Options for Reducing Oil Use by Light Vehicles: An Analysis of Technologies and Policy

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EXECUTIVE SUMMARY

Light vehicles (passenger cars and light trucks) are the dominant users of petroleum and the largest single contributors to carbon dioxide emissions in the United States. Although the energy efficiency of light vehicles has risen significantly over the past 15 years, current market conditions and a lack of forcing regulations are now allowing a decline in the efficiency of new light vehicles. Combined with increasing travel, the rising popularity of inefficient light trucks for personal transport, and a widening gap between fuel economy as rated and that actually achieved on the road, the result is significant ongoing growth in oil consumption and its attendant national security and environmental problems. This report discusses the technological options and public policies available to check this growth in light vehicle fuel consumption. There are three major parts to the report: (I) analysis of technical potential, (II) analysis of cost effectiveness, and (III) discussion of the policy options.

Part I: Technological opportunities for improvement

Our first focus is on the technologies available for near-term improvement of conventional light vehicles--gasoline powered cars and light trucks of today's size and performance characteristics. Technological improvement without reducing vehicle size and performance was behind most of the progress in fuel economy from 1975-1988. The opportunities for continued progress are far from exhausted; in fact, we are in the midst of a remarkable period of increasing technical capabilities, due to progress in electronic controls, computer-aided design and manufacturing, new materials, and other advances.

The types of technologies available for improving vehicle fuel economy fall into two broad categories. The first is load reduction, or decreasing the power required of the engine by reducing air drag, rolling resistance, weight, drivetrain friction, and accessory loads. The second is engine efficiency improvement, or increasing the effectiveness with which the energy in fuel is converted to useful work for powering the car. Part I of the report assesses the potential for improvements in both of these categories by simulation analysis of four prototypical vehicles whose characteristics span the range of size and power available in the current fleet. Most of the analysis is presented for a vehicle ("AVPWR") having a power-to-weight ratio that is average for the present fleet. The sensitivity of the potential efficiency improvements to different power characteristics is given for vehicles having lower- and higher-than-average power to weight ratios.

The analysis begins with an examination of the power required for realistic driving. Average power needs are an order of magnitude lower than the peak power producing abilities of typical engines. In contemporary vehicles, the result is a large amount of time spent operating the engine with a part-load efficiency much lower than its best efficiency. This suggests the importance of engine downsizing coupled with load reduction and aggressive transmission management as key strategies for improvement.

Available load reduction technologies include reducing aerodynamic drag, reducing tire rolling resistance, weight reduction, and regenerative braking. Drivetrain efficiency can be improved through transmission technologies such as torque converter lockup, electronically controlled standard gearing, and transmission friction reduction. Accessory loads--the largest of which is air conditioning--can be cut by running them only when needed, improving component efficiencies, and reducing the need to run the accessories. For today's average car, leaving maximum engine power unchanged, we find that every 10% reduction in load results in a 3-4% reduction in fuel use in urban driving and 5-6% reduction in highway driving. Using existing and near-term technologies, it should be straightforward to achieve a 20% reduction in load, yielding a 9% improvement in fuel economy.

Engine efficiency is analyzed in terms of two aspects: thermal efficiency, indicating how well the fuel is converted into power to drive the engine; and mechanical efficiency, indicating how well the engine delivers power net of what it needs to run itself. Five different major technologies for improving mechanical efficiency are considered: (1) aggressive transmission management (ATM) to reduce average engine speeds; (2) reducing displacement, or engine size, at constant power; (3) reducing rubbing friction and more efficient engine accessories; (4) engine stop-start (idle off); and reducing pumping losses (elimination of throttling). The installation of these technologies was independently simulated for a car of average power. The resulting potential fuel economy improvement, including the 9% improvement from load reduction, is 80%. The improvements by technology type, accounting for interactions, are summarized in Table 1.8.

The five technologies for improving mechanical efficiency fall into two groups: those that represent current technology (1-3) and those that are largely in hand but still require some development (4-5). For the first group, we establish the fuel economy improvement at 36%. Coupled with modest load reductions, these off-the-shelf technologies would provide an increase of well over 40% in fuel economy, without sacrificing power or size. As used here, current technology does not mean that there is no challenge for the industry in implementing such changes. It does mean that there need be no delay in pursuing the process of improvement.

Regarding the relation between fuel economy and tailpipe emissions, we note that in the first approximation, efficiency improvement is not necessarily effective in reducing tailpipe emissions (other than CO_2). This is because control systems--such as a properly designed and operated catalytic converter--play the dominant role in reducing emissions. A major source of excess emissions is degradation and failure of vehicles' emissions control systems. Nevertheless, there are some potentially important technologies which can provide both energy and emissions benefits. One is the use, in optimized engines, of intrinsically cleaner fuels. Another is lean-burn technologies, which may provide lower lifetime emissions because they enable reduced degradation and failure of emissions control, although NO_x control without a catalyst is difficult in lean-burn engines. Other technologies of interest include cycle-to-cycle control of engine characteristics, bringing cold engines rapidly up to warm operations, and using variable valve timing to recycle some unburnt hydrocarbons into the cylinder during cold operations.

Part II: Economics of improving fuel economy

The second part of this report analyzes the cost effectiveness of fuel economy technologies and the fuel savings that could result from their widespread use in the U.S. light vehicle fleet. Unfortunately, the cost data needed to fully analyze the technologies analyzed in Part I are not available. Here we analyze a more disaggregated set of technologies, which do not go quite as far as those considered in Part I. Working from a 1987 base year, estimates are derived for the potential fuel economy improvement and the resulting savings in the year 2000. The analysis is summarized by means of supply curves of conserved energy, which depict the nationwide oil savings that could be achieved through complete implementation of fuel economy technologies at a given cost.

The basic list of technologies analyzed is similar to the list considered in recent assessments sponsored by the U.S. Department of Energy. Brief descriptions of the technologies are provided along with references to published sources of their estimated fuel economy benefits. The cost-benefit analysis was performed by comparing the expected annual fuel savings with the annualized added first cost for each technology. Costs were discounted at a 7% real rate over a vehicle lifetime of 10 years. Ranking the technologies in order of increasing cost-to-benefit ratio and propagating the expected savings over the entire vehicle stock yields supply curves of conserved energy, which are shown in Tables/Figures 2.1 and 2.2. The cost-effective level of fuel economy improvement and resulting savings are then determined by going down the list until the assumed year-2000 gasoline price (taken to be $1.32/gallon) is reached. For technology group 2, the cost-effective new car fuel economy is 41.9 mpg and the corresponding annual oil savings are 1.9 quads (20% of what consumption would otherwise be with frozen efficiency). These savings can be achieved at an average cost of $0.53 per gallon saved.

Part III: Policies for reducing light vehicle energy use

The final part of the report turns to the issue of what governmental actions can be taken to reduce the energy consumption and attendant environmental impacts of light vehicles. We develop a context for policy development by noting that the goal of transportation policy should be to help provide better daily "access" for people, while reducing energy use and improving safety and environmental quality. Access means being able to reach places to work, shop, or engage in other activities. It does not, strictly speaking, mean mobility, with its implication of expanded travel. In a given situation, improving access may involve enabling people to travel further without increased energy use, but it may also involve reconfiguring land use patterns so that less travel is needed.

Policy areas relevant to improved access are those affecting land use; public transport; telecommuting and other substitutes for transportation; traffic and parking management, road controls, and road design; driver behavior, including vehicle maintenance and driving style, as well as improvements in light vehicles. We review the importance of these other areas but then focus on policies for improving light vehicles, which, while not sufficient to resolve all of the problems posed by our transportation system, is essential. The types of policies that can be considered to improve light vehicles include fuel pricing changes, fuel economy and emissions standards, fees and rebates on vehicle purchases, government support for the development of advanced technologies, and government efforts to create demand for improved vehicles.

The market price of gasoline does not reflect its real costs to the U.S. economy, which include environmental costs of pollution and risk of climate disruption as well as security costs of maintaining foreign oil supplies. Logically, these costs should be internalized through a general tax on oil, although a tax focused on transportation fuels would be more practical. Nevertheless, there is strong political opposition to raising fuel taxes, particularly if they are not used to support highways. Some of this opposition, particularly from consumer and low-income interests, is driven by questions of fairness. Moreover, while higher fuel prices are important in helping consumers value fuel economy, a review of fuel prices and vehicle efficiencies in other countries shows that even fuel prices of 2-4 times those in the U.S. may not be enough to push automobile fuel economies towards 40 mpg, that is, the levels that we found to be cost-effective in Part II.

One proposed way to increase the apparent price of fuel without imposing new taxes or increasing the overall cost of driving is by restructuring the way we pay for automotive insurance. "Pay as you drive" insurance would work by having consumers pay for a large fraction of their insurance fees at the gasoline pump instead of paying for all of it through independently arranged contracts with insurance companies.

Performance standards--Corporate Average Fuel Economy (CAFE) and tailpipe emissions standards--have been the principal policy means by which the U.S. has so far achieved relative reductions in vehicle fuel consumption and air pollution. While they have their limitations, regulatory standards remain an important policy option for bringing motor vehicle fuel use under control. They worked in the past, and market conditions and technological opportunities are such that they will likely work well again. Automobile manufacturers strongly oppose the legislation and claim, as they did in 1975 before the first CAFE standards were passed, that it is not practical to substantially improve fuel economy except by moving, on average, to much smaller cars. This argument is misleading, since, as we showed in Part I, technology exists to substantially improve fuel economy while maintaining the current size characteristics of the fleet. One valid concern is the major retooling investment needed to make the changes in the fleet. It is therefore important to create a schedule of strengthened standards that allows adequate time for manufacturers to adjust.

It is also important to enact complimentary policy measures to give fuel economy greater prominence in the light vehicle marketplace. One such policy tool which has been somewhat overlooked is the existing gas guzzler tax, which played an important role in improving fuel economy between 1983 and 1986. We recommend that the gas guzzler tax be established for light trucks and that for both passenger cars and light trucks, the fuel economy threshold for the tax be increased in step with the fuel economy standard.

An expansion of the existing gas guzzler tax would be a system of fees and rebates ("feebates") levied at time of purchase according to whether vehicles are above or below an average level of fuel economy. Such an approach has been introduced in the California legislature. This proposal, dubbed "Drive+," would set a vehicle's fee or rebate according to how much it was above or below an average level of emissions (including CO_2, which accounts for fuel economy). Feebates could be an important tool to improve fuel economy and reduce emissions, because consumers' sensitivity to first cost implies that it is easier to adjust for market imperfections at the point of vehicle purchase than to adjust for them in the course of operations, as, for example, with a gasoline tax.

It will be important to develop and introduce new vehicles and energy supply systems which could radically reduce energy requirements and emissions, but which are not close to being in mass production. Three potential types of new vehicles are (1) vehicles with conventional oil-based fuel use, size, and driving capabilities; (2) special-purpose vehicles requiring much less energy at the drive wheels, such as small commuter cars; and (3) alternatively fueled vehicles, including those which could flexibly operate on both gasoline and an alternative fuel.

The types of policies that can be used to advance such vehicle types are broadly classified as "technology push" and "technology pull." "Push"-type policies help create new technology, through research, invention, development, and demonstration, with either direct government support or government encouragement of private-sector efforts through tax incentives, patent law, etc. "Pull"-type policies help create demand for a new technology after it reaches initial commercial status, e.g., by direct government purchases and by encouraging the private purchases of the new technology. We propose providing extra fuel economy credits as a technology pull for the production of light vehicles with exceptionally high fuel economy, and lay out a schedule of rated fuel economy levels that might be required to earn such extra credits.

Finally, we address the issue of fuel economy and safety. This has been raised by opponents of fuel economy standards who claim that standards increase highway fatalities. We refute these contentions by pointing out how, as established in Parts I and II, the technology is available to increase fuel economy without downsizing; by examining the methodological flaws in studies proporting to link fatalities and fuel economy; and by noting the potential for technological improvements in crashworthiness. If new research were to indicate that vehicle attributes such as weight, exterior dimensions, or interior volume have a primary causal role in affecting safety, future fuel economy improvements should be based on technologies that do not adversely change these attributes.

Conclusion

Federal policies played a major role in improving light vehicle fuel economy since 1975. However, the upward trend is now stalled because the existing standards require no further improvements and real gasoline prices have fallen. This cessation in fuel economy improvement puts our nation's economy, security, and environment at risk. Among the near-term options for reducing oil imports and carbon dioxide emissions, none has a greater potential effect than substantially improving light vehicle fuel economy. The technology is presently available for cost-effectively improving fuel economy by 40%-50% over the next ten years. Substantially greater improvements are possible subsequently--we find the technical potential for an 80% improvement even in conventionally powered vehicles of today's size and performance characteristics.

The market can assist in pushing fuel economy levels higher, but because of inherent weaknesses, large externalities, and other barriers, market forces alone are insufficient for achieving cost-effective levels of fuel economy improvement. Strengthened fuel economy standards are needed, along with complementary policies such as pay-as-you drive insurance, an increased gas-guzzler tax or a system of fees and rebates linked to fuel economy, and technology policies to help develop, and create markets for, ultra-efficient vehicles. Government action to reduce light vehicle fuel consumption will not only benefit the United States directly, but given the enormous influence U.S. policies and technologies have on other countries, these policies could leverage large international reductions in oil use and its global environmental impacts.

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INTRODUCTION

The transportation sector in the United States is an important focus of both energy and environmental policy because it is a large consumer of energy, primarily oil, and a large source of air pollution emissions linked with both urban smog and global warming. About a quarter of all energy and 73% of all oil consumed in the United States is consumed in the transportation sector. Some 96 percent of the energy consumed in the transportation sector is from oil, 61% of which is attributable to automobiles and light trucks.[1]

Furthermore, transportation fuel use is responsible for about 35% of U.S. carbon dioxide emissions. Automobiles and light trucks alone account for about 22% (280 million metric tons of carbon) of these emissions, making them, among final users of energy, the single largest contributor of carbon dioxide emissions in the United States.[2] Cars and light trucks also emit about 40% of U.S. carbon monoxide emissions and large fractions of other important urban air pollutants (Gordon 1991).[3] Given their dominance of both energy and environmental problems in the transportation sector, this paper focuses on light vehicles.

Since 1973, new car fuel economy doubled, from 14 mpg to 28 mpg as measured by EPA tests, and light truck fuel economy increased 60%, from 13 mpg to 21 mpg (Heavenrich and Murrell 1990). Had this improvement not occurred, cars and light trucks (which now consume 6.5 million barrels of oil per day) would be consuming an additional 4 million barrels per day, more than twice as much as is being produced in Alaska, and over half our current level of imports.[4] Avoiding 4 million barrels per day of oil consumption means the United States lowered its retail fuel bill by at least $60 billion per year, lowered its trade imbalance by at least $25 billion, and is emitting about 170 million metric tons less carbon in the form of carbon dioxide. (About 1300 million metric tons of carbon are emitted annually as a result of fossil fuel combustion in the United States.)

Unfortunately, the fifteen-year trend of rising new vehicle fuel economy that has almost held fuel consumption by light vehicles in check has come to a halt. Low gasoline prices, a cessation of increases in fuel economy standards and in the threshold for gas guzzler taxes, has taken the pressure

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[1] The usual fraction of oil used by transportation cited from the Monthly Energy Review, Energy Information Administration, U.S. Department of Energy, is 63%. Our calculation, however, excludes secondary petroleum-based fuel use at refineries, power plants, and in other industries from total U.S. oil consumption, because it would not be used if the primary uses of petroleum did not exist. We believe this approach better reflects the extent to which the transportation sector is responsible for oil consumption in the United States.

[2] This calculation includes both the carbon emissions resulting directly from combustion in vehicles (20.2 kg C/10^9 J) and indirectly from production and transportation of the fuel (2.7 kg C/10^9 J) (MacDonald 1990).

[3] Carbon monoxide also plays an important role in global warming because it destroys hydroxyl radical (OH), which oxidizes methane, another important greenhouse gas. So, a lower atmospheric concentration of OH results in a longer life for methane (MacDonald, 1990).

[4] Based on light vehicle travel of 1.8 trillion miles in 1988 (passenger cars plus 75% of 2-axle, 4-tire trucks, from FHWA 1988, p. 172) and assuming an average shortfall of 15%. Net petroleum imports were 7.2 Mbbl/day in 1989 (EIA 1991, Table 1.8).

off automobile manufacturers to improve fuel economy. In the last few years, average new car and light truck fuel economy fell about 3% (Heavenrich and Murrell 1990).

Making matters worse, the number of highway vehicle miles traveled (VMT) in the United States continues to grow rapidly, seemingly inexorably. Since World War II, VMT has risen steadily and rapidly, with the two major oil crises of the 1970s represented by small, temporary shifts in the upward trend (**Figure I.1**). Recent analysis of the factors driving the growth in VMT indicates that VMT should continue to grow about 2.5% per year through the year 2000 (Ross 1989).

Yet another factor contributing to increased oil use is the growing number of light trucks in the U.S. light vehicle fleet. On average, new light trucks achieve 21 mpg, 24% below the new car average of 27.8 mpg (test values). In 1970 they only represented 15% of new light vehicle sales, but they now represent about one third of those sales. The large majority of light trucks are being used as passenger cars. A 1987 survey found that 81% of light trucks do not carry any freight (Bureau of the Census 1990, Table 9). As defined in this survey, freight even includes craftsman's tools. Thus, for most people, a light truck serves the same purpose as a car, but achieves much lower fuel economy.

Vehicles are also becoming much more powerful than they were in the early 1980s. Since 1982, average automobile 0 to 60 acceleration times have fallen from 14.4 seconds to 12.1 seconds, a 16% drop (Heavenrich and Murrell 1990). Using an EPA-developed estimation procedure, we estimate this move toward more powerful cars has reduced average new car fuel economy by almost 10%.

Furthermore, the on-road fuel economy of new cars and light trucks is falling further behind their EPA-rated fuel economy. The on-road fuel economy is estimated to have been 15% lower than the EPA laboratory test value in 1982 (Hellman and Murrell 1984). Analysts project that due to changes in driving patterns, primarily increasing traffic congestion, on-road fuel economy will fall 30% below test by the year 2010 (Westbrook and Patterson 1989).

Taken together, stalled fuel economy improvements, rapidly growing VMT, increasingly powerful vehicles, traffic congestion and substitution of trucks for cars, are putting strong pressure on oil demand. Only the final stages of the replacement of inefficient cars of the 1970s with today's more efficient cars is temporarily keeping oil consumption in check. At stake are national economic health, energy security, and the earth's climate. Among the many actions that can be taken to improve the situation, increasing the fuel economy of light vehicles should have a high priority.

Major changes will be required to reduce light vehicle energy use, or to even check its growth. Substantially improving light vehicle fuel efficiency will have the single largest effect on fuel consumption. As will be discussed below, it is within the range of technological and economic feasibility to improve the new car fuel economy to over 40 mpg within about ten years. Similar improvements could be achieved in light trucks. Although highly important, these major improvements, if achieved, will be largely offset by fuel consumption increases caused by growing traffic congestion and vehicle miles of travel. To achieve deep reductions in fuel use, the United States must not only improve fuel economies but slow the growth in vehicle miles of travel and provide attractive alternatives to single-occupancy vehicles. The focus of this report, however, is only on the fuel economy of light vehicles.

The effect of future fuel economy improvements on global warming will of course depend on the degree of those improvements. If U.S. new light vehicle fuel economy is improved 40% by 2001, as is being proposed in Congress, carbon emissions will 120 million metric tons per year lower by the year 2005 than they would be if new light vehicle fuel economy remains at today's levels. Although this is only 9% of current U.S. carbon emissions, no other single improvement in end use energy efficiency, or plausible switch to low-carbon, nuclear, or renewable fuel, will yield reductions as large by the year 2005.

If other countries were to also substantially increase their new vehicle fuel economy, much larger reductions in CO_2 emissions would be possible. A recent EPA report to Congress estimates that increasing the world's fleet fuel economy to 50 mpg by the year 2025 would reduce projected global warming by 5% in a future scenario that assumes rapid technological change and economic growth (Lashof & Tirpak 1989). (Note that this is not a 5% reduction in CO_2, but a 5% reduction in the projected average world temperature rise.) Again, although this may not seem large at first, one must consider the many greenhouse gases and their large number of sources. For perspective, EPA estimates that the 5% reduction is larger than the reduction in global warming that could be achieved through a near complete phaseout of CFCs by 2003, or through a rapid development of low-cost solar technology.

HOW THIS REPORT IS ORGANIZED

This report has three main sections. The first section addresses a number of technical issues related to improving light vehicle fuel economy. It also contains an analysis of how much light vehicle fuel economy might be improved with a select group of technologies. These technologies are especially effective at improving the mechanical efficiency of an automobile at part-load, an area the authors believe is especially promising for improving fuel economy.

The second section addresses the economics of improving fuel economy. The analysis is limited to those technologies for which cost data are available. Accordingly, some of the technologies analyzed in Section 1 are not analyzed in Section 2. The economic analysis is summarized in supply curves of conserved energy, which illustrate the cost and quantity of energy that can be saved by the year 2000 through improved automobile fuel economy.

The third and last section addresses numerous policy issues related to improving vehicle fuel economy and discusses several possible policies for reducing light vehicle fuel consumption.

Each of these sections is substantially abbreviated from other ACEEE reports: An and Ross (1991), Ledbetter and Ross (1990), and Ledbetter and Ross (1991), respectively.

PART I

OPPORTUNITIES FOR IMPROVING VEHICLE FUEL ECONOMY

Although this analysis addresses a time period of about 15 years, it is restricted to modifications to the present kind of vehicle; a vehicle with a gasoline-fueled, spark-ignition engine, and of today's size and power characteristics. This choice of focus is not due to lack of interest in alternative fuels, new light vehicle propulsion systems, and alternative transportation modes, all of which are very important for addressing energy and environmental problems in the transportation sector. Nevertheless, the petroleum-based personal transportation system of the U.S. involves an enormous investment in physical and human capital, which will not be quickly replaced. Accordingly, relatively near-term, moderate changes in light vehicles are a highly important means of addressing the energy and environmental problems of our transportation system.

Many believe that reduced vehicle size and weight is the principal way to substantially increase fuel economy; but lower maximum power per unit of vehicle weight can also make a major contribution without degrading acceleration performance under most conditions.

The subject of this analysis is yet a third kind of change -- technological improvement without reducing vehicle size and performance -- which was behind most of the progress from 1975-1988. We are in the midst of a remarkable period of increasing technical capabilities. Electronic controls, new materials, and the capability, through computers, to design a car in detail without having to go through many stages of trial and error with real engines and vehicles, is making it practical to do the things only dreamed of by earlier automotive engineers. Car designers can largely get rid of vibration and noise, control engines and transmissions using optimized electromechanical systems rather than simple mechanical linkages, and introduce much lighter materials to enable fast acceleration of vehicle parts. It is even becoming possible to control engine performance from one revolution to the next. This technological ferment can be sensed by reading papers of the Society of Automotive Engineers and attending their conferences.

Opportunities for reducing energy consumption by light vehicles can be broken into two broad areas: reduction of engine load and engine efficiency improvement.

LOAD REDUCTION

THE POWER REQUIRED FOR DRIVING

The power delivered to the drive wheels during typical patterns of driving is relatively low in today's cars. High power is required only in unusual driving conditions, such as acceleration at high speeds and climbing mountains at high speeds, which most drivers rarely encounter. The EPA urban driving cycle can be converted into a matrix as shown in **Fig. 1.1**. This matrix specifies the time distribution among velocities and acceleration rates in the urban driving cycle. It shows that the maximum acceleration rate during the driving cycle is about 1.5 meters/second^2, or about 3.3 miles per hour (mph) per second. (The maximum power requirement is lower in the highway cycle.) One sees that in the driving cycles, accelerations are much smaller than the maximum capabilities of today's cars. The 0-60 mph minimum acceleration time for the average cars is 12 seconds, corresponding to an average acceleration of 5 mph/second.

In recent years the maximum engine power of new cars has increased. The average new-car power to weight ratio, PMAX/W, has risen from a low of 32 horse power (hp)/1000 lbs. for the period 1980-'82 to 40 hp/1000 lbs. in 1990. (The major abbreviations used in this report are defined in **Appendix A.**) The average 0 to 60 mph acceleration time is estimated to have fallen from 14.4 to 12.1 seconds (Heavenrich, et.al. 1991). This increase in PMAX has apparently been a useful marketing tool, with many customers choosing the higher power version of a given model.

To accelerate at a rapid 3 mph/second (such that it takes 3 seconds to increase the car's velocity by 10 mph, corresponding to 20 second 0-60 mph acceleration time), the full power of a car with an average power to weight ratio is only needed at a speed of 70 mph (**Fig 1.2**). At lower speeds less power is required to achieve the same acceleration. A car with PMAX of, say, 140 hp and loaded weight of 3000 pounds can accelerate 3 mph/sec. at 80 mph. Usually such powerful engines are offered as an option. If the process of vehicle design by the manufacturer and selection by the customer is rational, then such high power is selected for: 1) accelerating rapidly at speeds already far above legal speed limits, 2) extensive high-speed driving on mountain freeways, or 3) pulling heavy loads. As **Fig. 1.2** shows, vehicles with engines of modest PMAX, like 80 hp, can readily be used (with appropriate transmissions) to accelerate rapidly at moderate speeds, so acceleration at moderate speeds should not be a rationale for high PMAX.

In **Fig. 1.2**, the polygon in the left-middle is the envelope of the urban driving cycle. The zero power line occurs at negative acceleration because, with no power, the vehicle will decelerate due to air and tire resistance. This figure clearly shows that the maximum power line penetrated by this urban driving contour is only about 40 horsepower, far less than the maximum engine power of today's average vehicle (about 125 hp).

At lower speeds, less power is needed to achieve the same acceleration. A car with PMAX of, say, 140 hp and a loaded weight of 3000 lbs can accelerate 3 mph/second at 80 mph. Usually such powerful engines are offered as an option. If the process of vehicle design by the manufacturer and selection by customers is rational, then such high power is selected for: 1) accelerating rapidly at speeds already far above legal speed limits, 2) extensive high-speed driving on mountain freeways or 3) pulling heavy loads. As **Fig. 1.2** shows, vehicles with engines of modest PMAX, such as 80 hp, can readily be used (with appropriate transmissions) to accelerate rapidly at moderate speeds, so acceleration at moderate speeds should not be a rationale for high PMAX.

Figs. 1.3a and 1.3b are from our car simulation results: a typical distribution of time spent with respect to the engine load in the EPA urban and highway driving cycles. These figures show that for a car having weight and power typical of new models in 1991, the time-averaged engine power outputs are 5.0 hp and 12 hp on the urban and highway driving cycles, respectively. (The characteristics of the car simulated in Figs. 1.3 and the other cars analyzed later in this section, can be found in **Table 1.1.**) These power levels are low compared to engine capabilities. At 5 hp output more fuel is being used to merely overcome the internal frictions of a typical powerful engine, than to provide the output power. That is, the fuel consumption at zero output is more than half of that at 5 hp output. In highway driving the situation is much more favorable, about 50% more fuel is used to provide the 12 hp output than to merely keep the engine turning over.

REDUCTION OF LOAD AT THE ENGINE

Load reduction at the engine can be decomposed into three categories: 1) reduction of load at drive wheels, 2) increase of drivetrain efficiency, and 3) reduction of load due to vehicle accessories. In today's average car, our analysis indicates that every 10% reduction in the load, leaving maximum engine output power unchanged, results in a 3-4% reduction in fuel use in urban driving and 5-6% reduction in highway driving.

Fig. 1.4 gives an example of shares of load at the drive wheels, among braking, air drag and tire drag, for both urban and highway driving cycles from our simulation. In the highway driving cycle, energy demand for overcoming air drag plays the biggest role. But in the urban driving cycle, energy consumed in braking and in tire resistance are the largest.

Load reduction at the drive wheels can be further categorized as follows:

1) **Air drag reduction.** Improvement of body aerodynamics offers great potential for reducing fuel consumption (Sovran 1983). Great strides have been made in the past few years in reducing the air drag coefficient of light vehicles. The best production model in this respect is the European OPEL Calibra with a coefficient of drag (Cd) of 0.26. GM's demonstration electric vehicle, Impact, has a Cd of 0.19, which might translate to a Cd of 0.21 if a fueled engine were used with its cooling requirements. The range of Cd in current U.S. cars is from 0.29 to 0.5. The average is about 0.36. It was about 0.5 in the early 1970s (Morel 1984). Even though there are some complaints about the lack of character in streamlined vehicles, the trend is obvious: The shape of vehicle bodies will be increasingly determined in the wind tunnel. Models with a Cd lower than 0.30 will be more popular in 1990s.

2) **Tire drag reduction**. Reduction of tire-rolling resistance also figures prominently in fuel economy improvement. The adoption of radial tires has led to a reduction in the rolling resistance coefficient of about 30% . Even better tires have been and are being developed. New fibers have greater stiffness. This improves capabilities for road handling and thus increases the freedom of engineers in designing tires. The recent introduction of high tenacity, "obround," polyamide monofilaments and tire reinforcement materials such as aramid yarns and short fiber aramid provides opportunities in tire design for reduced weight and improved fuel economy (Shellenbarger 1991). Higher pressure also reduces tire resistance, the resistance being inversely proportional to the square root of the pressure. For example, the demonstration model of GM's Impact uses tires with half the typical rolling resistance. Roughly half that improvement is due to doubling the pressure. There is a potential problem that a high-pressure tire will tend to lose contact on a rough surface. This could be corrected with wide tires and modified suspension systems.

3) **Weight reduction**. It is well known that weight reduction has a substantial effect on vehicle performance and fuel economy. We estimate that, every 10% reduction in vehicle weight will result in a 7% or 3% reduction in fuel use during a composite driving cycle, depending on whether the reduction includes the same percentage reduction in engine power and size or not. Statistics show that the weight to interior volume ratio has declined 14% in the past 10 years (Ross 1989). Further reduction in weight can be achieved by extended use of modern numerical design methods as well as by the use of alternative materials, such as high strength steel, aluminum, plastics and composites. The space frame concept with plastic panels has been suggested as providing a major opportunity for weight reduction. Mitsubishi has announced a major development and design program to reduce weight at constant interior size by, perhaps, 30% (Maskery 1991). Some expected changes in vehicles can add weight, such as some technologies for meeting environmental and safety regulations as well as other features like 4-wheel drive, 4-wheel steering, and anti-lock braking. The weight additions for expected environmental and safety regulations are relatively minor (Plotkin 1991) and we conclude that major weight reduction remains feasible.

4) **Regenerative braking**. During the urban driving cycle, roughly 40% of the drive-wheel load is dissipated in braking. In highway driving, this number is much smaller, about 10%. If 2/3 of the braking energy could be recovered and used (a difficult engineering target using batteries), fuel requirements could be reduced about 7%. The most prominent candidates for storing recaptured braking energy are, 1) batteries (fed by a motor-generator), 2) flywheels, and 3) hydraulic accumulators (fluid under pressure). The principle is straightforward. Implementation will be relatively costly unless considerable ingenuity is exercised. A concept at Volkswagen involving the conversion of the normal flywheel into the rotor of a motor-generator is promising.

Reduction of Load Due to Drivetrain and Accessory Losses

In the vehicle simulation completed for this report (explained later), 85 - 95% drivetrain efficiency and 0.5 - 1.0 hp average vehicle-accessory power is assumed (Stockton 1984). The largest energy loss in the drive train is in the torque converter (the fluid coupling of an automatic transmission). These losses are being substantially reduced with torque converter lock-up, or use of clutches, to minimize the resort to fluid friction. Lock-up is already being applied in most vehicles. The next generation of drive trains may use automated standard gearing, i.e., electrically controlled gears of the kind now used in a manual transmission. Other drivetrain losses come from the friction between moving solid parts. New materials will enable reduction of this friction (Seiffert & Walzer 1990).

Roughly speaking, vehicle accessories contribute about 10% to the engine load in the composite driving cycle. They include the air conditioner (on most cars), power steering and brakes, and alternator and battery losses associated with lights and other vehicle electrical loads, but not accessories specifically needed for running the engine. Generally, there are three ways to reduce accessory energy: 1) running accessories only when necessary, 2) improving their overall efficiencies, and 3) reducing the vehicle's need for the accessory services. (Bleviss 1988)

The accessory with the largest energy requirement, air conditioning, must be made substantially more efficient for a new generation of electric vehicles. Major reductions in energy use illustrating the three principles just mentioned are foreseen, involving a variable speed compressor, larger heat exchange surfaces and high-technology window glass (Dieckmann 1991).
In addition, vehicle ventilation during parking is important because air conditioners are sized according to the heat load they must overcome after a long, hot soak in a sunny parking lot. Such ventilation can be powered by photovoltaic cells on the roof.

There are no principles which impose a strict floor on the load an engine is subjected to, i.e., unless one specifies particular vehicle characteristics, the load can always be reduced by further reductions in weight, air drag, and tire resistance. On the other hand, the engine's performance potential is strictly circumscribed by efficiency factors. Nevertheless, efficiency improvement may be a more powerful tool than load reduction for improving fuel economy in the short to medium term.

EFFICIENCY IMPROVEMENT

THERMAL EFFICIENCY

The reasons for thermal inefficiency have been well studied and are extensively discussed in texts (Heywood 1988, Stone 1985) and elsewhere (Cole 1984). It will be difficult to increase thermal efficiency substantially. We are approaching, with present engines, a thermodynamic barrier which states that a perfect engine based on combustion cannot be more than about 80% efficient (Keenan 1941). In contrast, a fuel cell which converts fuel energy to electricity without an intervening thermal stage, can approach 100% efficiency in principle.

Moreover, thermodynamic limits for heat engines are very difficult to approach in practice. Even the best large and expensive, non-mobile, combustion-based engines (standard electric power plants) have thermal efficiencies of about 40%. About 50% can be achieved in electric power plants with the new combined cycle (and steam reinjection) technology for power plants, which involve energy recovery from the exhaust gases after the main energy conversion. (These efficiency estimates are based on the higher heating value of fuel).

It is quite a challenge for a much less expensive mobile engine to achieve similar efficiencies. Nevertheless, there are changes in characteristics which could be used to increase thermal efficiency somewhat: 1) increased compression ratio, 2) lean-burning, or increased air-fuel ratio, 3) recovery of work from the exhaust, 4) faster combustion, 5) effective control of working characteristics, such as the fuel-air ratio for each cylinder and cycle instead of only for the average, and 6) control of valve timing and enhancement of breathing so that intake and exhaust are optimized at each engine speed. The first three are briefly considered here. (Items (5) and (6) receive some further discussions in Appendix C and in the section on mechanical efficiency.)

