A REPORT ON

AUTOMOTIVE FUEL ECONOMY

U. S. ENVIRONMENTAL PROTECTION AGENCY
OFFICE OF AIR AND WATER PROGRAMS
MOBILE SOURCE AIR POLLUTION CONTROL
OCTOBER 1973

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I. INTRODUCTION

This report is the second of two EPA reports on automobile fuel economy. The first report, entitled "Fuel Economy and Emission Control," was published in November of 1972, and dealt with the subject of automobile fuel economy primarily as it was affected by vehicle weight, convenience devices, and emission controls. This report is a sequel to the earlier report in that it contains discussion of automobile fuel economy, but it differs in some respects, reflecting the results of further study. The data base has been expanded, the calculation procedures have been refined, certain areas have been reexamined using newer data and/or different analysis techniques, and additional vehicle design and operating parameters that affect fuel economy are discussed.

Since the earlier report was published, interest in the subject of automobile fuel economy has increased greatly. The earlier report was the subject of comment from within EPA, other Federal agencies, the Congress, state and local governments, citizens, fleet purchasers, motor vehicle manufacturers, and fuel producers. This report is intended to be of use to these same groups. While this report does not discuss the detailed technical analyses and background from which much of the data were derived, it does provide sufficient information upon which to make informed decisions regarding the purchase and operation of an automobile, and from which an understanding can be had of the most important parameters affecting automobile fuel economy.

For those seeking a more technical and detailed presentation of the topics discussed here, additional information can be obtained from the references listed in the bibliography at the end of this report.

II. SUMMARY AND CONCLUSIONS

A. SUMMARY

The Environmental Protection Agency has analyzed fuel economy data from more than 4,000 cars (of which over 1500 were equipped with emissions controls) tested on the Federal Driving Cycle. A carbon balance equation was used to calculate fuel economy. Statistical regression techniques were used to determine the effect of various design parameters on fuel economy.

The data were derived from EPA certification, surveillance and in-house evaluation testing. This is the most extensive data analysis known to have been performed on this subject to date. It is also considered by EPA to be the most accurate for the purpose of comparing changes in vehicle fuel economy because of the use of a single consistent driving cycle and controlled ambient conditions.

In addition, the EPA has evaluated a significant amount of new data which have recently become available (see bibliography) as well as older data which have recently come to light. Much of this data was generated by automobile manufacturers. Significant data were also developed by the U.S. Department of Transportation. Important information also came from a study on vehicle weight trends which was performed under contract to the EPA. Much of this additional data concentrated on the impact of changes in vehicle design and vehicle operation on fuel economy.

This study indicates that vehicle weight is the single most important vehicle design parameter affecting fuel economy. Past and future increases in vehicle weight have had, and will continue to have, a significant adverse effect on fuel usage. Weight is a parameter over which the car buyer has direct discretionary control, in terms of the size car he choses to purchase.

Other aspects of vehicle design (size, tires, axle ratio, engine compression ratio, air conditioning, transmission type, emission controls, and engine size and type) and operation (speed, trip length, acceleration, maintenance, road surface and grade, and elevation) were also examined. Changes in individual vehicle design parameters, including weight, are shown to affect fuel economy from - 50% to over + 100% of the nationwide average fuel economy. The most important of the operating parameters can individually vary the fuel economy of a given weight vehicle over a - 60% to + 25% range.

The sales weighted average fuel economy loss due to emission controls for 1973 vehicles compared to uncontrolled vehicles is 10.1%. This penalty, while significant, must be viewed in the context of the other penalties being experienced by today's car buyer. These include penalties of 9% to 20% for air conditioning and 2% to 15% for automatic transmissions. The loss due to emission controls has varied significantly with vehicle weight, with lighter cars showing a gain of about 3% and heavy vehicles suffering losses up to 18%. Despite the many statements regarding the loss in fuel economy due to meeting the 1975/1976 standards, it now appears that vehicles equipped with catalytic converters to meet the 1975 standards will have improved (0% to 15%) fuel economy over 1973 vehicles.

The use of engines other than the present spark-ignition, reciprocating engine could have a significant impact on vehicle fuel economy. Use of the spark-ignition, rotary engine presently results in significant losses in fuel economy, while the diesel engine offers a significant increase in fuel economy.

Clear trends have developed over the past ten years in motor vehicle fuel economy and factors affecting fuel economy. Vehicle weight has been increasing since 1962 for individual models and the population as a whole. This steadily increasing average weight trend has been accompanied by a steadily decreasing average fuel economy. The use of emission controls has had little impact on this trend. Whether the increasing market share of smaller vehicles will have a noticeable effect is yet to be seen.

B. CONCLUSIONS

1. Vehicle weight is the single most important parameter affecting urban fuel economy; a 5,000 pound vehicle demonstrates 50% lower fuel economy than a 2,500 pound vehicle.

2. Vehicle weight, for both individual models and the sales weighted average, has increased significantly from 1962 to 1973 and current trends indicate additional increases in the future. This weight increase has accounted for about one half of the total drop in the average fuel economy of these model year vehicles.

3. The sales weighted average fuel economy loss due to emission controls (including reduction in compression ratio) for 1973 vehicles, compared to uncontrolled (pre-1968) vehicles, is 10.1%. However, vehicles less than 3,500 pounds show an average 3% gain (attributable to carburetor changes made to control emissions) while vehicles heavier than 3,500 pounds show losses up to 18%. The size of these losses, however, is highly dependent on the type of control systems the manufacturer has chosen to use.

4. Prototype conventional engine powered vehicles equipped with catalytic converters designed to meet the statutory HC and CO standards are expected to show fuel economy improvement over 1973 vehicles up to 12%.

