, Nissan, Mazda, Mitsubishi)	29%	15%	25%

Shown here are the CAFE averages for a manufacturer's combined fleet, in contrast to the separate treatment of domestic and import fleets used for CAFE regulations. Therefore, the values shown here are not the same as those used by NHTSA for CAFE compliance purposes.

Source: NHTSA, Summary of fuel economy performance, Docket No. FE-GR-013, National Highway Traffic Safety Administration, Washington, DC, September 1991.

Table 7. Avoidable Hydrocarbon Emissions Proportional to Light Duty Vehicle Gasoline Consumption

SOURCE OF EMISSIONS	grams/gallon
Vehicle (non-tailpipe)	
Diurnal losses	3.7
Running losses	1.8
Local Fuel Supply	
Vehicle refueling	1.9
Filling station storage, loading	1.7
SUBTOTAL (in vicinity of vehicle operation)	9.1
Remote Sources	
Tank trucks	1.3
Crude processes	0.3
Other	0.3
TOTAL NON-TAILPIPE HC EMISSIONS	11.0

Source: DeLuchi et al. (1992) mid-range estimates, compiled here as average potentially avoided emissions over a 40% range of fuel economy improvement, assuming the future emission controls (post-2000) expected under Clean Air Act Amendments of 1990. Current emissions associated with fuel consumption are likely to be 2-4 times higher.

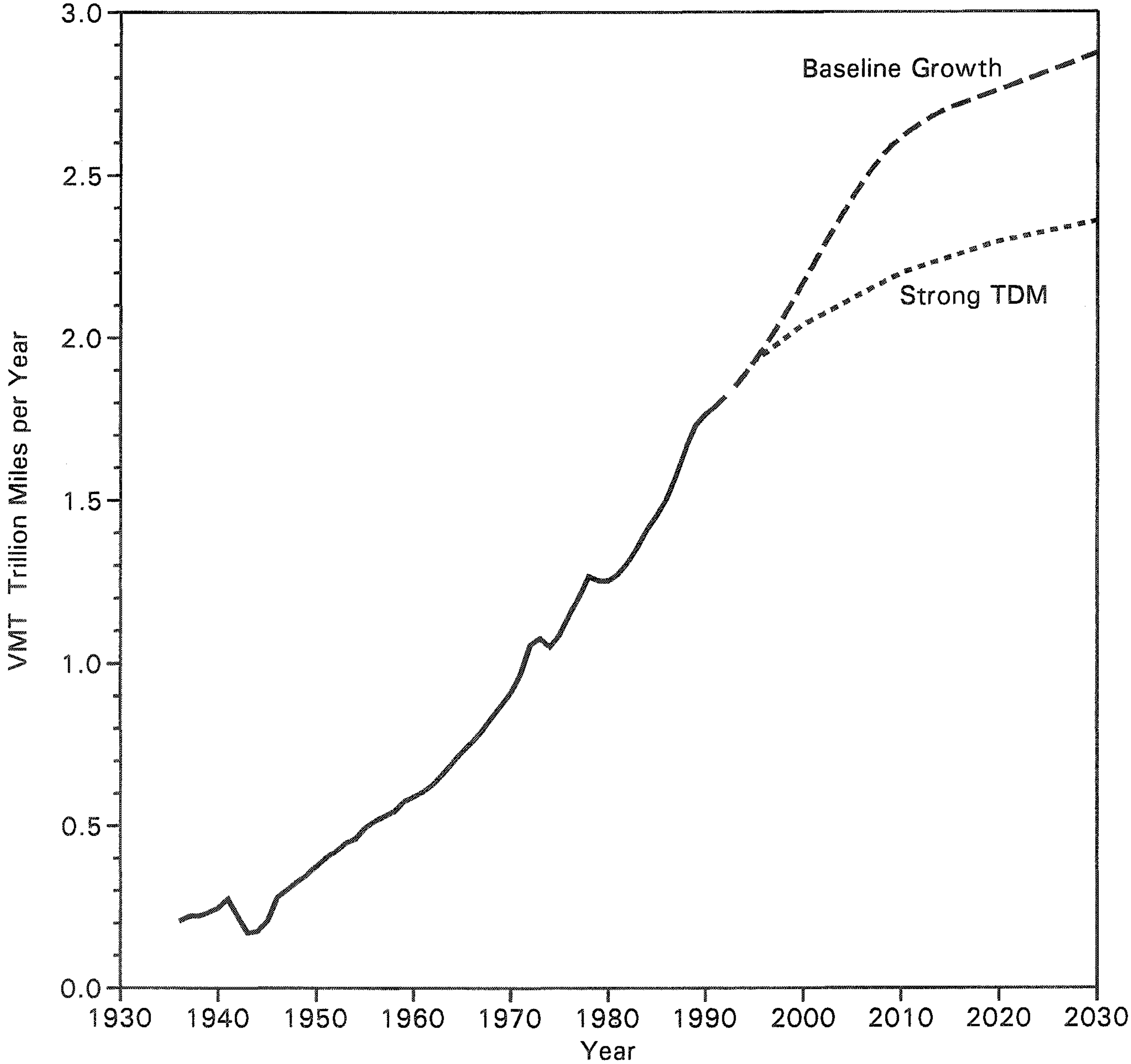


Figure 1. Past and Projected Light Duty Vehicle Miles of Travel in the United States.

