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AUTOMOBILE FUEL CONSUMPTION AND EMISSIONS: Effects of Vehicle and Driving Characteristics

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I. INTRODUCTION

Energy consumption by motor vehicles is a vexing issue across the world, because vehicle use is growing rapidly and the fuel is petroleum based. As a result, large balance-of-trade deficits are often involved, and transportation systems are sensitive to the actions of oil-exporting countries. In the United States, since the mid-1980s, vehicle-miles have grown about 3 1/2 percent per year (1), and, until 1991, the fuel intensity[1] of the average car had been declining about 3 percent per year (2). After accounting for the shift toward use of trucks as cars, the result has been an upward creep in gasoline consumption from 1984 to 1992 of about 1% per year (2). The fuel intensity of automobiles had been decreasing because of the regulatory standards for Corporate Average Fuel Economy, and the fact that older, low-fuel-economy vehicles were being retired. This process is now essentially complete. In fact, in 1992 the average fuel economy of automobiles in use declined for the first time since 1973. We can now expect motor-vehicle fuel use to increase as rapidly as vehicle-miles traveled, with a concurrent rise in US imports of petroleum.

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In this review, the factors that influence the energy intensity of light highway vehicles are presented in some detail, so that a reader can estimate for him- or herself the effects of changed vehicle or driving characteristics on fuel economy. Technologies to improve fuel economy are then discussed, and an example of a high-fuel-economy conventional car presented. Alternative vehicle-energy technologies are also briefly discussed, especially from a policy perspective, in the final section.

Vehicular emissions also cause vexing problems. Although some progress has been made in improving ambient air quality in major metropolitan areas, most of these areas still do not meet clean air standards. An important part of the cause of this shortfall in pollution reduction is that actual automotive emissions per mile are much higher than those measured in the regulatory test (3). Several sources for these excess emissions have been identified. With the present vehicle-energy system, each of several major sources has to be addressed with carefully designed regulations and, perhaps, with substantial costs for equipment on cars and/or at refineries. Because of the complexity of the emissions issues, only two sources of excess emissions are discussed, and those only for certain pollutants.

II. THE ENERGY INTENSITY OF AUTOMOBILES

Our subject is the potential for reducing the energy intensity of light-duty motor vehicles, or, if one prefers, increasing their fuel economy (miles per gallon or mpg). The effects of both changed patterns of driving and changed vehicle technology are discussed, with the emphasis on the latter. Many believe that reducing vehicle size is the most effective way to increase fuel economy. Reducing the maximum power per unit of vehicle weight can also make a major contribution. The general formalism presented here enables study of

[1] Or energy intensity. Amount of fuel or energy used per distance traveled, in units of e.g. gallons per mile.

these possibilities, but the focus of this discussion is yet a third kind of change—technological improvement without reducing vehicle size or performance. This type of change was behind most of the progress from 1975 to 1988 (4, 5).

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, are making it practical to do the things only dreamed of by the automotive pioneers such as Nikolaus Otto, Gottlieb Daimler, and Rudolf Diesel. This technological ferment can be sensed by reading papers of the Society of Automotive Engineers and attending their conferences.

Power Requirements

In recent years, the maximum power of new cars has increased rapidly. The average power/vehicle-weight ratio of new cars has risen from a low of 32 hp/1000 pounds for the period of 1980–1982 to 43 hp/1000 pounds in 1993, and acceleration times have fallen (4). This increase in maximum power has been a useful marketing tool, as can be seen from the fact that, for many models, most customers are sold a high-power version.

Maximum power requirements can be calculated from the loads on a vehicle. The five loads are: tire rolling resistance (resistance to the moving deformation of the tire as it rolls), air drag, vehicle acceleration, hill climbing, and vehicle accessories such as air conditioning, lights, audio system, power steering, and power brakes (6). (Engine accessories, such as water pump and fan, are considered separately below.) The five (in power units of kW) are, respectively:

$$P_{\text{tires}} = C_R M g v \qquad 1.$$

$$P_{\text{air}} = 1/2 \rho C_D A v^3/1000 \qquad 2.$$

$$P_{\text{inertia}} = 1/2[\Delta v^2/\Delta t] \qquad 3.$$

$$P_{\text{grade}} = M g v \sin\theta \qquad 4.$$

$$P_{\text{acc}} \qquad 5.$$

Here C_R is the coefficient of rolling resistance; M is the vehicle mass (including what it carries) in tonnes; g is the acceleration due to gravity, v is speed in m/s; ρ is the density of air (roughly 1.2 kg/m^3); C_D is the coefficient of drag; A is the frontal area in m^2; $[\Delta v^2/\Delta t]$ is in m^2/s^3; and $\tan\theta$ is the grade. The last two variables can be negative.

Consider three cases: (*a*) sustained hill climbing on a 6% grade, (*b*) sustained, or cruise, driving at high speed on the level, and (*c*) accelerating 3 mph/s (4.8 km/h)/s at high speed on the level. The engine power required, in the sales-weighted average 1993 model car (AVCAR '93) with characteristics shown in Table 1, is shown for the three cases as a function of speed in Figure 1. It is seen that roughly 30 kW might suffice for sustained driving in demanding situations, while the 105 kW maximum provided in the average car enables one to accelerate rapidly at speeds far above legal limits. (Weight dominates the hill climbing, air drag the high-speed cruise, and weight the peak acceleration.)

Table 1 Characteristics of two vehicles

	AVCAR '93	High-MPG
inertial weight[a] [lbs (curb weight plus 300 lb)]	3234	2749
inertial mass[a] (tonnes)	1.467	1.247
interior volume[a] (cubic feet)	108.4	108.4
engine displacement[a] (liters)	2.77	1.40
maximum power[a] (kW)	105	89
N over v (rpm/mph)	34.0	34.0
engine speed under power (rpm average)	1870	1870
idle speed (rpm)	731	731
engine friction at zero power k [kJ/(rev · l)] (see Eq. 7)	0.225	0.191
fuel use slope b (defined by Eq. 7)	2.5	2.5
thermal efficiency η_t (%)	38	39
power to weight ratio (hp/1000 lbs)	43.5	43.5
rolling resistance C_R	0.010	0.0075
air resistance $C_D A$ (m^2)	0.663	0.507
transmission efficiency ϵ	0.87	0.92
vehicle accessory power P_{acc} (kW average)	0.75	0.50

[a] For AVCAR '93, these are sales-weighted averages (Ref. 4, Table 1). The remainder of the AVCAR values roughly characterize modern cars of this size and power.

The power required of the engine during typical patterns of driving is relatively low, however. High power is required only in the unusual driving conditions just mentioned, conditions most drivers rarely encounter. Vehicles of average weight with modest engines, say 30 hp/1000 lbs or 72 kW maximum for a car of AVCAR '93 weight, can be used to accelerate rapidly at moderate speeds (Figure 1). So acceleration at moderate speeds is not a rationale for high power. (Rapid acceleration with a modest engine may, however, require downshifting of the gears, as discussed below.) The high power of most of today's cars is a major cause of engine inefficiency, because it is achieved with large engines with large frictional loads.

Engine Efficiency

The overall engine efficiency is the product of two factors: *thermal efficiency*, expressing how much of the fuel energy is converted into work moving the pistons, and *mechanical efficiency*, the fraction of that work that is delivered by the engine to the vehicle (the rest going to overcome frictions in operating the engine). Until recently, the best practical combustion-based engines (boil-

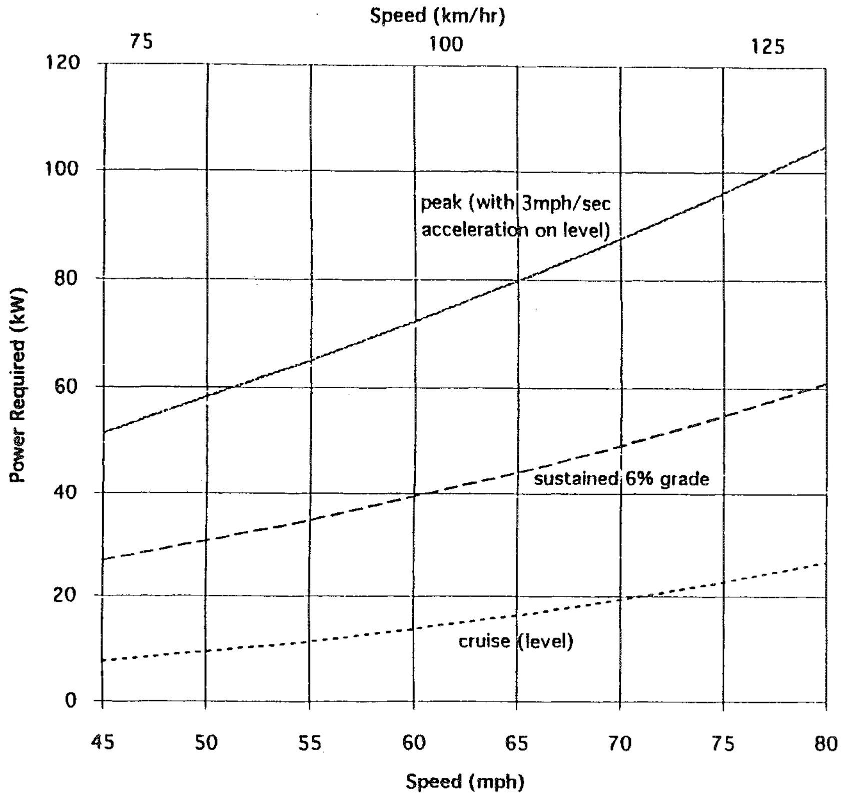


Figure 1 Power requirements, AVCAR '93.

ers combined with steam turbines at electric power plants) had overall efficiencies of only about 40%, and these engines are large, expensive, and stationary. About 50% efficiency is achieved in electric power plants with new combined-cycle technology, which involves energy recovery from the exhaust gases after the main energy conversion. (These efficiencies are based on the higher heating value of fuel.)

Before discussing automobile engine efficiencies, let us quickly review the two main kinds of internal combustion engines in use (7, 8). In the spark ignition engine, combustion occurs by means of a flame front that proceeds from the spark through the mixture of vaporized fuel and air. Variable (reduced) power output is achieved by reducing proportionately both the fuel and air admitted to the chamber. The amount of air is regulated by a throttle, which constricts the inlet to the intake manifold, thus creating a partial vacuum as each piston is pulled out during its intake stroke. The throttle thus uses friction to control power, resulting in a major fuel-economy penalty. (The associated energy loss, for "pumping," is discussed below.) The fuel is introduced through controlled injection into the manifold. (Only about 1/60th as much fuel vapor as air is needed, by volume.)