In principle, compression ratios could be increased from today's typical value of 9 toward the best value of, perhaps, 15, resulting in a nominal efficiency improvement by a factor of about 1.15. In practice, not only does rubbing friction increase with compression ratio, but, wall effects (cooling and unburnt fuel associated with the surfaces) increase, so the improvement is not as good as simple analysis suggests (Muranaka 1988). Moreover, high compression causes knock. Some further knock inhibition than already achieved is possible, but not much more, unless low-knock alternative fuels are adopted, like an alcohol, methane or hydrogen.

Lean burning is advantageous in terms of efficiency because a gas of simple molecules when heated increases its pressure more than a gas of complex molecules, like vaporized gasoline, because with complex molecules much of the thermal energy is diverted into internal motions. For example, radically increasing the air-fuel ratio by a factor of 2.5 (above the chemically correct stoichiometric value) would increase efficiency again by a nominal factor of 1.15. Moreover, if the air-fuel ratio could be greatly varied while still obtaining satisfactory combustion, this method could be substituted for a throttle to regulate engine power output. Significant additional efficiency benefits would result. But, a) lean operation prevents the 3-way catalyst from reducing nitrogen oxides (NOx); b) NOx emissions from the engine, at a given power level, are not as low as one would hope; and c) lean mixtures can fail to ignite (misfire) or lead to incomplete combustion.

Several engine manufactures are working to overcome these drawbacks. Recent announcements by Honda and Mitsubishi indicate that they are having success; Honda has announced that a lean-burn engine will be used in one of the 1992 models of the Honda Civic. In addition, a more radical approach to lean-burn also appears to be nearing commericialization. This is the 2-stroke engine with modern fuel injection and controls, exemplified by the recent developments announced by Orbital Engine Company of Australia (Schlunke 1991).

With regard to recovery of energy from the exhaust, we use the same analogy with the combined-cycle power plant just mentioned. Although the exhaust carries away about 40% of the fuel energy from the vehicle, the quality of this energy is low. The most work that could in principle be extracted from the exhaust is 15 to 20% of the initial fuel energy; and converting low-quality energy into work is costly and inefficient. The U.S. Department of Energy has, however, been conducting a development project on such "bottoming cycle" technology for large trucks. In addition, they are supporting research on thermal insulation for the cylinder (of a diesel engine), which would increase the work recoverable, in principle, from the exhaust. It is too early to tell if there is any promise for automobiles.

In summary, improving thermal efficiency by a factor of about 1.25, from roughly 40 to 50%, would be an important but difficult goal. One way to achieve this goal is to solve the environmental problems of the diesel and adopt modern direct-injection diesels such as those now in use in several European cars. This goal could also be met by the development of successful lean-burn engines. Another way is to switch to a fuel consisting of much simpler molecules and with high octane, such as methanol, methane, or hydrogen, and designing a high efficiency engine for that fuel. Achieving still larger improvement in the thermal efficiency of internal-combustion engines is likely to be impractical.

MECHANICAL EFFICIENCY

The mechanical efficiency of typical U.S. cars is, in the low 40's percent range when averaged over the urban driving cycle, and in the low 60s when average over the highway driving cycle. Over the composite cycle, the mechanical efficiency averages about 50%. It is lower for high-powered cars and higher for low-powered cars. The mechanical efficiency is zero when the engine provides no power output (an idling engine), and is correspondingly low when the engine is operated well below its power rating at wide open throttle, PWOT, at any engine speed. As mentioned earlier, the opportunity for improving mechanical efficiency lies in the poor match of the power capabilities of today's engines to the power needed. The typical engine with high PMAX, is large and requires a lot of power simply to operate. The discrepancy between the typical PMAX of about 125 hp and the time average power requirement of 5 hp is the reason why mechanical efficiency is only about 40% in the urban cycle.

At WOT, mechanical efficiency is 85 to 90%. Unlike thermal efficiency, where it is not practical to achieve efficiencies more than about 50%, it is practical to achieve near-perfect mechanical efficiencies. We will show that it is a practical goal to increase the average mechanical efficiency close to 80%, a factor of 1.6 above today's average of about 50% in the composite driving cycle.

Improving mechanical efficiency at a given load requires reducing the power necessary to operate the engine, or the energy used for overcoming pumping and rubbing friction and to drive engine accessories. Pumping refers to the work needed to pull air into the cylinder and to push out exhaust. There are many strategies for achieving this reduction: reducing engine size, reducing the sources of friction themselves, reducing engine speed, turning off the engine when it is not needed, etc. These opportunities are the main subject of Part 1.

ANALYSIS OF THE POTENTIAL TO IMPROVE VEHICLE FUEL ECONOMY, FOCUSING ON IMPROVEMENTS TO MECHANICAL EFFICIENCY

ANALYTICAL METHODOLOGY

Most recent analyses of the near-term potential to increase fuel economy have been based on comparisons of production models with and without certain named technologies (EEA 1986, Difiglio 1990). For example, cars are compared that are similar, but one has front-wheel drive and the other doesn't, or one has 4 valves per cylinder and the other has 2. Similarly one can compare the dependence of a sample of many models on variables denoting the incorporation of named technologies (Chrysler). Such statistical analyses can also look at the dependence of fuel economy on weight, maximum power and engine displacement (Amann 1989, Murrell 1975).

These analyses are valuable, but the time horizon used in this analysis is somewhat longer and the analytical approach is different. Here, physical analysis is used to evaluate general classes of fuel-economy technology.

A related approach is also taken in recent work by Energy and Environmental Analysis, Inc. (EEA 1990). There are advantages and disadvantages to each approach. Physical analysis is emphasized over statistical analysis in part to avoid defining a technology in terms of its implementation in recent production models. Analysis of the potential of new powertrain technologies, such as electronically controlled transmissions or four valves per cylinder, may be biased by looking at their implementation in recent models. In principle, most such technologies offer a wide range of fuel economy and other attributes, depending on the specific design. The design chosen usually emphasizes increased power rather than fuel economy. For example, the fuel economy benefit of an electronically controlled transmission depends on the degree to which the management algorithm selects gears to reduce engine speed. Other examples are engine breathing enhancements such as tuned manifolds, extra valves, or supercharging, which increase the power to displacement ratio. They are often not combined in production models with downsizing of engines, which is the fuel economy approach. Physical analysis provides explicit formulas for evaluating such technologies for fuel economy benefits.

Four standard cars will be simulated over the urban and highway driving cycles in order to evaluate the fuel savings. Fuel economy improvements for these four cars will be presented. No attempt is made to base fuel savings on a systematic survey of the existing vehicles and improvements that can be made in them.

A key variable distinguishing cars from a fuel economy perspective is the ratio of maximum power, PMAX, to vehicle weight, W, a characteristic closely correlated with acceleration capability at high speeds. For this reason, the cars are chosen to differ strikingly in PMAX/W. W and PMAX are held fixed while the fuel economy improvements are made for each of these cars.

The car designated LOPWR is similar to a 59 hp Volkswagen Golf sold in the European market. No car on the U.S. market has such a low power to weight ratio, although such a car would, we feel, have attractive performance characteristics (except at high speeds and hill climbing) if equipped with a suitable electronically managed transmission with many gear ratios.

The car designated Jetta is similar to the VW Jetta with a 4- cylinder 106 hp engine. The average new car sold on the U.S. market is about 12% heavier and has PMAX/W about 5% higher. The Jetta engine considered, while not a very high performance engine, is a modern engine with maximum power per unit of engine displacement, PMAX/V, higher than the average of about 50hp/liter. The reason for selecting VW cars for analysis is that detailed information is available. Volkswagen has been generally forthcoming about publishing technical information (Seiffert & Walzer 1990).

Much of the analysis is focused on a car designated AVPWR. This car has near average weight for U.S. new cars (1991) and has a 6-cylinder, 3.1 liter engine with PMAX = 140 hp. These are near average engine parameters for new cars. This car is roughly similar to a Chevrolet Beretta with the 3.1 liter V6 engine or to the Ford Taurus with its standard engine. The fuel consumption characteristics for the engine are made up by appropriate scaling from 4-cylinder engine characteristics (Appendix B).

The fourth vehicle, designated HIPWR, is one to which some of the U.S. market is moving. HIPWR does not correspond closely to any single model, although it is vaguely similar to the Chevrolet Camaro with its 5.0 liter V8 engine or to the Chevrolet Caprice with its 5 liter engine.

Major characteristics of these four vehicles are shown in **Table 1.1**. Further details of the engines on which the work is based are presented in Appendix B.

Two approaches are made to evaluate fuel economy technologies in these vehicles. The first is a vehicle simulation model, AUTOEFF, developed by Terry Newell for EPA in the late '70s, modified by Frank Von Hippel and Barbara Levi, and further modified by the authors. The second is a simple algebraic approximation presented in Appendix B. A combination of these two approaches is used for most of the analysis. A 1-cylinder engine simulation model from General Motors Research was also used to study variable valve timing.

THE ANALYSIS

Five different major technologies for improving mechanical efficiency are considered:

- aggressive transmission management (ATM) to reduce average engine speeds,
- reduced displacement, or engine size, at constant PMAX,
- reduced rubbing friction and more efficient engine accessories,
- stop-start (idle off), and,
- reduced pumping (elimination of throttling).

These technologies were independently evaluated and installed in the base car AVPWR.

Before discussing the analysis of these technologies, we briefly consider some of the other technologies that can be used with a spark-ignition engine to improve its mechanical efficiency. Continuously variable transmission (CVT) is already incorporated in a few production models. Whereas ATM involves selection of gear ratios when designing the car, and, when driving, selection of gears so as to reduce the average engine speed while maintaining "driveability", CVT involves selection of a gear ratio from a range within which it can be varied continuously. Designed to emphasize fuel-economy improvement, CVT can, in principle, be more effective than ATM. With many gears in an ATM system, however, CVT can only be slightly more effective. The fuel economy concept involved is essentially the same as for ATM: the reduction of engine speeds.

Other options are variable displacement and variable compression engines, e.g., a small engine with comparatively low operation power requirements, which is used when the load is low, but which can be converted to a larger engine at higher loads (Amann 1989). One way to obtain the variability is to provide for changing the length of piston travel; another is to disconnect some cylinders at low load; a third way is to use a composite engine, a small engine and a larger one such that the two can operate together or the small one can be used alone.

Another option is a hybrid engine, in which a standard engine is coupled with an energy storage device [such as batteries (Hamilton 1989), flywheels (Post 1991) or an hydraulic accumulator for pressurized fluid (Weber 1988)] combined with electronic management as mentioned in connection with regenerative braking. In one type of control, the engine is operated for a while near its optimal efficiency with the excess energy output being stored; then the engine is turned off and the vehicle is operated with the stored energy. This cycle is repeated. There are also other approaches to varying engine output (Brehob 1991).

The variable displacement and hybrid engines are potentially highly valuable options as alternatives to the set of measures considered here. Either one of these measures, if successfully developed, might accomplish as much as all of the five above measures together. But we find that the five technologies listed above are initially easier to apply to the full range of vehicles using present technological capabilities. Moreover these five technologies cover most of the opportunity. They illustrate how far one can go by improving mechanical efficiency.

Aggressive Transmission Management

When engine speed is reduced at a given power output, more power output is provided for each revolution, while the frictional energy loss remains roughly the same, so that output relative to the friction or operating requirements is increased. The mechanical efficiency is thus increased while specific fuel use is reduced. **In Fig. 1.5**, mechanical efficiency is shown as a function of engine load for a variety of engine speeds. One finds, for example, that at 5kw output, mechanical efficiency increases from about 50% to 70% if the engine speed is decreased from a typical value near 2500 rpm to near 1200 rpm.

Transmission modification to reduce engine speed at a given power level is one of the best established methods for improving fuel economy (Ludema 1984). To implement it, more gears and lower gear ratios can be built into the transmission and, in driving, gears can be shifted up as soon as feasible. A feel for very aggressive transmission management can be obtained by driving a Honda CRX HF with a shift indicator light on the dashboard. This car's relatively low first gear ratio requires that the clutch be slipped considerably in order to get the car moving smoothly. As the car accelerates, the upshift light comes on very soon. If a driver follows the shift light's suggestions, he shifts up at much lower engine speeds than is typical.

A critical consideration for fuel economy is the span, or the ratio of the highest gear ratio to the lowest gear ratio. Consider a standard manual transmission. In the lowest gear (highest gear ratio) clutch slip is involved in getting the car moving, but the gear ratio must still be high enough to enable the engine to begin to move a stopped car up a grade (Stone 1989). Good fuel economy performance in highway driving requires a low gear ratio, or low N/v, for the highest gear. But the large span desired will not be feasible unless the ratios of adjacent gears are close enough to make shifting convenient. This requires many gears. For fuel economy, six gears is preferable to five in a manual transmission.

For automatic transmissions of the present type, with fluid coupling, fewer gears are needed because the lowest gear provides, roughly speaking, the function of the two lowest gears in manual transmissions. Four-speed automatics are now being widely used and 5-speed are being discussed. Good, energy-efficient management of many gears in automatic transmission systems will require sophisticated electronic management, which manufacturers are moving to create (Frame 1990). For the future, an attractive option is to automate standard (manual) gearing so that the transmission can be controlled and optimized electronically, as well as eliminating the fluid coupling losses.

In the following, an example of ATM is examined. The base vehicle is assumed to have a 5-gear manual system. This is changed to an automated 6-gear system in which the span is increased by a factor of 1.25 and the most energy-efficient gear is always selected in driving. The minimum engine speed used under load 1500 rpm for the Golf and Jetta analyses, and 1250 and 1000 rpm for the AVPWR and HIPWR analyses, respectively. Today's typical minimum engine speed operating under load vary strongly with the number of cylinders and somewhat with the gear. For 4-cylinder engines a typical minimum speed is near 1800 rpm and for 6- and 8-cylinder engines, near 1400 and 1100 rpm, respectively. (These speed estimates are based, for manual transmissions, on the Federal Test Procedure (FTP) gear shift schedule, and for automatics, on anecdotal observation in cars with tachometers). The ATM prescription used here is aggressive, but we believe it would be acceptable, especially with electronic management. It is possible to be even more aggressive by going to lower minimum engine speeds.

Figs. 1.6a and b show where the engine is operating at each of the approximately 800 seconds of the urban driving cycle when the engine of a Jetta is not idling. The FTP gear shift schedule is used to generate **Fig. 1.6a**, and the ATM just defined is used to generate **Fig. 1.6b**. This example of ATM tends to move engine operations from the 1800 - 2800 rpm range to the 1250 - 2400 rpm range. The average engine speed falls from about 2170 rpm to 1580 rpm. The combined effect of this ATM is found in our vehicle simulation to improve fuel economy 9% in the urban cycle compared to the base car and 15% in the highway cycle; the composite improvement is 11%.

For comparison, the 1989 EEA analysis mentioned earlier concluded that transmission improvements such as electronic control and lock up would provide a 4.5% fuel economy improvement, and a 5-speed automatic transmission would increase fuel economy 2.5% over a 4-speed (Difiglio 1990). In our analysis, the transmission management is more aggressive, and electronic control is used to make the ATM effective.

Aside from the issue of creating the transmission technology, manufacturers may be reluctant to reduce engine speeds for two reasons. First, the engine usually runs smoother, with less vibration at higher speeds. And second, relatively high power is almost immediately available at higher engine speeds. Consider the maximum power available to a driver without changing the engine speed, i.e., at wide-open throttle, PWOT. **Fig. 1.7** is a sketch of an engine performance map with x and y axes being engine speed (N) and power output (P_{engine}). PWOT is the upper envelope, the output at wide-open throttle. If one is driving with a relatively high engine speed at point A, then one has access to much higher power, for example at point B, merely by depressing the accelerator pedal, and enabling more air and fuel to enter the cylinders. If instead one is driving with a low engine speed at point A' (same P_{engine} as at A) under ATM, then the fastest way to access substantially more power is to shift down to 3rd gear, speeding up the engine to point A, and opening the throttle to achieve point B.

This process is familiar to drivers of many cars with a 4-cylinder engine and an automatic transmission, in which a down-shift and engine speed-up occur when the accelerator pedal is floored. The action of declutching, engine speed up and reclutching takes time; if done well, it takes less than one-half second. This does, however, change the feel of driving, which some might interpret as a loss of amenity. In this respect, the ATM technology is not analogous to the many other technological changes that can be implemented without any loss of amenity, such as multi-point fuel injection or advanced engine friction reduction.

In order to limit the frequency of downshifting to achieve higher power, we require in the driving cycle simulations for all the vehicles except LOPWR that each operating point for the engine have power output no more than 2/3 of PWOT, the maximum available at the engine speed. This prevents excessive use of high gears and associated low engine speeds.

Gear usage in the urban driving cycle with standard and aggressive transmission management is shown in **Fig. 1.8**. In the particular form of ATM considered here, the number of shifts changes little. However, in another variation with different gear-ratio modifications and different NMIN, we found six gear changes per minute as compared with three for the base car in the urban driving cycle. Thus with ATM, there can be shift busy- ness.

In a more sophisticated version of ATM, called Drive-by-Wire, electronically controlled transmission management with a more complex algorithm than that just considered is used to reduce the amount of shifting (Ganoung 1990, Huber 1991). This technology rests on taking the driver's signal from the accelerator pedal electronically rather than mechanically. In addition, with Drive-by-Wire, the timing of power output and gear shifting are carefully controlled in order to make accelerations smoother. Almost the same energy savings are realized with Drive-by-Wire as with the example analyzed here.

A second potential drawback of ATM may also call for a high- technology correction. There is a tendency for engines to vibrate at low speed. Such vibration can be prevented by good engine balance and mounting, but this is a technical challenge. Some engines now have been equipped with a balance shaft, a redundant, carefully weighted rotating shaft which acts to cancel vibration. Another approach, once it is fully developed, is active engine suspension. This concept involves attaching sensors to the engine and to control one or more of the engine mounts in response to the signal. It would require some energy for operation. A similar approach is being widely considered for vehicle suspension in luxury cars, and has been applied in the Infiniti Q45.

Reduced Displacement

This subsection addresses engine size reduction to reduce the power required for operating an engine, while maintaining PMAX (and acceleration performance). The analysis is based on replacing the conventional engine in AVPWR with an engine of 25% less displacement, and substantially higher PMAX per unit of volume, so as to compensate for this 25% decrease in volume (V) (Ward 1990). *Ceteris paribus*, reducing an engine's displacement by 25% reduces its PMAX by roughly the same amount. A 33% increase in PMAX/V would be needed to compensate (1.33 x 0.75 is approximately equal to 1).

During the '80s, PMAX/V increased about 3.5% per year on average. At this rate PMAX/V would increase 33% in less than 9 years, enough to compensate for a 25% reduction in V. Among 1991 Big-Three cars there are six 4- and 6-cylinder engines (without turbochargers) with PMAX/V greater than 61 hp/liter. (See **Table 1.2.**) The Quad 4 engine has a PMAX/V of 78 hp/liter, the highest among these engines. The current average is about 50 hp/liter. Some of the techniques now being used to increase PMAX/V are multipoint fuel injection, more valves per cylinder, double overhead cam valving, combustion chamber redesign, tuned intake manifold, variable intake manifolds for low- and high-speed operations and higher engine speed capability (Amann 1989). In addition, variable valve timing, discussed below in the context of low power output, can be simultaneously managed to substantially increase PMAX (and torque at moderate engine speeds).

There are two broad approaches to reducing engine displacement. The engine can be scaled down, leaving its design roughly same, and the number of cylinders can be reduced while keeping each cylinder's volume at least as large. An important consideration in assessing these approaches is that the rubbing friction and most engine accessory work are associated with surfaces, and scale roughly as $V^{2/3}$, while the pumping work scales directly as V (Ludema 1984). For example, a statistical study of many motorcycle engines by Yagi, et al. of Honda R&D, shows that total frictional power losses can be taken to be proportional to the cylinder surface area (bore x stroke) and more weakly to the scale of crankshaft components. Another important consideration is the bulk of the work against rubbing friction is associated with pistons, rods and valves, which is proportional to the number of cylinders, while the remainder, such as that associated with crankshaft bearings, would vary less.

Preliminary analysis indicates that the fuel economy results for the two approaches are roughly similar, but a study by Muranaka, et al. of Nissan suggests that scaling down the size of the cylinder may be less effective for fuel efficiency than hoped. As mentioned in the earlier discussion on compression ratios, wall effects depress thermal efficiency, and wall effects increase with decreasing cylinder displacement. The decrease in thermal efficiency roughly cancels the increase in mechanical efficiency which is achieved by reducing the size of the engine.

It is not clear how general this result is. Our conclusion is that for 6- and, perhaps some 8-cylinder engines the route for downsizing is to adopt high-performance 4-cylinder engines and, for most 8-cylinder engines, to adopt high-performance 6-cylinder engines. For 4-cylinder engines, high performance 3- and, even 2-cylinder engines should be designed and studied. In addition, further work on scaling down 4-cylinder engines should be done to test the generality of Muranaka, et al.'s results.

The main targets for downsizing to 4-cylinder high-performance engines are the 3.0 liter and over 6-cylinder engines which have relatively low PMAX/V. Examples of such engines are the GM 191, 204 and 231 cubic inch engines used in many of GM's 1991 car lines. The PMAX/V for these engines ranges from 43 to 48 hp/liter.

Decreasing V, while using technologies for increasing PMAX/V to compensate, leaves engine torque somewhat reduced at low to moderate engine speeds. To roughly estimate the effect engine downsizing might have on torque, consider replacing the 1991 Buick Regal, 3.1 liter engine (maximum torque of 250 Newton meters (Nm) at 3200 rpm) with an engine whose torque characteristics are similar to the Jetta and Saturn 4-cylinder engines investigated in this analysis, both of which achieve torque of about 84 Newton meters (Nm) per liter of displacement at 2500 rpm. When the substitute 4-cylinder engine is scaled to 75% of the displacement of the 3.1 liter Buick engine, it is estimated to have 195 Nm of torque at 2500 rpm (84 x 0.75 x 3.1). Thus the torque reduction is less than 22% (190/250).

Both engine downsizing and ATM reduce the available torque, at a given engine speed. Consider the combined effect of these two technologies applied to AVPWR. (See **Table 1.3**.) The 25% engine downsizing at a typical urban cycle engine speed of 2200 rpm leads to an estimated torque reduction of 19% for the engine considered. Application of ATM reduces the engine speed to about 1600 rpm, causing a combined torque reduction of 27%. (Refer back to the discussion of Fig. 1.7 under ATM for they way the transmission system can be used to compensate for this reduced torque at low RPM.) The ATM was analyzed with the gear restriction that the torque at each operating point is less than 2/3 of the maximum at the engine speed. This 33% reduction is greater than the 27% reduction just estimated, so the additional gear shift activity discussed in connection with the ATM is greater than or equal to that which would be required by the engine downsizing plus ATM as physically implemented (i.e., without the analytical restriction). In other words, the extent of additional shifting associated with both of these technologies is no more than that discussed in the previous section. From an engineering standpoint one need not be satisfied with this reduction in torque at low engine speed. Depending on engine geometry, the WOT torque at low speeds can be enhanced by design of the intake manifold. Pressure waves can be set up so that the pressure at the intake valve is high at the right time. This intake manifold tuning has been widely implemented, but not for the very low engine speeds considered here. There is also a large literature on variable geometry turbocharging for enhancing low-speed torque (Bleviss 1988, Inoue 1989, McInerney 1990).

The improvement in fuel economy associated with the 25% reduced displacement as described is 23% in the urban cycle, 19% in the highway cycle, and 22% in the composite. This level of fuel savings will not be possible in all cars because some versions of a few models already incorporate high-performance engines, which could not be downsized without significantly reducing power. Some engines, however, with PMAX/V below 45 hp/liter could be downsiz ed more than 30%, enabling even greater fuel savings. We estimate that the average engine downsizing would be about 30%. Because of the synergism between reduced engine displacement and ATM, it may be most meaningful to assess their combined effect on fuel economy, which we estimate as a 34% improvement in the composite fuel economy of AVPWR.

A comparison of the 22% fuel economy improvement can be inferred from the interesting presentation of fuel economy statistics by Amann (Amann 1989). He plots a fuel economy index (vehicle weight in thousands of pounds times fuel economy) vs. 0 to 60 acceleration time. We have not reexamined the statistics, but keeping the acceleration time fixed one sees from his figure that moving from a vehicle with average conventional engine (with an index of about 80) to a high-performance engined vehicle (with index of about 92) might be a reasonable description of the downsizing program described here, and it corresponds to a 15% increase in fuel economy.

Reduced Rubbing Friction

The largest part of the power required to operate the engine, Pop, is to overcome rubbing friction and to run the fan, oil pump, fuel pump, fuel injectors and coolant pump. Where these accessories are operated electrically, the corresponding energy losses in the alternator and battery must be taken into account. Engine friction depends largely on the design of linkages, piston rings, valves, bearings, and lubricants. There is room both for ingenuity and for straightforward improvements that cost more.

Considerable improvement in accessory efficiency can be achieved by changing the drive for accessories to electric motors, which run only when they are needed, instead of being run continuously with a belt drive. Substantial savings could also be made by introducing efficient alternators.

Given the surprising paucity of published research and data on the topic of rubbing friction reduction, a definitive estimate of the practical reduction potential isn't possible. Examples in the literature suggest that a 10% reduction in energy requirements for engine friction and engine accessories is currently practical (Stone 1988). The improvement in fuel economy associated with a 10% friction reduction is 6% in the urban cycle, 5% in the highway cycle, and 6% in the composite. These results are similar to those estimated by EEA (Difiglio 1990).

Stop-Start or Idle Off

Volkswagen has fully developed a technology, with a diesel engine, that turns off the engine when no power is demanded, and restarts it when the accelerator pedal is depressed or the manual-shift lever is moved. A test car fitted with this technology works very smoothly and without noticeable delay. The technology is now being tested and probably will be included in production vehicles.

VW is working on second-generation technology in which a second clutch is inserted between the engine and flywheel, so that the flywheel continues to spin when the engine is stopped (Seiffert & Walzer 1990). Stored flywheel energy is used to restart the engine. The radical aspect of this technology is that VW has designed the normal flywheel to also serve as the rotor of a motor/generator. This motor would be used as the starter, enabling elimination of a separate starter; and an alternator, enabling elimination of a separate alternator. This, it is hoped, would enable a net reduction in weight and cost. In addition, having a motor generator in the drive train would enable regeneration of braking energy. This system is still in development.

The impact of first-generation stop-start on fuel economy is readily calculated using the vehicle simulation. The energy loss associated with restarting the engine has been estimated and is small. The use of vehicle accessories with heavy loads, especially air conditioning, is a serious issue, however. At times when the electrical load is high, the engine should not be stopped. Idle-off technology for gasoline engines should be also managed so that the engine is not turned off in conditions where it may not start rapidly. The uses of this system (battery, heavy-load accessories and stop-start) should be optimized with electronic management. In the following it is assumed that in 33% of all engine idling, stop-start would not be used. Engine idling occurs during 33% of the composite driving cycle, including time when brakes are used during deceleration, so the engine would be turned off 22% of the time.

With this characterization, the fuel savings are found to be 15% in the urban, 2% in the highway and 10% in the composite cycle. This estimation is somewhat unreliable because only 2 of the 5 engine performance maps studied to gain insight into parameters for the fuel use model (Appendix B) give fairly direct data on idle fuel consumption. Thus our information on the average rate of fuel use in idling over typical cars, or for AVPWR, is limited.

Pumping Reduction

A spark-ignition engine relies on a throttle to run at lower power output. The throttle introduces fluid friction in the air intake to create a partial vacuum in the intake manifold, and thus, in the cylinders. In order to reduce power output, air intake must be reduced in proportion to fuel intake for two reasons. First, the flame propagates well if the mixture is near stoichiometric, and second, the 3-way catalyst works well only at stoichiometric.

A diesel, or compression-ignition engine, is quite different; the amount of fuel injected is reduced without reducing the air intake to achieve low power. Ignition occurs at fuel droplets, whatever their location, rather than by means of a moving flame front in a homogeneous fuel-air mixture. Ultra-lean-burn engines like the new, spark-ignition 2-strokes, are also managed so that the air to fuel ratio can be varied, at least in part, to substitute for a throttle.

Variable valve timing, VVT, refers to controlling valve motion according to engine conditions, rather than having a fixed pattern of valve motion, as in conventional designs. Variable early closing of the intake valve, EIVC, can be designed to substitute for throttling to achieve low power (Lenz 1988, Asmus 1991). In this concept the intake valve is opened at the beginning of the intake stroke, and then closed at a controlled time so as to admit the required amount of air. The main throttle valve is not used, so the pressure in the intake manifold remains atmospheric. After closing the intake port valve, the piston continues to be drawn back, creating a partial vacuum in the cylinder. (The amount of air needed corresponds to a vacuum of about 1/7 atmosphere pressure, at idle.) This work by the piston is recovered as the piston goes back in, in the first portion of the compression stroke. In this way pumping energy is largely eliminated. It cannot be wholly eliminated since there remains some fluid friction at the intake valve.

One mechanism for actuating the valve is electro-hydraulic, which uses oil under pressure with pressure release electrically controlled by a solenoid (Popular Science 1990). This kind of technology has been developed previously for high-pressure fuel injection for diesel engines. Other VVT mechanisms have also been developed (Demmelbauer-Ebner 1991, McCosh 1990).

Using a detailed single-cylinder simulation model, we estimate that 85% of the pumping energy can be eliminated with EIVC in low-load conditions. (The model does not incorporate reactions in the intake manifold, i.e., the manifold pressure is constant. Nor does it evaluate the speed of combustion.) This excellent achievement requires that the valves be moved faster than they usually are at typical engine speeds, but not faster than they are at high engine speeds. This rapid response would be easier to achieve with the lightweight ceramic valves being developed. This simulation is not necessarily definitive; engines using this system have not yet been built. Furthermore, complete elimination of the throttle may not prove practical. Assuming a 200 watt load to operate the EIVC technology, the fuel economy improvements associated with the EIVC technology in AVPWR are 8% in the urban cycle, 6% in the highway cycle, and 7% in the composite.

Another application of VVT is optimization of performance at wide open throttle. As the speed of an engine increases, considerable optimization is feasible if valve motion can be tailored to conditions. Valve timing can be made a function of the engine speed and load, and power at wide open throttle can be maximized using the same equipment used to reduce pumping losses at low loads. The fuel economy implications of these additional benefits should be substantial, but have not been included in our calculations.

Improvements to Mechanical Efficiency and Their Interactions

This subsection, which is based on use of the model described in the previous section, reviews the results of the five technologies discussed above, and discusses their interactions. In this analysis, the load is kept fixed at that for the base car. That is, the drag coefficients, weight and vehicle accessories are not changed. Allowance, however, is made for the small direct effects of the conservation technologies, such as a lighter engine resulting from engine downsizing, and increased loads resulting from operation of the ATM and VVT technologies.

The parameters characterizing the conservation technologies and the energy savings for AVPWR are shown in **Table 1.4**. Rows marked 1 through 5 show the five technologies when they are applied independently to AVPWR. The final two columns in **Table 1.4** show specific fuel use and percent savings for the composite driving cycle. The bottom four rows show illustrative combinations of measures.

The fuel economy improvement from applying each technology independently are all in the 6 to 22% range. The improvement associated with application of all the technologies is 58%. Mechanical efficiency is improved from about 40% to 63% (composite cycle). This is more than half the way toward an ultimate goal of 80%.

The efficiency improvement associated with a particular technology when other fuel economy technologies are already incorporated in a vehicle may be less than when it is applied alone. The results in **Table 1.4** are recast to show this interaction (**Table 1.5**). One sees in **Table 1.5** that the percent savings of the added technologies are roughly the same in the two situations, i.e., the interaction is not strong, except that the last in the sequence of five technologies creates less than half of the percentage benefit it creates when used alone. If one sums the percent improvements of these interacting technologies one obtains a total fuel economy improvement very close to the actual cumulative improvement. For example, the sum of the five improvements is 56%, compared with the actual cumulative improvement of 58%. So summing percent improvements may be a good short cut to estimate the cumulative fuel economy improvement of combining several technologies. (This method is used in the following part of this report on the economics of fuel economy improvements.) On the other hand, non-interacting improvements affecting different aspects of the vehicle, such as three improvements, one in load, one in thermal efficiency and one in mechanical efficiency, yield a fuel economy benefit which is the product of their independent improvement factors.

The sensitivity of fuel economy improvements to the power-to- weight ratio of the base car is explored in **Tables 1.6 and 1.7**, based on LOPWR and HIPWR, respectively. The fuel economy improvement associated with all 5 technologies is 35%, 58% and 50% for LOPWR, AVPWR and HIPWR, respectively.

Results

The fuel economy increase achieved by improving the mechanical efficiency of engines using the five technologies is calculated to be 58% (**Table 1.8**), which would improve the simulated vehicle from its base fuel economy of 24.3 mpg to 38.4 mpg (EPA composite test rating). This is exclusive of any improvements in engine thermal efficiency or in load.

An interesting sidelight concerns the discrepancy between the E.P.A. test values for fuel economy discussed in this report and the actual on-road fuel economy. The latter was estimated to be 15% lower in 1982 (Heavenrich et al. 1991) and is now about 20% lower by our estimate. In urban driving, where congestion is leading to more stopping, the fuel economy measures evaluated in this report would be more effective than in the FTP driving cycle. Thus the actual percentage improvements (as well as the absolute fuel savings) could be larger than estimated in this report.

The five technologies fall into two groups: those that represent current technology (reduced displacement, reduced friction, and aggressive transmission management), and those that require some development, although the technologies are largely in hand (idle off and fully variable valve timing). With the first group, the fuel economy improvement is established to be 36%. These technologies coupled with modest load reductions (e.g., reductions in drag coefficient, tire resistance and accessory loads) would provide an increase of well over 40% in fuel economy, without sacrifice of power or size. As used here, current technology does not mean that there is no technological challenge in implementing such changes in millions of vehicles per year such that they are extremely reliable. It means that there need be no delay before beginning the design process.

As discussed in Appendix B, there are uncertainties in these fuel-economy-improvement estimates. The largest uncertainty concerns the assumption that the average engine in today's new cars can be represented by the engine in AVPWR. For example, if today's average engine has lower fuel consumption at zero power output than AVPWR (but poorer thermal efficiency), then these part-load measures would have smaller benefits. In addition, the dependence of efficiency on engine speed may be different from that of AVPWR. On the basis of the variations shown in **Table B.1 and B.2**, an overall error from these sources of plus or minus 15% in the fuel savings is not unlikely, e.g., the fuel-savings benefit of the engine downsizing described might be as low as 13% rather than 15%.

Further analysis would enable a substantial reduction in this uncertainty. In particular, a variety of engines now in use need to be characterized and analyzed for fuel economy improvement potential. The auto manufacturers could reduce these uncertainties and clarify the issues by providing more information on engine performance maps.

In addition, the ATM, idle-off and VVT measures have been described in ways that might be different from the way such technologies may have been described by others; since there are a variety of important design considerations in each case. Our descriptions correspond to giving first priority to energy efficiency, but not neglecting other considerations.