VMT for cars and light trucks in trillion (10^{12}) miles/year. Past data based on FHWA Highway Statistics. Projections based on ACEEE analysis, with baseline average growth rates of 2%/yr 1990-2010 and 0.4%/yr 2010-2030. The "Strong TDM" scenario is based on UCS *et al.* (1991) "Market" scenario, which includes aggressive policies to reduce VMT and shift to alternative modes.

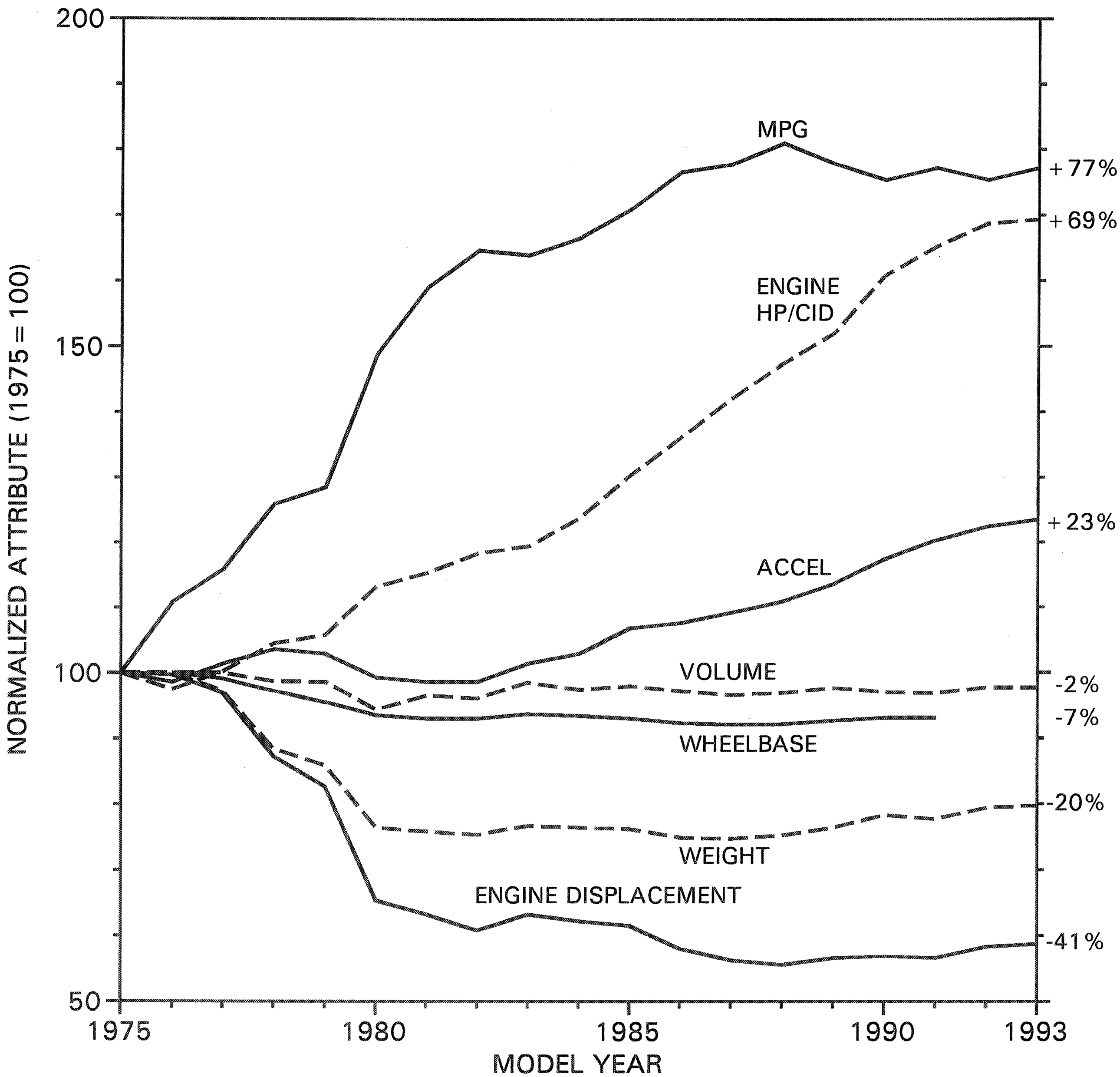


Figure 2. Trends in Fuel Economy Related Attributes of New Cars.