In spark ignition engines, the air-fuel ratio of the mixture is usually chemically correct, or stoichiometric, in that all the fuel and all the oxygen present could combine to form CO_2 and H_2O. (Ignition and flame front propagation are difficult to achieve if the air-fuel ratio is much higher than stoichiometric.) In cars sold in the United States, a "three-way" catalytic converter oxidizes CO and hydrocarbons in the exhaust, while simultaneously reducing (removing oxygen from) the NO_x. For this balanced reaction to be achieved, the air-fuel ratio of the mixture introduced to the engine must be stoichiometric.

The diesel engine utilizes fuel droplets and high compression. With the compression stroke, the temperature and pressure are high. After fuel injection, combustion spontaneously occurs on the surfaces of the droplets. At typical power levels, the overall fuel-air ratio is very lean (i.e. excess air compared to stoichiometric). Variable power output is achieved by changing the amount of fuel injected, the amount of air admitted always being the same (no throttle). Diesel engines are substantially more efficient than spark ignition engines because they do not use a throttle, they have high compression ratios, and they operate with lean mixtures (discussed further below). Three-way catalytic converters cannot reduce NO_x in the diesel exhaust because of the excess oxygen, so it may be difficult to achieve low NO_x emissions in the regulatory test. In addition, soot or carbon can be emitted when the fuel-air ratio of the mixture approaches stoichiometric at high power output. New diesel truck engines, are, however, meeting new emissions regulations. Reduction of sulfur content in the fuel helps reduce particulates. Diesel engines have a higher ratio of weight to power output than spark ignition engines but are more rugged. They are used in commercial vehicles where low weight and very high transient power are not important and fuel economy is. Automotive diesel engines, using turbocharging and direct injection, are, however, being successfully adopted in Europe, where NO_x regulations differ. In the following, spark ignition engines are the subject unless otherwise stated.

THERMAL EFFICIENCY The thermal efficiency (often called indicated efficiency) of typical internal combustion engines is about 38%, relative to the lower heating value of the fuel (or 35% relative to the higher heating value). This could, perhaps, be increased to near 45 or 50% through several changes: increased compression ratio; lean burn (increased air-fuel ratio); recovery of work from the exhaust; faster combustion; effective control of working characteristics, such as the air-fuel ratio for each cylinder and each cycle; and control of valve timing and enhancement of breathing so that intake and exhaust are optimized at each engine speed. These improvements may not all be practical (9).

One of the most interesting and promising of the above is lean-burn spark ignition engines. Lean burn is advantageous in terms of efficiency because a gas of simple molecules when heated increases its pressure more than a gas of complex molecules such as vaporized gasoline; with complex molecules much of the thermal energy is diverted into motions internal to the molecule. Increasing the air-fuel ratio by a factor of 1.67 (above the chemically correct stoichiometric value), for example, nominally increases efficiency by 10% (10). Moreover, if the air-fuel ratio could be widely varied while the engine still obtained satisfactory combustion, this method could be partly substituted for the throttle to regulate engine power output, with substantial mechanical efficiency benefits. But lean operation prevents the current three-way catalytic converter from reducing nitrogen oxides, so NO_x emissions from the engine might not be as low as one would hope. Moreover, lean mixtures can fail to ignite (misfire) or lead to incomplete combustion. Several engine manufacturers are developing designs to overcome these drawbacks, and Honda, Toyota, and Mitsubishi have first-generation lean-burn engines in production cars. Moreover, a more radical approach to lean burn, the two-stroke engine with modern fuel injection and controls, is said to be achieving success, although it is not yet being used in a production vehicle.

In summary, improving thermal efficiency, from roughly 38 to as much as 45%, is a potentially important goal. One way to achieve some of it is to develop successful lean-burn spark ignition engines. Another way to achieve this goal and perhaps more would be to solve the environmental problems of the diesel engine and adopt modern turbocharged direct-injection diesel engines such as those now in several European cars. (Direct injection means injecting the fuel directly into the cylinder.) Still another way would be to switch to a fuel with much simpler molecules and high octane—hydrogen or methane, for example—designing a high-efficiency engine for that fuel. Achieving still greater improvements in thermal efficiency in internal combustion engines is likely to be impractical.

MECHANICAL EFFICIENCY The mechanical efficiency of the engines in typical US cars—averaged over typical urban and highway driving—is about 52%. 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). Near wide-open throttle, a typical mechanical efficiency is about 90%. Unlike thermal efficiency, where it is not practical to achieve efficiencies above about 50%, it may be practical to achieve mechanical efficiencies approaching 100%.

The engine power output is the product of the mechanical and thermal efficiencies times the fuel energy input:

$$P_b = \eta_m \eta_t P_f \qquad 6.$$

For AVCAR '93 $\eta_t = 38\%$, and, in the US Environmental Protection Agency (US EPA) composite cycle, $\eta_m = 52\%$. Thus, the overall engine efficiency is $\eta_m\eta_t = 20\%$. Although η_m is greater than η_t, the opportunity for increasing η_m is larger because η_m is not restricted by thermodynamics, while η_t is.

The following analysis rests on a simple but accurate approximation for fuel use (11–13). The validity of this approximation is exemplified by the data shown in Figure 2, where fuel energy converted is shown on the y-axis and energy output on the x-axis, at various engine speeds. All the operating points lie essentially on a single straight line. The rate of fuel use has the form

$$\frac{P_f}{NV} = k + b\frac{P_b}{NV} \qquad 7.$$

where N is the engine speed (revolutions per second), V is the engine displacement in liters, and P_b is the engine power output or brake bower (in kW). The variables in Figure 2 are "specific" energy rates: kilojoules of energy per engine revolution and liter of displacement. (Often the quantity on the x-axis, P_b/NV, is referred to as brake mean effective pressure (in kPa): *bmep* = 2000 P_b/NV.) The constant b is very roughly the reciprocal of the thermal efficiency discussed above, and k is the fuel energy per revolution and per liter of displacement needed to overcome engine friction at zero power output.

This simple model of engine fuel use incorporates the fact that the intercept k and slope b vary only slightly from engine to engine, as shown by the systematic measurements performed on two dozen engines of different displacements V in the late 1970s at the Bartlesville, Oklahoma laboratory of the Department of Energy (13, 14).

Near wide-open throttle, on the right hand side in Figure 2, one can see that the rate of fuel use rises above this model. This is due to enrichment: Most spark ignition engines are designed so that the fuel-air mixture is increased as much as 30% near wide-open throttle, and the thermal efficiency drops. This is common practice and has major implications for emissions as discussed below. Since for most vehicles driving near wide-open throttle (accelerator pedal on the floor) is unusual, this enrichment has little effect on fuel economy.

A critical property of Eq. 7 is that the two engine-operating parameters speed and power (N and P_b) occur linearly. This means that if the equation is valid at engine-operating points N, P_b, it is also valid at any average operating point $\langle N \rangle$, $\langle P_b \rangle$ that characterizes a pattern of driving.

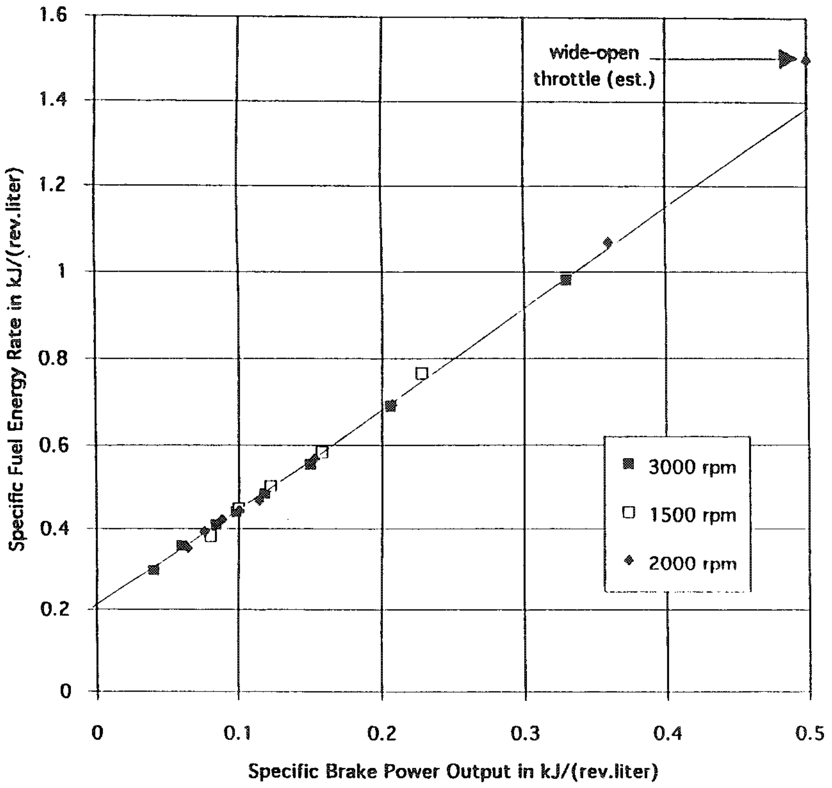


Figure 2 Measured fuel rate vs engine power (Quad 4 engine, 2.26 liter, 1987). Adapted from Ref. 13a.

We do not have a systematic set of measurements on modern engines such as those made in the late 1970s, and so must depend on information from a few individual measurements, which may not be consistent in treatment of accessories or in the fuel used. From the late 1970s to the early 1990s it appears that the average k among automotive engines has been reduced 20–25%, while b has hardly changed.