As noted above, these fuel economy improvements are associated with slight losses of amenity: occasional brief delays in accessing high power, and, perhaps, somewhat more gear shifting. In addition, there might be somewhat more engine vibration, although this is a problem which can probably be solved without resort to expensive equipment.

ON THE RELATION BETWEEN FUEL ECONOMY AND EMISSIONS

It is tempting for advocates of high fuel economy to believe that energy efficiency and emissions reduction are closely associated.
This is so for carbon dioxide, of course. However, in the first approximation, efficiency improvement in general is not important for reducing the other emissions of concern, because emissions control systems play the dominant role in reducing emissions. A properly designed and operated 3-way catalytic converter can convert 90% or more of the hydrocarbons, CO and NOx from the engine. Maintaining proper operation of the emissions control system, which includes control of engine parameters like fuel-air ratio, has a major effect on emissions, without having major impacts on fuel economy. Conversely, simply reducing fuel consumption as such has a weak impact on fuel economy. This physical perspective is supported by production model statistics.

While there is some statistical tendency for high fuel economy cars to have lower grams/mile emissions among 1989 models, if one omits the cars made by Suzuki the effect is modest.

A critical aspect of the overall emissions picture is that for HC and CO, total emissions averaged per vehicle mile are 5 to 10 times higher than the tailpipe standards (See Part III). Much of these emissions are due to older vehicles still on the road. One major source of excess emissions is degradation of vehicles' emissions control systems, another is failure of these systems (although the incidence of failure is not well known because budgets for testing of in-use vehicles have been inadequate).

Many energy-efficiency technologies are not emissions-reduction features. For example, reducing engine size keeping the same number of cylinders tends to increase the surface to volume ratio and thus increase fraction of unburned hydrocarbons associated with surface deposits and crannies. This effect may roughly cancel the emissions reductions associated with reduced fuel use.

Another example is ATM, which may lead to increased HC and CO emissions, because operations are closer to WOT at lower engine speed and use of a rich fuel-air mixture near WOT is now common.

While we are persuaded that fuel-economy improvements are, in general, not important to emissions reduction (other than CO2), there are potentially important technologies which can provide both energy and emissions benefits. The best known has already been mentioned: the use of a fuel with very simple molecular structure (including designing the engine for that fuel). We have also mentioned lean burning with conventional fuel (or high air/fuel ratio) in this connection. Two key aspects of lean-burn gasoline engines are: 1) Adequate NOx emissions control without a catalyst is difficult. 2) These engines may be able to provide lower lifetime emissions because they may be more robust in their emissions performance than present engines, enabling reduced degradation and failure of emissions-control performance. We do not discuss these further.

At least three other technologies are of interest: 1) cycle-to- cycle control of engine characteristics, 2) bringing cold engines rapidly up to warm operations. and 3) using VVT to recycle some unburnt hydrocarbons into the cylinder during cold operations.

In addition, the elaboration of closed loop control systems, based on measurement of both inputs and actual engine outputs, and the move toward recording and communicating data on engine performance relevant to emissions (on-board monitoring) should lead to both fuel economy and emissions improvements.

Control of cycle-to-cycle fluctuations is potentially very important for emissions reduction because catalytic conversion functions much better right at the stoichiometric mixture than even 1% away (Katashiba 1991). So control at the level of tenths of a percent would be beneficial, but combustion completeness, for example, typically varies over several percent (Sztenderowicz 1990 & Heywood 1988). Such control may be difficult to achieve because the variation appears to be associated with factors like the amount of fuel injected, the amount of fuel left in the cylinder from the previous cycle, and leakage past valves and piston rings. The possibilities of control should be enhanced by advances like improved fuel injection, variable valve timing and improved fuels.

Automobiles are often used for short trips. In a 1983 survey it was found that the average trip length is 9 miles in connection with earning a living, 6 miles for family & personal business, and 11 miles for social & recreational trips (FHA 1986). Thus trips of about 8 miles and less constitute half the travel. There is a substantial fuel economy penalty for trips shorter than this, especially in cold weather, although modern lubricants have substantially reduced the 20 to 30% reductions in fuel economy reported as typical for trips of this length in the 1960s (Cole 1984).

A substantial part of total tailpipe emissions are, moreover, associated with cold start, before the catalytic converter becomes operative, or "lights up." Although there are proposed measures to hasten the onset of catalytic performance, such as heating the catalyst electrically or placing the catalyst much closer to the engine, there are also proposed measures to heat the engine quickly, simultaneously reducing both emissions and fuel use. Volkswagen R&D is developing a scheme to store thermal energy from one use of the vehicle to the next. Another German firm has developed a barium hydroxide heat storage device (Schatz 1991). Schatz reports up to 50% reduction in CO emissions and up to 30% reduction in HC emissions. His results suggest that the cold start fuel economy degradation might be cut in half or better.

Tailpipe emissions of carbon monoxide and hydrocarbons are especially large when the engine is cold, before catalyst light up. The HCs tend to be associated with unburnt fuel on the cylinder walls and crevices; they tend to be swept up at the end of the exhaust stroke. Early closure of the exhaust valve (and opening of the intake valve) could efficiently recirculate much of this fuel material for the next cycle (Stone 1989). With fully variable valve timing this strategy would be practical, and should be pursued if research shows that there would be a substantial benefit. The development of synergistic technologies such as these should receive support from public sources (R&D funding and other encouragement).

PART II

THE ECONOMICS OF IMPROVING FUEL ECONOMY: USING SUPPLY CURVES OF CONSERVED FUEL TO ESTIMATE COSTS AND FUEL SAVINGS

This section analyzes the cost effectiveness of light vehicle fuel economy technologies and the fuel savings that could result from their widespread use in the U.S. vehicle fleet. Estimates are derived for the year 2000. The technologies analyzed here do not exhaust the list of technologies that may be available for improving fuel economy. The list is simply limited to those technologies for which adequate cost information is available, and which are relatively well understood. Unfortunately, the cost information necessary to analyze the five technology categories emphasized in the previous section is not available. A separate, more specific list of fuel economy technologies is analyzed in this section. The analysis uses 1987 as its technology base year, i.e., the technological characteristics of new cars in 1987 were the base to which technology changes were applied and from which fuel economy improvements were measured. Supply curves of conserved energy are developed to illustrate the results of the analysis.

COSTS OF TECHNOLOGIES

Developing a supply curve of conserved energy for light vehicles is difficult at best, largely because cost information on light vehicle technologies is very difficult to obtain. Vehicle manufacturers consider the information proprietary and therefore withhold it. For many fuel economy improvements and technologies, manufacturers themselves don't even have reasonable estimates of their costs. Furthermore, technologies that improve fuel economy often have benefits that serve other purposes. For example, multi-point fuel injection improves fuel economy, but it also decreases emissions and improves performance. Such multi-purpose benefits make it difficult to determine how much of the total cost of a technology should be allocated to fuel economy. Even further complications arise in trying to adjust costs for retooling expenses, amortization periods, and manufacturer markup.

Despite these and other unspecified difficulties, Energy and Environmental Analysis, Inc.(EEA), Arlington, VA, has compiled a set of cost estimates for fuel economy technologies that the U.S. Department of Energy uses to analyze fuel economy policies. These cost estimates and related information have recently appeared in several publications (Difiglio, et al. 1988 EEA 1988, EEA 1986, EEA 1985). Given the amount of scrutiny and revisions to which these numbers have been subjected, and given the difficulty in developing alternative estimates of costs, this analysis relies heavily on the cost estimates derived by EEA.

EEA derived its costs using "normal costing," that is, estimates of variable manufacturing costs for each technology were multiplied by an estimate of an industry average ratio between variable costs and retail vehicle prices to determine consumer cost. Costs used in this analysis are thus estimates of the change in consumer retail prices that would result from use of these technologies.

Despite the care taken in development of EEA's cost estimates, the reader is cautioned not to consider these numbers to be firm. These are reasonable estimates, given the difficulties and inaccuracies encountered in compiling these kinds of numbers. For fuel economy technologies that are pieces of equipment added to a car, such as fuel injection, costs are more easily determined. As noted above, however, if this equipment serves more than one purpose, the portion of the equipment costs that should be allocated to fuel economy is still difficult to determine and subjective. For fuel economy technologies that are simply a new way of building an existing part of the car and require little or no extra materials, such as some aerodynamic improvements, costs are more difficult to determine; and often times, the costs for these technologies disappear over time as costs are amortized.

TECHNOLOGIES ANALYZED

Two supply curves of conserved energy are developed in this analysis, one each for two groups of technologies. Technology Group 1 is limited to those technologies appearing in a paper that summarizes some recent Department of Energy-sponsored research on automobile fuel economy, hereafter referred to as Difiglio, et al. 1988. (See **Table 2.1**) According to Difiglio, et al., these technologies are proven technologies that are already available in existing cars or prototypes; other technologies were omitted because, "1) they are not market-ready, or 2) they do not presently meet vehicle emission standards, or 3) they detract significantly from performance, ride, or capacity, or in some other way are not acceptable to consumers." Furthermore, the selected technologies "would not reduce performance, ride, or capacity over 1987 levels." Estimates of fuel economy improvement associated with each of these technologies are the same or are very similar to those used in Difiglio, et al. Some small adjustments were made to allow consolidation of some technologies into groups. In sum, Technology Group 1 is a close approximation of the technologies and their associated fuel economy improvements used in Difiglio, et al.

Technology Group 2 includes all the technologies in Group 1, plus idle off and aggressive transmission management. Although these technologies were not included in the analysis by Difiglio, et al., they are included here because they offer significant potential for improving fuel economy, they could be installed in production vehicles before 2000, and because, like other technologies in this group, they do not significantly degrade ride, performance, or capacity over 1987 levels.

These two additional technologies included in Group 2 will change the feel of driving a car. For example, more gear shifting will occur with aggressive transmission management and a car will operate in higher gears more of the time, causing a slight delay for downshifts needed to accelerate quickly. Electronic transmission control can minimize the effect these changes will have on the feel of driving.[5] The **Technology Descriptions** section describes each of the technologies in Technology Groups 1 and 2.

METHODOLOGY

All curves are calculated from a base year of 1987, i.e., improvements in fuel economy and costs are relative to 1987 levels. (The average nominal, or EPA-rated, fuel economy of all domestic and import new cars sold in the United States in 1987 was 28.3 mpg.) The average interior volume, and acceleration capability are held at their 1987 levels.[6]

The technologies and costs used in developing the Year 2000 Automobile Fuel Economy Supply Curves are listed in **Tables 2.1 and 2.2**. (A key to the acronyms used to identify the technologies is given in Tables 2.3 and 2.4) Some of the listed technologies are combinations of technologies (e.g., TRANS represents electronic transmission control and torque converter lock up), and some aren't technologies in the sense of new devices or equipment (e.g., aerodynamic improvements represent an advancement in design, not a new technology.)

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[5] The continuously variable transmission included in Technolgy Group 1 would also change driving feel, but it was left in Group 1 to produce a technolgy list identical to Difiglio, et al.

[6] Average interior volume and performance levels have increased somewhat since 1987. Therefore, this analysis cannot be strictly interpreted as holding these measures constant. If performance and interior volume levels were held at their 1991 levels, a slightly lower fuel economy level would result.

In **Tables 2.1 and 2.2**, the consumer costs estimated for each of these technologies are listed in the second column of the table (CONSUMER COST), and are annualized in the third column (ANNUAL COST) using a 7% discount rate, a ten year estimated useful life, and a distribution for miles driven per year, by car vintage, as estimated by the U.S. Department of Transportation.[7] The costs are approximates of those developed by EEA (with the exception of the costs for idle off and aggressive transmission management, which were independently estimated). All costs are stated in constant 1989 dollars.

Estimates of the fuel economy increase associated with each technology were also derived from Difiglio et al. (These estimates are listed in INDIVID NEW CAR MPG INCR - %.) The fuel economy increase associated with two technologies, aggressive transmission management and idle off, were independently estimated by the authors.

Values in the fifth column in **Tables 2.1 and 2.2** (MARKET SHARE INCREASE) reflect the projected increase in market share -- relative to the total new car market -- for each technolgy. Values in the sixth column (NEW CAR FLT MPG INCR-%) reflect the new car fleet mpg increase expected from use of each technology to the extent projected in MARKET SHARE INCR. Estimates of market share increase were taken from Difiglio et al., except for idle off and aggressive transmission management, which were estimated by ACEEE. Market shares taken from Difiglio et al. were taken from their maximum technology scenario because the authors believe these rates of new technology penetration better reflect the future of the rapidly changing automotive industry, where competitive pressures are forcing manufacturers to redesign car lines much more rapidly than in the past.

Estimates of how much each technology can increase new car fuel economy are found in the ninth column (ACTUAL NEW CAR FLT MPG). These values are estimates of actual, on-road fuel economy, calculated by adjusting EPA-rates combined city/highway fuel economy to account for its growing over-estimation of actual fuel economy. The EPA fuel economy test procedure substantially over-estimates on-road fuel economy because of differences between the official EPA driving cycle and actual driving conditions. Increased urban congestion, higher highway speeds, and a larger fraction of total miles being driven in urban areas are projected to increase the difference between EPA fuel economy and actual fuel economy from 15% in 1987 to 30% in 2010 (Patterson and Westbrook 1989). Based on this estimate, year 2000 fuel economy levels in this analysis are 23% below the EPA-rated level. All fuel savings estimates in this paper are based on the adjusted EPA fuel economy ratings.

The marginal cost of conserved fuel (COST CNSRV FUEL, TECH N) was calculated using a 7% real discount rate and miles driven per year, by vintage, as specified by the U.S. Department of Transportation (U.S. Department of Transportation 1985). All technologies with costs lower than projected fuel prices are deemed cost effective. The projected price of gasoline for the year 2000 was $1.32, as estimated by the Energy Information Administration (Energy Information Administration 1989).

The values in the cost of conserved fuel column can roughly be interpreted as the societal cost effectiveness of adopting the specified technologies in that the discount rate (7%) and the length of time over which fuel savings were estimated (10 years) more closely reflect a social perspective than

[7] The mileage distribution was taken from the U.S. Department of Transportation's 1983-1984 Personal Transportation Study. Since cars are driven many more miles in their first years of use than in their latter, capital recovery for technology improvements is accelerated, resulting in a lower annual capital charge. Using the DOT mileage distribution results in annual capital charge equal to 96% of what it would be were capital recovered in equal increments over ten years.

a car buyer's.[8] A truer test of societal cost effectiveness would value gasoline at a higher level, to include such things as the environmental, security, and health costs of consuming gasoline.

Levels of fuel economy deemed cost-effective here assume that automobile size and acceleration performance are held constant at their 1987 levels. Since both performance and size have increased slightly since then, this analysis assumes a small reduction of vehicle size and acceleration performance.

The fleet fuel economy in the next to the last column (ACTUAL FLEET MPG) was calculated using a vintaging model based on survival probability data and annual-miles-travelled-by-vintage data (Davis, et al. 1989). The model calculates fleet fuel economy on the basis of each vintage's new car fuel economy, and assumes a fixed distribution of new and old cars for each year. The new car fuel economies specified in the ninth column (ACTUAL NEW CAR FLT MPG) are assumed to be achieved by the year 2000, after a straight line ramp up in new car fuel economy over the period 1992 to 2000. For example, row 10 in **Table 2.1** specifies a new car fuel economy of 29.3 mpg [(29.3-21.7)/2]. Calculating the new car fuel economy similarly for all years from 1992 to 2000, and knowing or estimating the new car fuel economy for other vintages, yields, after use of the vintaging model, the fleet fuel economy estimate of 25.6 MPG in the year 2000.

The energy savings associated with each technology (2000 ENERGY SAVINGS) are based on the assumption that light vehicle miles traveled in the United States grow at the rate of 2.5% per year to the year 2000 (Ross 1989). Two-thirds of vehicle miles traveled in 2000 are assumed to be attributable to automobiles, with the remaining one-third attributable to light trucks. Cumulative energy savings are calculated relative to a vehicle fleet whose new car fuel economy is frozen at the 1987 level.

RESULTS

The marginal cost of conserved fuel estimates in **Tables 2.1 and 2.2** are plotted in Figures 2.1 and 2.2. (Keys to the technology and column heading abbreviations used in these tables can be found in **Table 2.3 and 2.4.**) The supply curves in **Figures 2.1 and 2.2** illustrate how much fuel could be saved in the year 2000 (horizontal axis), the cost of achieving this level of savings (vertical axis). Each step on these curves represents a technology from **Tables 2.1 and 2.2**, and reveals the cost of the technology, and the potential savings associated from its adoption. As can be seen, the technologies are ranked in order of cost effectiveness. The technologies whose costs are less than $1.32 per gallon saved are cost effective.

Care should be taken in interpreting the results of these supply curves. The order in which these curves suggest technologies be adopted is not necessarily ideal or reasonable. Schedules for vehicle redesign and introduction, amortization schedules for capital equipment, and other industry characteristics will probably dictate a different order of adoption. Furthermore, other technologies not considered in the development of this curve are likely to become feasible and cost effective by the year 2000, especially if the federal government mandates substantial fuel economy improvements in automobiles.

Supply Curves (Figures 2.1 and 2.2)

Table 2.1 shows that, using Technology Group 1, the maximum cost-effective level of new car fuel economy in 2000 is 30.7 mpg (40.1 mpg, EPA-rated). Only two technologies on the list, weight reduction and Tires II are more expensive than EIA's projected gasoline price in 2000, and thus fail this test of cost effectiveness. The cost and energy savings of each technology in **Table 2.1** are

[8] An individual new car buyer typically has a much higher discount rate and might only be willing to consider the fuel savings he achieves over four years, the typical period of time a new car buyer holds onto his car before reselling it.

plotted in **Figure 2.1** as a supply curve of conserved energy. As can be seen, this mix of fuel economy technologies and costs yield cost-effective fuel savings in the year 2000 of about 1.7 quads (quadrillion or 10^{15} Btu). This level of savings represents an 18% reduction in the fuel that would be consumed by automobiles in the year 2000, relative to a scenario in which new car fuel economy is held to its 1987 level of 28.3 mpg (21.7 mpg actual in 2000).

Using the cost-effective technologies in Group 2 (**Table 2.2**) would result in a new car fuel economy level of 33.6 mpg (43.8 mpg EPA-rated). The costs and energy savings for each technology in **Table 2** are plotted in **Figure 2.2**. As can be seen, all but the last two technologies are cost effective. Fuel savings of 2.1 quads (22%) are achievable using cost-effective technologies. Again, this level of savings is relative to how much fuel would be used if new car fuel economy were held at 1987 levels.

Comparison of Fuel Saving Results to Market Scenarios

Up to this point, fuel savings have been calculated relative to how much fuel would be consumed in the years 2000 if new car fuel economy were frozen at 1987 levels through the year 2000. It is also useful to calculate fuel savings relative to a market scenario, in which new car fuel economy is allowed to rise above 1987 levels in response to market mechanisms. Both of these calculations are summarized in **Table 2.5**.

Researchers at the Argonne National Laboratory developed some projections of market driven increases in fuel economy that were used by the U.S. Department of Energy in estimating future energy conservation potential (Carlsmith, et al 1989). They estimate in their base case market scenario that average automobile fleet (all cars on the road) fuel economy will reach 21.8 MPG (actual) in 2000. This estimate is based on a fuel price projection for the year 2000 that is the same as this study's, $1.32/gallon.

In the year 2000, fuel savings from using all cost-effective technologies in Group 1, relative to the market scenario, are only slightly less than fuel savings relative to the frozen efficiency scenario (1.7 quads vs. 1.6 quads). This small difference is attributable to the very small increase Argonne projected in new car fuel economy by 2000 for their base case market scenario. Likewise, savings for Group 2 relative to a market scenario is only slightly less than savings relative to a frozen efficiency scenario (2.1 quads vs. 2.0 quads).

DESCRIPTION OF TECHNOLOGIES USED IN GROUPS 1 AND 2

The following section contains brief descriptions of the technologies and their fuel savings estimates used in this analysis. The primary source for this information is the documentation developed for the Difiglio et al. analysis (EEA 1986, EEA 1985). Other sources used are as noted. For technologies already described in Part 1 of this report, readers are referred to those earlier descriptions.

Intake Valve Control

See Part I.

Roller Cam Followers

The interface between a cam and flat-faced cam followers is the second largest source of engine friction (the largest source is the piston rings) and may account for 25% of total engine friction. Roller cam followers can reduce this friction. They are now used in over half of new engines. They are estimated to provide a 1.5 percent increase in fuel economy (U.S. Department of Transportation 1988).

Multi-point Fuel Injection

Carburetors are rapidly being replaced by fuel injection systems. Fuel injection systems offer more control over fuel metering, resulting in more power, better fuel economy, lower emissions, and better drivability. One form of fuel injection, throttle body injection (TBI), uses one or two injectors to inject fuel upstream of the intake manifold. These systems offer about a 3 percent gain in fuel economy. A more precise form of fuel injection, called multi-point fuel injection (MPFI), injects fuel just upstream of the intake valves. MPFI can improve fuel economy an additional 3 percent above TBI (Seiffert and Walzer 1984).

For this analysis, both TBI and MPFI were used to displace carburetors. MPFI, however, was used to displace all TBI by the year 2000. After adjusting for existing levels of use of both technologies, the combined estimated fuel economy increase associated with full use of MPFI is 3.5%.

Four Valves Per Cylinder Engines

Conventional spark ignition engines contain two valves per cylinder, one intake and one exhaust. In recent years, four valves per cylinder engines have become commonplace. Gasses entering and exiting cylinders in four valve engines encounter less friction, providing better volumetric efficiency. Smaller and lighter valve train parts reduce valve train inertia, and allow higher engine speeds. Four valve engines can typically produce 25 to 35 percent higher horsepower than their two valve counterparts (although, this is achieved at higher rpm). This higher power output allows a smaller engine to be substituted for a larger engine.

Holding horsepower roughly constant, and substituting a 4-valve 6-cylinder engine for an 8-cylinder engine, a 4-valve 4-cylinder engine for a 6-cylinder engine, and a 4-valve 4-cylinder for a 4-cylinder engine, fuel economy can be improved by approximately 10 percent, 10 percent, and 5 percent, respectively. Together, these substitutions will result in a fuel economy improvement of about 6.8 percent, assuming that 18 percent of the substitutions are 6-cylinder for 8-cylinder, 23 percent are 4-cylinder for 6-cylinder, and 64 percent are 4-cylinder for 4-cylinder.

Aerodynamic Improvements

Aerodynamic drag is the resistance encountered by moving a vehicle through air, and is a function of both vehicle size and shape. The coefficient of drag is a measure of the shape-related resistance. The larger the coefficient, the higher the drag. The coefficients of drag for 1987 car models vary widely, but average about .37. Rounded, aerodynamic styling has become popular in recent years. Widespread use of more advanced aerodynamic designs could drop the coefficient to approximately .3 by the year 2000, and improve fuel economy by about 4.6 percent.

Transmission Improvements

Two transmission improvements are included here, torque converter lockup and electronic transmission control. A torque converter in an automatic transmission transfers drive power from the engine to transmission gears. It serves a purpose similar to the clutch in a manual transmission. The torque converter allows slippage between the engine and transmission when a vehicle begins moving and when it shifts gears. However, its also allows a small amount of slippage after cruising speed is attained, resulting in energy loss. A torque converter lockup prevents this unintended slippage, and yields a fuel economy improvement of about 3 percent (Bleviss 1988).

Electronic transmission control provides more precise control of gear shifting than conventional controls. Transmissions controlled electronically operate in more fuel efficient gears a larger portion of the time, resulting in about a 1.5 percent increase in fuel economy (Shiga 1986).

When combined into the same measure in Technology Group 1, electronic transmission control and torque converter lockup produce a 2.2 percent increase in fuel economy.

Overhead Cam

Overhead cams have less parts and mass than their pushrod counterparts, and thus have lower inertia. Lower inertia reduces the energy required for valve operation, and allows the valves to stay open longer, improving engine breathing. As used here, overhead cams represent a modern, higher power density engine that is substituted for an older push rod engine. These new overhead cam engines provide about a 6 percent improvement in fuel economy.

Front Wheel Drive

Front wheel drive is a weight saving measure. The driveshaft is eliminated, and the resulting body redesign improves the interior space/weight ratio. Although the fuel economy improvement that results from converting to front wheel drive is large, 10 percent, the potential for improving automobile fleet fuel economy is relatively small because most cars, 76% in 1987, already used front wheel drive.

Continuously Variable Transmission

Manual and automatic transmissions use discrete gearing to adjust the ratio of engine to axle speed. Engine speed is often well above a speed that is sufficient for delivering the power needed at the wheels and that maximizes fuel economy. Continuously variable transmissions (CVT), on the other hand, have a continuum of gear ratios between a minimum and maximum gear ratio. Better management of engine speed is thus possible, resulting in improved fuel economy.

Several CVT designs have been researched, but the most common type contains variable diameter pulleys connected with a belt. A small number of CVTs of this design have been installed in production vehicles, including the Subaru Justy. Current materials and designs limit use of CVTs to small cars with low-torque engines. As analyzed here, CVTs are assumed to replace both three and four speed automatics, providing an average 4.7 percent increase in fuel economy (Bleviss 1988; Seiffert and Walzer 1984).

Improved Accessories

Engine accessories, such as the water pump, power steering pump, cooling fan, and alternator, can account for a significant fraction of fuel consumption. Improved accessories are thus an important target for fuel economy improvements. Electric cooling fans, which operate intermittently, reduce fuel consumption. Reducing heat rejection to the engine coolant can reduce the amount of work done by the water pump. Replacing a hydraulic power steering pump with an intermittently operated electric motor also reduces energy consumption. Variable displacement air conditioning compressors are also in important energy saving innovation. Together, these measures are estimated to improve fuel economy 1.7 percent (Bleviss 1988, Sieffert and Walzer 1984).

Advanced Friction Reduction

See Part 1.

Five-Speed Automatic Overdrive Transmission

As discussed above in the section on CVTs, automatic transmissions use discrete gearing to adjust engine to axle speed ratios, and because these ratios are fixed, the engine often operates at a speed that is not optimal for fuel economy. Adding an extra gear reduces the ratio difference between gears and/or increases the range of gear ratios, allowing the engine to operate closer to optimal speeds.

This measure includes a transition from three, to four, to five speed automatics. As analyzed here, the five-speed replaces some three-speeds and some four-speeds, resulting in an average fuel economy improvement of 4.7 percent.

Improved Tires and Lubrication

New lower viscosity lubricants (5W-30 for engine oil), with friction reduction additives can reduce engine and transmission friction. Furthermore, wider use of high-pressure P-metric radials would reduce rolling resistance. Together, these measures are estimated to improve fuel economy 1 percent.

Weight Reduction

Average new passenger car weight was reduced about 900 pounds in the late 1970s. Since then average inertia weight has remained at about 3100 pounds. (It has risen about 100 pounds since 1987.) Despite previous deep reductions in vehicle weight, weight can be reduced substantially more without reducing vehicle size. More use of lighter weight materials, primarily aluminum and fiber reinforced plastics, would enable manufacturers to reduce vehicle weight by 10 percent, resulting in a 6.6 percent increase in fuel economy.

Tires II

Tire rolling resistance consumes about a third of the energy delivered to the wheels in the EPA urban driving cycle. Tires with lower rolling resistance would, therefore, improve fuel economy. Use of new low-profile radials would improve fuel economy about 0.5 percent.

Aggressive Transmission Management

See Part I.

Idle-Off

See Part I.

PART III

POLICIES FOR REDUCING LIGHT VEHICLE ENERGY USE AND ENVIRONMENTAL IMPACT

Cars and light trucks are responsible for a large fraction of our energy and environmental problems. In recognition of this, several strong public policies were enacted to curtail their fuel use and emissions. In some respects, these policies have been very successful, yet in others, the policies have been less successful. Increasing vehicle travel, traffic congestion, and technology failure have greatly eroded the gains made by these public policies. Although market forces will help address the growing energy and environmental problems caused by light vehicles, they will not be sufficient. If we are to curtail growing light vehicle energy use, limit greenhouse gas emissions, and speed our progress in reducing urban smog, we must adopt new, aggressive public policies that encourage both the production and purchase of vehicles with lower fuel use and emissions.

THE SCOPE FOR POLICY

We first consider the full range of policies to improve energy efficiency and reduce greenhouse gas emissions, while providing daily "access" for people, and maintaining or improving values such as safety and environmental quality. Daily access means being able to reach places to work, shop, or engage in other activities. This does not, strictly speaking, mean mobility with its implication of expanded vehicle miles or passenger miles. In a given situation, improving access may involve enabling people to travel further without increased energy use, but it may instead involve reconfiguring land use patterns so that less travel is needed.

Policy areas which bear directly on improved access are:

- land use;
- public transport;
- substitutes for transportation;
- traffic and parking management, road controls, and road design;
- driver behavior, including vehicle maintenance and driving style, and;
- improvements in light vehicles.

Land use and public transportation policies are a major focus of those interested in improved access (Pushkarev & Zupan 1977, Burchell & Listakin 1982, and Holtzclaw 1990). Their potential impact is suggested by the fact that per capita gasoline use in the Toronto metropolitan area is roughly half that in Houston, Phoenix, Denver, or Detroit (Newman & Kenworthy 1988). Yet Toronto is not that different. It is a relatively affluent, high-quality-of-life North American metropolis. The key characteristics of Toronto that appear to be associated with Toronto's low gasoline use are regional control of land use and a well-developed, widely used public transportation system.

A major insight on provision of access is that while almost all passenger miles traveled (87%) are due to autos and light trucks, a relatively small increase in the use of public transport can be associated with a major decline in driving. Recent research indicates that one new mass transit passenger mile may offset as many as 5-10 personal vehicle miles (Holtzclaw 1990). This large leverage is argued to be a consequence of the synergism of mass transit with higher density housing, work sites, shopping, etc., resulting in the need for many fewer vehicle miles. With that kind of leverage, mass transit and appropriate land use policies should offer far more potential for reducing VMT than suggested by the small share of passenger miles provided by transit.

Substitutes for transportation, such as telecommunications, which enable some people to work and shop at home, and satellite places of work, which rely heavily on telecommunications, also have major potential. These are not primarily issues for public policy, but technology policies and regulation of communication systems are important to their success.

Traffic management in the form of high occupancy vehicle lanes, and car pooling assistance have had some success in reducing travel demand and fuel consumption (Burke 1990). A key to the success of many of these programs is charging full cost for parking privileges (Replogle 1990). Road charges in congested areas have long been considered in Europe and Asia and have been successful in Singapore, where they have been combined with provision of extensive modern public transport (Ang 1991).

Highway controls, such as sophisticated signal management to encourage smooth traffic flow in congested areas, have been successfully developed, especially in Australia where resulting fuel savings of up to 20% were estimated (Watson 1990). In addition, roads can be designed to mitigate stop and go driving, and the rate of vehicles entering expressways can be controlled to successfully limit congestion (Institute for Transportation Engineers 1989). Enforcement of speed limits also contributes to efficiency.

Driving behavior is also important, but very difficult to influence. Proper vehicle maintenance, such as regular engine tuning and maintaining correct tire pressure, can contribute perhaps 10% to the fuel economy of the average car. Driving style, i.e., smooth flow as contrasted with rapid starts and rapid stops, significantly affects efficiency. Public education may be somewhat useful in this area.

While all these areas are highly important to efforts to reduce the environmental impacts and energy consumption of light vehicles, the focus of this section is policies that encourage technological improvements in light vehicles. Improving light vehicle technology will not, by any stretch of the imagination, be a sufficient means of resolving the enormous environmental and energy problems created by light vehicle use, but it may be the most important.

Several aspects of improving vehicle fuel economy are of interest to policy makers:

- modest modifications to conventional vehicles;
- alternative fuels;
- radical vehicle technology, such as the fuel cell vehicle, or the very light, small commuter car;
- interactions with vehicle safety, and;
- interactions with emissions of regulated pollutants.

Our emphasis will be on the first topic in the above list and its associated issues, i.e, near-term technological changes. We will also discuss some issues in the other areas.

FUEL PRICING

The market price of gasoline does not reflect its real cost to the U.S. economy. Some studies estimate that the national security cost of importing oil amounts to at least 30 cents per gallon (Broadman & Hogan 1986). The costs of air pollution and the risks of climate change make the cost even higher. Logically, these costs should be internalized through a tax on transportation fuels. However, while fuel prices can play an important role in spurring fuel economy improvements, as they have in the past, we cannot assume that fuel prices alone are a strong enough motivator to improve fuel economy to levels that are cost-effective from a societal perspective. This conclusion is based on two reasons:

First, the cost of fuel is a relatively small part of the cost of driving a new car. At the price of gasoline that prevailed during the late 1980s, about $1.00 per gallon, annual fuel costs were only about 10% of the cost of driving for the average new car driver. **(See Figure 3.1.)** If fuel prices were twice as high, and the amount of driving remained the same, fuel costs would still only be about 20% of the cost of driving.

Second, buying a more fuel efficient car only has a small effect on annual driving costs. For example, purchasing a 35 mpg car instead of a 30 mpg car will reduce annual fuel costs only $50 per year. If the two cars are identical in every respect except fuel economy, the more fuel-efficient car will be more expensive because of additional manufacturing cost. The extra up-front cost, converted into an annual cost, is about $25 per year, making the net savings to the buyer of the 35 mpg car only $25 per year. With fuel costing twice as much, the net annual saving would still only be $75. Most new car buyers probably don't do such calculations, but they are probably aware that for most cars, fuel economy performance does not greatly affect the economics of buying and owning a new car.

It is not surprising that new car buyers find fuel economy to be a secondary consideration. Many other attributes have higher priority: brand, safety, interior volume, trunk size, handling, price, reliability, etc. (McCarthy 1989). Indeed, manufacturers have decided that fuel economy is of so little interest to buyers that they only offer it as part of a package in bottom-of-the-market vehicles (such as the Geo Metro), making it impossible for buyers to simply choose added fuel economy at extra cost while preserving the other vehicle attributes in which they are interested.

A different way of expressing these observations is that the value new-car buyers appear to place on future fuel savings is low. That is, their implicit discount rate is high, perhaps 30 to 50% (as with other household energy conservation investments), rather that the 5 to 10% real interest on most new car loans.[9] This implicit undervaluing of future fuel costs will probably continue to characterize new vehicle purchases, except perhaps in times of fuel crises.

Other evidence that higher fuel prices won't push passenger car fuel economy into the high 30s or 40s mpg is found in industrialized countries with gasoline prices that are two to four times higher than U.S. prices. **Table 3.1** compares fuel economies and gasoline prices in selected countries. Of course vehicle ownership and use are different in these countries than in the United States, so quantitative comparisons may be misleading. Nevertheless, it is impressive that much higher fuel prices are associated with new vehicle mpg values at most in the mid-30s.