Statistics from Murrell et al. (1993), except wheelbase from Williams and Hu (1991).
"ACCEL" is inverse of 0-60 mph acceleration time; "HP/CID" is engine power to displacement ratio.

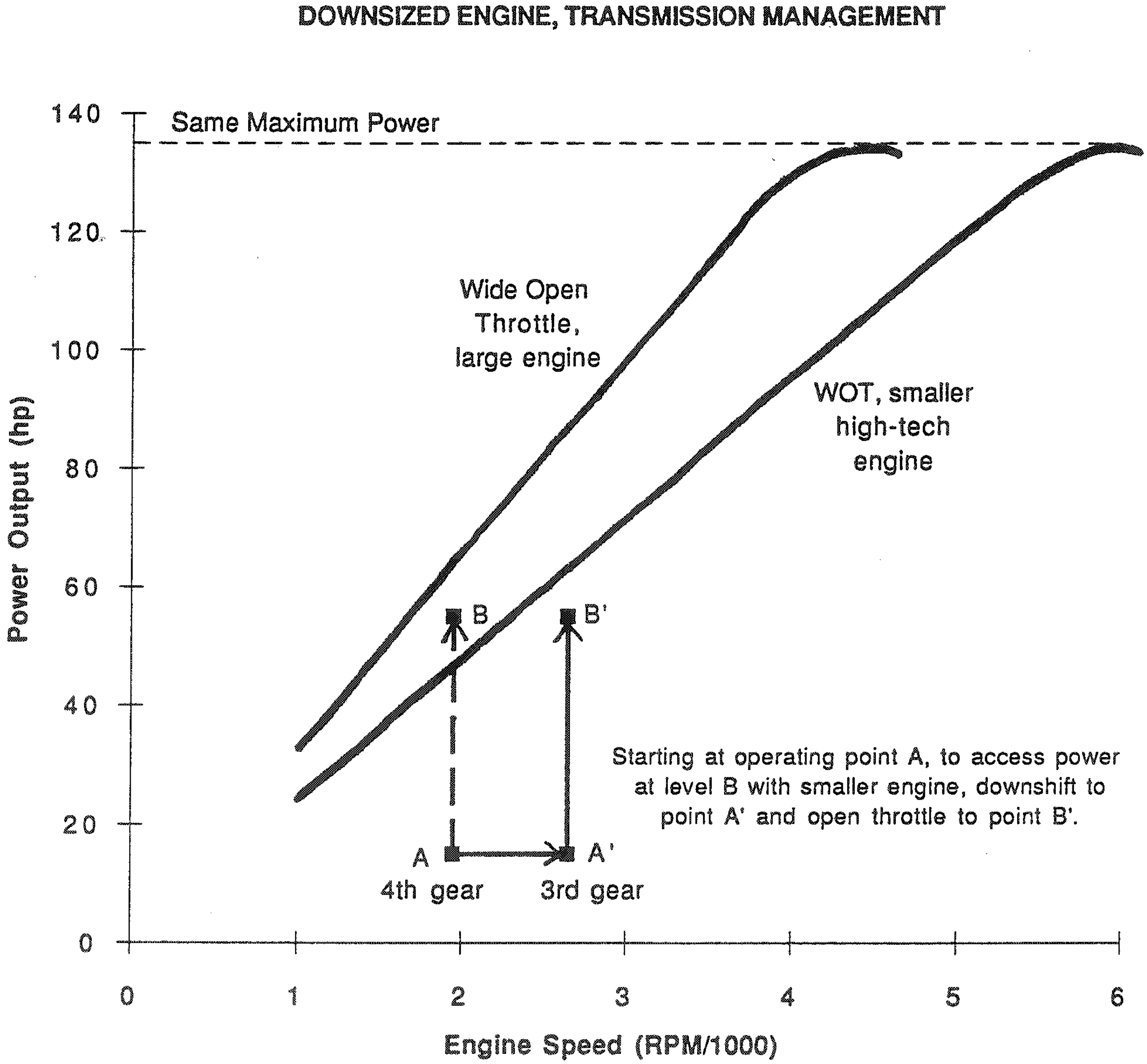


Figure 3. Downshifting to Achieve Power with a Small, High-Tech Engine, Shown on a Plot of Power Output vs. Engine Speed.

See text Section 2.2 (p. 19) for discussion.