There are three kinds of friction involved in operating the engine: the energies used for pumping, for overcoming rubbing friction, and for driving the engine accessories. Pumping refers to moving the air and vaporized fuel into the cylinders and the combustion products out through the exhaust system. Although engine friction has been studied extensively, less is known than one would like, because most measurements are made under artificial conditions rather than in operating engines. (We need research to create improved instrumentation.) A detailed engine-friction model, which has been empirically validated using engines from the mid-1980s, is available (15). The friction model is combined with the model in Eq. 7 to create Figure 3. The lower curve,

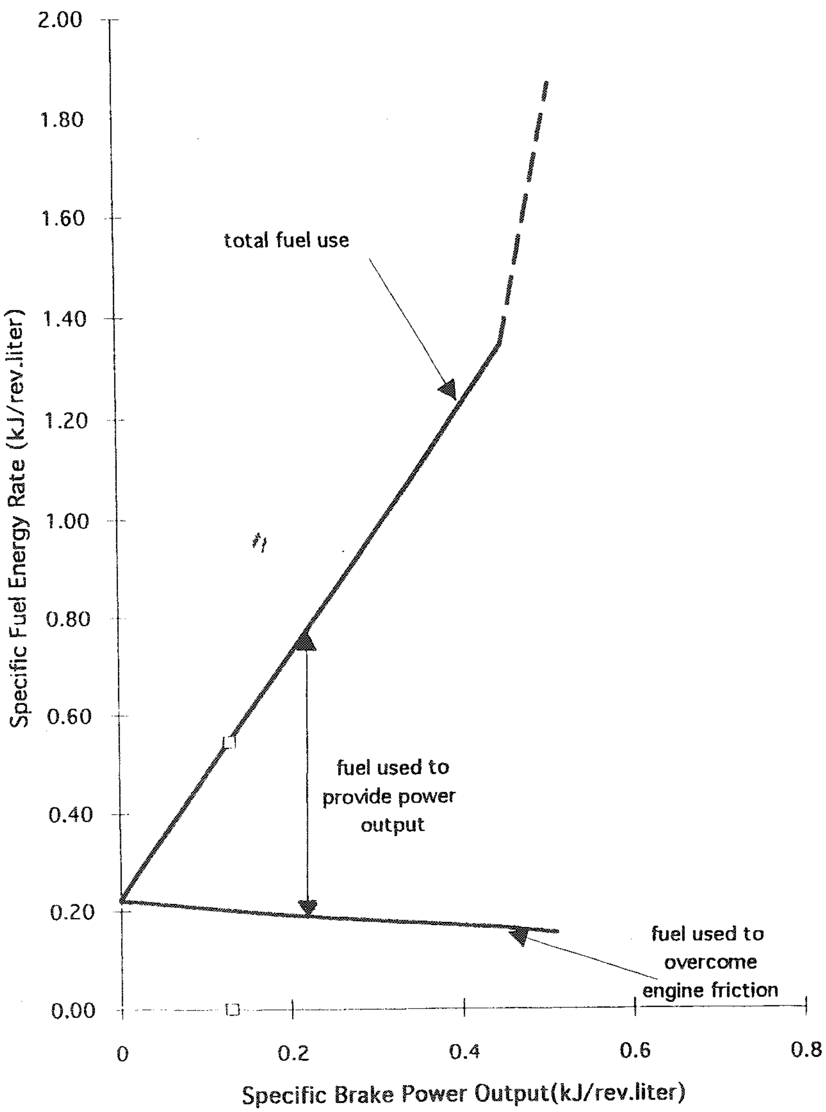


Figure 3 Thermal and mechanical efficiencies.

sloping down to the right, is the friction term. It declines as power output is increased because the pumping work decreases as the throttle is opened.

Figure 3 illustrates the two efficiencies. The thermal efficiency is essentially independent of the output, P_b. It is the ratio of output (on the x-axis of Figure 3) to the portion of fuel use, P_f, used to provide the output (as shown in Figure 3). Because the fuel used to overcome fiction declines with increasing output, the slope, b, of the total fuel use line is slightly less steep than $1/\eta_t$.

The mechanical efficiency varies strongly with the output. Solving Eq. 5 for η_m, one obtains

$$\eta_m = \frac{P_b}{\eta_t} / P_f = \frac{1}{\eta_t} \frac{x}{k + bx} \qquad 8.$$

where x is the specific output variable in Figures 2 and 3: $x = P_b/NV$.

At the point indicated in Figure 3, $x = 0.13$ kJ/(revolutions•liter) and $P_f/NV = 0.55$ kJ/(revolutions•liter), so $\eta_m = 0.62$ or 62%. This is a typical highway driving situation.

In a typical urban driving situation, the mechanical efficiency is about 48%, but is not well represented by a single point in Figure 3. In urban driving the car also spends some time idling, where $\eta_m = 0$, and some at high power, where η_m is high. At the top of the solid line in Figure 3, the mechanical efficiency is 88%.

Fuel Economy

FUEL ECONOMY REGULATION In the United States, fuel economy is defined for regulatory purposes in terms of a standardized laboratory test. It involves two second-by-second sequences of vehicle speeds, the urban and highway driving cycles. A stationary vehicle is driven on rollers such that the speed of the drive wheels on the rollers matches the speeds in the driving cycle. The rollers are coupled to an adjustable rotator in a viscous bath, to add a component that roughly simulates air resistance and other factors not accounted for by the rollers. The test equipment is called a dynamometer. The driving cycles were selected after measuring on-road driving patterns (16). (It has also been remarked that both the cycles and the tests were designed to accommodate limited dynamometer capabilities. New rollers of larger diameter and with electromagnetic loads are now coming into use. These will enable simulation of, for example, higher speeds and accelerations.)

The fuel economy used in determining the Corporate Average Fuel Economy (CAFE) for regulatory purposes is the composite: $FE_{comp} = (0.55/FE_{urban} + 0.45/FE_{hwy})^{-1}$.

This program of measurement has been a great success. Although vehicles in use tend to have lower fuel economy, on-road fuel economies are on roughly the same order as the test results (17). Thus different vehicles of the same model, although driven differently and under different maintenance and road conditions, have roughly similar on-road fuel economies; and the fuel economies of different vehicle models have on-road fuel economies that relate roughly to their test values. This success is partly associated with the relatively simple physics of energy use: There are not many normal mechanisms that will change fuel use per mile by, say, 50%, and these mechanisms would usually be obvious and lead to correction.

The difference between the test and in-use fuel economy has many sources: vehicle conditions, road and weather conditions, driving patterns, etc (17–20). An estimate for 1982 showed a shortfall of 15%; more recent estimates show larger shortfalls, near 20%. One expects some growth in this gap because of the increasing speeds on open roads and increased driving in congested situations.

ESTIMATION OF FUEL ECONOMY The linear equation for fuel use by an engine leads to a relatively simple summary form for fuel intensity and fuel economy in a driving cycle (e.g. fuel energy use per mile and miles per gallon, respectively). In terms of vehicle characteristics, the engine power output at any time is

$$P_b = (P_{tires} + P_{air} + P_{inertia} + P_{grade})/\varepsilon + P_{acc} \qquad 9.$$

where ε is the efficiency of the transmission (engine to wheels). Over a cycle of driving where both ends of the cycle are at the same altitude, the fuel energy use per unit distance driven (kJ/mile) is, from Eq. 7:

$$\varepsilon_{fuel} = 3600k \frac{V\langle N\rangle}{v_{av}} + \frac{1}{\eta_t} \{1609 \frac{C_R M g}{\varepsilon} + \frac{3.6\rho C_D A}{\varepsilon} \frac{\langle v^3\rangle}{v_{av}} + \frac{E_{brake}}{\varepsilon} + \frac{3600 P_{acc}}{v_{av}}\} \qquad 10.$$

Here < > denotes the full-cycle time average, as does v_{av}. E_{brake} is the energy deposited in the brakes per unit distance. An approximate form for driving on level ground is (21):

$$E_{brake} \approx \beta M^* v_p^2 n/2 \qquad 11.$$

where M^* is the vehicle mass increased to account for rotational inertia ($M^* \approx 1.035\ M$), v_p is the root-mean-square of the peak velocities of subcycles, n is the number of stops per unit distance, and β is a dimensionless characteristic of the driving cycle approximately equal to one.

For numerical evaluation, one can use the approximations (21):

$$\langle N\rangle \approx [N/v] \langle v_{gear}\rangle t_{pwr} + N_{idle} (1 - t_{pwr}) \qquad 12.$$
$$\langle v^3\rangle \approx \lambda\ v_r^2 v_{av} \qquad 13.$$

Here *[N/v]*, called "*N* over *v*," is the ratio of engine speed to vehicle speed in the highest gear; and v_{gear} is the speed of the vehicle in highest gear, which yields the same engine speed when in any gear. In driving over a variety of moderate and low speeds, with modern transmissions, v_{gear} averages about 55 mph. In addition, t_{pwr} is the fraction of time the engine delivers power; N_{idle} is the engine speed when idling (both during braking and during vehicle stop); v_r is the average running speed (excluding vehicle stop time); and λ is a dimensionless measure of speed variability in the cycle.

Equation 10 and approximations 11–13 have units to yield kJ/mile of fuel energy use, where n is in stops/mile, v_{av} in Eq. 10 is in mph, <N> is in revolutions per second (rps), and all remaining quantities, including the velocities in Eqs. 11 and 13, are metric as defined in Eqs. 1–4. The standard fuel economy is obtained:

$$MPG = 120{,}600/\varepsilon_{fuel} \qquad 14.$$

where ε is in kJ/mile and 120,600 kJ/gal is the lower heating value of the test fuel.

Study of Eq. 10 shows that the most important driving variable determining energy use is the overall average speed v_{av}. This is the well established result of Leonard Evans and others (22–25). The equation here enables one to (*a*) calculate the fuel economy from vehicle characteristics, and (*b*) estimate corrections due to driving characteristics.

Let us illustrate these two applications. First, the energy flows of AVCAR '93 are calculated in the EPA composite driving cycle, and the results are shown in Figure 4. Essentially one half (52%) of the fuel use provides for engine output while the remaining half provides for engine frictions. The engine output is just 20% of the fuel energy, and only 15% of the fuel energy reaches the wheels. In the lower right-hand corner of Figure 4, energy use at four sinks is shown using three different accounting conventions. The tires (rolling resistance), air drag, and brakes are seen to absorb approximately equal energies.

As another example of fuel economy calculations, one can simplify Eq. 10 so its vehicle dependence is expressed only in terms of *M*, *V*, and *[N/v]*, i.e. vehicle mass, engine displacement, and engine-to-wheel speed ratio (21). For 50 1991 cars with five-speed manual transmissions, one obtains the comparison between model and fuel consumption test shown in Figure 5 (composite driving cycle). The standard deviation for the model predictions shown is 4%. Similar, but slightly poorer, results apply for four-speed automatic transmissions.