Although fuel pricing alone is not an adequate policy mechanism for controlling motor fuel use, it can be an important part of a larger policy package. While small federal and state gas tax increases (on the order of $0.05 per gallon) have been adopted lately, large increases, especially those not earmarked for highway improvements, are strongly opposed. Some of this opposition, particularly from consumer and low-income interests, is driven by questions of fairness. Imposing large, immediate new fuel costs on people who earn their living driving cars and trucks, or those who have made living arrangements that require long-distance driving could unfairly shoulder a disproportionate share of the tax burden. And low-income individuals, whose fuel expenses represent a higher fraction of their incomes than higher income persons, could be unfairly burdened. Any efforts to substantially raise fuel taxes needs to address these issues.

However, there is at least one way to substantially increase the apparent price of gasoline without imposing new taxes or increasing the cost of driving: by restructuring the way we pay for

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[9] There is little quantitative information on this from automotive markets because, as mentioned below, buyers are not offered an opportunity to spend more to get higher fuel economy. High implicit discount rates have been determined in other areas, like household appliances and industrial equipment. Auto manufacturers behave as if their marketing surveys show buyer indifference to fuel economy.

automotive insurance. Instead of paying for all of our automobile insurance in independently arranged contracts with insurance companies, we could pay for a large fraction of our insurance needs at the gasoline pump. The price of gasoline at the pump could include a charge (in the range of \$0.50-\$1.00 per gallon) for basic, driving-related, automobile insurance that would be organized by state governments and auctioned in blocks to private insurance companies. All registered drivers in the state could automatically belong. Supplementary insurance above that provided by the base insurance purchased at the pump could be independently arranged, as we presently do for all of our insurance. For example: owners of expensive cars, or people who desire higher levels of liability coverage could purchase supplemental insurance. Drivers with especially bad driving records could be required to purchase supplemental liability insurance (El-Gasseir 1990).

Such an arrangement has several advantages:

1) Insurance costs become much more closely tied to the amount of driving done. The more miles a person drives, the more insurance he pays. Since accident exposure is closely correlated with miles driven, the proposed system would be fairer than the present system in which people who drive substantially less than the average miles per year are given only small discounts, and people who drive substantially more than the average, don't pay any additional premium.

2) Uninsured motorists would be brought into the system. By making insurance part of the cost of gasoline, a person couldn't drive without paying for insurance. In California, for example, uninsured motorists increase premiums for insured motorists by about \$150 per year. Bringing uninsured motorists into the system would substantially lower the cost of driving for insured motorists.

3) The apparent cost of gasoline at the pump would rise substantially, roughly between 50 cents to a dollar per gallon. Such a price rise would encourage the purchase of more fuel efficient vehicles and help slow the growth in vehicle miles of travel. The increase in the price of fuel would be offset by a decrease in the annual insurance premium motorists would pay directly to insurance companies, resulting in no net increase in driving costs. At least one financial analyst argues this system would result in a net decrease in driving cost because of the substantial savings in insurance brokerage and other insurance industry expenses (Tobias 1982).

4) Unlike a gasoline tax, this system would not be regressive. Low-income persons drive substantially less miles per year than their higher income counterparts. They would, consequently, see a substantial drop in the money they pay for auto insurance.

Another way to reform automobile insurance that would achieve similar results and would require a much simpler change in the insurance industry would be to have motorists pay for a part of their auto insurance on the basis of how many miles per year they drive, according to annual odometer readings reported to insurance companies. The National Organization for Women, which believes the current auto insurance system is biased against women, supports this approach. Pointing out that women, on average, drive about half as many miles per year as men, they argue that women are overcharged for auto insurance, and that insurance payments based on miles driven would more fairly allocate insurance costs (Butler, et al. 1988). Although this approach would avoid the difficulty and political problems of setting up a state organized insurance pool, it would not encourage the purchase and use of more efficient autos.

In conclusion, regarding fuel pricing, we favor a gradual introduction of fuel tax increases, totaling to \$0.50 per gallon. Although such a value is small compared to European levels, it is large in the U.S. context. In addition, we would like to see the pay-as-you-drive insurance concept further developed and an equitable form adopted.

PERFORMANCE STANDARDS

Fuel Economy

The Motor Vehicle Information and Cost Savings Act of 1975 set corporate average fuel economy (CAFE) standards that required the fuel economy of new cars to increase from about 14 mpg in the early 1970s to 27.5 mpg by 1985. (See **Figure 3.2.**) The Act provided flexibility to manufacturers by applying the standard to the sales-weighted average for each corporation, instead of each, individual vehicle. Further flexibility is provided by allowing manufacturers to earn credits for exceeding the standard in any year, and then allowing those credits to offset penalties in years when a manufacturer may fall short of the standard. Moreover, the Secretary of Transportation was given the discretion to set a lower standard, as was done for 1986 through 1989 on appeal from manufacturers (especially General Motors and Ford). The discretion to set standards for light trucks is also left to the Secretary of Transportation.

In hearings on the 1975 Act, the manufacturers stated that the technology to achieve 27.5 mpg was not available on the proposed time scale, and that the only way to achieve the standard would be by making the average car much smaller. They said it would "outlaw full-size sedans and station wagons" (Chrysler), "require all sub-compact vehicles" (Ford), and "restrict availability of 5 and 6 passenger cars regardless of consumer needs" (GM) (Energy Conservation Coalition 1989). Indeed, there was some reduction in the ratio of maximum-power to weight, although almost none in interior volume, in the early 1980s. (See **Figure 3.3.**) By the mid- and late-80s, however, the manufacturers were achieving the mandated standards with vehicles of interior volume and maximum-power equal to and higher than those of the early 1970s. The CAFE standards were thus an important example of successful "technology forcing" by regulation.

Some have claimed that the CAFE regulations were unnecessary, and that the increased price of gasoline in the late '70s and early '80s was responsible for the fuel economy improvements (Mayo 1988, Crandall, et al. 1986). This argument is unconvincing on two related grounds:

- The estimated fuel price elasticities for vehicle purchase are moderate (Bohi & Zimmerman 1984), whereas the increase in fuel economy in that period was more rapid than that for fuel price (**Figure 3.2**).
- Statistical analysis of separate manufacturer's CAFE achievements show that "the CAFE standards were a significant constraint for many manufacturers and were perhaps twice as important an influence as gasoline prices" during that period (Greene 1990).

GM and Ford have argued that the CAFE formulation placed them at a disadvantage because their mix of vehicles includes large cars while the Asian manufacturers' doesn't. As a consequence, they argue, it is much easier and less expensive for the Asian manufacturers to meet the standards, and the domestic, full-line manufacturers are forced to compete with new Asian large car introductions with one hand tied behind their back. Some evidence for bias against full-line manufacturers in the CAFE standards can be found in individual manufacturer CAFE trends. In recent years, with the regulated CAFE floor essentially fixed, the CAFE's achieved by domestic manufacturers have declined somewhat from '88 to '90 models (3% for both GM and Ford), while the CAFEs achieved by Asian manufacturers declined substantially more (6% on average, 9% for Toyota) as they introduced larger, less fuel-efficient cars (Murrell & Heavenrich 1990). Of the major manufacturers, all now have CAFEs below 30 mpg except Honda.

Most recent fuel economy legislation introduced in the U.S. Congress seeks to address this problem by changing the basis of the standards so that each manufacturer is required to improve its fuel economy by the same percentage above its base year fuel economy.

Other industrialized countries have also adopted programs to improve fuel economy. Most have adopted voluntary programs, but some, including Sweden and Japan, have adopted mandatory programs like that of the United States. (See **Tables 3.2 and 3.3**) Even though Japan has a mandatory fuel economy program, the average fuel economy of their new cars has slipped from 30.5 mpg in 1982 to 27.3 in 1988 as they have moved to progressively larger cars (MacKenzie & Walsh 1990). The inability of Japan's fuel economy program to prevent this slippage is apparently a result of their fuel economy standards being based on weight classes.

Emissions

Early Clean Air Act provisions required emissions reductions in the late '60s and early '70s which could be accomplished by improved control of engine operations. While Europe continued with this weak policy, subsequent U.S. regulations required reductions of tailpipe emissions to much lower levels. By 1981 emissions of hydrocarbons (HC) and carbon monoxide (CO) were limited to 10% of the levels of 1970 and nitrogen oxides (NOx) to 25% of those levels (**Table 3.4**). This became another example of successful technology forcing. Catalytic converters and supporting control systems were rapidly developed and have proved highly effective. (See below, however, on failures of emission control systems.) The present 3-way catalyst, which oxidizes HC and CO and deoxidizes NOx, is a major accomplishment. The system requires that the exhaust contain very little oxygen or unburnt fuel, or specifically, that the initial quantities of fuel and air be correct to within 1% (or better) of the chemically correct combustion ratio. This is achieved with a closed-loop control system, in which catalytic converter operation parameters are fed back to engine controls to change the mixture of gases entering the converter.

The Overall Results: Mixed

Depending on one's perspective, the fuel economy and emissions regulatory programs could be viewed as ineffective or remarkable successes. If one were to take a static perspective, in which we compare the absolute level of emissions and fuel consumption today with the levels that existed when the regulatory programs were begun, one wouldn't declare success. Despite the fact that a new car today has approximately twice the fuel economy and 10% of the emissions of cars built 10 to 15 years ago, the overall use of gasoline has actually grown somewhat and air quality has improved only slightly. But from a dynamic perspective, where one asks oneself what fuel consumption would have been without fuel economy improvements or emission reductions, the programs have been very successful. As pointed out earlier, had average light vehicle fuel economy not risen since 1973, the United States would be consuming an additional four million barrels of oil per day. Nonetheless, it is important to explore reasons for why such large improvements in fuel economy and emissions control have not produced large, absolute reductions in emissions and fuel use.

The fuel economy picture is relatively clear. Vehicle miles traveled on highways increased 59% from 1973 to 1989 (**Figure I.1**). In the same period, the average fuel economy of all cars on the road also improved, but not quite enough to compensate for the higher VMT. Average fuel economy grew about 45%, much less than the 100% improvement in the new-car test value. This discrepancy is primarily due to three factors: the long time required for retirement of old, inefficient vehicles, the increasing share of light trucks with their poorer fuel economy, and the increasing gap between EPA-rated fuel economy and actual, on-road fuel economy, as discussed in the introduction.

The disappointment as seen from a static perspective is not that fuel economy regulation has been unsuccessful, it is that new-vehicle fuel economy is only one aspect of the problem. As discussed, increased vehicle miles of travel and changes in driving patterns also have important effects on fuel use. The conclusion for policy making is the need for a package of policies that addresses all these problems, so that the gains in one aspect of the problem are not cancelled by losses in another.

The record on air quality regulations is more complex. Part of the story is the increase in vehicle miles traveled just mentioned, but the discrepancy between test tailpipe emissions and total emissions is much greater than the fuel-economy discrepancy. Average emissions are estimated to be larger by as much as a factor of 10 than they would be if total emissions equaled the allowed tailpipe level (U.S. EPA Motor Vehicle Emissions Laboratory 1988). As **Table 3.5** shows, much of the HC emissions are not from the tailpipe but from evaporation from the vehicle and from vehicle fueling.

In addition, a small fraction of vehicles are probably responsible for average tailpipe emissions far in excess of the limit for new cars. These are vehicles: 1) whose emissions control systems have severely deteriorated or failed, or 2) which are old enough to have had legal high emissions when new. As suggested by **Table 3.4**, if the catalytic converter system fails, emissions will increase by a factor of 5 or more. The average CO and NOx emissions are also much higher in practice than the limits even though there is no evaporative component.

There are EPA mandated programs to address evaporative emissions and failure of vehicle emissions control systems. Recently, powerful steps have been taken to reduce evaporation into the air, but it is too soon to evaluate the effort. With respect to emissions control systems, inspection and maintenance programs have been in place many years in metropolitan areas with serious ambient pollution. Many of these programs have been disappointing: 1) The test used in most regions measures emissions while the engine idles. Many vehicles will pass an idle test but emit heavily under load. 2) The inspection is carried out in many regions at individual garages. Often the mechanic and the vehicle owner have a mutual interest in avoiding the cost of repairing the emissions control system.

A fundamental complication is that the ambient pollutant of most concern, ozone, is the result of atmospheric chemistry involving two precursors, HCs and NOx. It is believed that, for most high-ozone events, one or the other precursor is critical, i.e., reducing it would reduce ozone while reducing the other may even increase ozone levels. There is not a consensus on which, HC or NOx, is typically the more important target.

In summary, emissions are much more sensitive to things going wrong than is fuel economy. Where fuel economy can be cut 10 to 20% by an engine going out of tune, emissions can increase an order of magnitude when something goes wrong, e.g., when an oxygen sensor fails. Moreover, the fuel economy problem may be noticeable in terms of poor performance, which often induces corrective action. The same can't be said for degradation in emissions performance. The apparent failure of emissions regulations to be effective over the life of many vehicles, such that actual emissions are much higher than envisioned by the regulations' authors, is a major deficiency of present policies.

THE NEXT GENERATION OF REGULATORY STANDARDS

Regulatory performance standards are an important policy option for bringing motor vehicle fuel use under control. They have worked well in the past, and market conditions and technological opportunities are such that they will likely work well again. Since substantially higher fuel economies are practical and cost effective (as discussed in previous sections), and since society has a major interest in reducing petroleum demand, it is not surprising that stronger regulatory standards for fuel economy are actively being considered in Congress. Senator Bryan sponsored a bill that would have required each manufacturer to increase its average fuel economy 40% above its 1988 level of fuel economy by 2001. On average the bill would require new cars to reach 40 mpg. It was supported by a majority of the Senate, but failed to overcome a filibuster in late 1990. The bill was re-introduced in early 1991.

Automobile manufacturers strongly oppose the legislation, and claim, as they did in 1975 before the first CAFE standards were passed, that it is not practical to substantially improve fuel economy except by moving, on the average, to much smaller cars. Manufacturers are stonewalling on this point. Other, more compelling reasons for their opposition are: 1) major tooling investments would be needed to make the changes, especially if a moderately rapid timetable is required as proposed; 2) the required rate of improvement in fuel economy would prevent manufacturers from fully exploiting sales opportunities for low-fuel economy models already in production, and; 3) high fuel economy standards would somewhat restrict designers' options in developing new vehicles and markets, e.g., there would be a premium on streamlining and on certain kinds of transmission shift management.

It is important to address such concerns by creating a schedule of strengthened standards allowing adequate time for manufacturers to adjust, and by enacting a policy package (with components discussed elsewhere in this chapter) such that the burden of compliance would not fall entirely on the manufacturer. Policies should be enacted that motivate buyers to select high fuel economy vehicles. The underlying concept in these suggestions is that we recognize the difficulties of substantially raising vehicle fuel economy, and that an increase in the standards by itself is not a sufficient policy for boosting average fuel economy to the full cost-effective potential.

FEES AND REBATES ON VEHICLE PURCHASES

The Gas Guzzler Tax

The gas guzzler tax, enacted as part of the Energy Tax Act of 1978, has been overlooked as an effective policy tool for improving fuel economy. (See **Table 3.6.**) However, there is strong evidence that the gas guzzler tax played an important role in improving fuel economy, especially between 1983 and 1986.

Figure 3.4 shows a plot of the average fuel economy of cars whose average fuel economy was below 21 mpg in 1980, the year before the gas guzzler tax took effect. Also plotted on the graph are the gas guzzler tax threshold and the real price of gasoline for the years 1980 through 1987. As can be seen, the fuel economy of low-mpg cars rose after the guzzler tax threshold was raised high enough to pose a tax threat. Domestic manufacturers clearly decided to improve fuel economy rather than to pay a even a small gas guzzler tax. This improvement in fuel economy occurred during a period of sustained decreases in the price of gasoline. As can be seen in **Figure 3.5**, this improvement in low mpg cars occurred when the fuel economy of the remainder of the new car fleet hardly improved, suggesting that the gas guzzler tax played a major role in post-1983 fuel economy improvements.

Gas guzzler taxes have a number of desirable features. Since the tax only applies to new cars, low-income persons will be largely unaffected by the tax. And since the tax is a large penalty imposed at the point of automobile purchase, instead of very small sums stretched out over many years (as caused by a gasoline tax), it is likely to have a strong effect on the willingness of car buyers to seek higher mileage cars.

We also recommend that a gas guzzler tax be established for light trucks, and as for passenger cars, the guzzler tax threshold should be increased by the same percentage as the light truck fuel economy standard.

Drive +

An extension of the concept of the gas-guzzler tax is a system of fees and rebates that would be levied on new cars according to whether they were above or below the average fuel economy. Such an approach has been introduced in legislation in California, and has been dubbed, "Drive+" (Gordon & Levenson 1990). As proposed there, fees and rebates would also be set according to whether a car's emissions were above or below an average level. Drive+ would thus encourage cars to be produced that are certified for emissions at levels below the legal limits. There is good evidence, from cars made by Volkswagen, Suzuki and others, that such low emissions can be achieved at modest cost, at least by high-fuel-economy vehicles. The program is designed to be revenue neutral, so that total rebates roughly equal total fees. The concept is just as appropriate at the federal level as it is at the state level. The Drive+ program was passed overwhelmingly by the California state legislature in 1990 but was vetoed by the former Governor; it has been subsequently re-introduced.

Fees and rebates at the point of purchase of a new vehicle are an important tool to improve fuel economy and emissions (Geller 1989). Given our society's sensitivity to first cost, it is easier and more effective to adjust for market imperfections and influence new car fuel economy and emission levels at the point of capital equipment purchase than it is to adjust for imperfections in the course of operations, as, for example, with a gasoline tax.

TECHNOLOGY POLICY

The policies discussed above indirectly encourage the creation of new technology to meet the changed economic conditions or regulatory constraints. Experience shows, however, that a more direct policy focus on new technology can be highly effective. Before considering such policies, let us briefly suggest the possibilities for new technology to meet our goals.

By new technology we mean vehicles and their energy supply systems which could radically reduce energy requirements and emissions, and which are not close to being in mass production. There are three potential types of vehicles:

1) vehicles with much higher fuel economy, but still based on gasoline or diesel fuel and still serving four or more passengers with, roughly, today's driving capabilities;

2) special-purpose vehicles requiring much less energy at the drive wheels, such as a small commuter car, and;

3) alternative-fuel vehicles including those which could flexibly operate on both gasoline and an alternative fuel.

In Group 1 the engine could be an advanced, direct-injection diesel, now entering production in Europe, which is about one third more efficient than corresponding conventional gasoline-powered engines. High-fuel-economy prototype vehicles incorporating advanced diesels have been built or partially developed by Volvo, Volkswagen, Renault, Peugeot, and Toyota, with in-use fuel economies estimated to be almost 70 mpg and higher (Bleviss 1988).

In Group 2, there are vehicles such as the proposed Lean Machine and the demonstration electric vehicle called Impact, both developed by General Motors. The Lean Machine is a two seater with one passenger behind the driver. Both the Lean Machine and the Impact are small, have little air and tire drag, and require very little power to be delivered to the wheels in typical driving. (The fact that the Impact is an electric vehicle is incidental to this discussion.) Both of these prototype vehicles happen to have rather high acceleration performance. It is not clear if that is an important attribute for marketing such a vehicle. Safety is a critical issue for such vehicles. It may be important to consider separate lanes on high speed roadways.

In Group 3 there is an enormous range of possibilities. We mention only two of the most exciting: hybrid electric and fuel-cell vehicles. The hybrid electric is powered by both batteries and an internal combustion engine. A common configuration is for the car to use the batteries (and electric motor) on short day trips, and to use the internal combustion engine for longer trips. The batteries would be expected to be recharged overnight, when electricity demand is low and there is substantial unused electricity generating capacity. The hybrid overcomes the severe disability of electric vehicles: their short daily range and long battery recharge period.

The fuel cell, essentially a large battery, has the advantage of relying on a stored fluid fuel like methanol or hydrogen (DeLuchi et al. 1991). The fuel cell converts the chemical energy of the fuel to electricity without combustion. Extremely little, if any, pollution emissions are associated with fuel cell operation, with the possible exception of carbon dioxide. Much higher efficiencies of conversion are possible than with the present kind of engine.

Emissions regulations and control is another area where new technology could have a revolutionary impact. Inexpensive equipment to measure, record, and communicate information about emissions into the air may be able to alter the strategy for regulation of emissions from its focus on design criteria and isolated tests to a focus on actual performance. To illustrate, it is now becoming possible to measure emissions from the tailpipe of a car driving down a road, using a source of light and a receiver on opposite sides of the road (Stedman 1990). When this technology is developed, it will be possible, first, to determine quantitatively how important the most polluting cars are to overall emissions from the automobiles in a particular airshed. And second, if the problem is indeed dominated by a small number of serious offenders, it may be that identifying these offenders will become a particularly cost-effective approach to clean-up. A competing, or perhaps complementary, approach for vehicles may be to measure and record emissions performance with on-board technology that is beginning to be developed.

TECHNOLOGY PUSH AND PULL POLICIES

The U.S. government has been highly effective in encouraging new technology in some sectors, like agriculture, commercial aircraft, and semiconductors. The tools used are, broadly, technology push and technology pull.

Technology push concerns the creation of technology: research, invention, development, and demonstration. This is not a linear sequence of activities, in which one follows the next, but a complex interaction in which new technologies are created. Technology push policies involve government support for research, development and demonstration (R, D & D) and government encouragement of private-sector R, D & D through tax incentives, patent law, etc.

Technology pull concerns the demand for new technology, i.e. demand for it after it reaches initial commercial status. It cannot be over-emphasized that the existence of a likely market for a new or improved process or product strongly motivates development and production of new technologies, and the apparent absence of a market strongly inhibits them. Government policies can provide technology pull through government purchases and by encouraging the private sector's propensity to purchase new technology (Ross & Socolow 1990).

A major example of a technology-push policy is government-supported research and development on generic technologies that could form the basis for many new product developments. Modest government involvement is proving very beneficial in electrochemistry (new and improved batteries), combustion (understanding of knock and soot formation), and ceramic insulation (for the combustion chamber). It would be valuable to continue support in these areas and greatly expand the government's efforts in, e.g., engine friction and control systems for hybrid-electric vehicles.

It may seem that it is the private sector's responsibility to conduct research on generic technologies such as those just mentioned. It is well known and well documented, however, that the private sector under-invests in research (Young 1986). The roots of this under-investment lie in a firm's inability to prevent its competitors from capturing many of the benefits of its research. Other contributing factors are the short time horizons and the heavily cyclical earnings patterns experienced by many firms. The private sector cannot support research leading to innovation in many socially useful areas of technology, at least not nearly at a level consonant with today's needs.

An attractive example of a technology pull policy is providing extra fuel economy credits to manufacturers that produce automobiles or light trucks that attain exceptionally high levels of fuel economy. Such a provision would reward manufacturers for aggressively introducing new technology, an incentive for manufacturers to take a significant leap forward with fuel economy technologies, as opposed to taking more conservative, incremental steps. The incentive could be made especially strong for improving the fuel economy of mid-size and large cars.[10]

A schedule of fuel economy thresholds for the major EPA automobile size classes could be established as part of a strengthened fuel-economy-standards law. The schedule could define, for each size class and for specified years, which level of fuel economy would have to be exceeded for a manufacturer to qualify for the credits. A schedule that would be consistent with fuel economy standards requiring a 40% increase in fuel economy might be as shown in **Table 3.7**. If a manufacturer produced a car that exceeded the above specified levels, it could count the fuel economy of that car (for purposes of complying with CAFE standards) as being, for example, 50% higher than its test fuel economy. Present fuel economy regulations already include similar CAFE credits for alternate fuel vehicles.

FUEL ECONOMY AND SAFETY

Opponents of efforts to improve automobile fuel economy have recently argued that the standards increase highway fatalities. Fuel-efficient cars are commonly equated with small, light cars. However, the record shows that fuel economy can be substantially increased without reducing vehicle weight. The average new car fuel economy began to improve sharply after 1974. Initially, much of this fuel economy improvement was due to reducing average vehicle weight. It was the easiest and cheapest way for manufacturers to improve fuel economy. But since 1980, the average vehicle weight has remained almost constant, while the fuel economy increased by about 20%. (See **Figure 3.6**.) Manufacturers were able to improve fuel economy without reducing vehicle weight by relying on technological improvements in engines, transmissions, aerodynamics and other means. The potential for making further fuel economy improvements without reducing vehicle weight remains large.

Points in **Figure 3.7** represent the weight and safety performance of 1984 to 1988 model year cars crash tested by the U.S. Department of Transportation's National Highway Traffic Safety Administration. These cars were crashed into a fixed barrier at 35 mph. The measure of safety performance is the driver head injury criterion (HIC), which reflects the potential for injury to a driver's brain. The higher the number, the higher the potential for injury. As shown here, there is no relationship between automobile weight and head injury criteria. In fact, there are some heavy vehicles that perform poorly (upper right portion of the figure) and some light vehicles that perform very well (lower left portion of the figure). A plot of the passenger side HIC yields very similar results.

Crashing a car into a fixed barrier does not necessarily measure how weight affects a car's performance in a crash. Nonetheless, **Figure 3.7** illustrates that there are large differences in the crash worthiness of automobiles, independent of weight. A 1982 study pointed out that the differences in crash performance within weight classes were greater than the differences among weight classes (Office of Technology Assessment 1982).

There are many existing light-weight cars that perform well in crash tests. But much safer and more fuel-efficient cars are possible. The Volvo LCP 2000, a prototype high-efficiency car, was designed with both safety and fuel economy in mind. The car weighs 1500 pounds (less than half today's average new auto weight of about 3200 pounds), achieves 63 mpg in the city and 81 on the highway,

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[10] As pointed out above, high fuel economy has been associated with bottom-of-the-market vehicles. One of the major policy challenges is to inspire and encourage manufacturers to create "green" cars in the middle of the market.

and can withstand frontal and side impacts of 35 mph, and a rear impact of 30 mph (Bleviss 1988). U.S. regulations require only that vehicles can withstand a frontal impact of 30 mph.

The U.S. Department of Transportation's Research Safety Vehicle Program, which existed from 1977 to 1980, developed an experimental car that was both safe and fuel efficient (U.S. Department of Transportation 1980). The program concluded that a car using then-current technology (ten years old now) could carry five passengers; achieve 43 mpg; and withstand 80 mph frontal impacts, 50 mph side impacts, and 45 mph rear impacts.

Evidence that fuel economy and automobile safety can be improved simultaneously is also found in the statistical record established in the United States. Since 1973, the average fuel economy for all cars on the road rose from 13 mpg to 20 mpg. During the same period, traffic fatalities fell from 3.5 per 100 million vehicle miles traveled to 2.4. Safer cars and highways, increased use of seatbelts, and anti-drunk driving campaigns are widely recognized as major reasons for the improvement.

Despite the evidence that improving fuel economy and automobile safety are compatible goals, adherents to the view that improved fuel economy means higher traffic fatalities cite studies of actual automobile crash data that demonstrate a relationship between car size and fatalities, or between car weight and fatalities. A common problem, however, with studies based on actual accident data is that it is difficult to separate the effects of driver behavior from vehicle characteristics when estimating the propensity of certain cars to be involved in fatal accidents. For example, the bad fatality record of a few high-performance sports cars may lead one to conclude that these cars are inherently unsafe. But dangerous driving practices of people who most commonly own and drive these cars may be partly or fully responsible for their bad safety record. Similarly, the worse- than-average safety record of a few small, inexpensive, and fuel-efficient cars may be due to the atypical driving behavior of people who tend to buy these cars, e.g., drivers of small cars tend to be young.

In summary, research has shown that with careful design, cars can be both fuel efficient and safe. Nonetheless, the results of some recent studies justify a close look at the effect of car size and weight on crash performance. If new research indicates that, as vehicles evolve, weight or size will be a primary consideration in designing cars to achieve lower fatality rates, then future fuel economy improvements should be based on approaches other than weight or size reduction. With either approach, current and future technologies provide a broad range of ways to substantially improve auto fuel economy while simultaneously improving auto safety.

CONCLUSIONS

Federal policies made a major contribution toward the fuel economy improvements achieved since 1975. But because they require no further improvements, and because real gasoline prices have fallen for years, the long upward trend in fuel economy has stalled. This cessation in fuel economy improvement puts our nation's economy and security at risk. Among the options for reducing our oil imports and carbon dioxide emissions within the next ten to twenty years, none will have greater effect than substantially improving light vehicle fuel economy. (See **Figures 3.8 and 3.9**.) The market could be of great assistance in pushing fuel economy levels higher, but because of large externalities and other barriers, it will not be sufficient.

Policies to reduce light vehicle fuel consumption will not only benefit the United States directly, but given the enormous influence U.S. policies and technologies could have on other countries, these policies could leverage large international reductions in transportation fuel use.

In addition to fuel economy improvements, it is imperative that we slow growth in vehicle miles of travel, and offer attractive transportation alternatives to low-occupancy light vehicles. Otherwise, even with fuel economy improvements, we could find ourselves looking back on the fifteen years that follow 1990, with the same sense of running-in-place that we get when looking back on the fifteen years since 1975.

REFERENCES

An, F., and M. Ross, 1991. "Automobile Energy Efficiency at Part-Load: the Opportunity for Improvement." Ann Arbor, MI: Dept. of Physics, University of Michigan (forthcoming).

Ang, B.W., 1991. "Traffic Management Systems and Energy Savings: The Case of Singapore," Transportation and Energy in Developing Countries: Experiences and Options, D. Bleviss and M. Birk, eds. New York: Quorum Books, (forthcoming).

Amann, C.A., 1989. "The Automotive Engine - A Future Perspective," Society of Automotive Engineers (SAE), # 891666.

Asmus, T.W., 1991. "Perspectives on Applications of Variable Valve Timing," SAE, # 910445.

Bleviss, D.L., 1988. The New Oil Crisis and Fuel Economy Technologies, Westbury, CT: Quorum Books.

Bohi, D., and M.B. Zimmerman, 1984. "An Update on Econometric Studies of Energy Demand Behavior." Annual Review of Energy, Vol., 9. Palo Alto, CA: Annual Reviews Inc.

Bosch (Robert Bosch GmbH), 1986. Automotive Handbook, 2nd Ed., Warrendale, PA: SAE.

Brehob, W.M., and D.D. Brehob, 1991. "Fuel Efficiency and Response of Load Control Methods for Premixed Charge Engines," SAE, # 910389.

Broadman, H.G. and W.W. Hogan, 1986. "Oil Tariff Policy in an Uncertain Market," Energy and Environmental Policy Center, Harvard University.

Burchell, R.W., and D. Listakin, 1982. Eds., Energy and Land Use. Piscataway, NJ: Center for Urban Policy Research, Rutgers University.

Bureau of the Census, 1990. "Truck Inventory and Use Survey." 1987 Census of Transportation. Washington, DC. Table 4.

Burke, M., 1990. "High Occupancy Vehicle Facilities: General Characteristics and Potential Fuel Savings." Washington, DC: American Council for an Energy-Efficient Economy.

Butler, P., et al., 1988. "Sex-Divided Mileage, Accident, and Insurance Cost Data Show That Auto Insurers Overcharge Most Women." Journal of Insurance Regulation, 6(3), Part 1, and 6(4), Part 2.

Carlsmith, R., et al., 1989. "Energy Efficiency: How Far Can We Go?," Oak Ridge, TN: Oak Ridge National Laboratory.

Cole, D., 1984. "Automotive Fuel Economy," in John C. Hilliard and George S. Springer, eds., Fuel Economy in Road Vehicles Powered by Spark Ignition Engines, Plenum Press.

Crandall, R.W., et al., 1986. Regulating the Automobile. Chapter 6. Washington, DC: The Brookings Inst.

Davis, S.C., et al., 1989. Transportation Energy Data Book: Edition 10, Oak Ridge National Laboratory, ORNL-6565, September.

DeLuchi, M.A., E.D. Larson, and R.H. Williams, 1991. "Hydrogen and Methanol: Production from Biomass and Use in Fuel Cell and Internal Combustion Engine Vehicles. A Preliminary Assessment." PU/CEES Report No. 263, Princeton University.

Demmelbaner-Ebner, W., A. Dachs, and H.P. Lenz, 1991. "Variable Valve Actuation Systems for the Optimization of Engine Torque," SAE, # 910447.

Dieckmann, J., and D. Mallory, 1991. "Climate Control for Electric Vehicles," SAE, # 910250.

Difiglio, C., K.G. Duleep and D.L. Greene, 1990. "Cost Effectiveness of Future Fuel Economy Improvements," Energy Journal, August.

El-Gasseir, M., 1990. "The Potential Benefits of Pay-As-You-Drive Automobile Insurance." Submission to the California Energy Commission. Docket No. 89-CR-90. Sacramento, CA.

Energy Conservation Coalition, 1989. "The Auto Industry on Fuel Efficiency: Yesterday and Today," Fact Sheet, Washington D.C.

EEA, (Energy and Environmental Analysis, Inc.), 1985. "Documentation of the Characteristics of Technological Improvements Utilized in the TCSM," prepared for Martin Marietta Energy Systems, Inc.

EEA, 1986. "Analysis of the Capabilities of Domestic Auto-Manufacturers to Improve Corporate Average Fuel Economy," a report to the Office of Policy, Planning and Analysis, U.S. D.O.E.

EEA, 1988. "Developments in the Fuel Economy of Light-Duty Highway Vehicles," prepared for the Office of Technology Assessment.

EEA, 1990. "An Assessment of Potential Passenger Car Fuel Economy Objectives for 2010," a report to the Air and Energy Policy Division, U.S. E.P.A.

EIA (Energy Information Administration), 1989. Annual Energy Outlook 1989, U.S. Department of Energy.

EIA 1991. Monthly Energy Review, February 1991, U.S. Dept. of Energy, Washington, DC.

FHWA (Federal Highway Administration), 1986. "1983-1984 Nationwide Personal Transportation Study, Personal Travel in the U.S., V.1, Washington DC.

FHWA, 1988. Highway Statistics 1988, U.S. Dept. of Transportation, Washington DC.

Frame, P., 1990. "GM Upshifting to Electronics," Automotive News, Sept. 17, p3.

Geller, H., 1989. "Financial Incentives for Reducing Auto Emissions: A Proposal for Clean Air Act Amendments." Washington, D.C.: American Council for an Energy-Efficient Economy.

Gordon, D., 1991. Steering a New Course: Transportation Energy and Environment, Cambridge, MA: Union of Concerned Scientists.

Gordon, D., and L. Levenson, 1990. "Drive +: Promoting Cleaner and More Fuel-Efficient Motor Vehicles Through a Self-Financing System of State Sales Tax Incentives." Journal of Policy Analysis and Management, Vol. 9. 3, pp. 409-415.

Greene, D.L., 1990. "CAFE or Price?: An Analysis of the Effects of Federal Fuel Economy Regulations and Gasoline Price on New Car MPG, 1978-89." The Energy Journal, Vol. 11, # 3 pp. 37-57.