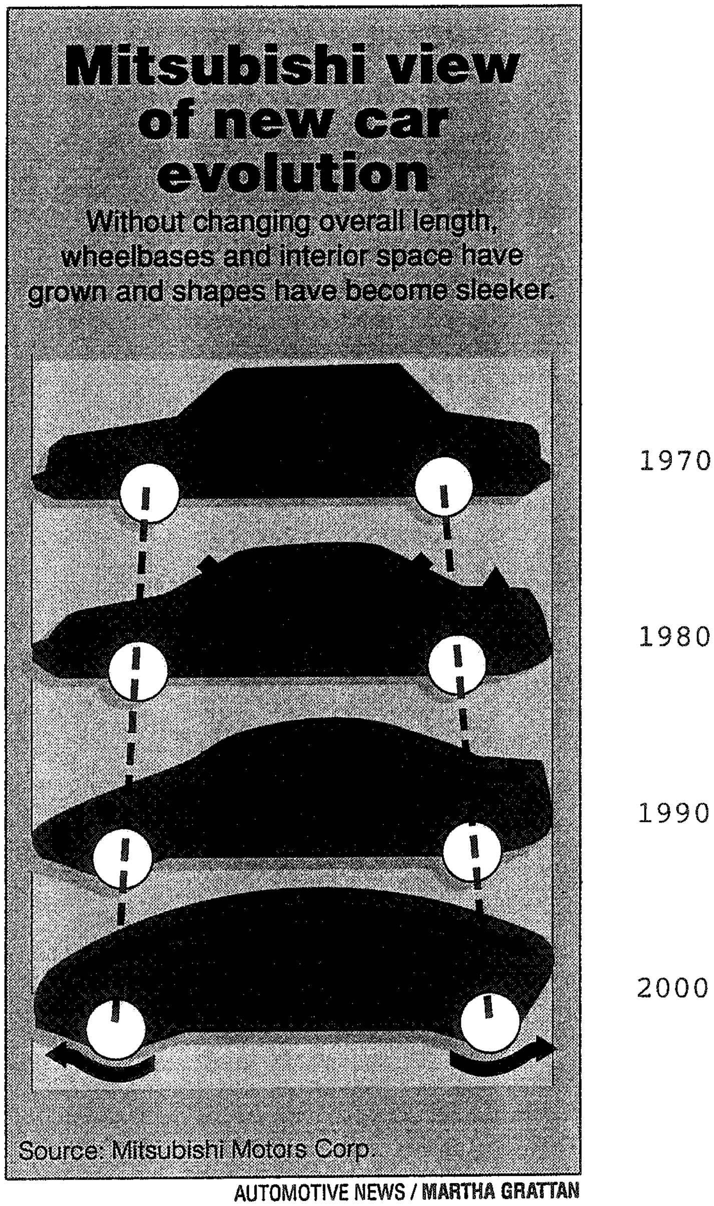


Figure 4. Trends in Passenger Car Design Geometry.

 Appeared in April 1, 1991 issue of Automotive News with article "Mitsubishi: Weight, not Size, is MPG Ticket" by M.A. Maskery, p. 1.