Five of the 50 predictions differ by more than 10% from the corresponding measurements, points that are readily indentifiable on Figure 5. The very low point at left is a Honda CRX HF. There are many reasons why some vehicles have fuel use high or low relative to this model. For Honda CRX HF, the reasons are: (*a*) The gear ratios above first are spaced more closely than typical

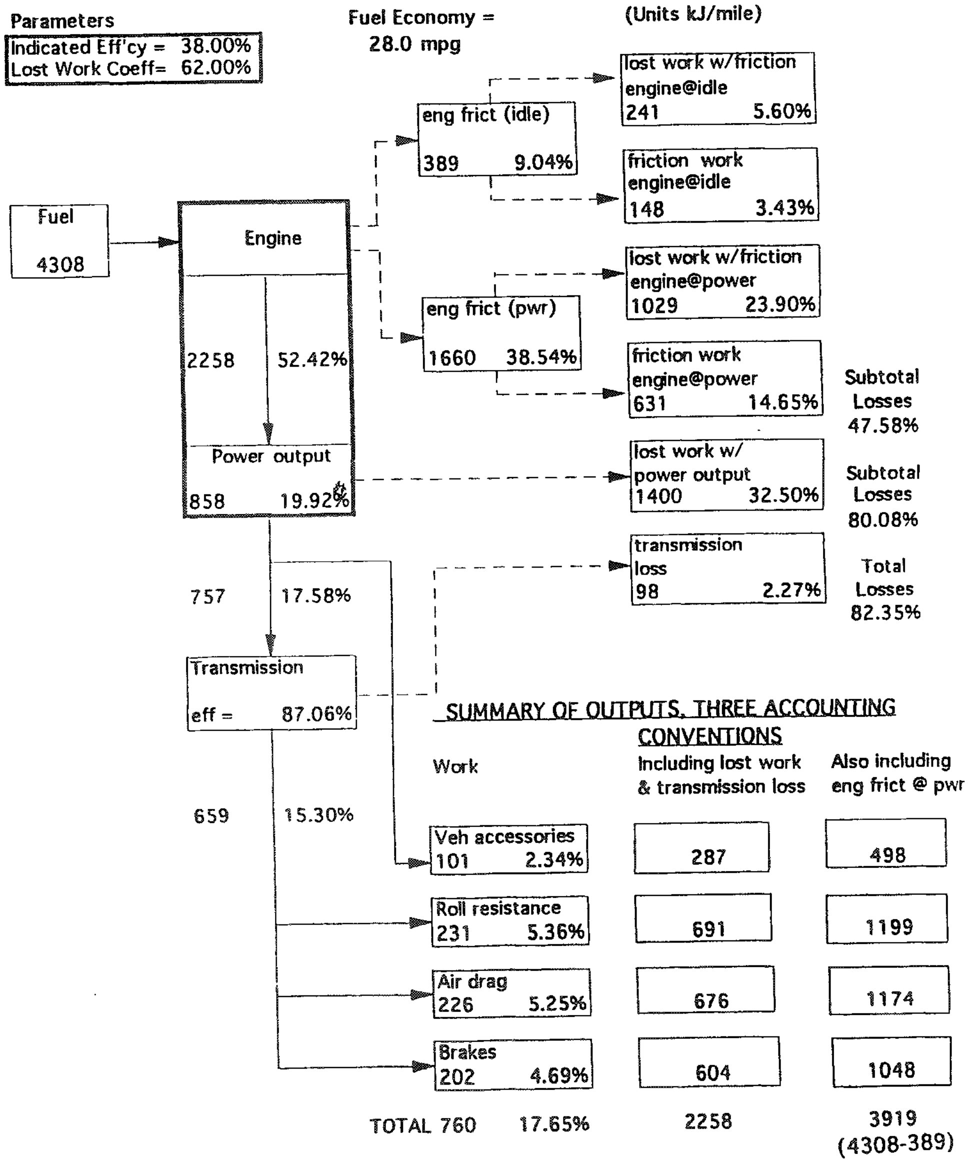


Figure 4 Energy flows, AVCAR '93, EPA composite cycle.

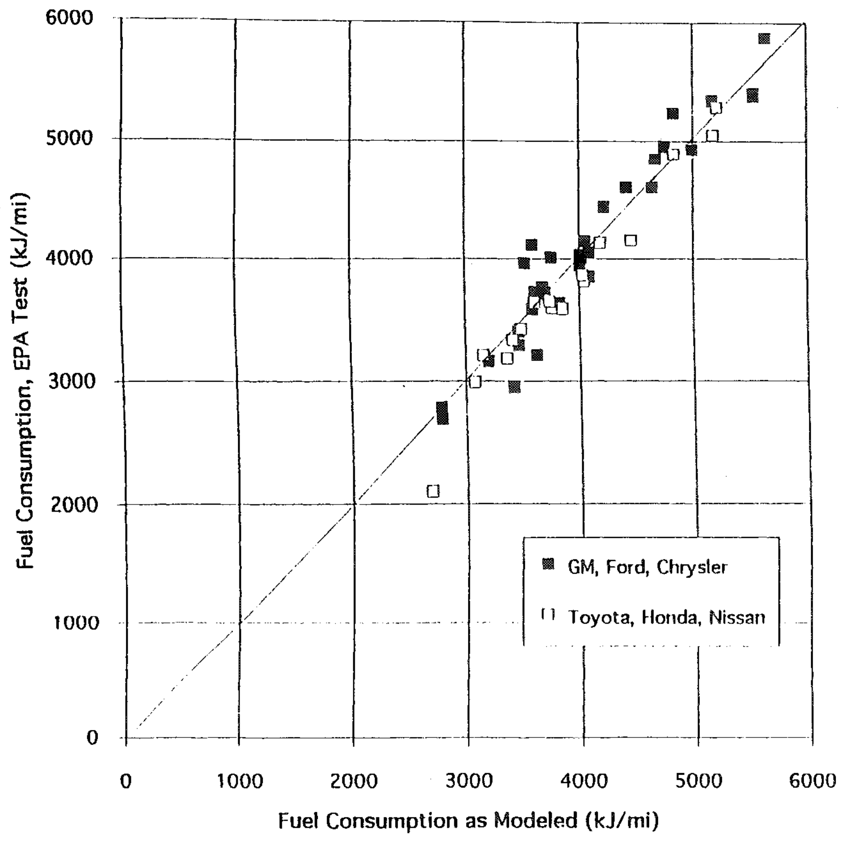


Figure 5 Fuel consumption, model vs test. 50 1991 M5 cars.

so that v_{gear} is less in gears 2, 3, and 4 than assumed. (*b*) The idle speed is relatively low. (*c*) The efficiency η_t is relatively high (high compression ratio). (*d*) The tires are high pressure, so C_R is relatively low. (*e*) The air drag coefficient C_D is unusually low. (*f*) There are few vehicle accessories, and so on. Many attributes of the CRX HF are designed to enhance fuel economy even where there are noticeable trade-offs. To model such a vehicle accurately, typical attributes, such as those used in the three-parameter model of Figure 5, are not satisfactory.

For the second kind of application, modify Eq. 10 to replace the interdependent peak- and running-speeds (v_p, v_r) with the essentially independent variables free-flow speed, v_{ff}, and vehicle stop time (26). Here $v_{ff} = v_p^2/v_r$ can be estimated as the average speed drivers desire to achieve, and would achieve, in uncongested conditions. One finds that v_{ff} is the most important driving variable after v_{av} from the perspective of fuel use in typical driving cycles (27).

As an introduction to the issues, see Figure 6, the dependence of fuel use

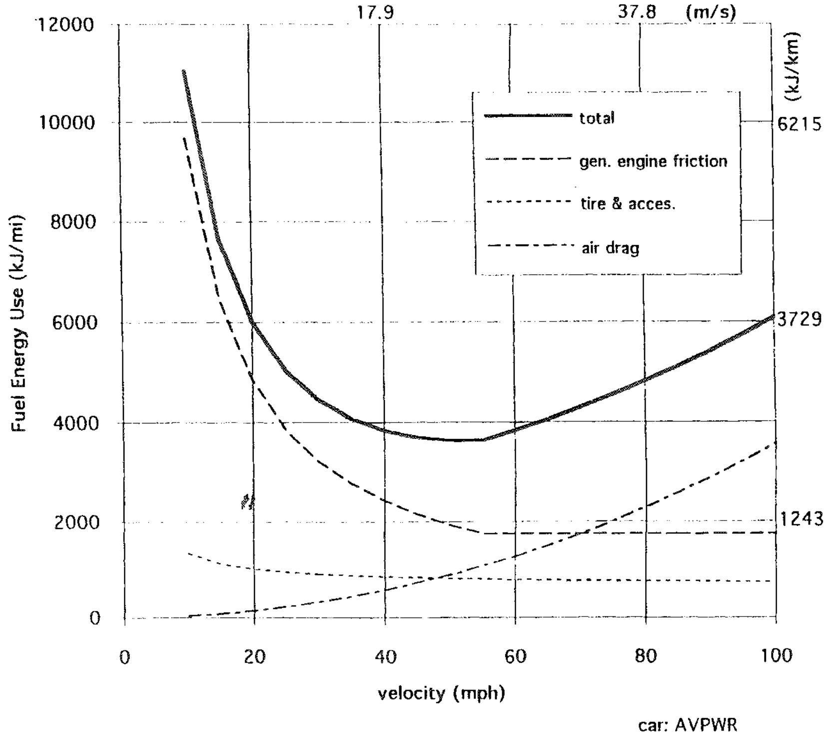


Figure 6 Specific fuel use in cruise driving.

per unit distance in constant-speed driving for a typical new car.[2] The most efficient cruise speed is roughly 50 mph with newer streamlined cars. The strong $1/v_{av}$ term is evident. It is essentially the $kV\langle N\rangle/v_{av}$ term of Eq. 10. Engine friction thus dominates energy use by today's cars, except at high speeds, and the associated energy use is proportional to the number of revolutions the engine makes during the trip. (In cruise driving with a particular car there would be irregularities in energy use at speeds where gears are shifted—these are smoothed in Figure 6.) The engine friction term is constant for $v > v_{gear}$ in Figure 6, because at increasing vehicle speed in fixed gear the engine speed increases so the frictional effect per unit distance is constant.

The relationship of fuel economy to free-flow speed, i.e. to traffic smooth-

[2] The car modeled, AVPWR, is slightly different from AVCAR '93, especially in being heavier and with a larger engine (26).

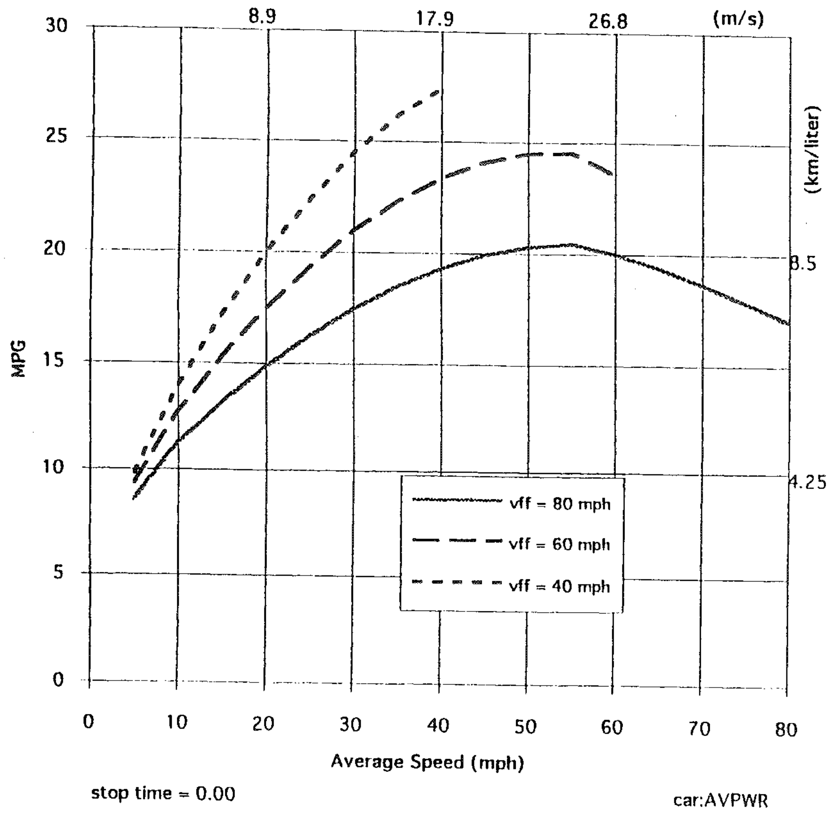


Figure 7 Fuel economy and average speed.

ness, is shown in Figure 7. The fuel economy is substantially higher in smooth driving, i.e. when v_{ff} and v_{av} are similar, than when v_{ff} is much higher than v_{av}. In the latter case, with typical driving patterns the brakes are used frequently as vehicles speed up on a crowded road and then quickly slow down. The acceleration part of such a subcycle is not inefficient in itself; the braking that usually follows is. If drivers could coast to slower speeds, they could even achieve higher fuel economy speeding up and coasting down than in cruise driving at the same average speed (26). This coastdown technique has limited practical application, but the average driver can reduce fuel use by about 10% by following simple rules: avoid excessive use of brakes, shift up early, avoid excessive speeds, and maintain the vehicle (28).