Greene, D.L. 1991. "Vehicle Use and Fuel Economy: How Big is the Rebound Effect?" Oak Ridge, TN: Oak Ridge National Laboratory.

Hamilton, W., 1989. "Electric and Hybrid Vehicles, Technical Background Report for the DOE Flexible and Alternative Fuels Study," a report to EG & G Idaho, July.

Heavenrich, R.M., and J.D. Murrell, 1990. "Light Duty Automotive Technology and Fuel Economy Trends Through 1990," U.S. EPA Office of Mobile Sources, Ann Arbor, MI.

Hellman, K., and J.D. Murrell, 1984. "Development of Adjustment Factors for the EPA City and Highway MPG Values," SAE, # 8400496.

Heywood, John B., 1988. Internal Combustion Engine Fundamentals, McGraw-Hill Book Co.

Hiromu Shiga, 1986. "Electronic Transmission Control," SAE, # 861032.

Holtzclaw, J., 1990. "Explaining Urban Density and Transit Impacts on Auto Use." Testimony before the California Energy Commission, docket 89-CR-90, April 23.

Horton, E. J., and W.D. Compton. 1984. "Technological Trends in Automobiles." Science 225, pp. 587-593.

Huber, W., B. Lieberoth-Leden, W. Maisch and A. Reppich, 1991. "New Approaches to Electronic Throttle Control," SAE, # 910085.

Institute of Transportation Engineers, 1989. "A Toolbox for Alleviating Traffic Congestion." Washington, DC.

Katashiba, H., and M. Nishida, S. Washino, A. Takahashi, T. Hashimoto and M. Migake, 1991. "Fuel Injection Control Systems That Improve Three Way Catalyst Conversion Efficiency," SAE # 910390.

Khazzoom, D.J., 1988. "Quantifying the Environmental Impact of a Gasoline Tax: A Study in the Use of Energy Conservation as a Strategy for Emission Abatement in the Transportation Sector," San Jose State University.

Lashof, D.A. and D. Tirpak, 1989. "Policy Options for Stabilizing Global Climate." Washington, DC: Office of Policy, Planning and Evaluation, U.S. Environmental Protection Agency.

Ledbetter, M., and M. Ross, 1990. "Supply Curves of Conserved Energy for Automobiles." American Council for an Energy-Efficient Economy, Washington, DC, March 1990.

Ledbetter, M., and M. Ross, 1991. "Light Vehicles: Policies for Reducing their Energy Use and Environmental Impacts." American Council for an Energy-Efficient Economy, Washington, DC, forthcoming, 1991.

Lenz, H.P, K. Wichart and A. Grudent, 1988. "Variable Valve Timing - A Possibility to Control Engine Load Without Throttling," SAE, # 880388.

Ludema, K.C., 1984. "Mechanical Friction and Lubrication in Automobiles," in John C. Hilliard and George S. Springer, eds., Fuel Economy in Road Vehicles Powered by Spark Ignition Engines, Plenum Press.

MacDonald, Gordon, 1990. "The Future of Methane as an Energy Source," Annual Review of Energy, vol. 15.

MacKenzie, J. and M. Walsh. 1990. Driving Forces: Motor Vehicle Trends and their Implications for Global Warming, Energy Strategies, and Transportation Planning. Washington, DC: World Resources Institute.

Maskery, M., 1991. "Mitsubishi: Weight, Not Size Is MPG Ticket," Automotive News, Apr. 1.

Mayo, J., and J. Mathis, 1988. "The Effectiveness of Mandatory Fuel Efficiency Standards in Reducing the Demand for Gasoline," Applied Economics, 20, pp. 211-219.

McCarthy, P.S., and R. Tay, 1989. "Consumer Evaluation of New Car Attributes," Transportation Research. Vol. 23A, #5, pp. 367-375.

McCosh, D., 1990. "Variable Valve Timing," Popular Science, March, p82.

Motor Vehicle Manufacturers Association, 1990. "MVMA Facts and Figures '90," Detroit, MI.

Morel, T., 1984. "Aerodynamics of Road Vehicles," in J.C. Hilliard and G.S. Springer (eds.), Fuel Economy in Road Vehicles Powered by Spark Ignition Engines, Plenum Press.

Muranaka, S., Y. Takagi and T. Ishida, 1988. "Factors Limiting the Improvement in Thermal Efficiency of S.I. Engines at Higher Compression Ratios," SAE, # 870548.

Murrell, J.D., 1975. "Factors Affecting Fuel Economy," SAE, # 750958.

Murrell, J. D. and R.M. Heavenrich. 1990. "Downward Trend in Passenger Car Fuel Economy - a View of Recent Data," Technical Report EPA/AA/CTAB/90-01. Ann Arbor, MI.

NHTSA (National Highway Traffic Safety Administration), 1984. "Federal Motor Vehicle Safety Standards: Transmission Shift Lever Sequence," Federal Register 49(10), March 27, p. 11692.

Newman, P.G. and J.R. Kenworthy, 1988. Cities and Automobile Dependence: A Sourcebook, Aldershot, England: Gower Technical.

Office of Technology Assessment, U.S. Congress. 1982. "Increased Automobile Fuel Efficiency and Synthetic Fuels." Washington, D.C.

Patterson, P. and F. Westbrook, 1989. "Changing Driving Patterns and Their Effect on Fuel Economy," Presentation at 1989 SAE Government/Industry Meeting, Washington, D.C., May.

Plotkin, S. (Office of Technology Assessment), 1991. "Estimating feasible level of Corporate Average Fuel Economy." Statement before the Committee on Energy and Natural Resources, U.S. Senate, Washington, DC, March 20, 1991.

Popular Science, 1990. "Jekyll & Hyde Engines," Automotive Newsfront, Sept., p4.

Post, R., 1991. Lawrence Livermore Laboratory, personal communication.

Pushkarev, B.S. and J.M. Zupan, 1977. Public Transportation and Land Use Policy. Bloomington, IN: Indiana University Press.

Reilly, D.J., R.P. Anderson, R.J. Casparian and P.H. Dugdale, 1991. "Saturn DOHC and SOHC Four Cylinder Engines," SAE, # 910679.

Replogle, M., 1990. "U.S. Transportation Policy: Let's Make it Sustainable." Washington, D.C.: Institute for Transportation and Development Policy.

Ross, M., 1989. "Energy and Transportation in the United States," Annual Review of Energy 14, pp. 131-171.

Ross, M. and R. Socolow, 1990. "Technology Policy and the Environment," presented at "Toward 2000: Environment, Technology and the New Century," Annapolis, MD. Washington, D.C.: World Resources Institute.

Schatz, O., 1991. "Cold Start Improvements With a Heat Store," SAE, # 910305.

Schlunke, K., 1991. "The Orbital Combustion Process Engine--Fuel Economy Potential." Report to the National Research Council Committee on Fuel Economy of Automobiles and Light Trucks, Irvine, CA, July 1991.

Seiffert, U. and Peter W., 1990. Automobile Technology of the Future, Warrendale PA: SAE.

Shellenbarger, R.M., G.N. Henning, R.L. Keefe, P.E. Rusek and T.K. Venkatachalam, 1991. "Reinforcing Materials for More Fuel Efficient Tires," SAE, # 910169.

Sovran, G. and M.S. Bohn, 1981. "Formulae for the Tractive-Energy Requirements of Vehicles Driving the EPA Schedules," SAE, # 810184.

Stockton, T.R., 1984. "Power Train Matching and Fuel Economy Projection Methods," in J.C. Hilliard and G.S. Springer (eds.), Fuel Economy in Road Vehicles Powered With Spark-Ignition Engines, Plenum Press, 1984.

Seiffert, U. and Peter W., 1984. The Future for Automotive Technology, London: Frances Pinter.

Stedman, D., 1990. University of Denver, private communication.

Stone, R., 1989. Motor Vehicle Fuel Economy, London: Macmillan Education Ltd, London.

Sztenderowicz, M.L., and J.B. Heywood, 1990. "Cycle-to-Cycle IMEP Fluctuations in a Stoichiometrically-Fueled S.I. Engine at Low Speed and Load," SAE, # 902143.

Tobias, A., 1982. The Invisible Bankers, New York: Pocket Books.

U.S. Department of Transportation, 1988. "Low Tension Piston Rings and Roler CAM Followers for Engine Friction Reduction -- Costs of Retooling and Fuel Economy Benefits," DOT HS 807 332.

U.S. Department of Transportation, 1980. "The Safe, Fuel-Efficient Car: A Report on its Producibility and Marketing."

U.S. EPA Motor Vehicle Emissions Laboratory, 1988. MOBILE4 Workshop, Ann Arbor, MI, Nov.

von Hippel, F., and B. Levi, 1983. "Automobile Fuel Efficiency: the Opportunity and the Weakness of Existing Market Incentives," Resources and Conservation, V10, pp 103-124.

Ward, D., 1990. "Smaller Engine, More Power," Automotive News, Feb. 26.

Watson, H.C., 1990. University of Melbourne, private communication.

Weber, T., 1988. "Analysis of Unconventional Powertrain Systems," SAE, # 885023.

Yagi, Shizuo, Yoichi Ichibasi and Hiroshi Sono, 1990. "Experimental Analysis of Total Engine Friction in Four Stroke S.I. Engines," SAE, # 900223.

Young, J.A., 1986. "Global Competition -- The New Reality: Results of the President's Commission on Industrial Competitiveness," The Positive Sum Strategy, R. Landau and N. Rosenberg, eds., Washington, D.C.: National Academy Press.

APPENDIX A

ABBREVIATIONS USED IN PART I AND IN APPENDIX B

ATM	aggressive transmission management (used to reduce engine speed)
AVPWR	a base vehicle for analysis with PMAX and weight fairly near the US average
EIVC	early intake valve closing (variable)
FTP	Federal Test Procedure
HIPWR	a base vehicle with high PMAX/W
LOPWR	a base vehicle with low PMAX/W
N	engine speed
NMIN	minimum engine speed used when the engine is delivering substantial power
N/v	ratio of engine speed (rpm) to vehicle speed (mph) in highest gear
PMAX	maximum power capability of an engine
P_{engine}	power output by engine to the rest of vehicle
PWOT	maximum power at a given N, i.e., at wide-open throttle
V	engine displacement or volume
VVT	variable valve timing
W	vehicle weight including typical load
WOT	wide-open throttle

APPENDIX B

A SIMPLE MODEL FOR VEHICLE ENERGY USE

There is a good approximate description of engine performance maps which greatly simplifies the visualization of energy savings mechanisms and allows for analysis of details about pumping and friction. The essential fact is the linearity of the rate of fuel use as a function of P_b:

$$P_{fuel} = f(N) + g(N)\,P_b \qquad \text{(B.1)}$$

(Here the notation P_b is used instead of P_{engine}.) The approximation is good from zero power output to the approach to WOT. For P_b greater than about three-fourths PWOT, richer mixtures are used in most modern engines and P_{fuel} moves above the straight line. This relationship is known (Bosch 1986); but it is not well known nor used. For example, contour maps and tables of brake-specific fuel consumption are widely used, but they are ineffective for describing fuel use at the low power level where most driving is done. In this application, equation B.1 would be excellent. In part, perhaps, it's a question of style. Engineers often want numbers that describe specific situations while physicists get considerable satisfaction from a simple and powerful analytic expression, even if the expression is somewhat inaccurate.

In addition, the engine speed (N) dependence can be adequately represented by $f \propto N$ in the relatively narrow range of N used in a driving cycle with a particular vehicle, and by g(N) = constant. This approximate simple proportionality to N is statistically supported by study of a large sample of engines, as long as the range in N is kept small (Yagi 1990). Then we have:

$$P_{fuel} = \left\{ \begin{array}{ll} aN + bP_b & \text{for } P_b > 0 \\ A & \text{for } P_b = 0 \end{array} \right\} \qquad \text{(B.2.)}$$

for powered operation and idling, respectively.

This form can also, of course, be used to calculate other quantities. The overall efficiency is

$$\eta = P_b / (aN + bP_b)$$

Where P_b is in kW, a in kJ/rev, and N in rps. For typical gasoline, we use 44.0 kJ/gram or 81.8 gram per kWh, so the brake specific fuel consumption is:

$$\text{bsfc} = 81.8 / \eta \qquad \text{g/kWh}$$

(For the calculation of EPA test fuel economy, the fuel is indolene with 120.5 MJ/gallon.)

Fits to empirical points for four relatively modern 4-cylinder engines are shown in **Figures B.1** (a), (b), (c) and (d). We have examined the relationship Eqn. (B.2) in more detail for these four engines. Linear regressions in P_b are made using the engine maps at several engine speeds in the range 1500-3000 rpm. The results are shown in the **Table B.1**. The agreement with the straight line form is good, and is especially useful in the low to medium P_b/PWOT region where most engine operation occurs. The parameter a is not determined accurately enough by these fits to definitively evaluate the friction in these engines. The evidence suggests, however, that the Quad 4 has relatively low friction because its displacement is relatively high, but the a value is not high.

The Model

The dependence on downsizing of the frictional losses embodied in the parameter a is assumed to be:

rubbing friction and accessories $\propto$ n $(V/n)^{2/3}$

pumping $\propto$ V,

where V is the total displacement and n the number of cylinders.

Equation (B.2) can be written out in more detail:

$$a = a_f + a_p = [df(V/V_o)^{2/3} (n/n_0)^{1/3} + (1 - d)p(V/V_0)]a_0$$
$$b = b_f + b_p + \eta_{th}^{-1} \approx \eta_{th}^{-1} \qquad (B.3)$$

Here the subscript p refers to pumping and f to rubbing friction and engine accessories. The thermal efficiency η_{th} is, to a good approximation, constant over the ranges of N and P_b /PWOT of primary interest. Parameters f, V/V_0, p, and s, each of which equals one for a base engine, have been introduced to explicitly describe changes in an engine from its base configuration.

We have compared the equation for a (Equation B.3) with two points for large engines. A fit to an engine map for a 1987 Nissan V6 2.96 liter engine yields a=0.71 kJ/rev and the formula, with a_0 = 0.45, V_0 = 1.8, a=0.72, better agreement than expected (Nishimura 1987). A fit to an engine map for a 1966 Mercury V8 4.74 liter engine yields a = 1.35 kJ/rev and the formula, with the same inputs, a = 1.11 (Obert 1973). Not surprisinly, about 20% friction reduction was achieved in the intervening years.

Over a driving cycle, equation (B.2) becomes

$$E_{fuel} = a\, N_{ave}\, t^{pwr} + b\, L_{engine} + a\, N_{idle}\, t_{idle} \qquad (B.4)$$

where t_{pwr} and t_{idle} are the times spent delivering power and idling, respectively, and N_{ave} is the average engine speed while the engine delivers power. This is the model we use for analyzing the technologies and their interactions in Part I.

There are seven engine-specific parameters in Eq. (B.4). Both $a \equiv a_p+a_f$ and $b \equiv b_f+b_p+\eta_{th}^{-1}$ can be estimated from an engine map. Data on the idle fuel consumption rate is also needed. In addition the pumping requirements can be approximately determined from the basic physics of the process, yielding values for a_p and, roughly, b_p. Since the magnitude of b_f is expected to be relatively small, we approximate it on the basis of published examples of the dependence of friction on load, rather than on data specific to the engine in question. (In this draft b_f and b_p are neglected.) The remaining four quantities in Eq. (B.4), N_{ave}, t_{pwr}, L and t_{idle}, are determined from analysis of a driving cycle (which requires specification of gear ratios and gear management).

The parameters in Eq. (B.3) with subscript zero refer to a 4-cylinder engine with V_0 = 1.8 liter, d=0.75, d_0=0.45 and b=2.5. Specific values for a and b for the four base vehicles, as well as other parameters in Eq. (B.4) are shown in **Table B.2.** Load information for Eq. (B.4), calculated using the vehicle simulation, is shown in **Table B.3.**

Uncertainties in the Model

While the plots in **Fig. B.1**, look good, with points from different engine speeds appearing to lie on a single straight line, detailed examination shows variation in a and b. Data for the 1.8 liter VW engine used for most of our analysis was analyzed at several values of N to explore variation in a and b, **Table B.4.** The map for this engine shows a strong qualitative change at low engine speed, with poorer efficiency at low load and excellent efficiency at high load, corresponding to large a and small b. (This is not a general characteristic. Many engines show little change.)

The implications for use of the model, Eq. (B.4) are clear: Analysis of fuel use based on average values for a and b which don't depend on N can yield a somewhat different result than analysis involving the details of the engine map. We obtain a feeling for the size of the error by comparing the results for ATM using the two methods. This error affects the results for ATM. Analysis of the other technologies, which do not emphasize changing N, does not suffer from this source of error.

A second source of error from use of the simple formula (B.2) is the departure from the linearity in P_b at high levels seen in the **Figs. B.1**. Since relatively few operating points of an engine occur in this regime during the engine cycle, this is not a major source of error.

A third source of error is lack of measurement information about fuel use by an engine at or near $P_b = 0$. Engine maps for modern engines are not generally available; and when they are available, data on fuel use at $P_b = 0$ is often not provided, so the value of a has to be inferred by extrapolation, creating an uncertainty in the relative roles of friction as represented by a, and efficiency in providing for the load, as represented by b.

This kind of error is compounded with another source of error, the deviation of the AVPWR engine from that of a truly representative engine or group of average engines. Pending creation of a better sample of vehicles and engines, we estimate that the parameter a has an uncertainty of + or - 20% and that of b, a correlated uncertainty of + or - 10%. Analyzing AVPWR, a 20% error in a is found to imply a 13% error in the estimated fuel savings of a technology associated with a, the displacement reduction, friction reduction, idle off and EIVC. Thus, for example, if a 10% fuel savings was calculated, the savings is estimated to lie in the interval (10 + or - 1.3)%.

Table 1.1

STANDARD VEHICLES USED IN THE ANALYSIS OF FUEL ECONOMY TECHNOLOGIES*				
	LOPWR	JETTA	AVPWR	HIPWR
PMAX (hp)	59	106	140	200
W^a (lbs)	2625	2750	3500	4000
PMAX/W (hp/1000lbs)	22	38	40	50
V (displacement, liters)	1.29	1.8	3.1	4.9
Cylinders	4	4	6	8
PMAX/V (hp/liter)	46	59	45	41
Transmission	M5	M5	M5	M5
N/v (rpm/mph)	41.8	41.8	35.0	26.0
Fuel Economy $(MPG)^b$	35.5	32.2	24.3	22.6

a) Vehicle with full complement of liquids plus 300 lbs

b) EPA composite of urban and highway cycles. The values of AVPWR and HIPWR are from our vehicle simulation.

* See Appendix A for abbreviations

Table 1.2

HIGH PERFORMANCE ENGINES IN 1991 BIG-THREE CARS*

Car	Displacement liters	Cylinders	PMAX/V (hp/liter)	engine manufacturer
Chev. Beretta (Quad 4)	2.3	4	78	GM
Chevrolet Lumina	3.4	6	62	GM
Saturn	1.9	4	65	GM
Dodge Stealth	3.0	6	74	Mitsubishi
Ford Escort GT	1.8	4	71	Mazda
Ford Taurus SHO	3.0	6	73	Yamaha

* defined as PMAX/V > 61 hp/liter (1 hp/CID)

Table 1.3

ESTIMATED TORQUES: AVPWR WITH ENGINE DOWNSIZING AND ATM

	Engine Speed (rpm)		
	2200	2000	1600
Empirical torque/disp. (Nm/liter):			
Current V6 engines[a]	78 (est.)	75	
Quad 4[b]	84	80	76
Estimated torque (Nm):			
AVPWR[c]	242		
downsized AVPWR[d]	195		177
decrease in torque[e] (%)	19%		27%

a) Torque for 204 CID Buick Century and 231 CID Buick LeSabre (Consumer Guide).

b) Adapted from Thomson *et al*.

c) 242 = 3.1 * 78.

d) 195 = (0.75 * 3.1) * 84, 177 = (.75 * 3.1) * 76.

e) relative to AVPWR at 2200 rpm.

Table 1.4

FUEL SAVINGS FROM FIVE PART-LOAD TECHNOLOGIES, NO LOAD REDUCTION (AVPWR)

Vehicle/ technology	load L/L_0	displ. V/V_0	frict. f	pump. p	idle-off s	URBAN engine speed N_{ave}	URBAN fuel economy MPG	URBAN MPG improve. %	HIGHWAY engine speed N_{ave}	HIGHWAY fuel economy MPG	HIGHWAY MPG improve. %	COMPOSITE fuel economy MPG	COMPOSITE MPG improve. %
base	1.00	1.00	1.00	1.00	1.00	1855	20.3	0	2016	32.0	0	24.3	0
1) displacement red.	0.96	0.75	1.00	1.00	1.00	1855	25.0	23	2016	38.3	19	29.6	22
2) friction reduction	1.00	0.98	0.90	1.00	1.00	1855	21.5	6	2016	33.6	5	25.7	6
3) ATM	1.01	1.00	1.00	1.00	1.00	1492	22.2	9	1475	36.7	15	27.0	11
4) idle-off	1.00	1.00	1.00	1.00	0.33	1855	23.3	15	2016	32.7	2	26.7	10
5) pumping reduction	1.05	1.00	1.00	0.43	1.00	1855	21.9	8	2016	33.8	6	26.0	7
1+2	0.96	0.69	0.90	1.00	1.00	1855	26.3	30	2016	39.8	24	31.0	28
1+2+3	0.97	0.69	0.90	1.00	1.00	1492	28.4	40	1475	44.5	39	33.9	40
1+2+3+4	0.97	0.69	0.90	1.00	0.33	1492	32.2	59	1475	45.4	42	37.1	53
1+2+3+4+5	1.02	0.69	0.90	0.43	0.33	1492	33.7	66	1475	46.4	45	38.5	58

Table 1.5

EFFECT OF INTERACTION AMONG η_{mech} TECHNOLOGIES APPLIED IN ORDER 1 THROUGH 5 (AVPWR)

	Fuel Economy Improvement (Percent)		
	technology when used alone (relative to base)	technology when used with others (relative to vehicle with previously applied techs)	cumulative improvement (relative to 24.3 MPG)
1) displacement red.	22	22	22
2) friction reduction	6	5	28
3) ATM	11	9	40
4) idle-off	10	9	53
5) pumping reduction	7	4	58

Table 1.6

FUEL SAVINGS FROM FIVE PART-LOAD TECHNOLOGIES, NO LOAD REDUCTION (LOPWR)						
	URBAN		HIGHWAY		COMPOSITE	
Vehicle/ technology	fuel economy MPG	fuel economy improvement %	fuel economy MPG	fuel economy improvement %	fuel economy MPG	fuel economy improvement %
base	31.2	0	42.7	0	35.5	0
1) displacement red.	35.0	12	46.6	9	39.4	11
2) friction reduction	32.8	5	44.4	4	37.2	5
3) ATM	33.0	6	46.2	8	37.9	7
4) idle-off	34.7	11	43.3	1	38.1	7
5) pumping reduction	33.1	6	44.0	3	37.3	5
1+2	36.7	18	48.2	13	41.1	17
1+2+3	38.6	24	51.4	20	43.4	22
1+2+3+4	42.5	36	52.0	22	46.3	30
1+2+3+4+5	44.4	42	52.9	24	47.8	35

Table 1.7

FUEL SAVINGS FROM FIVE PART-LOAD TECHNOLOGIES, NO LOAD REDUCTION (HIPWR)						
	URBAN		HIGHWAY		COMPOSITE	
Vehicle/ technology	fuel economy MPG	fuel economy improvement %	fuel economy MPG	fuel economy improvement %	fuel economy MPG	fuel economy improvement %
base	18.9	0	29.8	0	22.6	0
1) displacement red.	23.5	25	35.8	20	27.8	23
2) friction reduction	20.0	6	31.2	5	23.8	6
3) ATM	19.4	3	31.5	6	23.5	4
4) idle-off	21.6	15	30.4	2	24.8	10
5) pumping reduction	20.3	8	31.3	5	24.1	7
1+2	24.7	31	37.2	25	29.1	29
1+2+3	25.3	34	38.9	31	30.0	33
1+2+3+4	28.4	51	39.6	33	32.6	44
1+2+3+4+5	29.7	57	40.6	37	33.8	50

Table 1.8

SUMMARY OF FUEL ECONOMY IMPROVEMENTS BY MODIFYING AVPWR WITH 5 PART-LOAD-EFFICIENCY TECHNOLOGIES WITHOUT & WITH LOAD REDUCTION

Technology	No Load Reduction	Load Reduction Included*	
	cumulative increase (%)	cumulative increase (%)	cumulative fuel economy (MPG)
base	0	0	24.3
load reduction	-	9	26.3
displacement reduction	22	34	32.6
friction reduction	28	41	34.3
aggressive transmission management	40	56	37.9
idle off	53	73	41.9
pumping reduction (VVT)	58	81	44.0

* 20% reduction in engine load assumed

Table 2.1
CONSERVATION SUPPLY CURVE, AUTO FUEL EFFICIENCY
TECHNOLOGY GROUP 1
SAVINGS IN 2000

TECH	CONSUM COST ($)	ANNUAL COST ($)	INDIVID NEW CAR MPG INCR (%)	MARKET SHARE INCR (%)	NEW CAR FLT MPG INCR (%)	INDIVID NEW CAR MPG INCR (MPG)	NEW CAR FLT MPG INCREASE (MPG)	ACTUAL NEW CAR FLT MPG (MPG)	EPA-RATED NEW CAR FLT MPG (MPG)	COST CNSRV FUEL TECH N ($/GALLON)	AVG COST CNSRV FUEL TECH 1..N ($/GALLON)	ACTUAL FLEET MPG (MPG)	2000 ENERGY SAVINGS (QUAD BTU
BASE, 1987 MPG								21.7	28.3			21.6	
1 RCF	15	2.06	1.5	37	0.56	0.33	0.12	21.8	28.4	0.25	0.25	21.7	0.03
2 OHC	74	10.14	6.0	69	4.14	1.30	0.90	22.7	29.6	0.33	0.32	22.2	0.21
3 ADV FRIC	80	10.96	6.0	80	4.80	1.30	1.04	23.8	31.0	0.38	0.35	22.8	0.23
4 IVC	80	10.96	6.0	75	4.50	1.30	0.98	24.7	32.3	0.42	0.37	23.3	0.20
5 FWD	150	20.55	10.0	23	2.30	2.17	0.50	25.2	32.9	0.50	0.39	23.5	0.10
6 4V	105	14.39	6.8	100	6.80	1.48	1.48	26.7	34.8	0.55	0.43	24.3	0.28
7 ACCESS	29	3.97	1.7	80	1.36	0.37	0.30	27.0	35.2	0.66	0.44	24.5	0.05
8 AERO	80	10.96	4.6	85	3.91	1.00	0.85	27.9	36.3	0.70	0.47	24.9	0.15
9 TRANS	39	5.34	2.2	80	1.76	0.48	0.38	28.2	36.8	0.74	0.48	25.1	0.06
10 MPFI	67	9.18	3.5	56	1.96	0.76	0.43	28.7	37.4	0.83	0.50	25.3	0.07
11 CVT	100	13.70	4.7	45	2.12	1.02	0.46	29.1	38.0	0.95	0.52	25.5	0.07
12 LUB/TIRE	22	3.01	1.0	100	1.00	0.22	0.22	29.3	38.3	1.00	0.53	25.6	0.03
13 5AOD	150	20.55	4.7	40	1.88	1.02	0.41	29.7	38.8	1.48	0.56	25.8	0.06
14 WT RED	250	34.25	6.6	85	5.61	1.43	1.22	31.0	40.4	1.86	0.69	26.4	0.18
15 TIRES II	20	2.74	0.5	100	0.50	0.11	0.11	31.1	40.5	2.05	0.70	26.4	0.02
													1.76

Table 2.2

CONSERVATION SUPPLY CURVE, AUTO FUEL EFFICIENCY

TECHNOLOGY GROUP 2

SAVINGS IN 2000

TECHNOLOGY	CONSUM COST ($)	ANNUAL COST ($)	INDIVID NEW CAR MPG INCR (%)	MARKET SHARE INCR (%)	NEW CAR FLT MPG INCR (%)	INDIVID NEW CAR MPG INCR (MPG)	NEW CAR FLT MPG INCREASE (MPG)	ACTUAL NEW CAR FLT MPG (MPG)	EPA-RATED NEW CAR FLT MPG (MPG)	COST CNSRV FUEL TECH N ($/GALLON)	AVG COST CNSRVD FUEL TECH 1..N ($/GALLON)	ACTUAL FLEET MPG (MPG)	2000 ENERGY SAVINGS (QUAD BTU)
BASE, 1987 MPG								21.7	28.3			21.6	
1 TRANS MAN	60	8.22	9.0	75	6.75	1.95	1.46	23.2	30.2	0.18	0.18	22.4	0.35
2 RCF	15	2.06	1.5	37	0.56	0.33	0.12	23.3	30.4	0.29	0.19	22.5	0.03
3 TCLU	35	4.80	3.0	16	0.48	0.65	0.10	23.4	30.5	0.34	0.20	22.6	0.02
4 OHC	74	10.14	6.0	69	4.14	1.30	0.90	24.3	31.7	0.37	0.25	23.0	0.19
5 IVC	80	10.96	6.0	75	4.50	1.30	0.98	25.3	32.9	0.44	0.30	23.6	0.20
6 ADV FRIC	80	10.96	6.0	80	4.80	1.30	1.04	26.3	34.3	0.47	0.33	24.1	0.20
7 FWD	150	20.55	10.0	23	2.30	2.17	0.50	26.8	34.9	0.56	0.35	24.3	0.09
8 4V	105	14.39	6.8	100	6.80	1.48	1.48	28.3	36.9	0.62	0.40	25.1	0.25
9 IDLE OFF	250	34.25	15.0	50	7.50	3.26	1.63	29.9	39.0	0.75	0.45	25.9	0.26
10 ACCESS	29	3.97	1.7	80	1.36	0.37	0.30	30.2	39.4	0.82	0.46	26.0	0.04
11 AERO	80	10.96	4.6	85	3.91	1.00	0.85	31.1	40.5	0.87	0.49	26.4	0.12
12 MPFI	67	9.18	3.5	56	1.96	0.76	0.43	31.5	41.0	1.00	0.50	26.6	0.06
13 CVT	100	13.70	4.7	45	2.12	1.02	0.46	31.9	41.6	1.14	0.52	26.9	0.06
14 LUB/TIRE	22	3.01	1.0	100	1.00	0.22	0.22	32.2	41.9	1.20	0.53	27.0	0.03
15 5AOD	150	20.55	4.7	40	1.88	1.02	0.41	32.6	42.5	1.78	0.57	27.1	0.05
16 WT RED	250	34.25	6.6	85	5.61	1.43	1.22	33.8	44.0	2.22	0.68	27.7	0.16
17 TIRES II	20	2.74	0.5	100	0.50	0.11	0.11	33.9	44.2	2.44	0.69	27.8	0.01
													2.12

Table 2.3

KEY TO TECHNOLOGIES LISTED IN TABLES 2.1 and 2.2
(Technology Groups 1 and 2)

ACCESS	Improved Accessories, including Electric Power Steering
AERO	Aerodynamic Improvements
ADV FRIC	Engine Friction Reduction
5AOD	Five-Speed Automatic Overdrive Transmission
CVT	Continuously Variable Transmission
FWD	Front Wheel Drive
IDLE OFF	Idle off (Group 2 only)
IVC	Intake Valve Control
LUB/TIRE	Improved Lubrication and Tires
MPFI	Multi-point Fuel Injection
OHC	Overhead Cam Engine
RCF	Roller Cam Followers
TCLU	Torque Converter Lockup (Group 1 only)
TIRES II	Advanced Tires (improvements beyond those included in LUB/TIRE)
TRANS	Torque Converter Lockup and Electronic Transmission Control (Group 1 only)
TRANS MAN	Aggressive Transmission Management (Group 2 only)
4V	Four Valves per Cylinder Engines

Table 2.4

KEY TO COLUMN HEADINGS IN TABLES 2.1 and 2.2

ACTUAL FLEET MPG	Average actual (on-road) fuel economy of all cars (the entire automobile stock) given in the new car fleet cumulative adoption of specified technologies
ACTUAL NEW CAR FLT MPG	Actual (on-road) fuel economy of new car fleet after adoption of the specified technology
ANNUAL COST	Retail cost of each technology, annualized over ten year period at 7% discount rate
AVG COST CNSRV FUEL, TECH 1..N	Average cost of conserved fuel for specified and all preceding technologies, per gallon saved
CONSUM COST	Retail cost of each technology, per car
COST CONSRV FUEL, TECH N	Cost of conserved fuel of specified technology, per gallon saved
EPA-RATED NEW CAR FLT MPG	Federal test procedure MPG rating of new car fleet, after adoption of specified technology
2000 ENERGY SAVINGS	Energy savings in the year 2000
INDIVID NEW CAR MPG INCR (%)	Percentage increase in fuel economy attributable to each technology when applied to an individual car
INDIVID NEW CAR MPG INCR (MPG)	increase in an individual car's MPG as a consequence of using specified technology (same as above, but expressed as MPG)
MARKET SHARE INC	Projected percentage increase, relative to total new car market, in the use of each technology (i.e., penetration increase)
NEW CAR FLT MPG INCR	Percentage increase in fuel economy of new car fleet, calculated by multiplying INDIVID CAR MPG INCR by MARKET SHARE INCR
NEW CAR FLT MPG INCREASE	Increase in fuel economy for the new car fleet from implementing the specified technology at the given market share increase
TECHNOLOGY	Fuel economy technology or measure, as listed in Table 2.3

Table 2.5

SUMMARY OF RESULTS FROM PART II ANALYSIS

	Projected Auto Fleet MPG	Relativ to Froz. Eff. (Quads / % Reduction)	Relative to Market (Quads / % Reduction)
Frozen Efficiency Scenario			
EPA	28.3		
Actual	21.6	NA	NA
Market Scenario			
EPA	28.4		
Actual	21.8	0/0%	0/0%
Group 1 Cost Effective			
EPA	38.3		
Actual	29.3	2.0/26%	2.0/26%
Group 2 Cost Effective			
EPA	41.9		
Actual	32.2	2.5/33%	2.5/32%

NOTE: Analysis assumes 1,675 billion miles of automobile travel in the year 2000.