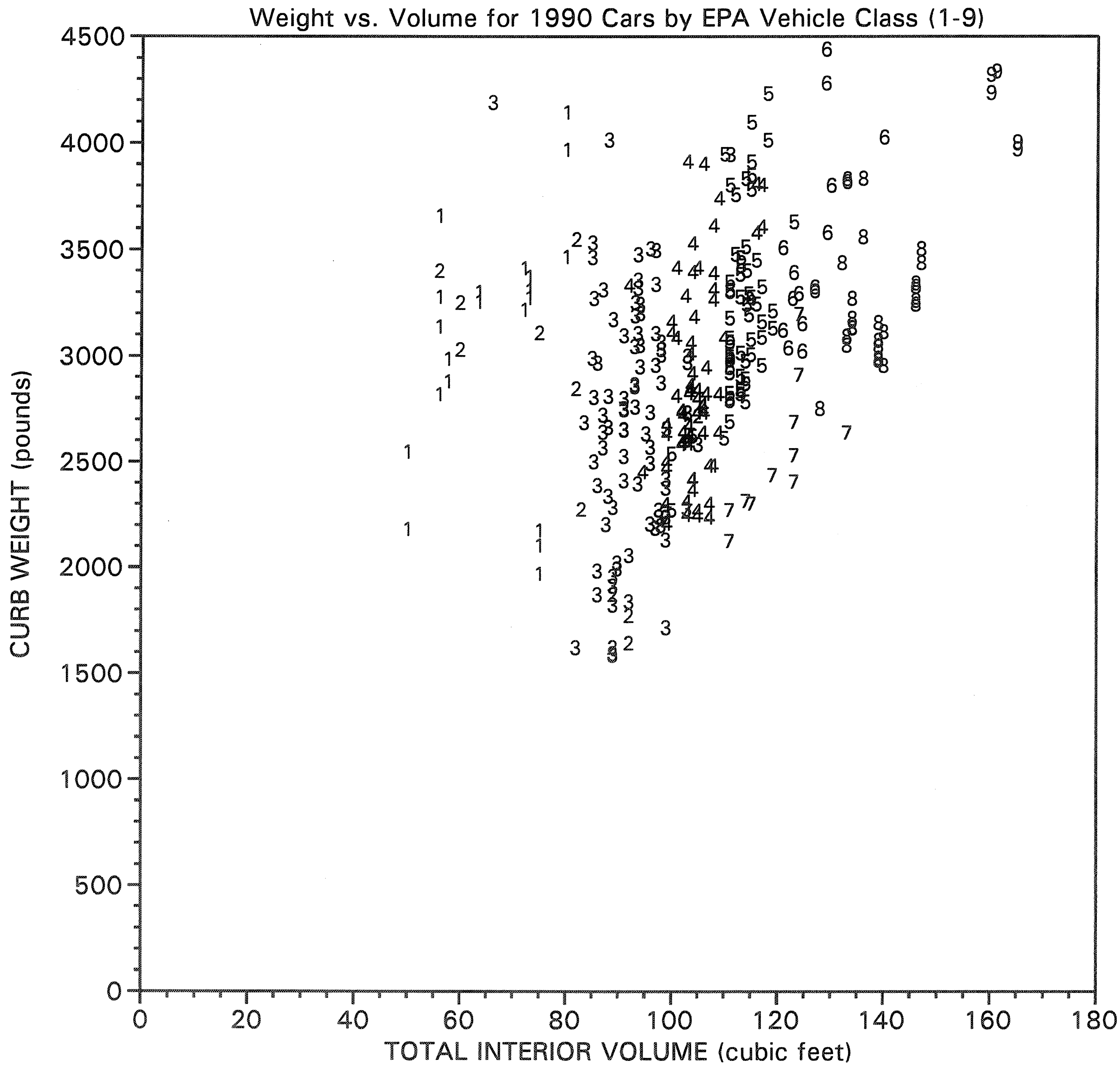
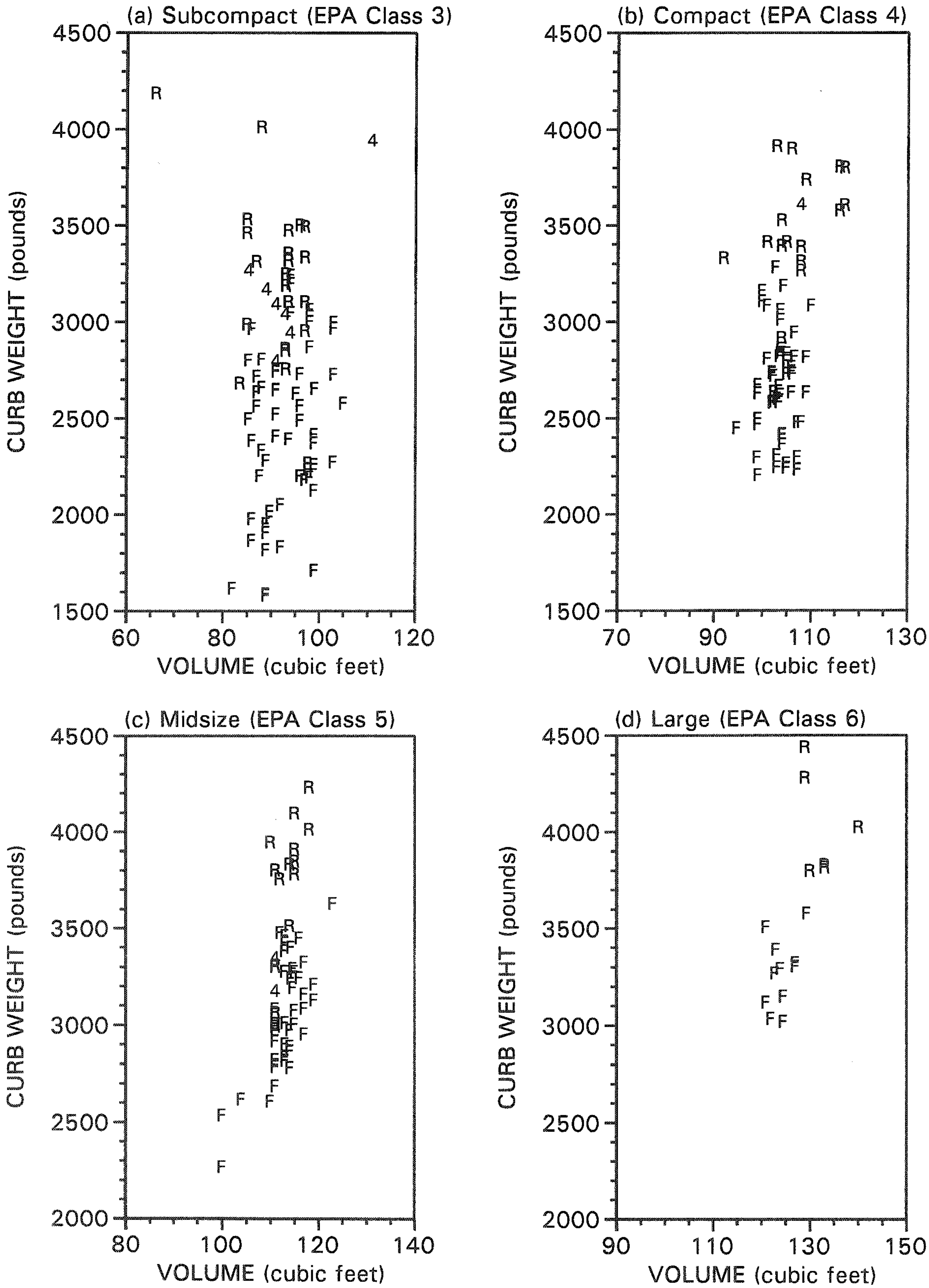