Fuel Economy Technologies

The technologies for improving vehicle fuel economy fall into two categories. One is efficiency improvement of the engine—increasing the effectiveness with which the energy in fuel is converted to useful work. (The focus here is mechanical efficiency; thermal efficiency improvement has already been briefly discussed.) The other is load reduction—decreasing the power required of the engine by reducing air drag, rolling resistance, weight, drivetrain friction, and vehicle accessory loads.

INCREASED MECHANICAL EFFICIENCY Five kinds of technology for improving average mechanical efficiency are:

1. aggressive transmission management (ATM) to reduce average engine speeds,
2. reduced displacement, or engine size, at constant maximum power, to reduce engine friction,
3. variable valve control (VVC), to reduce throttling and increase specific power,
4. reduced rubbing friction and more efficient engine accessories, to reduce friction at fixed engine size, and
5. stop-start (idle-off).

Technologies to progress in these five directions have been extensively discussed (29–34). It is of interest to consider briefly the first three categories, ATM, engine downsizing, and VVC. Not only are these important, but they illustrate the rapid change in technology that is occurring, and the possible conflict between some efficiency technologies and the product or service being offered.

ATM Modifying the transmission to reduce engine speed at a given power output is a long-established method for improving average mechanical efficiency (35). The elegant way to implement it is to build more gears and lower gear ratios into the transmission and then, in driving, gears are shifted up as soon as feasible. A feel for aggressive transmission management can be obtained by driving a 1990–91 Honda CRX HF with a shift indicator light on the dashboard. As the car accelerates, the upshift light comes on very soon. If one follows the shift light's suggestion, one shifts up at the much lower engine speeds than is typical.

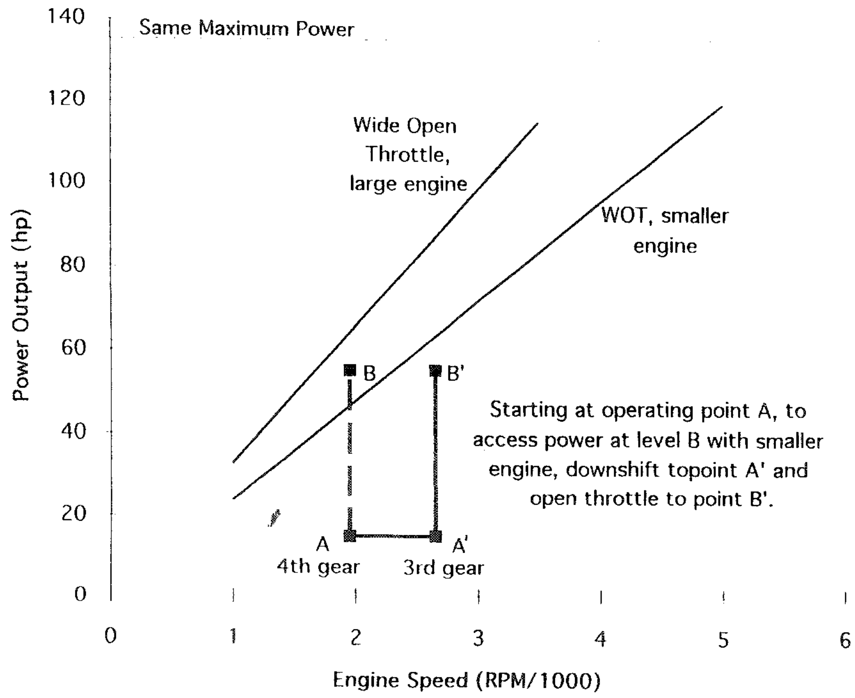
A critical consideration for fuel economy is the span—the ratio of the highest to the lowest gear ratio. Consider a standard manual transmission. In the lowest gear (highest gear ratio), clutch slip is involved in getting the car moving, but the gear ratio must still be high enough to enable the engine to begin to move a stopped car up a grade (36). On the other hand, good fuel economy in highway driving requires a low gear ratio in 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 are preferable to five in a manual transmission. For automatic transmissions 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 and five-speed manuals are now widely used, and five-speeds automatics and six-speed manuals will begin to be used in high-volume cars in the late 1990s (37).

Aside from the issue of creating the transmission technology, manufacturers may be reluctant to reduce engine speeds for two reasons. First, the engine may not run as smoothly at low speed. Second, relatively high power is not immediately available at low engine speeds (see below).

A smaller high-technology engine The most rapid change in vehicle technology in recent years has been in specific power, the ratio of maximum engine power to engine size or displacement. The average specific power increased 3.3% per year from 1976 to 1993 (4). This trend is expected to continue. The technologies are: much higher engine-speed capability involving extra valves per cylinder; high-tech valve cams; higher compression ratios; advanced fuel injection; sophisticated controls, e.g. of ignition timing; and tuning of the intake and exhaust manifolds. Variable valve control is also beginning to come into play (see below). More sophisticated controls are in the offing, enabling management of cycle-to-cycle and cylinder-to-cylinder variations.

If engine displacement were reduced in proportion to the increase in specific power, then maximum power could be maintained, while the friction characteristic kV is reduced essentially in proportion to the displacement. With today's average new car, a 10% engine downsizing results in a 6.6% increase in efficiency (average over urban and highway driving cycles), taking credit for vehicle weight reduction.

Both engine downsizing and ATM reduce the available power at a typical engine speed. Consider the combined effect of these technologies: In Figure 8 two overlapping engine maps are shown. Two variables fix the point at which an engine is operating at a given time. In this figure, engine speed and power output are, again, the variables. A low engine-speed point A, and a higher engine-speed point A', with the same power level, are shown. With an older-design large engine, we can move directly from point A to power at level B by opening the throttle (depressing the accelerator pedal). On the other hand, with a small high-tech engine, high power at point B' is immediately available if one starts from the higher engine speed at A', but downshifting is necessary if one starts from A.



Starting at operating point A, to access power at level B with smaller engine, downshift topoint A' and open throttle to point B'.

Figure 8 Downsized engine, transmission management.

Downshifting is familiar to drivers of many cars with a four-cylinder engine and automatic transmission, in which downshift and engine speedup occur when the accelerator pedal is floored. The action of declutching, engine speedup, and reclutching takes time; if done well, however, it takes half a second or less. Although this delay is a small loss of amenity, it is a loss of amenity. In this respect, the ATM and engine downsizing technology is not analogous to many other energy-efficiency technologies that can be implemented without any loss of amenity.

VVC Variable valve control refers to controlling valve motion according to engine speed and power, rather than the fixed pattern of valve motion. Variable early closing of the intake valve can be designed to substitute for throttling to achieve low power (38, 39). The concept is to control the intake valve, opening it at the beginning of the intake stroke, then closing it early so as to admit only 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 valve, the piston continues to be drawn back, creating a partial vacuum. (The amount of air needed corresponds to a vacuum of about 1/7 atmospheric 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 loss is largely eliminated; it cannot be wholly eliminated since there remains fluid friction at the intake valve.

Another application of VVC is optimization of power at wide-open throttle. The power capability at fixed engine speed can be maximized using the same VVC equipment used to eliminate the need for a throttle at low loads. The fuel economy implications of this additional power are substantial in terms of further engine downsizing. Unlike ATM, VVC can provide these benefits without loss of amenity.

LOAD REDUCTION In urban driving, a typical new US car requires an average engine power output of 5 kW (7 hp). Because this is low compared to engine capabilities, more fuel is consumed merely to overcome the internal frictions of the typical large engine than to provide the output. This suggests that engine downsizing and aggressive transmission management coupled with load reduction are the key strategies for improving fuel economy.

For today's average new car, leaving the engine-transmission unchanged, a 10% reduction in load results in a 4% reduction in fuel use in urban driving and a 5% reduction in fuel use in highway driving (21). Technologies include reducing aerodynamic drag, reducing tire rolling resistance, and reducing weight at fixed vehicle size—all discussed immediately below. Drivetrain efficiency can also be improved through technologies such as torque converter lockup, electronically controlled standard gearing, and reducing transmission friction. Accessory loads—the largest of which is air conditioning—can be cut by running accessories only when needed, improving component efficiencies, and reducing the need to run the accessories. Overall, there is a near-term potential for roughly a 25% reduction in load, which would alone yield a 12% improvement in fuel economy (i.e. without associated engine downsizing).

Aerodynamic drag has experienced a long historic decline (40), with fairly rapid reductions in recent years as the styling associated with low drag has proven popular. For new cars in the mid-1970s a drag coefficient $C_D = 0.45$ was typical (30). In 1987 the new-car average was estimated to be 0.38 (31), and in 1990 it was about 0.35 (34). Several current production cars have coefficients below 0.30, with the Opel Calibra the lowest at $C_D = 0.26$. The GM prototype vehicles Impact and Ultralite both have C_Ds of 0.19. Drag coefficients achieved in several prototypes and the associated design features are discussed by Bleviss (41).

Tire rolling resistance can be decreased by increasing tire pressure (6), and through improved materials and design. Tire manufacturers have recently claimed reductions of 20–35% for specialized models, without specifying the baselines from which the reductions are calculated (34). Electric vehicles, for which there is a critical need to reduce loads, are being prototyped with very low rolling-resistance tires. Reductions in rolling resistance are, however, constrained by road handling and safety considerations.

Weight reduction at fixed interior volume is the most important load-reduction challenge. As can be seen from Table 3 (below), a 10% reduction in the inertial weight of AVCAR reduces composite fuel use through the tire and braking loads by 2.7% and, indirectly, through 10% engine downsizing, by 5.4%, for a total reduction of 8%.