Table 3.1

A COMPARISON OF 1988 NEW CAR VEHICLE FUEL ECONOMIES AND GASOLINE PRICES

	New Vehicle Fuel Economy (MPG)	Gas Price (U.S. $)
United States	28.3	0.95
West Germany	30.9	2.18
France	35.8	3.04
Japan	27.3	3.47
Norway	31.8	3.09
Italy	34.1	3.90

Sources: World Resources Institute and Lawrence Berkeley Laboratory

Table 3.2

European Agreements for Improved New Car Fuel Economy

Country	Requirements
U.K.	Compulsory reporting of fuel consumption data. 10 percent increase in mpg (9.1 percent reduction in fuel consumption) from 1978 levels, by 1985, for passenger cars only (diesels excluded).
France	Compulsory reporting of fuel consumption data. Mean fuel consumption in new automobiles to be less than 7.5 liters/100 km (greater than 31 mpg) by 1985.
West Germany	Ten to twenty percent reduction in fuel consumption in new autos, relative to 1978, by 1985.
Italy	Ten percent lower consumption in new autos, from 1978 levels, by 1985.
Sweden	New Car Fleet Averages: 8.5 l/100 km (28 mpg) by 1985 7.5 l/100 km (31 mpg) by 1990 Voluntary, but will be made mandatory in the event of noncompliance.

NOTE: All above fuel consumption targets are voluntary, except Sweden, as noted.

Table 3.3

JAPANESE NEW CAR FUEL EFFICIENCY STANDARDS
Liters/100 km (mpg)

	Inertia Weight (kg) 625	750-875	1000-1250	1500-2000
1978 Actual	5.38 (44)	6.94 (34)	9.01 (26)	13.16 (18)
1985 Mandated	5.05 (46)	6.25 (38)	8.00 (29)	11.76 (20)
% Improvement	6.1	9.9	11.2	10.6

Table 3.4

FEDERAL TAILPIPE EMISSION CONTROL STANDARDS
FOR AUTOMOBILES AND LIGHT TRUCKS[a]

Model Year	Automobiles HC[c]	CO	NOx	Light Trucks[b] HC[c]	CO	NOx
pre-control[d]	10.6	84	4.1	8.0	102	3.6
1972-1974	3.0	28	3.1	-	-	-
1975-1976	1.5	15	3.1	2.0	20	3.1
1984-1987	0.41	3.4	1.0	0.8	10	2.3
1988-1993	0.41	3.4	1.0	0.8	10	1.2
1994[e]	0.25	3.4	0.4	0.25	3.4	0.4

KEY
HC: Hydrocarbons
CO: Carbon Monoxide
NOx: Nitrogen Oxides

NOTES:

(a) Standards for non-diesel fuel engines, certified for five years or 50,000 miles.

(b) Before 1984, trucks include all less than 8500 gross vehicle weight. After 1984, above standards apply to trucks from 0 to 3750 loaded vehicle weight (curb weight + 300 lbs.). HC, CO, and NOx standards for light trucks with LVW from 3751-5750 must meet 0.32, 4.4, and 0.7, respectively. Standards for light trucks with LVW greater than 5750 are 0.39, 5.0, 1.1, respectively.

(c) Before 1994, listed standards apply to all hydrocarbon emissions. After 1994 the listed standard applies to non-methane hydrocarbons (the pre-1994 standard continues to apply to total hydrocarbons in 1994 and afterwards).

(d) Estimate by Motor Vehicle Manufacturers Association.

(e) 1994 and later standards from 1990 Clean Air Act Amendments. Standards listed here are Tier 1, 50,000 mile/5 year, non-diesel standards. Many changes in emissions standards are not reflected here. Refer to law for more detail.

Table 3.5

TYPICAL LIGHT DUTY VEHICLE EMISSION RATES[a]
(grams/mile)

	from vehicle tailpipe	evaporation from fueling facilities[b]	evaporation from vehicle	total	tailpipe standard for cars
HC[c]	1.9[d]	0.5[e]	0.6[f]	3	0.41
CO	20[d]			20	3.4
NOx	1.6[g]			1.6	1.0

a) Light-duty gasoline fueled vehicles.
b) Refinery and distribution system losses not included.
c) Non-methane.
d) Fleet estimate from MOBILE4 (U.S. EPA Motor Vehicle Emissions Laboratory). Emissions vary strongly with model year, tampering, maintenance.
e) Emissions are strongly dependent on season and region. Estimates adapted from Argonne National Laboratory.
f) During both running and parking. Emissions vary strongly with season and region. Crude estimate based on preliminary MOBIL4 analyses.
g) Author's estimate.

Table 3.6

GAS GUZZLER TAX, ENERGY TAX ACT OF 1978

MPG	1980	1981	1982	1983	1984	1985	1986 & After
0-12.5	$550	$650	$1200	$1550	$2150	$2650	$3850
12.5-13.0	550	650	950	1550	1750	2650	3850
13.0-13.5	300	550	950	1250	1750	2200	3200
13.5-14.0	300	550	750	1250	1450	2200	2700
14.0-14.5	200	450	600	1000	1150	1800	2250
15.0-15.5	0	350	600	800	1150	1500	2250
15.5-16.0	0	350	450	800	950	1500	1850
16.0-16.5	0	200	450	650	950	1200	1850
16.5-17.0	0	200	350	650	750	1200	1500
17.0-17.5	0	0	350	500	750	1000	1500
17.5-18.0	0	0	200	500	600	1000	1300
18.0-18.5	0	0	200	350	600	800	1300
18.5-19.0	0	0	0	350	450	800	1050
19.0-19.5	0	0	0	0	450	600	1050
19.5-20.0	0	0	0	0	0	600	850
20.0-20.5	0	0	0	0	0	500	850
20.5-21.0	0	0	0	0	0	500	650
21.0-21.5	0	0	0	0	0	0	650
21.5-22.0	0	0	0	0	0	0	500
22.0-22.5	0	0	0	0	0	0	0

*The tax rate has been doubled as of January 1991.

Table 3.7

PROPOSED SCHEDULE: MINIMUM FUEL ECONOMIES
TO EARN EXTRA FUEL ECONOMY CREDITS*
(MPG)

	1996	1997	1998	1999	2000	2001
Subcompact	43.0	44.5	46.0	47.5	49.0	50.5
Compact	41.0	42.5	44.0	45.0	46.5	48.0
Mid-size	37.5	39.0	40.0	41.0	42.5	44.0
Large	33.0	34.0	35.0	36.5	37.5	39.0

*Minicompacts and two-seaters are left out of this schedule because the kinds of cars that fall under these classes are very diverse, and their fuel economies are widely divergent.

Table B.1

LINEAR REGRESSION ANALYSIS (EQ. B2), FIVE 4-CYLINDER ENGINES WITH ENGINE SPEEDS 1500-3000 RPM

Engine	Points at $P_{engine} = 0$?	a (kJ/rev)	b	R^2
Jetta 1.8 L, 79 kW	No	0.43	2.48	1.00
Golf 1.29 L, 44 kW	Yes	0.41	2.53	0.99
	No[c]	0.37	2.64	0.99
Pontiac 1.8 L, 62 kW[a]	No	0.40	2.46	0.97
GM Quad 4 2.26 L, 112 kW[b]	No	0.40	2.53	1.00

a) Marr, W.

b) Thomson, M. W., The power rating has since been increased to 134 kW.

c) regression to data not including zero power points.

Table B.2

MODEL PARAMETERS

Vehicle	cycle	a kJ/mi	b	N_{idle} rpm	L_{engine} kJ/mi	N_{ave} rpm	t_{pwr} sec/mi
LOPWR	urban	.41	2.53	1100	669	2209	786
	highway	.41	2.53	1100	662	2381	691
JETTA	urban	.55	2.30	1000	725	2188	783
	highway	.45	2.47	1000	659	2357	686
AVPWR	urban	.85	2.45	1000	857	1855	768
	highway	.85	2.45	1000	722	2016	674
HIPWR	urban	1.2	2.45	750	959	1384	763
	highway	1.2	2.45	750	799	1497	674

Table B.3

ENERGY CHARACTERISTICS (kJ/MILE) OF AVPWR BASE CAR IN THE MODEL

cycle	engine output	fuel consumption			
	L_{engine}	engine operations under power $a\ N_{ave}\ t_{pwr}$	idling $A\ t_{idle}$	provision of load $b\ L_{engine}$	total
Urban	857	2709	1149	2101	5959
Highway	722	1878	126	1770	3773
Composite	796	2335	689	1952	4975

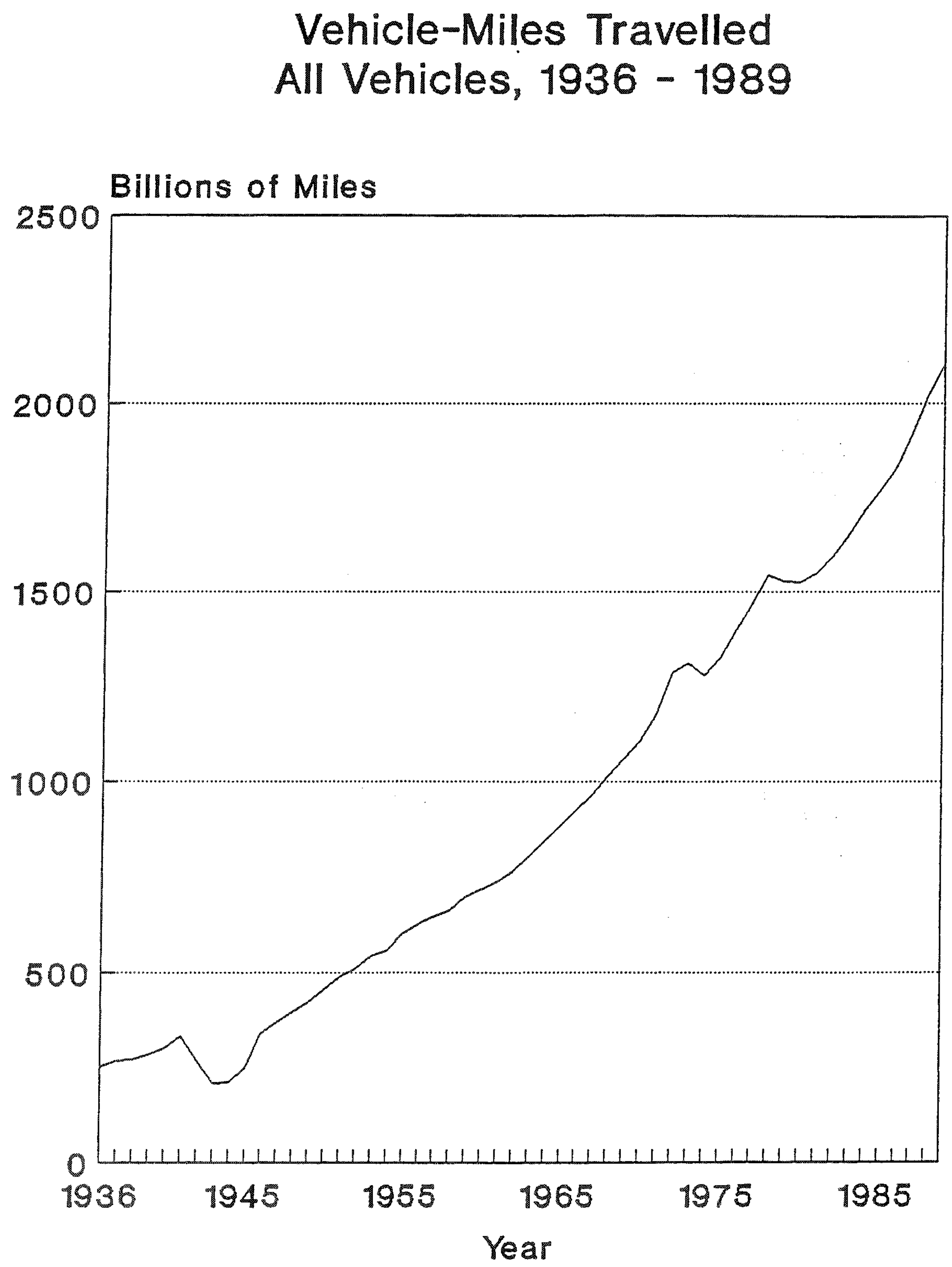
Table B.4

LINEAR REGRESSION ANALYSIS (EQ. B.1), AVPWR ENGINE MAP*, AT VARIOUS ENGINE SPEEDS

N(rpm)	a(kJ/rev)	b	R^2	range of P_{engine} (kJ/rev)
1250	.61	2.05	.998	0.2-0.7
1500	.44	2.45	.998	0.1-0.8
2500	.45	2.48	.999	0.1-0.8
3000	.49	2.48	1.000	0.2-0.85

* VW 1.8 L, 79 kW engine

Figure I.1



Source: Federal Highway Administration

Figure 1.1

Distribution in Time of a (m/s^2) vs. v(m/s) in Urban Driving Cycle

v: a:	Idle	0-3	3-6	6-9	9-12	12-15	15-18	18-21	21-24	24-27
1.2 to 1.6		19	30	18	3	3	1			
0.8 to 1.2		11	8	17	15	3	1			
0.4 to 0.8		1	6	36	43	14	3	5	1	2
0.0 to 0.4		4	6	19	132	69	22	1	20	18
cruise	243	6	1	8	38	24	14		9	9
0.0 to -0.4	5	1	10	16	83	68	21		20	15
-0.4 to -0.8	5	10	16	23	10	4	6	5		
-0.8 to -1.2	5	5	4	15	12	4	2			
-1.2 to -1.6	2	30	34	24	13	1				

Total Time : 1371 (s)

$1\ m/s^2 = 2.24$ mph/s

Figure 1.2

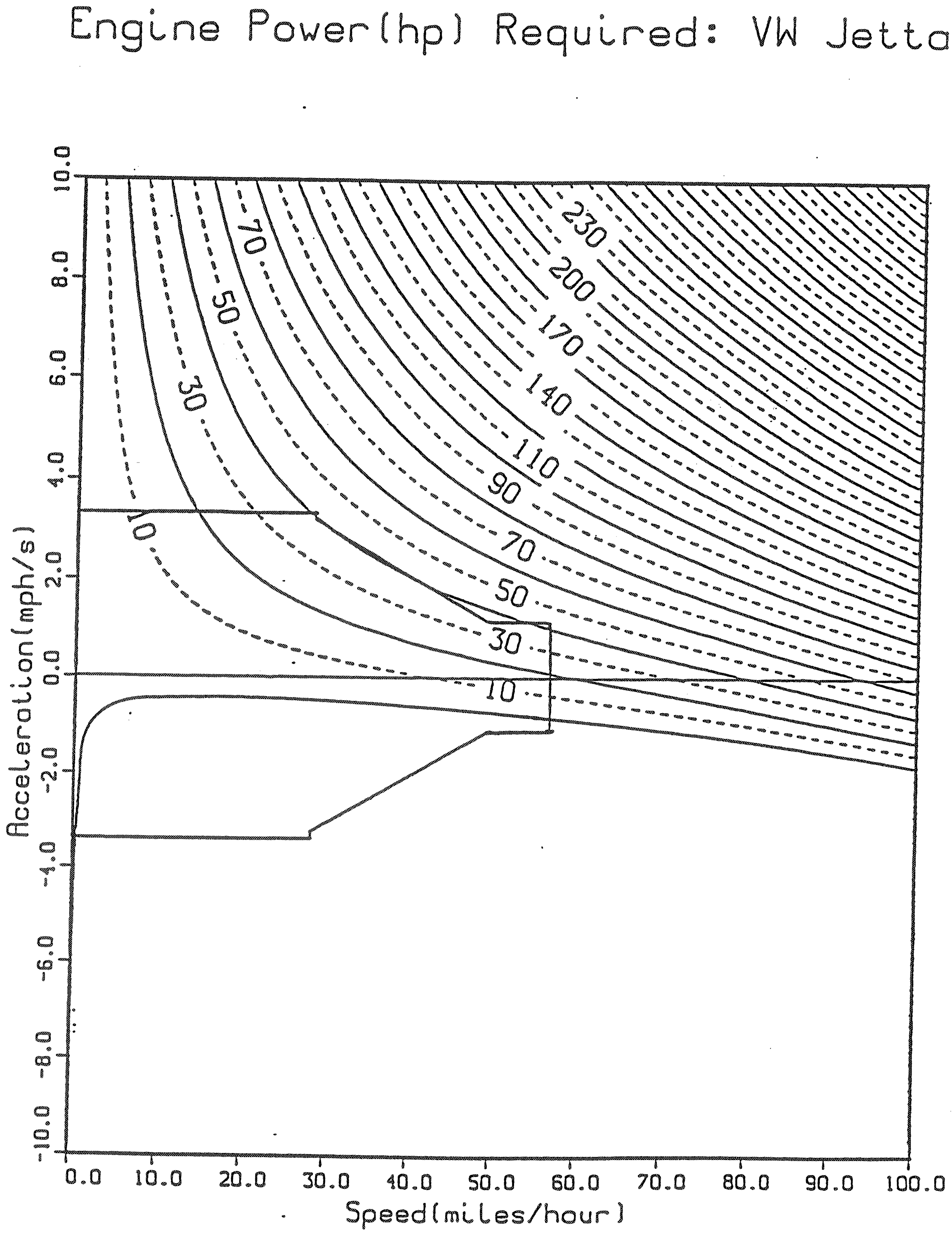

Engine Power(hp) Required: VW Jetta
230
200
170
140
110
90
70
50
30
10
Acceleration(mph/s)
10.0
8.0
6.0
4.0
2.0
0.0
-2.0
-4.0
-6.0
-8.0
-10.0
0.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
80.0
90.0
100.0
Speed(miles/hour)

Figure 1.3a

Distribution of Time Spent with respect to Engine Load in the Urban Driving Cycle

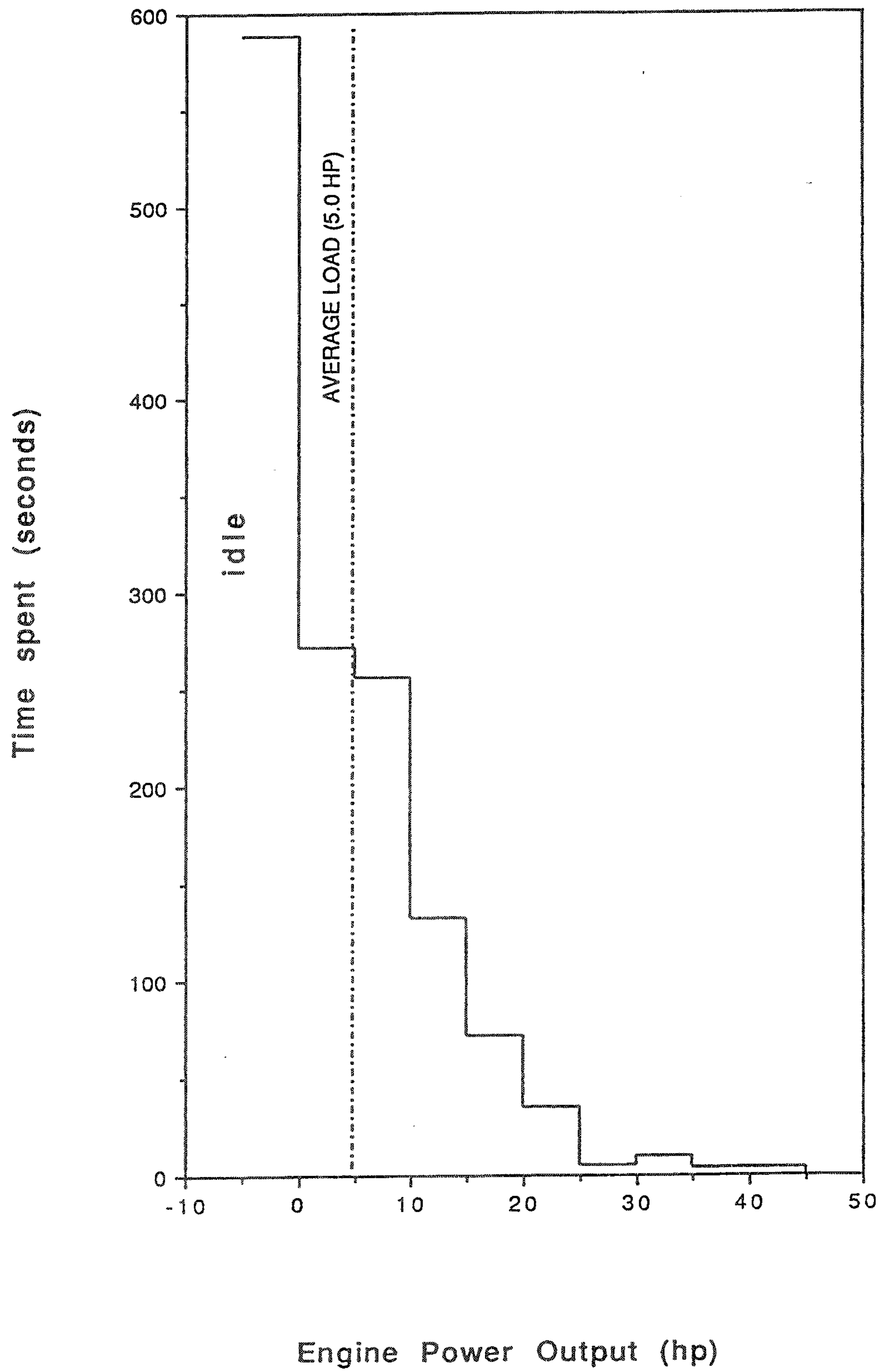


Figure 1.3b

Distribution of Time Spent with respect to Engine Load in the Highway Driving Cycle

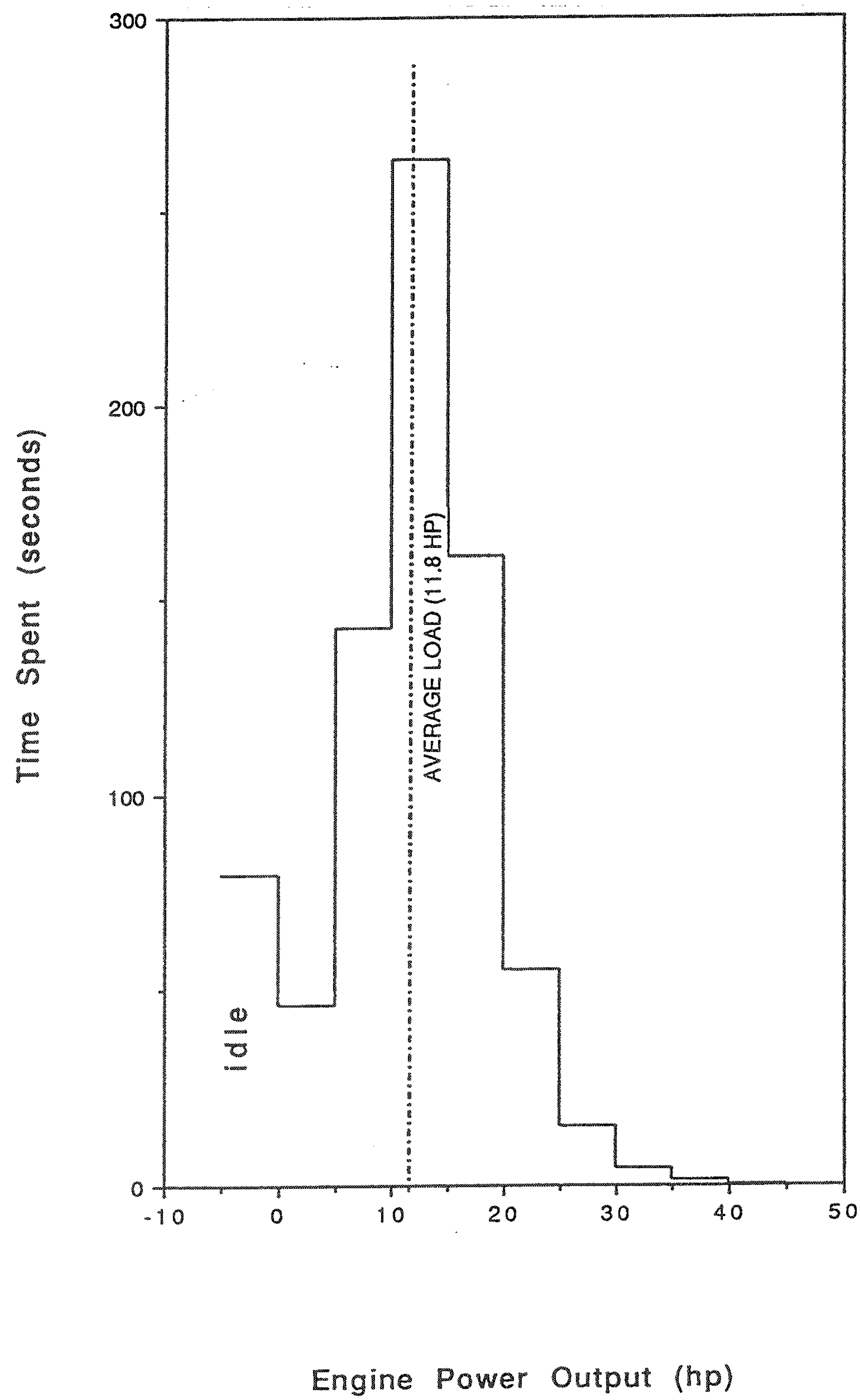
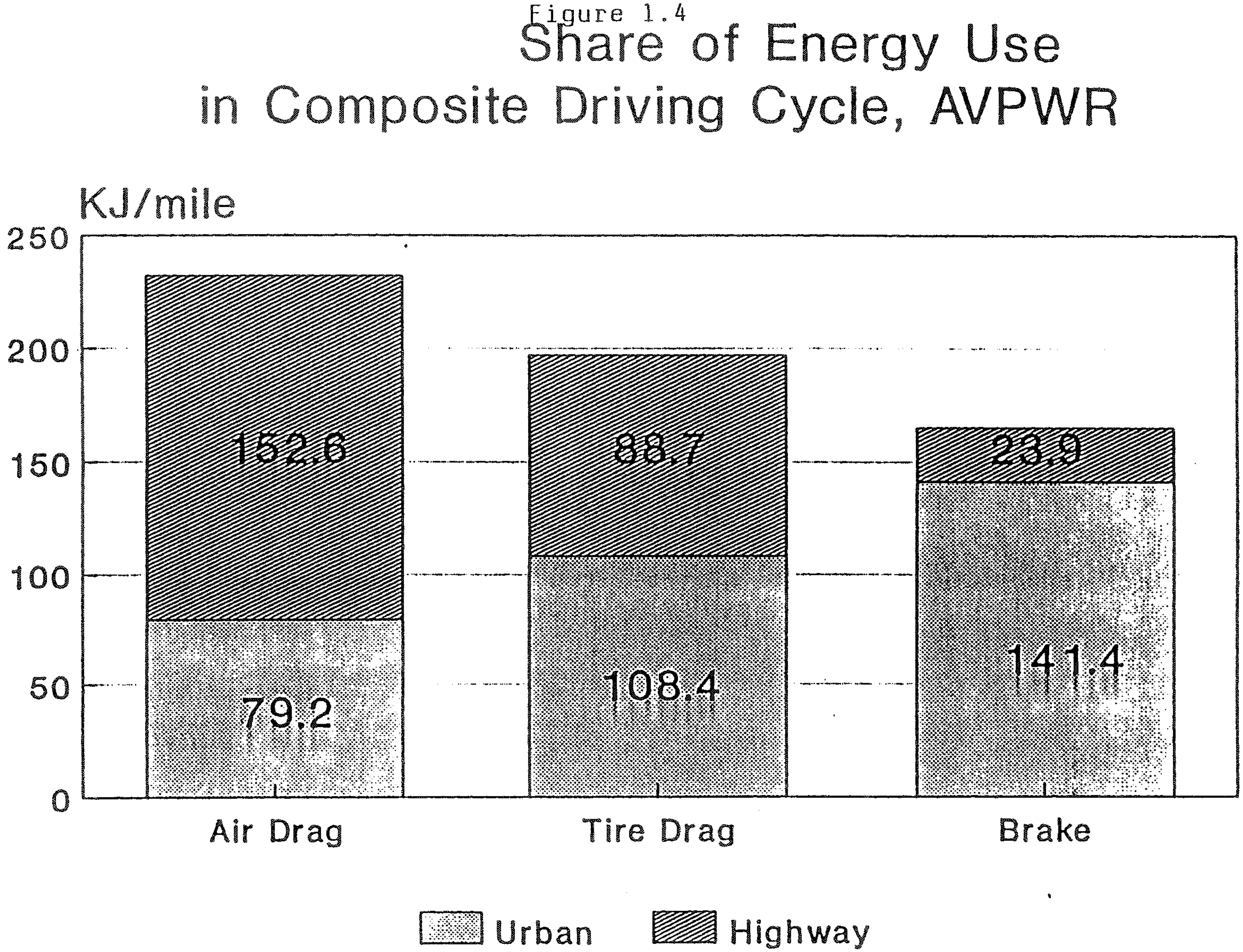


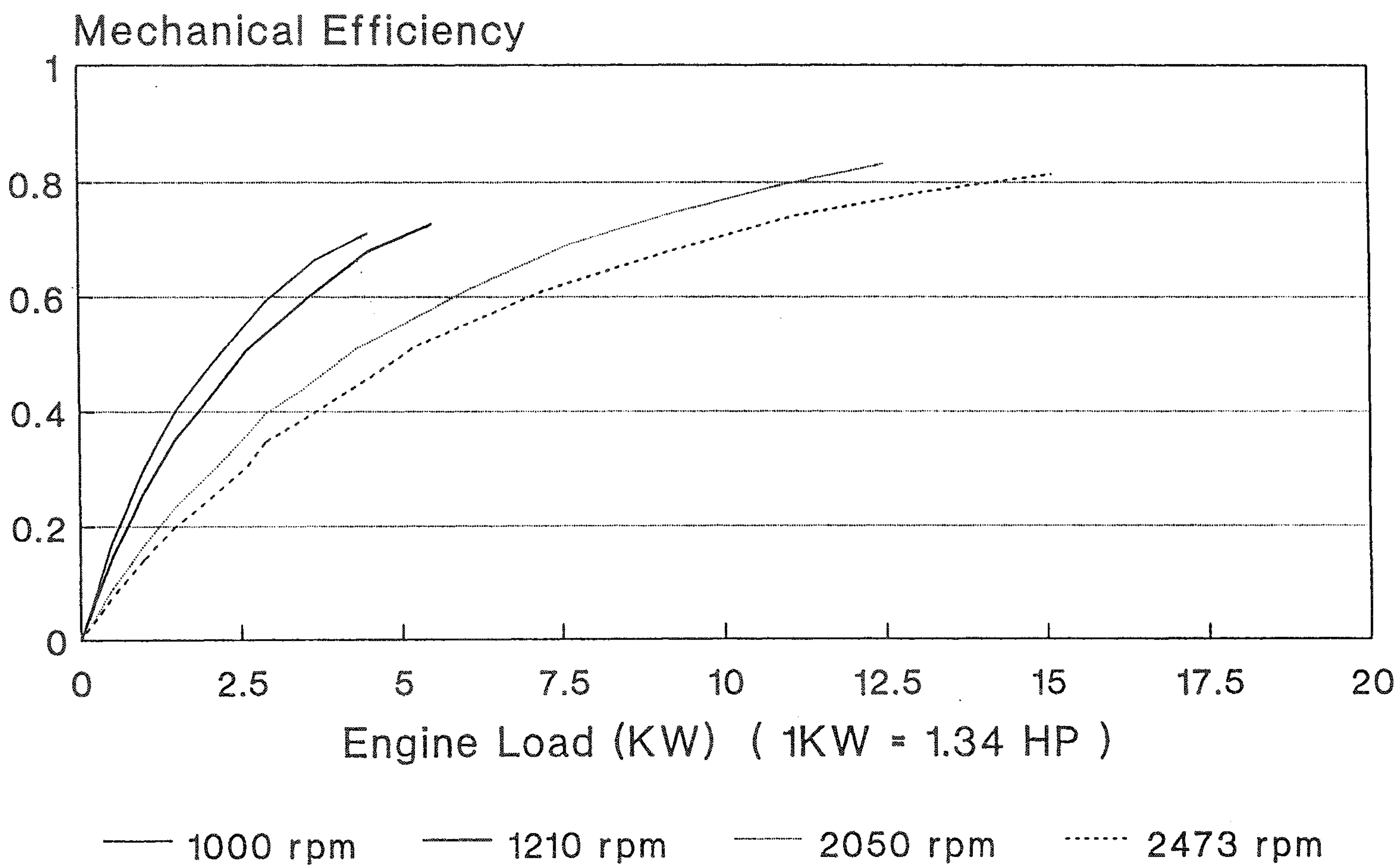
Figure 1.4



55 / 45 mix

Figure 1.5

Mechanical Efficiency vs. Engine Load



Golf 44 KW

Figure 1.6a

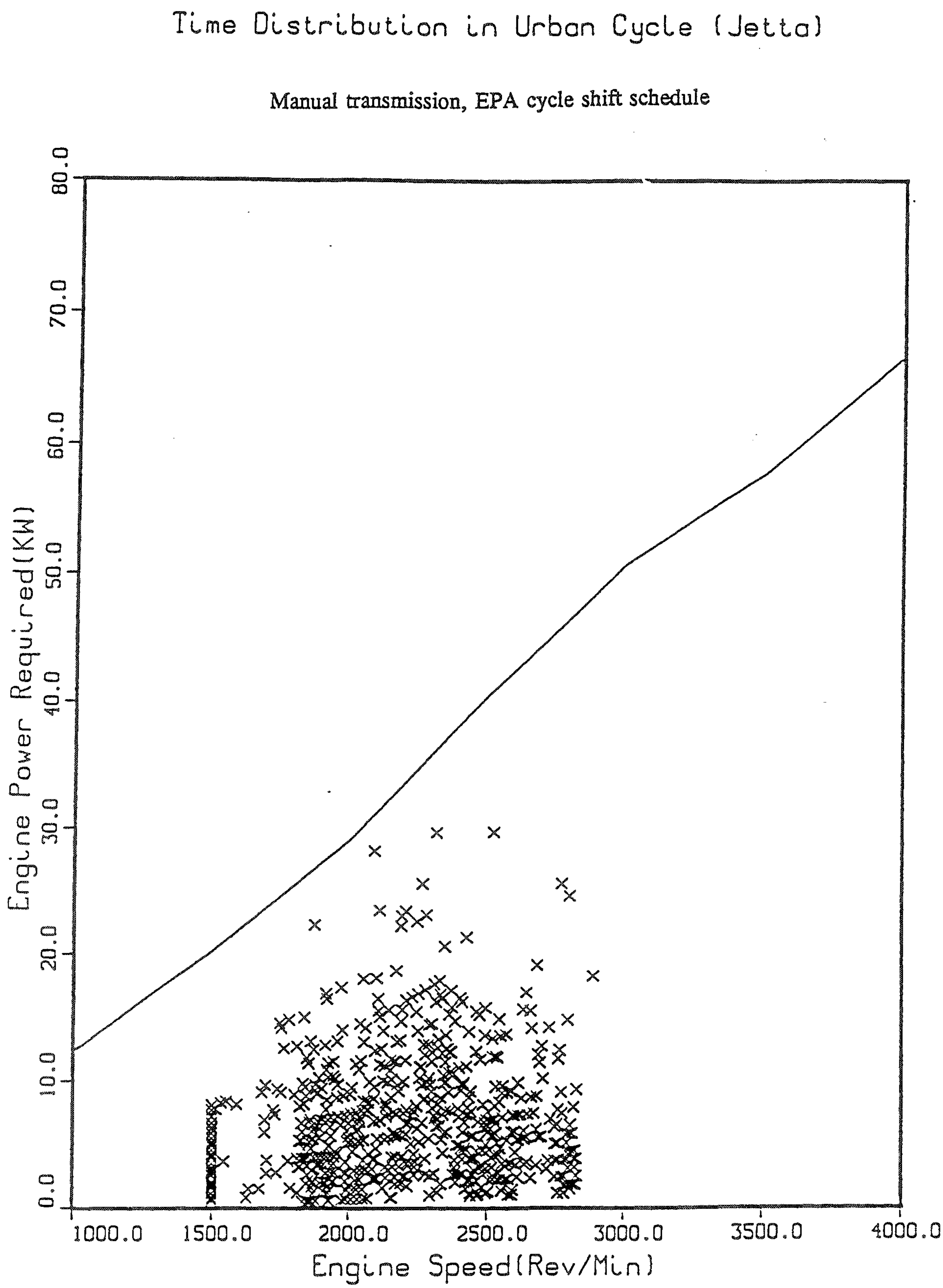

Time Distribution in Urban Cycle (Jetta)
Manual transmission, EPA cycle shift schedule
Engine Power Required(KW)
0.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
80.0
1000.0
1500.0
2000.0
2500.0
3000.0
3500.0
4000.0
Engine Speed(Rev/Min)