Figure 5. Curb Weight vs. Interior Volume for 1990 Passenger Cars by Class.

EPA Car Classes: 1 = Two Seater, 2 = Minicompact, 3 = Subcompact, 4 = Compact, 5 = Midsize, 6 = Large, 7 = Small Wagon, 8 = Midsize Wagon, 9 = Large Wagon.

Figure 6. (next page) **Curb Weight vs. Interior Volume, Shown Separately for Principal Classes of 1990 Passenger Cars and Plotted by Drive Type.**

Drive Types: F = Front Wheel Drive, R = Rear Wheel Drive, 4 = Four Wheel Drive.


(a) Subcompact (EPA Class 3)
(b) Compact (EPA Class 4)
(c) Midsize (EPA Class 5)
(d) Large (EPA Class 6)
CURB WEIGHT (pounds)
VOLUME (cubic feet)

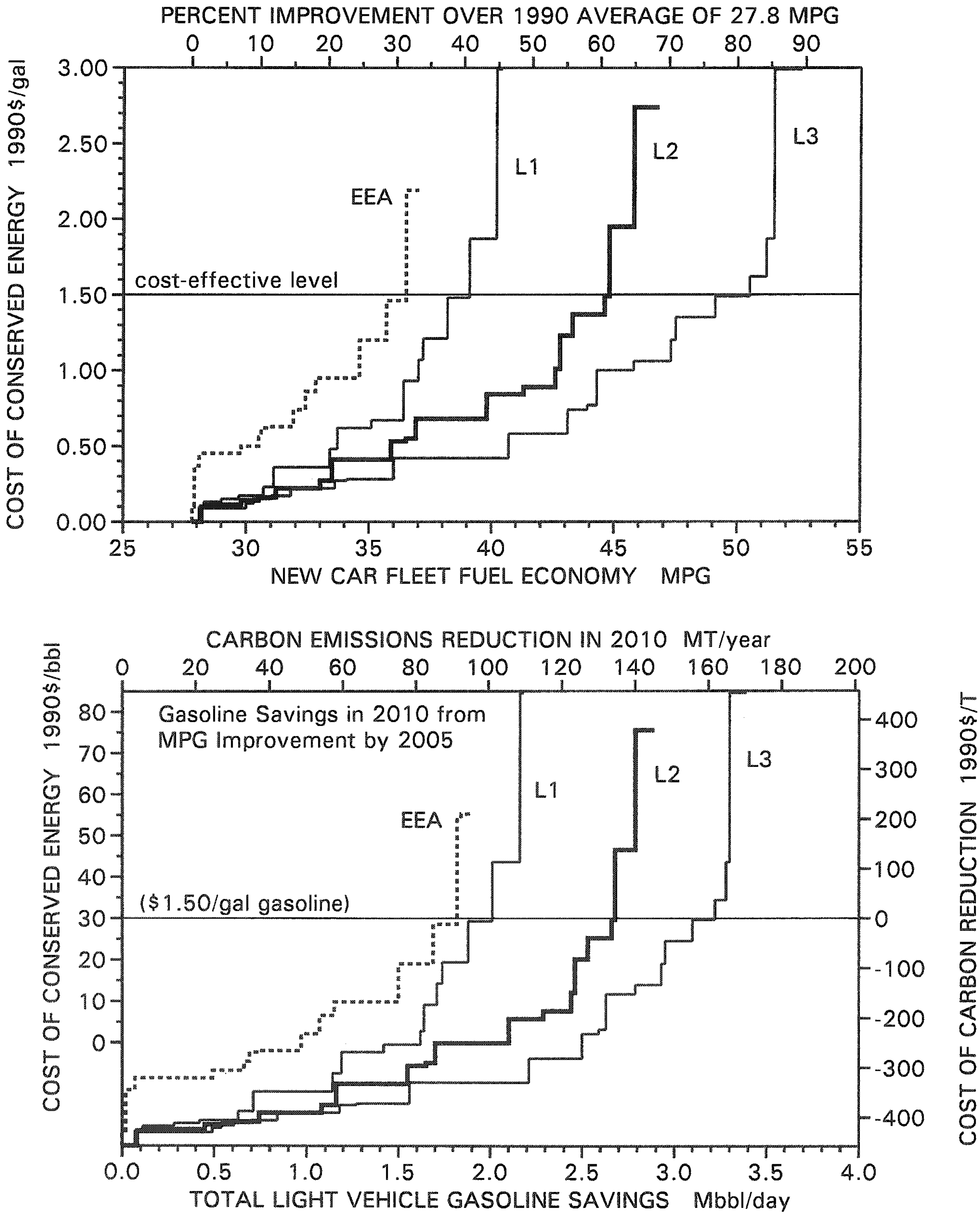