There are two stages to weight reduction: best practice with today's materials, and new designs using new materials (or materials that are new to the application). Design is critical to the first stage. The spread in weight for cars of a given interior volume[3] is about ±33% about the mean for 1990 models (42). This means, for example, that if all cars were redesigned so as to be distributed evenly in the lower half of the 1990 distribution, the average weight would be reduced 15% or more. In addition, further design changes, such as the space frame and increased use of new materials such as aluminum (43) and fiber-reinforced composites (as well as stronger steels), are in very active development. The General Motors prototype Ultralite, with its carbon-fiber composite body, has roughly half the curb weight of comparably sized vehicles.

A Scenario for Improved Automotive Efficiency

Substantially improving the average mechanical efficiency involves a combination of reductions: (*a*) reductions in the three engine frictions per revolution at fixed engine size, (*b*) reduction of the size of the engine while maintaining power capabilities, and (*c*) reduction of the average engine speed. The three reductions are in the three variables k, V, and N, respectively, of Eq. 7.

To improve fuel economy one wants, in addition, to improve thermal efficiency and to reduce the vehicle load. Load reduction is important both overall and for weight reduction: Since we are considering a fixed ratio of maximum power to weight, weight reduction means additional reduction in the engine displacement.

Consider the following technological scenario for a car denoted High-MPG (Table 1). This car has the same interior volume and acceleration capabilities (maximum power to vehicle weight) as AVCAR. With an engine of today's general type, the thermal efficiency would be 39%, while the slope b in Eq. 7 is kept the same. With a vehicle of today's general type, inertial weight is reduced 15% and overall load is reduced 25%. The average mechanical efficiency is increased by a factor of 1.25 to 65% by the following steps: k is

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[3] Interior volume is calculated by EPA using a carefully thought-out formula for the useful space.

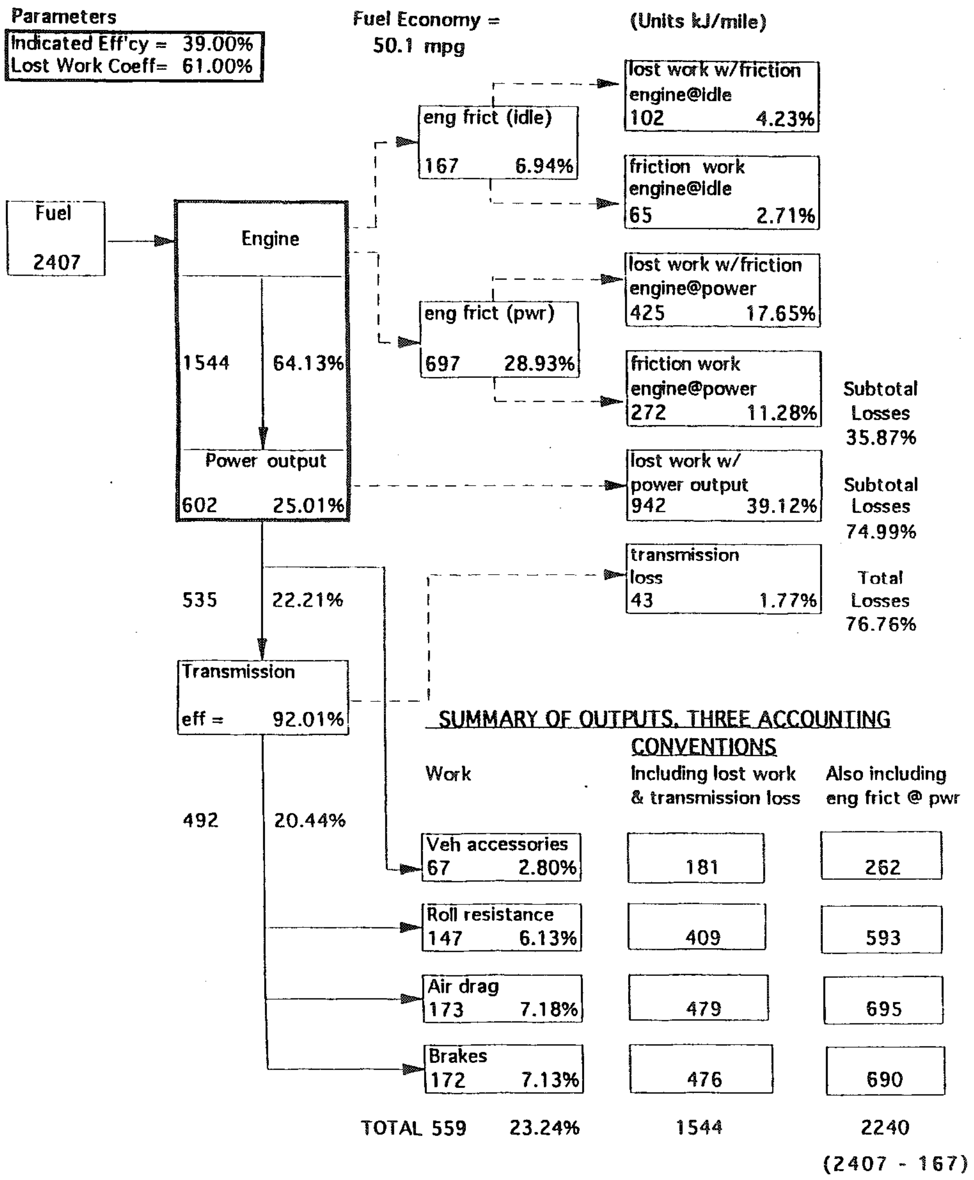

Figure 9 Energy flows, High-MPG car, EPA composite cycle.

reduced 15%, mostly through reduced pumping and accessory losses. The displacement, *V*, is reduced 15% because of the corresponding vehicle weight reduction and about 40% more through continuing specific-power increases. This almost 50% reduction in displacement to 1.4 liters still enables the power-to-weight ratio of the vehicle to remain the same. The specific power is increased from 51 to 85 hp/l, well within achievements by today's high-tech engines. Average engine speed, <*N*>, is maintained at its base level through ATM (in spite of the move to a four-cylinder engine just over half the displacement of that in the base car).

In this scenario, fuel economy (calculated with the same formalism as for Figure 4) is increased by 79% to 50 mpg (Figure 9). This goal has already been reached by two production cars, Geo Metro and Honda Civic VX. However, unlike the latter two cars, the car considered here is of average size for 1993 models and has the average power-to-weight ratio. The fuel use to overcome engine friction (Table 3) is reduced a whopping 58%, but a good indication of the feasibility is the mechanical efficiency achieved—65%—still well below technical limits.

The wide-open-throttle power achieved by the 1.4 l engine of High-MPG at a speed such as 1800 rpm would be much less than achieved at that rpm in AVCAR '93. Downshifting as described in connection with Figure 8 would be needed from time to time in ordinary driving to access higher power. However, a well-designed 1.4 l engine could provide about 22 kW (30 hp) at 1800 rpm and 30 kW (40 hp) at 2400 rpm; so that with its 15% lower mass, High-MPG would have plenty of power in this engine-speed range for most purposes. (See Figure 1, which is based on the higher mass and coefficient of drag of AVCAR.)

The car High-MPG is not the ultimate in fuel economy that can be achieved with a petroleum-fueled and internal-combustion vehicle. The thermal efficiency is not pushed to a high value: Neither a diesel engine nor a lean-burn spark ignition engine is considered. Nor is the load pushed to an extremely low value. In particular, radical new materials would enable inertial weight reduction by perhaps 1/3, instead of the 15% assumed.

A radical alternative, still based on the internal combustion (IC) engine, is the hybrid car, using an energy storage device that emphasizes power capability over energy capacity (such as flywheels or an electric capacitor). In this scheme the IC engine would only operate in the zone of its high mechanical efficiency, and would be turned off most of the time. Efficient storage technology, which is reliable and of moderate cost, is needed. Such a car could achieve 80 mpg or, perhaps, much more (44). Such a fuel-based hybrid (rather than an electricity grid–based hybrid) could have most of the extraordinary sustained-and-peak-power capabilities as well as the range and quick-refueling capabilities of the current type of vehicle.

It must be said that the scale of fuel economy improvement cited here for the car High-MPG is controversial. The manufacturers, who do not want to be constrained in their planning and vehicle design and marketing by stiffer fuel economy regulations, argue that such improvements are not practical or will have small effects. Other analyses, not associated with the manufacturers, have found that the cost-effective opportunity for improving the average fuel economy of new cars in a 10-year time frame is only about 30% (45). Let us briefly consider the cost issue.

The Cost of Improved Automotive Efficiency

The analysis of technologies available for improving conventional vehicles and their costs has been updated by John DeCicco and the author to include recent technological advances (34). The central result of this analysis is that a 70% improvement in average new-car fuel economy at fixed performance would be cost effective, and could be implemented in 8–11 years. The incremental retail cost of a new car, associated with these measures, is $770 (in 1993$), an amount similar to the estimated cost of improvements to improve fuel economy at fixed performance made since the mid-1970s. The criteria behind this cost-effectiveness result are 5% per year real discount rate, similar to actual automobile loan rates, and 12-year life, corresponding to vehicle life (rather than the period of initial ownership).

There are two major problems with cost estimates. First, the incremental manufacturing cost of an added technology depends on the entire manufacturing process in which the change will be embedded. In the first generation there may be substantial costs; in the second generation, after the production process has been redesigned for all kinds of reasons, the incremental cost is often very small. Often no one has a reliable estimate, not even the manufacturer. Second, while it may be reasonable to estimate incremental manufacturing cost, what are the incremental development, design, tooling, administrative, and distribution costs? At Energy and Environmental Analysis, Inc., Duleep, a preeminent researcher in automobile efficiency improvement, introduced the concept of multiplying the incremental manufacturing cost of a technology by the long-term ratio of retail prices for cars to variable manufacturing costs, a factor of roughly four. This is a powerful idea, but not accurate for particular cases.

However, while the incremental retail cost implied by implementing many of the particular technologies is rather uncertain, the cost of a major group of the technologies is limited on the high side. The reason is that almost all of them have been implemented in low- to moderately priced production vehicles, without major impact on the vehicle's prices (45a). There simply isn't room for this group of measures to add costs much greater than those estimated, if they are brought into production when models and components are being changed for other reasons.

Perhaps more important than the steady-state costs, are the up-front development and retooling costs. Even though almost all the technologies mentioned are incorporated in some version in a production car, these up-front costs could be substantial for manufacturers who are not adept at changing the manufacturing technology, or if the pace of change were rapid, not permitting the changes to be made when major changes would be made for other reasons.

These problems are particularly acute for engines, the site of most of the efficiency technologies. Engine manufacture has become highly automated with the perhaps surprising consequence that it is inflexible. The time between major changes in engines is long. Some Japanese manufacturers have, however, succeeded in moving to the next generation of engine-manufacturing technology, where conversion of production lines for a new high-tech engine is relatively easy. The US manufacturers are catching up in this respect.