Figure 1.6b

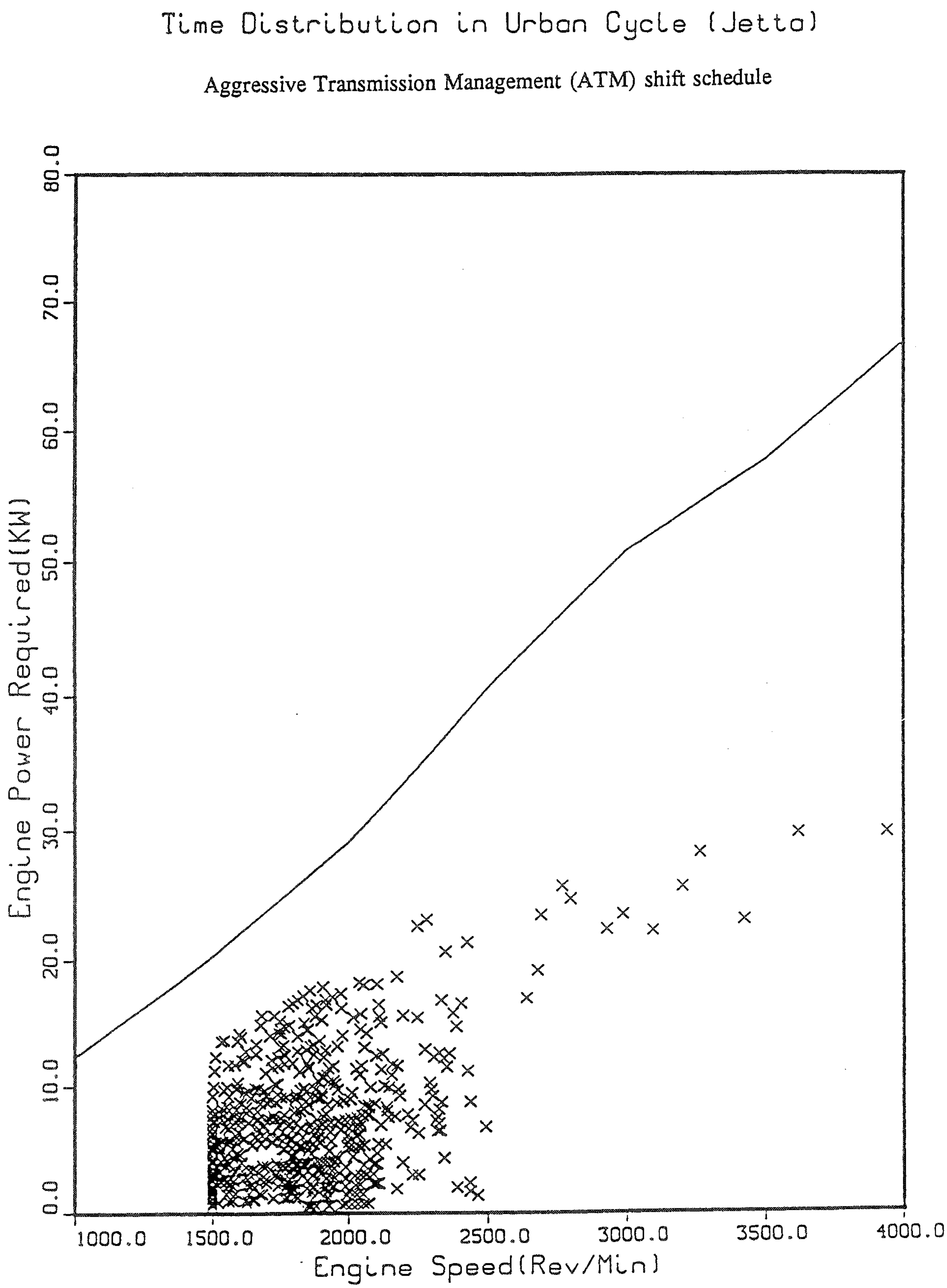
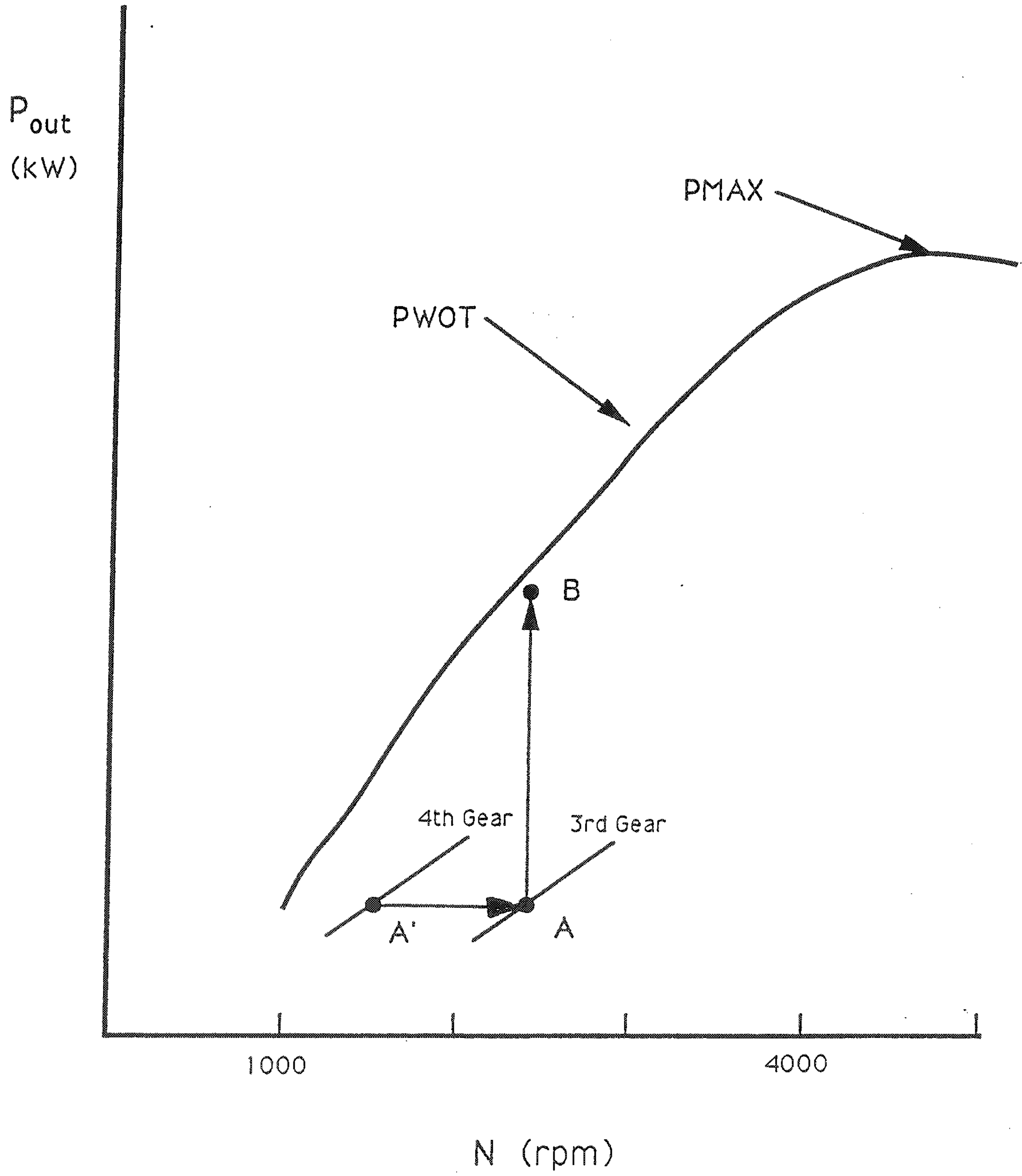

Time Distribution in Urban Cycle (Jetta)
Aggressive Transmission Management (ATM) shift schedule
Engine Power Required(KW)
0.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
80.0
1000.0
1500.0
2000.0
2500.0
3000.0
3500.0
4000.0
Engine Speed(Rev/Min)

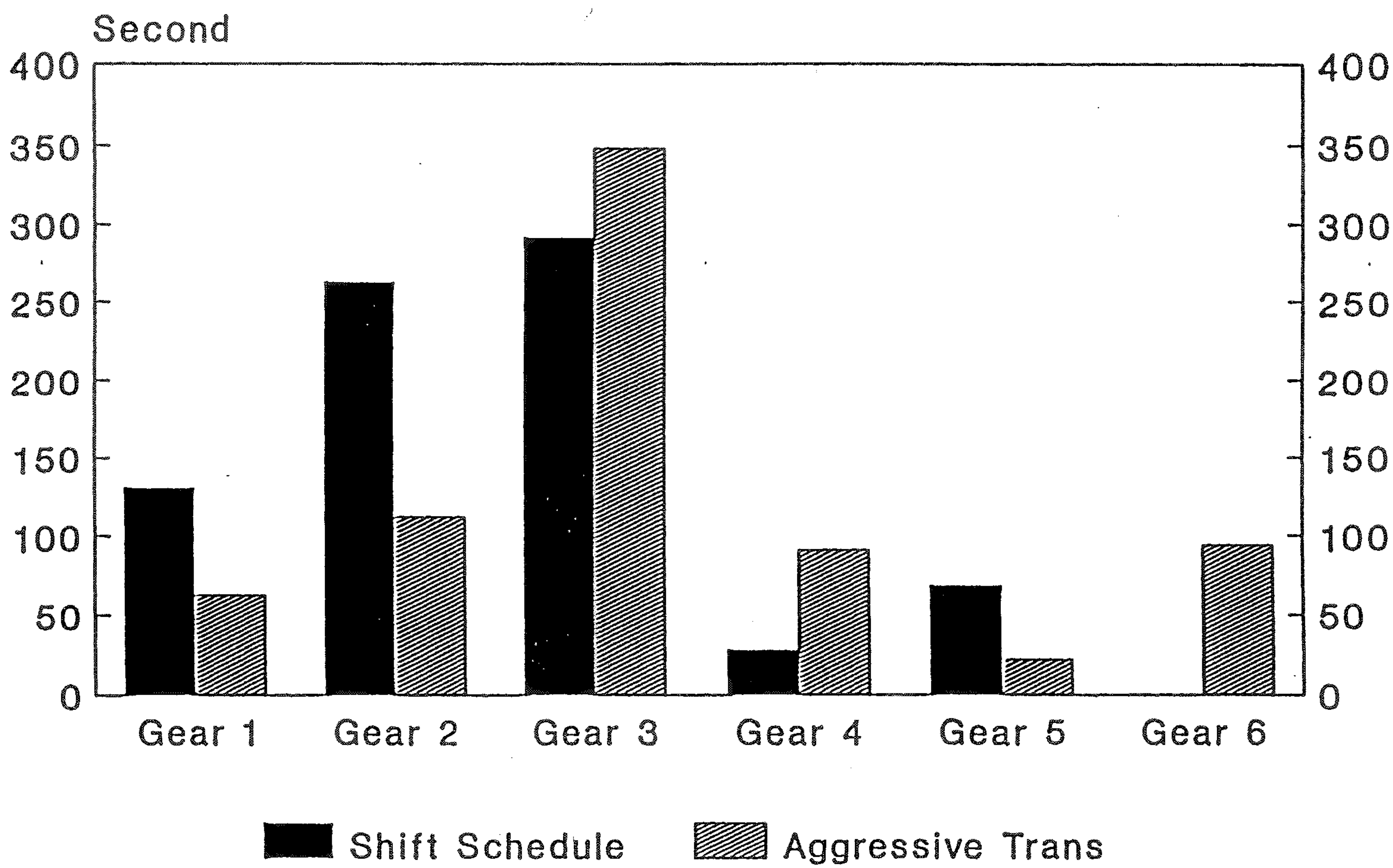
Figure 1.7



The gear lines show engine use at constant vehicle velocity.

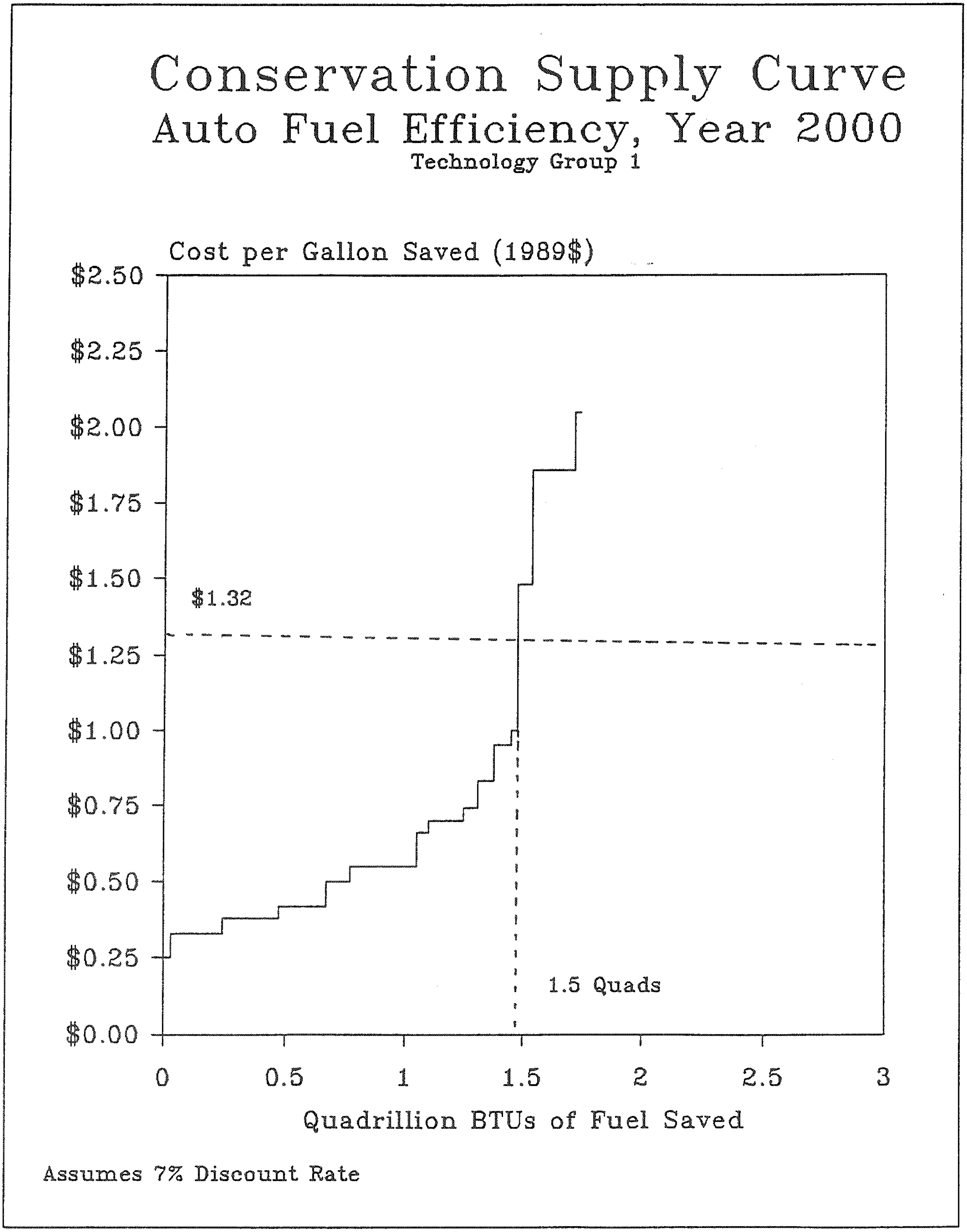
Figure 1.8

Gear Distribution in Urban Cycle (Jetta)



Total: 1371 seconds

Figure 2.1



Conservation Supply Curve
Auto Fuel Efficiency, Year 2000
Technology Group 1
Cost per Gallon Saved (1989$)
$2.50
$2.25
$2.00
$1.75
$1.50
$1.32
$1.25
$1.00
$0.75
$0.50
$0.25
1.5 Quads
$0.00
0
0.5
1
1.5
2
2.5
3
Quadrillion BTUs of Fuel Saved
Assumes 7% Discount Rate

Figure 2.2

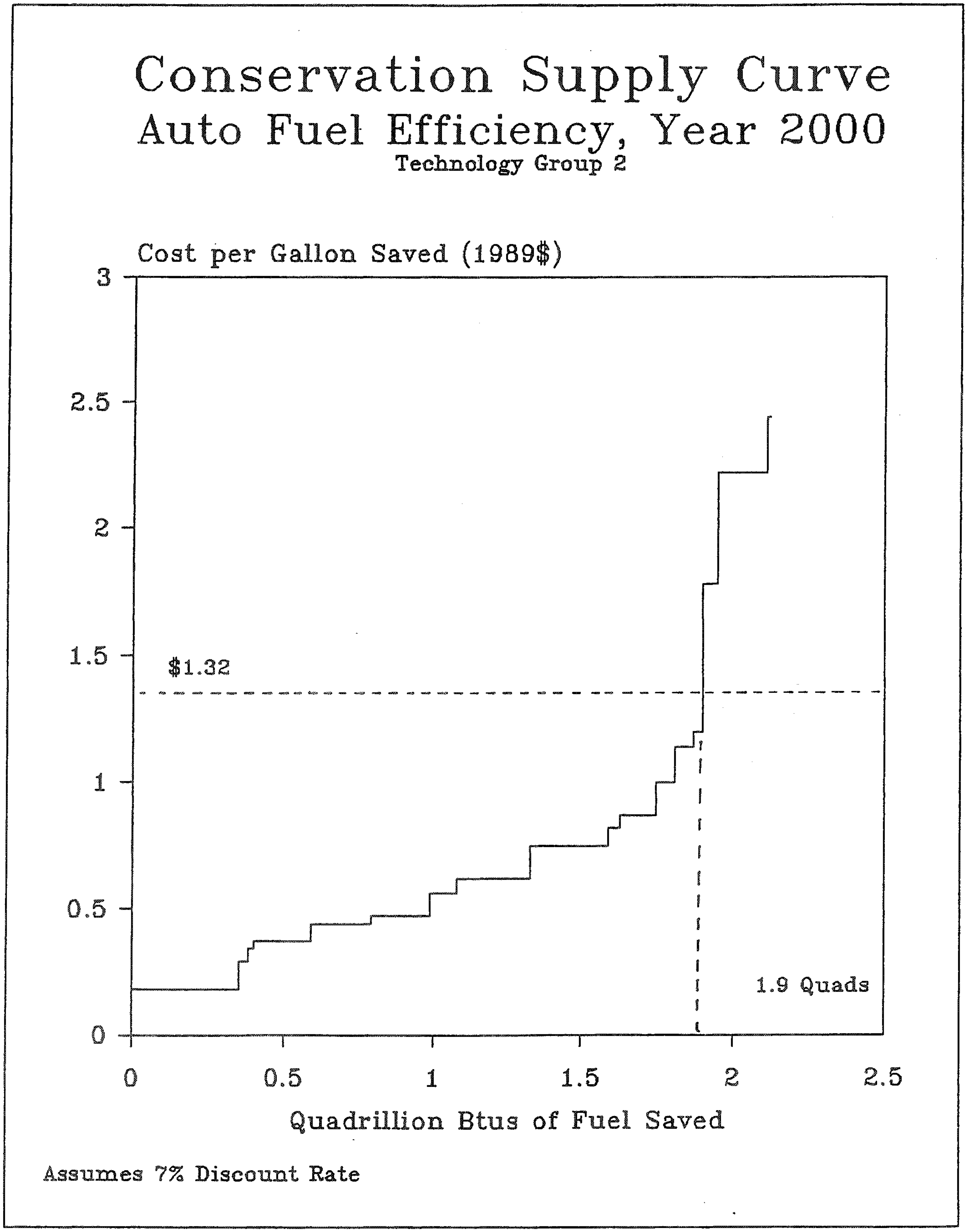

Conservation Supply Curve
Auto Fuel Efficiency, Year 2000
Technology Group 2
Cost per Gallon Saved (1989$)
3
2.5
2
1.5
1
0.5
0
$1.32
1.9 Quads
0
0.5
1
1.5
2
2.5
Quadrillion Btus of Fuel Saved
Assumes 7% Discount Rate

Figure 3.1

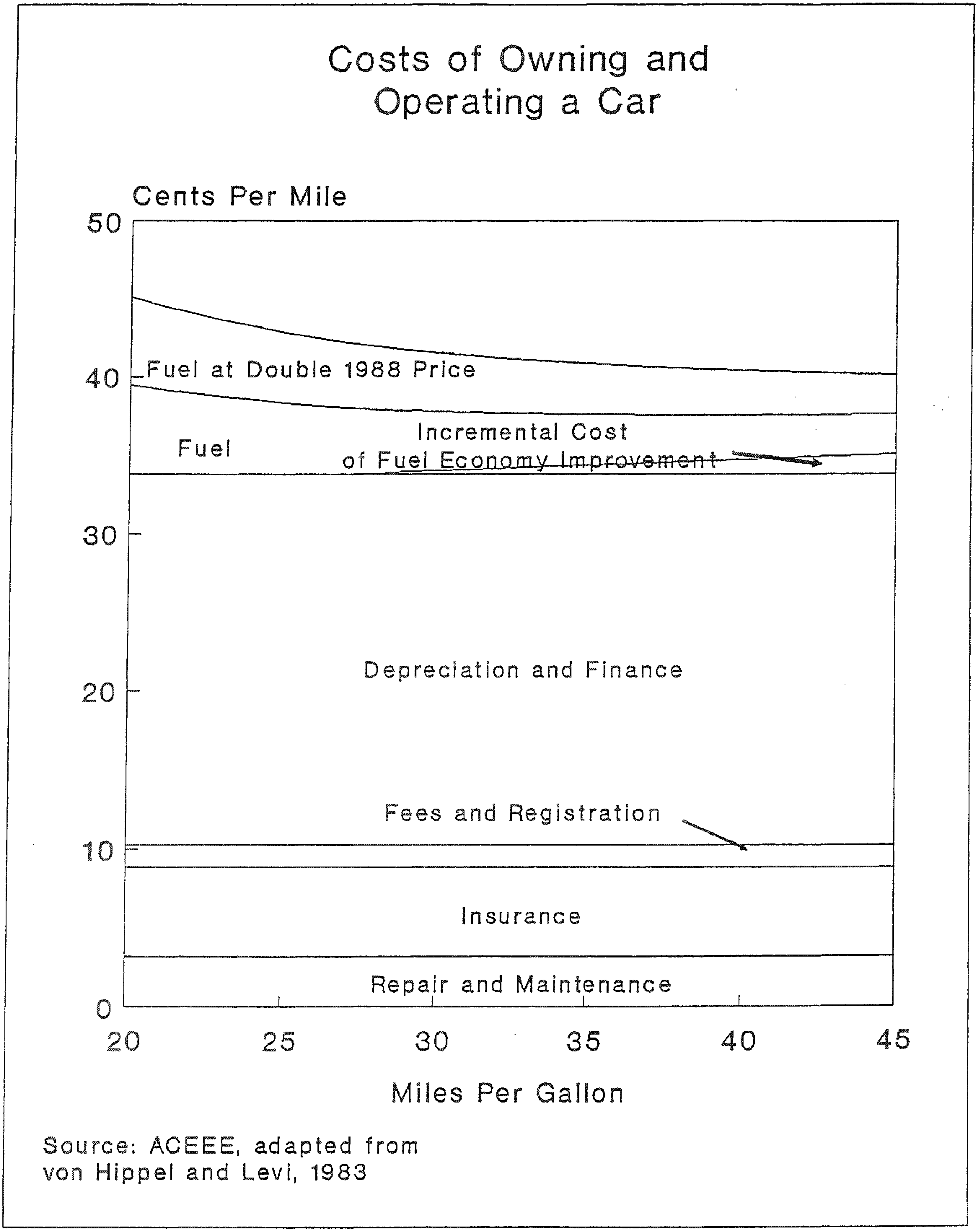
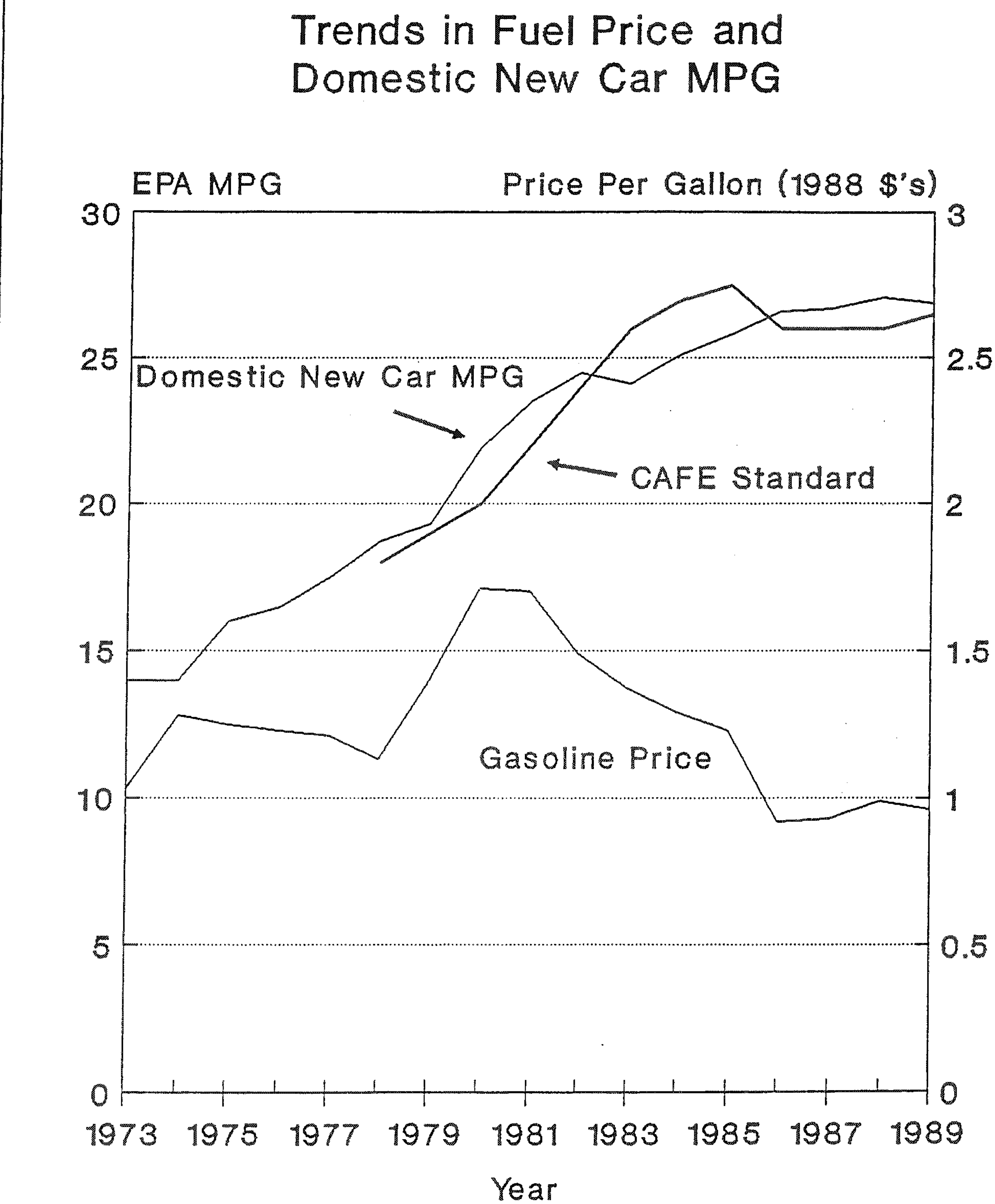

Costs of Owning and Operating a Car
Cents Per Mile
50
40
30
20
10
0
Fuel at Double 1988 Price
Fuel
Incremental Cost of Fuel Economy Improvement
Depreciation and Finance
Fees and Registration
Insurance
Repair and Maintenance
20
25
30
35
40
45
Miles Per Gallon
Source: ACEEE, adapted from von Hippel and Levi, 1983

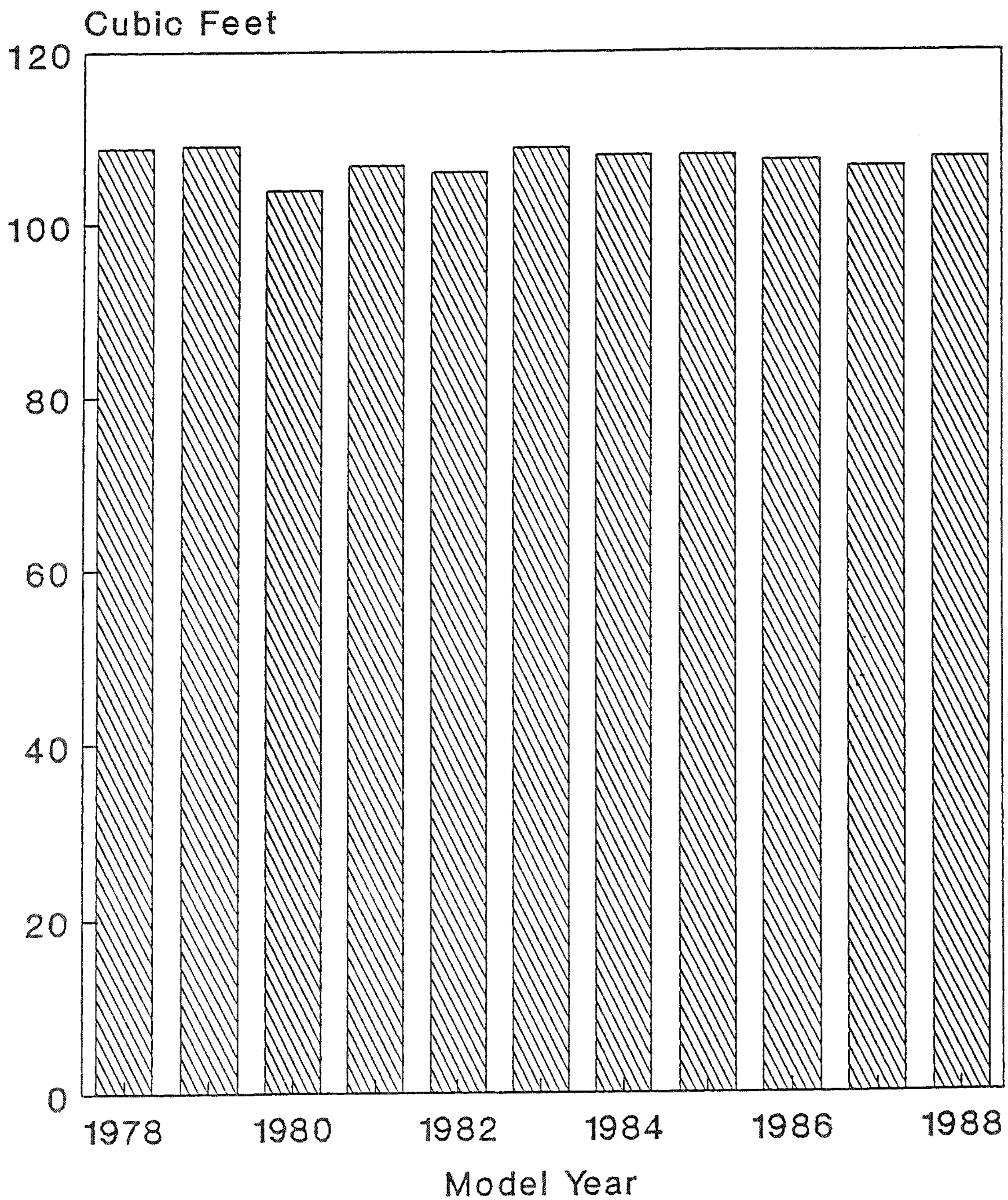
Figure 3.2



Source: ACEEE, adapted from U.S. EPA and U.S. DOE

Figure 3.3

Average Interior Volume, New U.S. Cars
1978-1988



Source: U.S. EPA

Figure 3.4

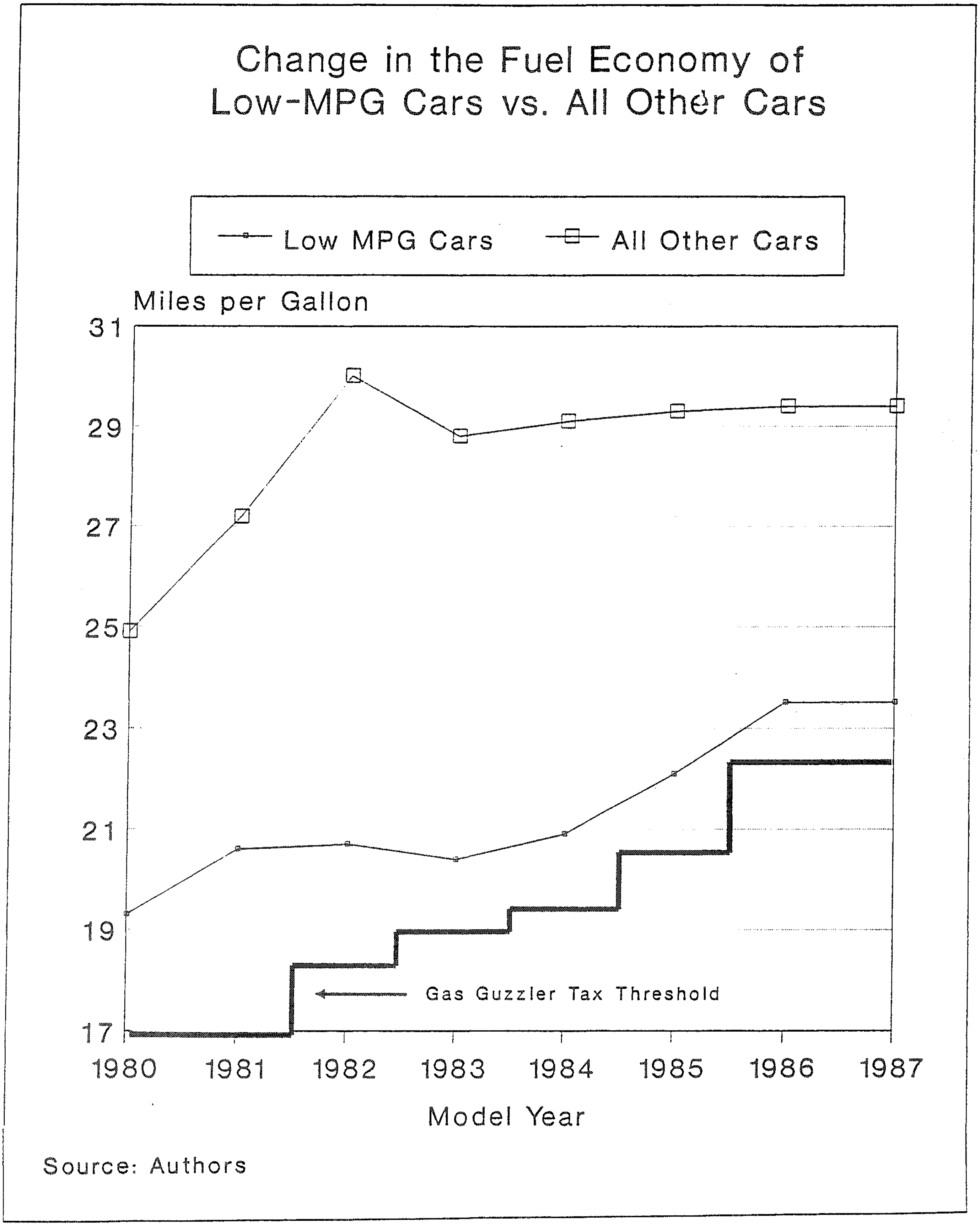

Change in the Fuel Economy of
Low-MPG Cars vs. All Other Cars
Low MPG Cars
All Other Cars
Miles per Gallon
31
29
27
25
23
21
19
17
Gas Guzzler Tax Threshold
1980
1981
1982
1983
1984
1985
1986
1987
Model Year
Source: Authors