Figure 7. Cost Curves for Fuel Economy Improvement and Gasoline Savings.

(a) CCE vs. new car fleet average fuel economy; (b) CCE vs. nationwide gasoline savings and net cost of CO_2 emissions reductions. Based on 5% real discount rate over 12-year, 10,000 mi/yr vehicle life, for technology Levels 1-3 and with results using EEA (Greene and Duleep 1992) assumptions shown for comparison.

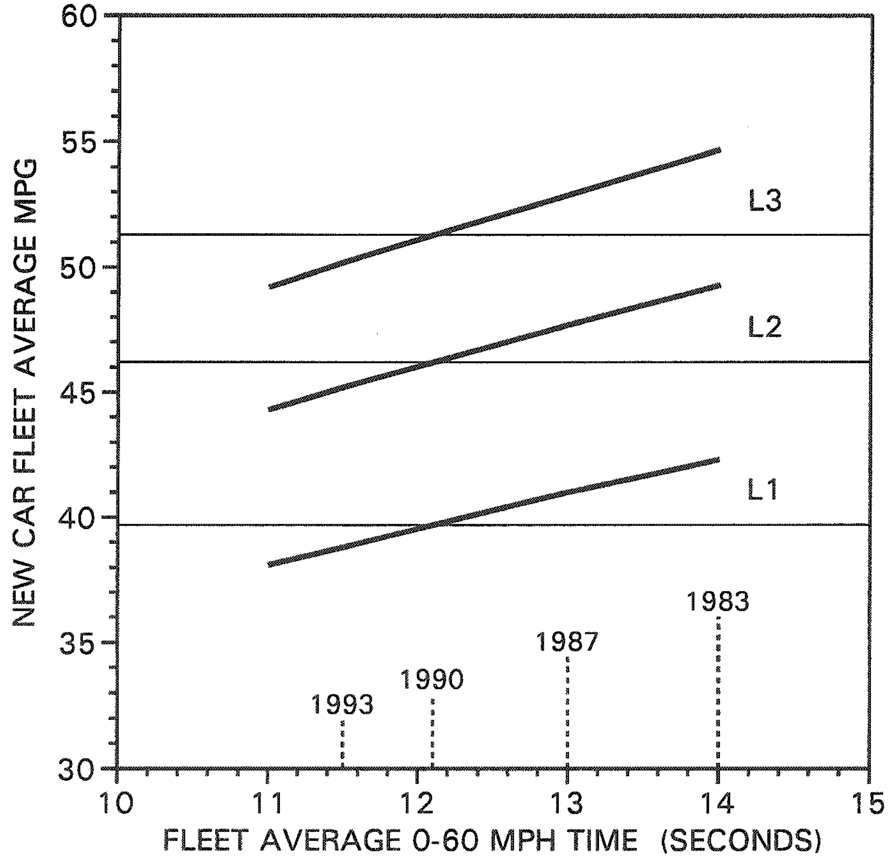


Figure 8. Projected New Car Fleet Average Fuel Economy vs. Acceleration Performance.
Based on sensitivity analysis of estimated achievable improvements in new car fleet average fuel economy, for technology certainty Levels 1-3.