CONCLUSIONS Personal vehicles based on the internal-combustion engine and petroleum fuel have developed into an extraordinary technology. The maximum performance capability is remarkable in terms of both transient and sustained power. The long vehicle range on one fueling, and short refueling time are also remarkable. The reliability of vehicles has greatly improved in the past two decades, to the point where cars now are expected to perform on demand, as do a telephone, refrigerator, or light. The cost of basic vehicles is relatively low, and operating costs are quite low. (Although the price of an average car has gone up in constant dollars, it has become a much better car. The Department of Labor Consumer Price Index suggests that in terms of fixed value, the price of an average new car has fallen 26%, relative to the price of all products, since 1973.) It will be very difficult for any alternative kind of vehicle to compete with these attributes.

The energy efficiency of conventional vehicles can be improved substantially with reliable and cost-effective technology. A scenario for a 50-mpg car with performance and size of today's cars has been outlined. Somewhat better fuel economy could even be achieved, although the particular form of US NO_x emissions regulations may inhibit the wide use of lean-burn or diesel engines that would help the move beyond 50 mpg. As suggested in the next section, the procedures on which emissions regulations are based are not satisfactory for distinguishing between different vehicle technologies. So we may be arbitrarily inhibiting valuable technology. That is not to say that NO_x emissions are not important; they may be very important (46).

In any case, it is hard to conceive of a conventional vehicle of today's capabilities that could achieve more than 80 mpg—the goal of "up to 3 times better fuel economy" set for the recently announced government-industry initiative. To achieve such a fuel economy with a large all-purpose car, alternative technology is probably required.

Table 2 Passenger car exhaust emission reduction progress: Federal 49-state standards (grams per mile)[a]

	Hydrocarbons		Carbon monoxide		Nitrogen oxides	
Model year	Grams	% Reduction	Grams	% Reduction	Grams	% Reduction
Precontrol	10.6	—	84.0	—	4.1	—
1968–1971	4.1	62	34.0	60		—
1972–1974	3.0	72	28.0	67	3.1	24
1975–1976	1.5	86	15.0	82	2.0	51
1977–1979	1.5	86	15.0	82	2.0	51
1980	0.41	96	7.0	92	2.0	51
1981–1982	0.41	96	3.4	96	1.0	76
1983–1993	0.41	96	3.4	96	1.0	76

[a] Source: (48). Excludes California.

Under today's market conditions, the 50-mpg car described would probably not sell well. Although it has high fuel economy, it would cost perhaps $700 more (34). Moreover its performance, although nominally the same as that of the comparable vehicle without the fuel-economy technology, could be slightly less luxurious: with slightly more engine vibration and noise, and more shifting as discussed above in connection with Figure 8. But although there is little interest in high fuel economy on the part of individual car buyers, there is substantial interest on the part of people as citizens concerned with the energy problems of society. In effect, people are quite rationally much more interested in increasing fuel economy through public policies, where everyone participates (47).

III. THE EMISSIONS INTENSITIES OF AUTOMOBILES

According to regulatory standards, carbon monoxide and hydrocarbon emissions in automotive exhaust should have been reduced to 4% of their late-1960s levels in grams per mile. (See Table 2.) Since the amount of driving has doubled, automotive emissions should be at 8% of their late-1960s levels. If one breathes heavily in a US city, or looks from a height at the air above the city, one senses that it hasn't happened. Of course, this is a simplistic argument. Some pollution is odorless and invisible, and depending on the region and pollutant, there are large sources of pollution other than motor vehicles. Moreover, the impacts of pollution are complex, depending on chemical processes in the atmosphere that, in turn, depend on sunlight, temperature, and residence time. So vehicle emissions do not necessarily bear a simple relation to the pollution that does the most damage. Nevertheless, vehicle emissions are in fact much higher than the levels sanctioned by law.

Quantitative information about actual motor vehicle emissions is indirect and incomplete. It comes from dynamometer tests of vehicles for regulatory compliance, from sampling of air along and above highways (49, 50), from measurements of air quality in tunnels in Los Angeles (51) and on the Pennsylvania Turnpike, from "remote sensing" of the composition of air behind vehicles (52–54), and from computer modeling of observed ambient air quality (55). The information is good enough to estimate that average hydrocarbon (HC) and carbon monoxide (CO) emissions are actually 5–10 times higher than the grams per mile tailpipe standard. This means that emissions of these pollutants have been reduced overall by 50% or less, rather than by 92%. A similar, if less dramatic, story can be told about nitrogen oxide (NO_x) emissions.

The regulatory regime for vehicle emissions, established in the 1970s, is based on the Federal Test Procedure (FTP). It involves a dynamometer test using the urban driving cycle both with the vehicle cold and with it hot (56, 57). The exhaust is collected in bags and chemically analyzed. It must meet the grams per mile standards for CO, HC, and NO_x. Evaporation of fuel from the vehicle is also measured and regulated.

There are many reasons why emissions as measured in the FTP do not agree with the information we have about emissions of vehicles in use. The reasons are similar to those that have been analyzed for the corresponding issue of fuel economy, as measured vs in use (17). There is a critical practical difference, however: The incremental or excess in-use emissions are often larger than the emissions as tested. Major physical sources for the excess emissions are listed in Table 3 (3). The first source is well known to all: Old vehicles were subject

Table 3 Sources of excess emissions relative to the tailpipe standards for new cars[a]

1. Old vehicles
2. Malfunctioning emissions controls and/or engine-exhaust components
3. Increase in the use of light trucks
4. Evaporation of fuel
    standing and running
5. Frequent cold starts
    rich fuel-air mixture
    cold catalyst
6. High-power driving
7. Poor fuel quality
8. Long idle (with catalyst cooldown)?

[a] Note that sources 3–8 apply to properly functioning new vehicles.

to less stringent regulation. But their role has been exaggerated. Failures in the engine-exhaust system, such as leaky valves, and in the emission-controls are an important source, briefly discussed below. Light trucks are permitted higher emissions, even though 80% of them are simply used as cars (58). The remaining sources apply to properly functioning new cars as well as to old or failed vehicles. Considerable effort is going into measurement and control of fuel evaporation, including improved fuel, which is not discussed further here. Substantial progress is also being made in development of emission-reduction technology for cold start. Let us focus on one interesting and important source, high-power operation of vehicles, and its CO and HC emissions.

Emissions at High Power

Present-day vehicles incorporate an emissions-control system in order to meet the stringent emissions standards based on the FTP. The heart of the system is a three-way catalytic converter in the exhaust line. To be effective, the catalyst must be hot and the fuel-air mixture input to the engine must be stoichiometric, i.e. have the chemically correct balance, so that the catalyst can work on exhaust that has balanced residues of partially burned fuel, nitrogen oxides, and oxygen. To help achieve this chemical balance, an oxygen sensor is installed in the exhaust line and its signal used to adjust the input fuel-air mixture.

Unfortunately, rich fuel-air mixtures, with 20–30% excess fuel, are routinely designed into vehicle operations under certain conditions, defeating the emissions control system. When the engine is cold, the fuel injectors are instructed to introduce excess fuel to improve combustion stability; this was the role of the choke in old cars with carburetors. And when high power is required of the engine, the fuel injectors are again instructed to introduce excess fuel. The excess fuel leads to very high CO and HC emissions—tens, hundreds, and even thousands of times higher per second than in driving requiring less power. The driving cycle used in the FTP incorporates one cold start, and involves no high-power operation (except, in effect, for a few cars with very low power-to-weight ratios). So the rich operations associated with more frequent cold starts and with high-power driving are "off-cycle." Since they are not literally part of the regulatory standard, the associated high emissions are quite legal. It is the enforced letter of the law that governs commercial behavior.

The level of high power that causes high emissions is essentially driving with the accelerator pedal on the floor; that is, at wide-open throttle. (Enrichment also occurs at part throttle at high engine speed.) It's not only cowboys that drive at wide-open throttle. Those of us who have moderate-power cars often find ourselves keeping up with 70-mph expressway traffic, or on hills, by driving for long stretches at wide-open throttle. Use the factors: Each second of driving with the pedal down in a high-power episode corresponds very roughly to half an hour of CO emissions and one minute of HC emissions in moderate, or FTP, driving (59). But are such bursts of emissions large enough and frequent enough to make them important in the overall picture? No one knows for sure; let us make a rough estimate.

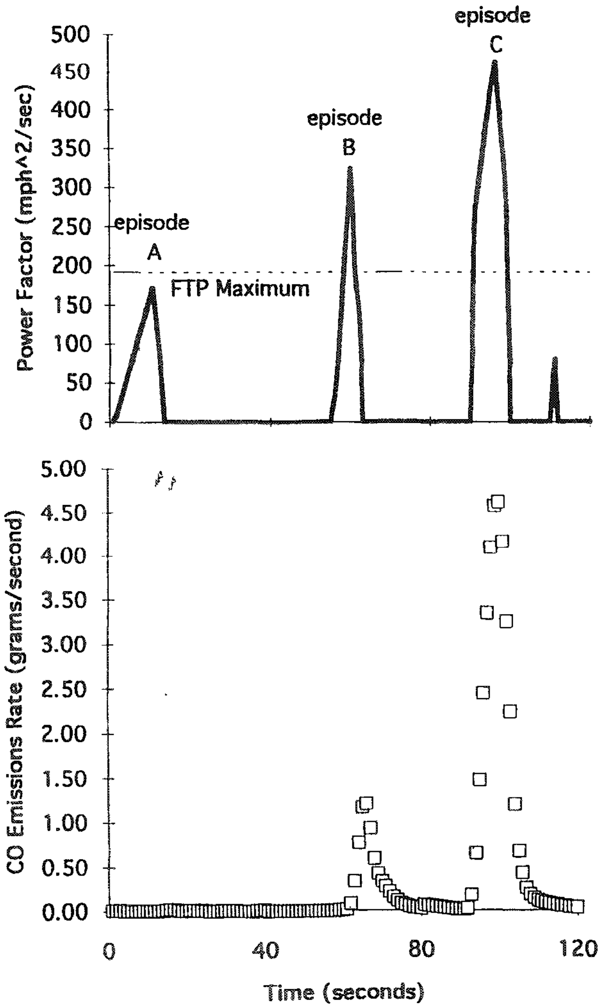

Figure 10 CO emissions in three high-power episodes.