Figure 3.5

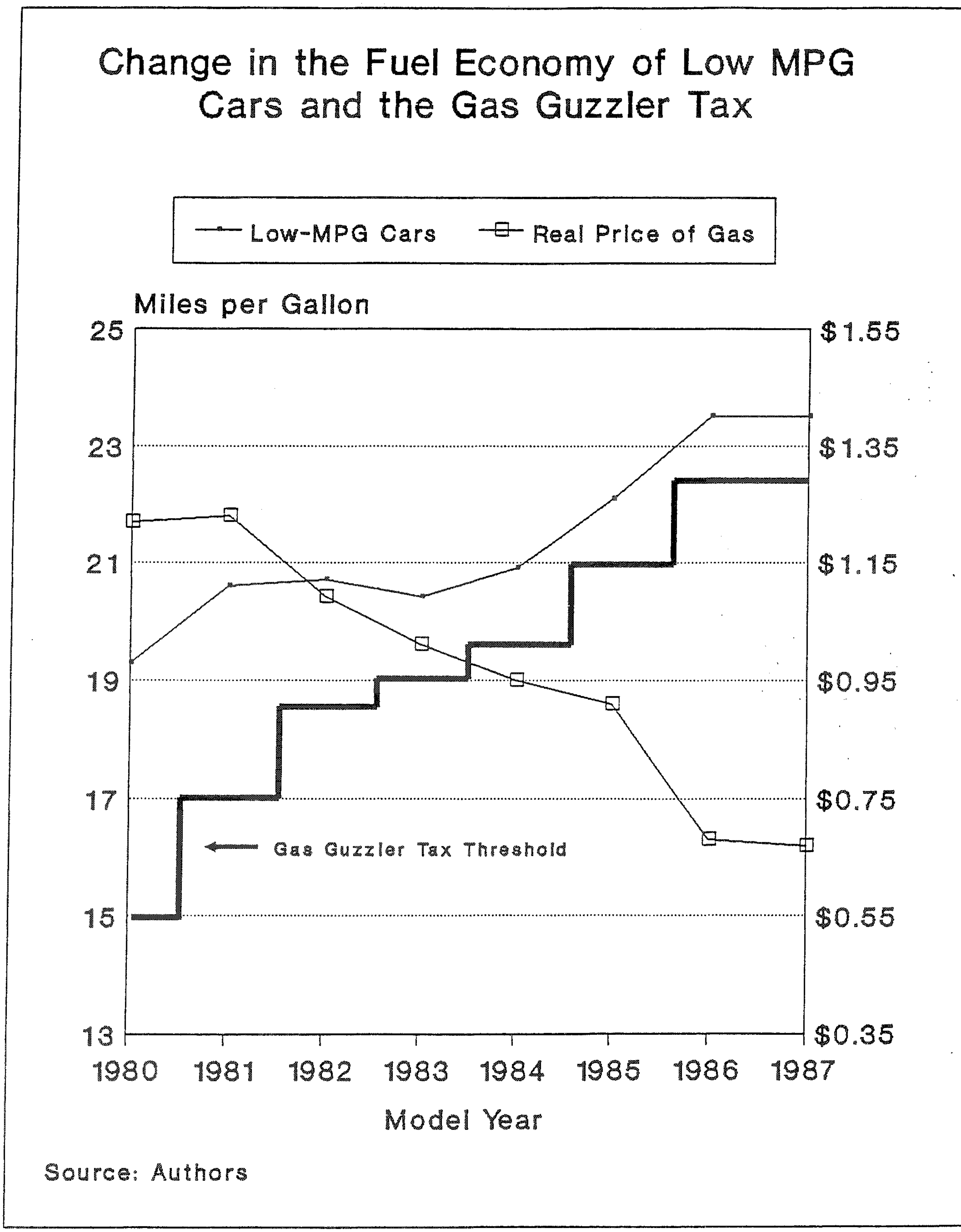
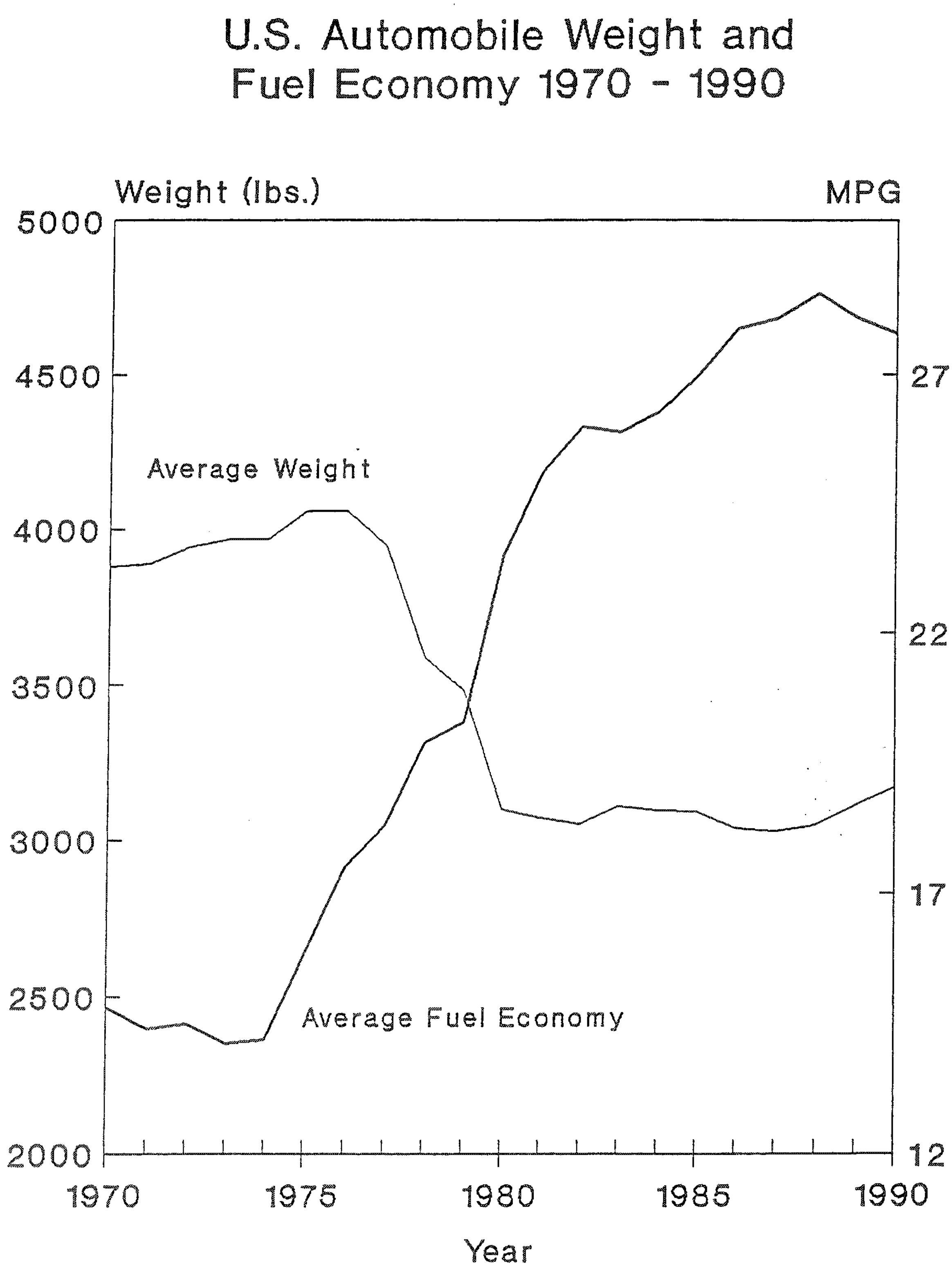

Change in the Fuel Economy of Low MPG Cars and the Gas Guzzler Tax
Low-MPG Cars
Real Price of Gas
Miles per Gallon
25
23
21
19
17
15
13
$1.55
$1.35
$1.15
$0.95
$0.75
$0.55
$0.35
Gas Guzzler Tax Threshold
1980
1981
1982
1983
1984
1985
1986
1987
Model Year
Source: Authors

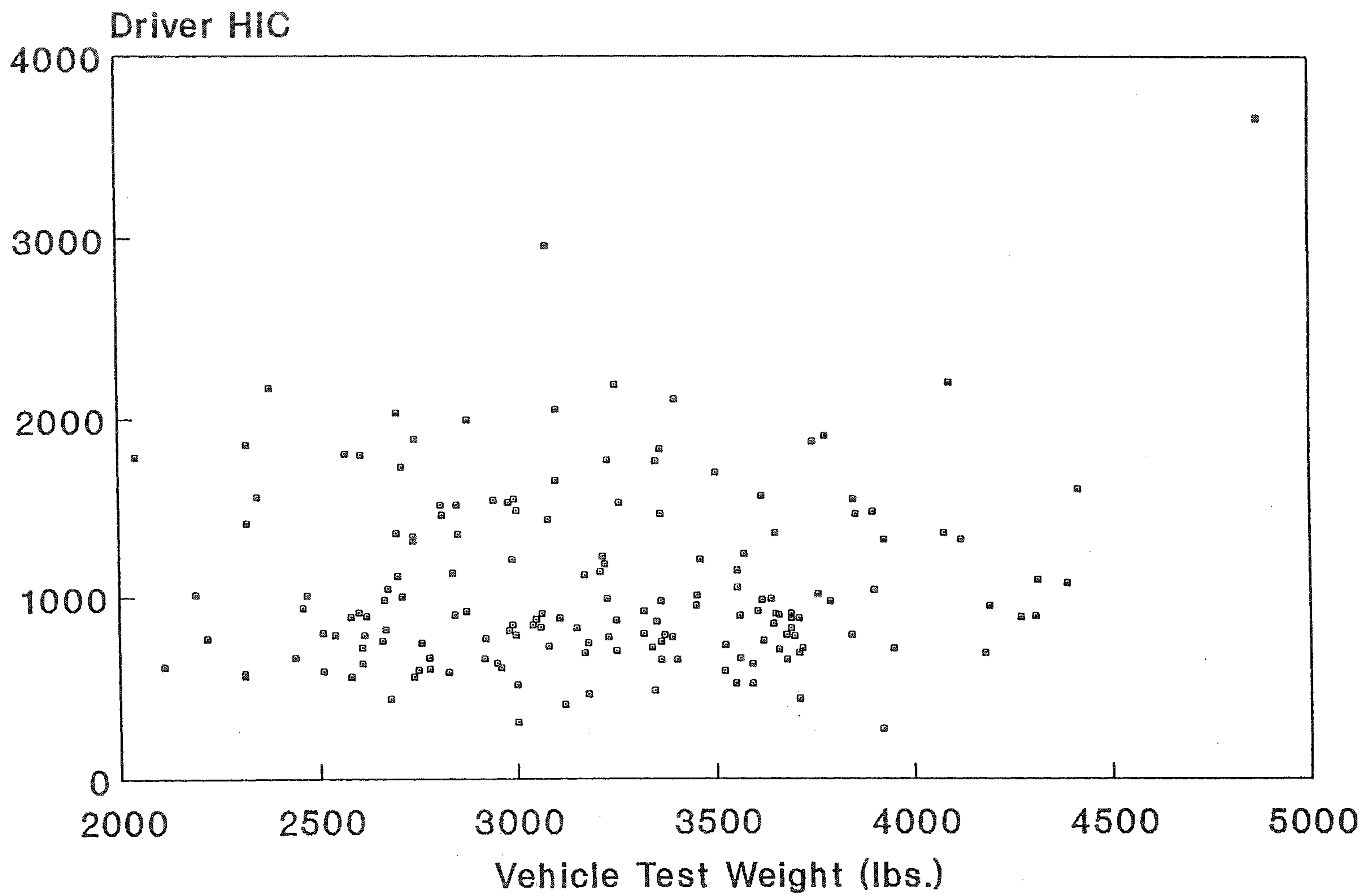
Figure 3.6



Source: ACEEE, adapted from U.S. EPA

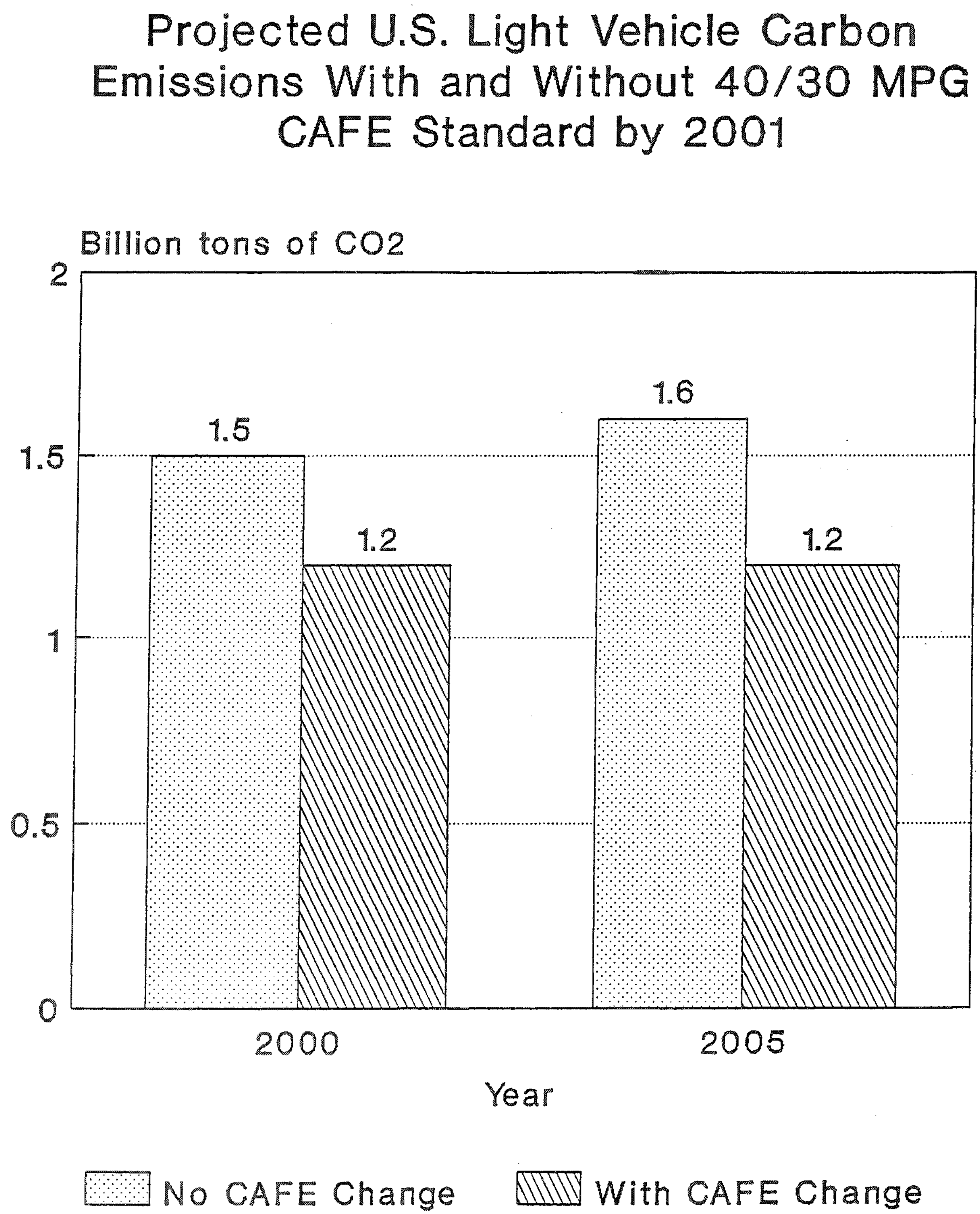
Figure 3.7

Auto Weight vs. Driver Head Injury Criterion (HIC)



Source: ACEEE based on NHTSA data

Figure 3.8



No CAFE change scenario assumes new vehicle fuel economy does not rise above current levels. Source: ACEEE

Figure 3.9

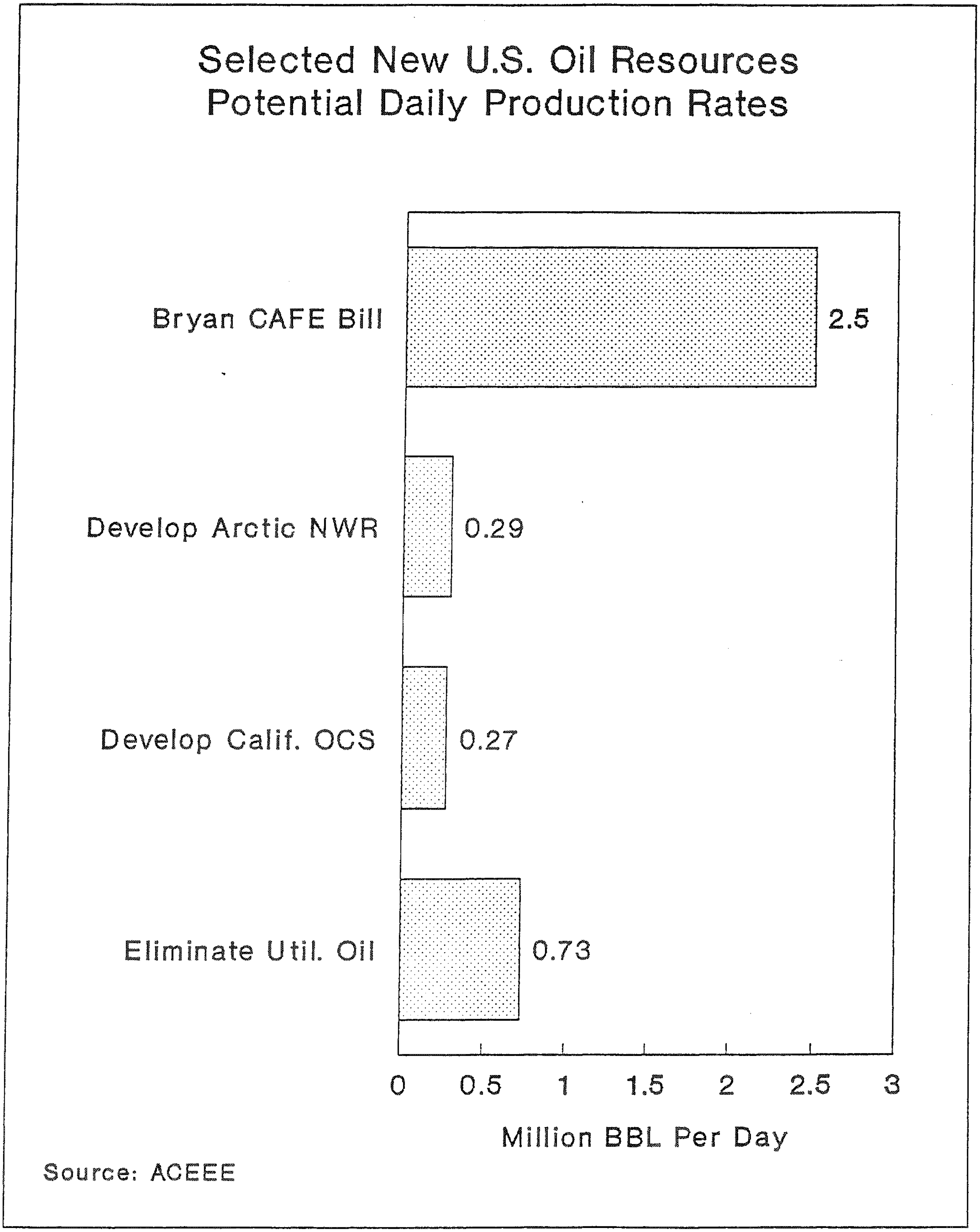

Selected New U.S. Oil Resources
Potential Daily Production Rates
Bryan CAFE Bill
2.5
Develop Arctic NWR
0.29
Develop Calif. OCS
0.27
Eliminate Util. Oil
0.73
0
0.5
1
1.5
2
2.5
3
Million BBL Per Day
Source: ACEEE

Figure B.1a

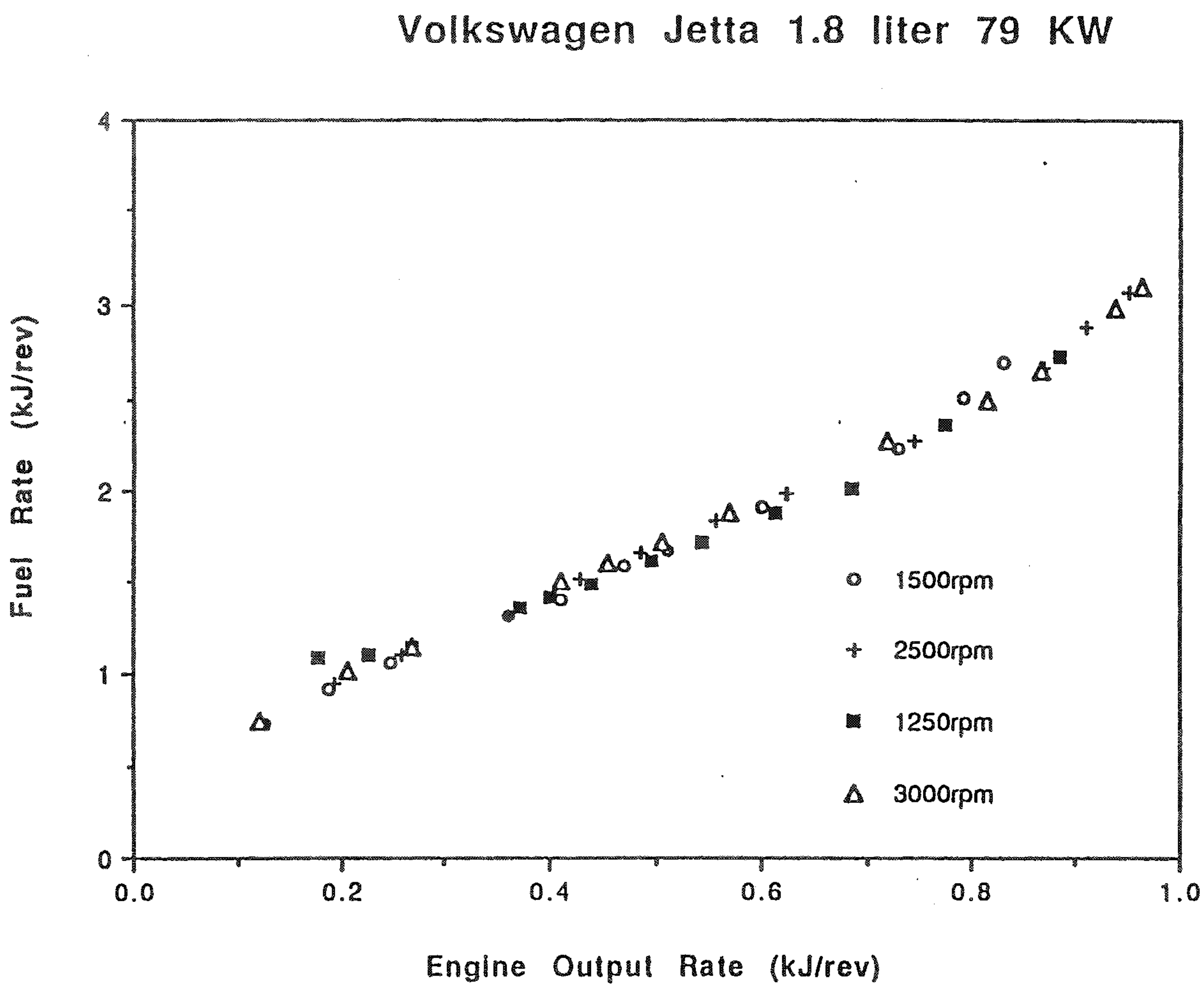

Volkswagen Jetta 1.8 liter 79 KW
Fuel Rate (kJ/rev)
Engine Output Rate (kJ/rev)
0
1
2
3
4
0.0
0.2
0.4
0.6
0.8
1.0
1500rpm
2500rpm
1250rpm
3000rpm

Figure B.1b

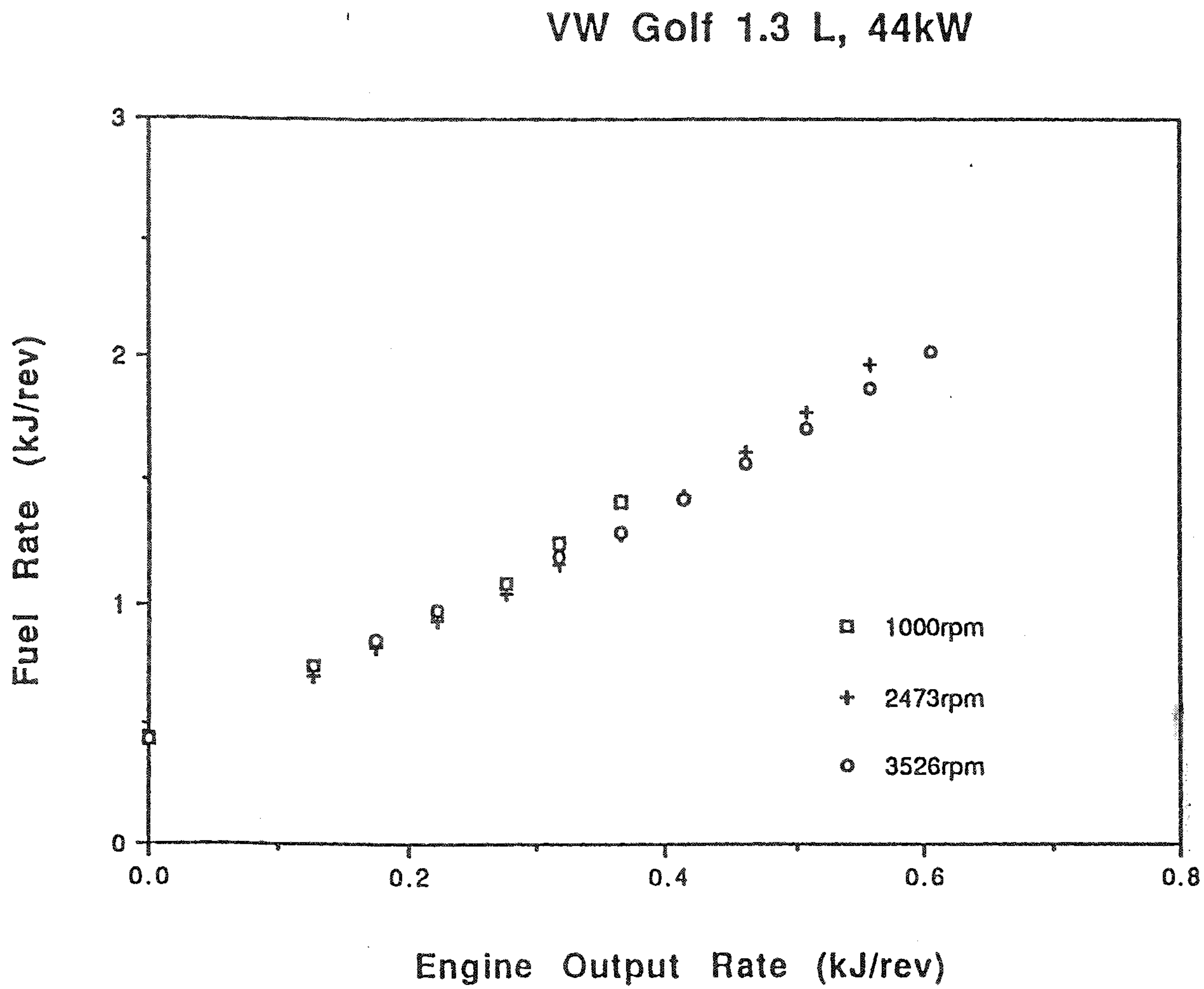
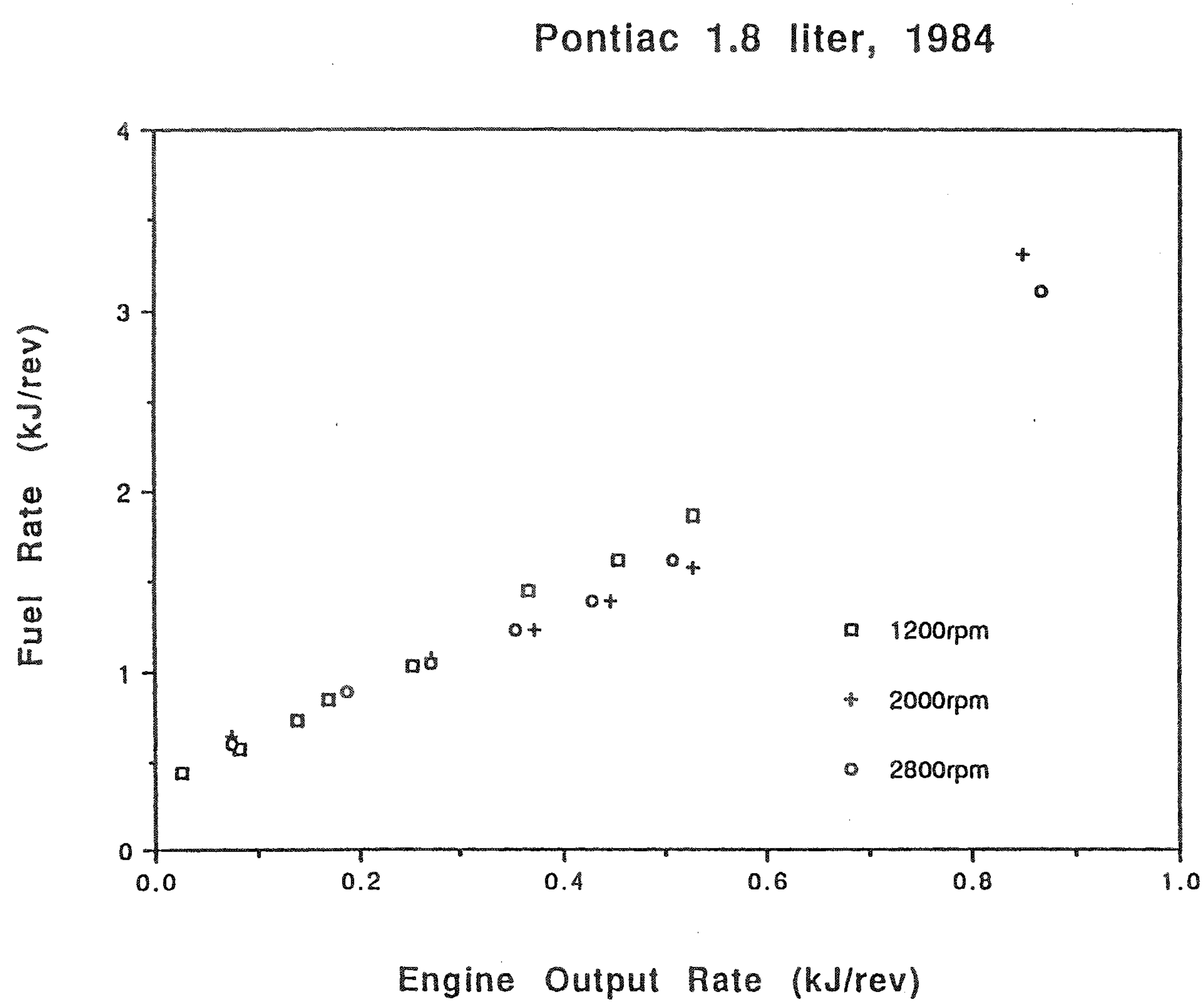

VW Golf 1.3 L, 44kW
Fuel Rate (kJ/rev)
Engine Output Rate (kJ/rev)
0
1
2
3
0.0
0.2
0.4
0.6
0.8
1000rpm
2473rpm
3526rpm

Figure B.1c



Pontiac 1.8 liter, 1984
Fuel Rate (kJ/rev)
Engine Output Rate (kJ/rev)
0
1
2
3
4
0.0
0.2
0.4
0.6
0.8
1.0
1200rpm
2000rpm
2800rpm

Figure B.1d

GM Quad 4 2.3 liter