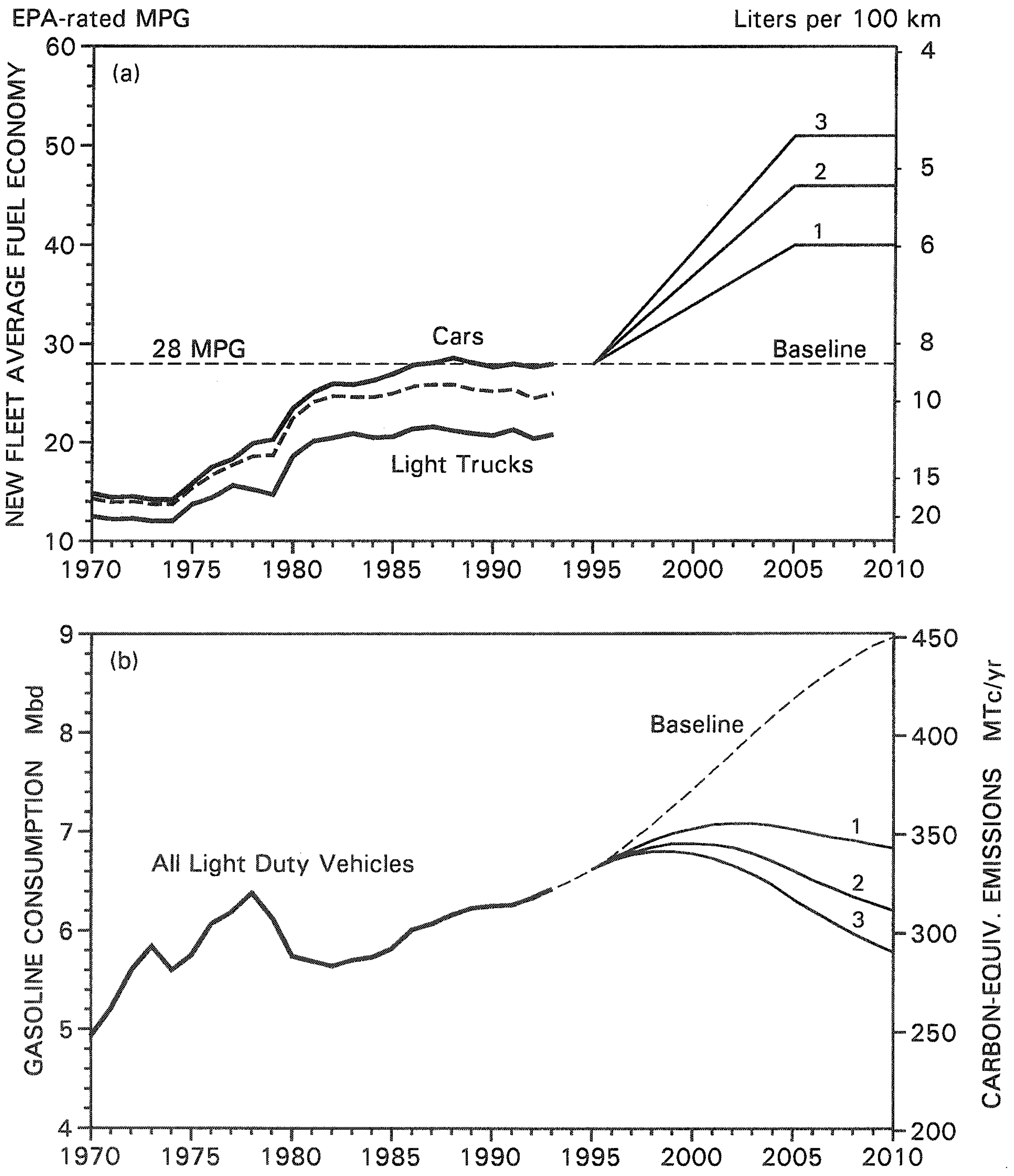


Figure 9. **U.S. Light Vehicle Fuel Economy and Fuel Consumption: Past History and Projections for Level 1-3 Scenarios of Improvement.**

(a) EPA-rated (unadjusted composite) fuel economy of new vehicles; dashed curve is new car and light truck average for 1970-93. Lines show ramp-up during 1996-2005 according to scenarios of improvement by 43%, 65%, and 85% over the 1990 average (Levels 1-3, for new cars at 40, 46, and 51 mpg, respectively).

(b) Gasoline consumption (million barrels per day) and carbon-equivalent greenhouse gas emissions (million metric tons per year) from U.S. light vehicle stock, with baseline of frozen new vehicle efficiency and scenarios of improvement as shown in (a).

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