One part of the evidence is second-by-second emissions at higher power than in the urban driving cycle. Recent measurements by California's Air

Resources Board show that brief high-power episodes can dominate emissions from properly functioning cars. Figure 10 shows CO emissions from a typical vehicle in three separate 40-second periods. In each there is an episode requiring some extra power: one with fairly low power, one with moderate power, and one with high power, as shown in the top part of the figure. The "power factor" shown is $\Delta v^2/\Delta t$ in mph^2/s. (Compare Eq. 3.) This inertial power factor causes the dominant load on the engine in a high-power episode on level ground. Also shown is the maximum power factor, 192 mph^2/s, involved in the urban driving cycle. In episode A, maximum power occurs when the car accelerates 3 mph/s at a speed of 28 mph. This power level and more occurs in the urban driving cycle of the FTP. In episode B, the power level is higher and briefly rises above the maximum in the urban driving cycle. In episode C, the maximum power is well above that of the regulatory cycle. (The total emissions in each of a variety of other high-power episodes are roughly similar to that for episode C.)

A threshold for high emissions at power levels above that tested in the FTP is demonstrated in Figure 10. In addition, the dominance of emissions in high-power episodes is shown by the lower part of the figure. In the Air Resources Board measurements, typical CO emissions in a high-power episode, like episode C in the figure, are 28 grams for CO and 0.7 grams for HC. These emissions are to be compared with the FTP standards of 3.4 and 0.41 grams per mile for CO and HC, respectively (Table 2). But the comparison doesn't mean much unless we know the frequency of high-power episodes per mile of typical driving.

Some measurements of driving patterns have recently been undertaken by the US EPA, the Air Resources Board, and the automobile manufacturers. Speed sensors in two groups of cars, in Spokane, Washington and Baltimore, Maryland, detected power levels that exceed those in the regulatory diving cycle occurring 1–5% of the time (60). From these data and other characteristics, one can roughly estimate that CO and HC peaks associated with rich operation occur about once every three miles in typical driving with modern vehicles. Using these estimates, one finds that high-power episodes produce excess CO emissions more than twice as high as the grams per mile tailpipe standard, and excess HC emissions about half the standard. There are, unfortunately, substantial uncertainties in these estimates.

Why do manufacturers design cars to behave in this antisocial manner? Ask specialists and you get divergent answers. Rich operations at wide-open throttle increase the maximum power available at any engine speed by roughly 5% (61–63). There may also be a transient drivability issue. When the throttle is first opened to access high power, air rushes in to the intake manifold, which may briefly result in too little vaporization of the injected fuel (64, 65). If that happened (and it might not with modern fuel injection), the engine might hesitate when you floored the accelerator. Yet other rationales for injecting excess fuel at high power are that it provides needed cooling for the engine or for the catalyst.

Whatever the validity of these arguments, preliminary evidence from emissions measured at high power by EPA and by the Air Resources Board suggests that some European manufacturers have substantially reduced the practice of enrichment at high power in their current vehicles. Perhaps the practice can be minimized through simple design changes; the manufacturers should be challenged on this.

Gross Emitters

Let us briefly consider another major source of excess emissions: equipment failures (including equipment damaged in repairs or by tampering) in the engine-exhaust system and/or its emissions controls. A relatively small fraction of vehicles, perhaps 5–10%, appear to be "gross emitters," responsible for much of the emissions (53, 54). Many believe that this is the largest source of excess emissions. Currently we attempt to correct these failures through Inspection and Maintenance (I & M) programs. These programs are designed to test all vehicles in air-quality non-attainment areas and to make the owners responsible for curing the deficiencies.

The I & M design does not work well on either count. The first problem is that the test used in most programs, with the vehicle idling, is inadequate. Secondly, it is difficult to follow through so that there are effective repairs. Sometimes there is an understanding between the driver and mechanic on this point, such that repairs are not undertaken. Moreover, in many jurisdictions the motorist is excused from the repair if there is an estimate that it would be expensive.

Two major efforts are being made in some metropolitan areas to improve I & M: (*a*) replacing the idle test at garages with a dynamometer test at centralized locations, and (*b*) using remote sensing technology to identify vehicles on the road that are likely to be gross emitters (66, 67). In a third effort, the federal government will require, starting in 1996, that electronic records of measured physical characteristics be kept on board every vehicle. (These characteristics do not include the emissions themselves, since they are not measured, but what is recorded may allow emissions-control failures to be detected.)

The potentially most successful aspect of these efforts is somewhat indirect: identification of types of equipment failure and the reduction of such failures by manufacturers in their new vehicles (even in cases where failures have tended to be caused by tampering and mistakes by repairpersons). The programs should be redesigned to make this the primary goal. In this approach, progress would be made through changes in vehicle design rather than through attempted repairs. An important topic for research is to study the occurrence of types of malfunctions and their consequences to see if a predictive model can be created for gross emitters and their emissions.

Conclusions

Emissions testing requirements are being extended to include a low-temperature cold start. Evaporative emissions are the focus of more-stringent standards. A supplementary test requirement may be introduced for driving at high power. In addition, onboard recording of some vehicle functions will be introduced. A major effort is clearly being made by manufacturers and regulators. But is this effort well designed?

The root of the problem with our emissions-testing procedures is that they do not cover enough of what an actual vehicle experiences, both real-world driving and real-world maintenance practices. Inextricably bound up with this lack of observation is that we have an inadequate understanding of the physical phenomena. This lack of knowledge would not be so important if the excess emissions associated with the mechanisms listed in Table 3 were small. The two sources discussed above are probably both large. Equally important, several of the sources are physically unrelated to the emissions measured in the FTP. For example, neither of the two sources discussed above can be viewed as even roughly proportional to the emissions measured in the FTP, since the mechanisms associated with enrichment and with system failures are quite different from those in moderate driving with a properly functioning vehicle. So emission rates from the FTP should not be used as the basis for considering emissions differences among types of vehicles, driving patterns, or control policies. Manufacturers, regulators, and other policy makers need to stop thinking that current test procedures and models based on them are related to total vehicular emissions as they occur.

It should be clear that while we understand energy use by vehicles rather well, vehicular emissions and their consequences are poorly understood in many respects. Important research and development topics that need attention include the development of new measurement equipment and techniques, especially for inexpensive and accurate real-time measurement of tailpipe emissions onboard the vehicle. Such an R&D program has been described by Calvert et al (3). Attitudes toward emissions on the part of manufacturers and the public are such that if and when much better information becomes available, the will to act on that information would probably lead to major improvements.

IV. ALTERNATIVE VEHICLE-ENERGY SYSTEMS

Although world petroleum reserves are large enough to last several decades and there may be follow-up fossil fuel sources from which a fuel similar to gasoline might be economically manufactured, the oil-price shocks of the 1970s demonstrated that, as petroleum resources shrink, continuity of supply becomes less secure. In addition, petroleum imports have become a major trade issue for many countries. These developments suggest that more energy-efficient vehicles and alternative-fuel vehicles need to be explored.

In addition, and perhaps more important, the environmental problems of the present system are serious. Metropolitan-area ozone and CO pollution episodes are common, and vehicles contribute most of the CO and much of the ozone precursors. Vehicles are also important contributors of greenhouse gases. Vigorous exploration of low-emissions petroleum-fueled vehicles and alternative-fuel vehicles is needed.

There is no dearth of proposed alternative vehicle-energy systems (Table 4). How to cope with this plethora of alternatives is a serious problem for

Table 4 Alternative automobile-energy systems[a]

IC engine with alternative fuel
reformulated gasoline and diesel fuel, with advanced emissions controls
methanol
ethanol, gasohol
natural gas (CNG, LNG)
hydrogen
. . .
Alternative engines (alternatives to four-stroke and diesel)
rotary
advanced two-stroke
turbine
Stirling
low-heat-rejection diesel
Hybrid electricity-fuel vehicle
emphasizes batteries and grid energy
emphasizes fuel energy, engine operates near optimum, batteries for storage
emphasizes fuel energy, but with "power-storage" equipment (flywheels, capacitor)
All-electric, battery vehicle
advanced lead-acid
nickel-cadmium
nickel-metal hydride
sodium-sulfur
. . .
Fuel cell (fuel-based, electrically operated vehicle)
hydrogen fueled
methanol with reformer

[a] a partial list.

policy. Some of the alternatives are supported by powerful constituencies. This support, including lobbying of government and histories of special relationships with agencies, is important because the alternatives will probably be more costly, for a given level of service, than the present vehicle-energy system. Large government and other subsidies will probably be needed to move any particular alternative into large-scale production, and might also be needed over the long term.

Depending on how radical the departure of the alternative vehicle-energy system, vehicular capabilities, especially for sustained power and for range, are expected to be poorer, and the first cost is expected to be higher, than for typical current vehicles. For example, an estimate of the incremental cost for an all-electric vehicle with substantially reduced capabilities is 5600 in 1987$ (68). (This is long-run cost, i.e. mature technology.) That is how it appears today. However, R&D and design work (and perhaps some initial production experience) might confound these gloomy predictions and lead to an economically attractive system with major fuel and emissions benefits. These efforts would require considerable time and investment, and would be gambles.

This raises the difficult policy question: If early introduction is desired, and if natural economic forces will not select among the alternatives, then government will have to choose among them. We already see this process beginning in the regulatory attempt in California to force the introduction of large numbers of all-electric vehicles, under the misnomer of Zero Emissions Vehicles (ZEVs), starting in 1998. In the opinion of the author, satisfactory all-electric technology for general-purpose vehicles cannot be available on this time scale. The ZEV program is likely to give regulatory forcing and perhaps all environmentally motivated technology a bad name, if mandated and subsidized electric vehicles perform poorly, as energy analysis suggests they would. It seems strange indeed that a regulatory body would decide among the alternatives (Table 4), rather than create a process through which different technologies could compete against a real standard. Perhaps the California regulators became frustrated with the complexity and inertia of some aspects of vehicular emissions (just described). One can hope that the new government-industry initiative (the "Partnership for a New Generation of Vehicles" announced at the White House in September 1993) will be a better thought-out policy.

In our zeal to develop a glamorous alternative vehicle-energy system, we should not continue our neglect of fundamentals. Two examples of research needs have been mentioned, state-of-the-art techniques for measuring engine friction, and low-cost onboard instruments for emissions measurement. Unfortunately, neither the private sector nor agencies such as the National Science Foundation have been willing to support much fundamental research by automotive engineers at our universities.

The technological opportunities to create high-fuel-economy cars with much

lower lifetime emissions are good. Technologies for efficiency improvement of conventional cars and research programs directed at emissions reduction have been discussed. Alternative vehicle options abound. In the opinion of the author, hybrid propulsion in the nearer term and fuel-cell propulsion in the longer term are good possibilities.

Policies are needed to support these developments. In addition to research and development, we need a foundation of stronger fuel-economy standards, and emissions standards based on reasonable prediction of lifetime emissions. Policies are also needed to shift the new car market toward consonance with these social goals. Most promising appear to be fees and rebates based on fuel economy. (We already have a gas-guzzler tax.) Emissions should be included in such a scheme once good predictive information becomes available.

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