5. The fuel economy penalty due to the use of convenience devices such as air conditioning (a/c) or automatic transmission (a/t) is comparable to that due to emission controls, and can range from 9% to 20% for a/c and 2% to 15% for a/t.

6. The reduction in compression ratio employed by most manufacturers to enable their vehicles to operate on 91 octane gasoline has resulted in a 3.5% fuel economy loss. However, a large share of the cost penalty due to that loss can be regained by using the (presently) less expensive 91 octane fuel for which the engine was designed.

7. The way in which a vehicle is operated significantly affects vehicle fuel economy. Among the most important parameters, high vehicle speeds and short trips can have an adverse effect on fuel economy of up to 60%.

8. Future trends, including increased vehicle weight and possible use of the rotary engine, may result in significant (20%-35%) fuel economy penalties.

9. The diesel and open chamber stratified charge engines show better fuel economy than the conventional engine with the diesel showing a fuel economy improvement of more than 70%.

10. Today's car buyer has available a choice of vehicles in terms of the size and weight, engine type, and convenience devices. These choices can influence a vehicle's fuel economy over a range of 4 to 1.

III. DATA SOURCES AND CALCULATION PROCEDURES

The data used to derive the fuel economy information for this report originate primarily from EPA Certification and Surveillance programs, as a byproduct of the emission tests run to determine compliance of new motor vehicles with the emission standards and to determine emissions from in-use vehicles. Other data originate from in-house EPA testing of exhaust emission control retrofit devices and advanced prototype vehicles, contracts funded by EPA, statistics from the Department of Transportation, the existing literature, and information submitted to EPA by automobile manufacturers.

The fuel economy data derived from the emission tests are obtained by the carbon balance method. Basically this involves taking the unburned hydrocarbon (HC), carbon monoxide (CO), and carbon dioxide (CO_2) emissions from the emission test and calculating the fuel consumption for the test, using the fact that the HC, CO, and CO_2 represent all carbon containing constituents of the exhaust, and the fact that the fuel itself consists of hydrocarbon compounds. The formula used to calculate the fuel economy from the emission data from a 1972 Federal Test Procedure (FTP) test is:

1/ miles per gallon, mpg $= \frac{2423}{.866\ (HC) + .429\ (CO) + .273\ (CO_2)}$

where HC, CO, and CO_2 are the emissions of HC, CO, and CO_2 expressed in grams per mile. This formula is different than the one that was prsented in the earlier report, and is more precise, due to the inclusion of the HC term and the fact that the numerator has been modified to more closely reflect the actual density of the fuel used in the tests.

1/ Designates footnotes which can be found on page 35.

The manner in which the average mpg values for classes of vehicles are calculated also differs in this report compared to the earlier report. The results in this report are based on total miles traveled by all vehicles in the class divided by the total gallons used by all of them. The example given in footnote 2/ demonstrates why this is important in attempting to accurately determine fuel economy. In statistical terms, the harmonic mean of the data is used rather than the arithmetic mean.

The test procedure from which the fuel economy data are derived is the same test procedure used for determining exhaust emissions, the 1972 Federal Test Procedure. This procedure consists of simulating a trip of 7.5 miles in length on a chassis dynamometer, a device which allows tests simulating actual driving to be conducted indoors under closely controlled experimental conditions. The driving cycle used for this procedure represents a mix of urban and suburban driving including several cruises and speeds up to 57 mph. One important feature of this test procedure is the "cold start". The vehicle is allowed to sit or "soak" 12 hours before the test. As a result, the engine temperature is about 70°F at the time of the test (much below its normal operating temperature of 180°-200°F), and the engine is not warmed up before the test. Other components of the drivetrain are also at about 70°F. Therefore, the results of the test are influenced by the warm-up characteristics of the engine and vehicle, which have a significant effect on fuel economy.

IV. GENERAL FACTORS AFFECTING AUTOMOBILE FUEL ECONOMY

Fuel economy [3/] in miles per gallon (mpg) is a measure of efficiency. It is the measure of what you get (miles traveled) for what you put in (gallons of fuel). Automobile engines produce the work required for operation of the automobile by burning the fuel in the cylinders of the engine. Part of the chemical energy in the fuel is converted to useful work done by the engine; the rest ends up as waste heat. This is why automobiles have hot exhausts and cooling systems and radiators to get rid of this heat. The ratio of the useful work delivered by the engine to the total energy in the fuel defines the thermal efficiency of the engine. Current vehicle engines show thermal efficiencies between approximately 10 and 30 percent, depending on the engine type, speed, and load.

Engine efficiency is only indirectly related to the fuel economy of an automobile because, although engine efficiency is a measure of how well the engine converts the energy in the fuel to useful work, the total amount of work required of the engine to drive the automobile depends on the characteristics of the automobile (engine and vehicle design) and on how the vehicle is operated. Therefore, the total fuel consumed depends on the engine, the vehicle, and the operator. Since the fuel economy of the complete automobile is of most interest, this report uses mpg values to denote fuel economy, and not any measure of engine efficiency by itself.

A. ENGINE/VEHICLE DESIGN

There are many aspects of automobile design that influence the fuel economy of automobiles. However, it is not a simple matter to optimize all of the important factors simultaneously in order to achieve the best fuel economy.

Today's vehicle designers are faced with a host of sometimes conflicting requirements. Since the automobile must sell, it must incorporate features that appeal to the buying public. Styling, convenience, comfort, cost, durability, driveability, performance, and fuel economy are among the factors considered by the buying public. Trends in these consumer preferences must be anticipated years in advance, since the total automobile design and development process takes several years before it reaches production and the consumer.

Within the last five to ten years other requirements have been added to the list. These requirements, which must also be satisfied by the vehicle designer, are Federal requirements in the areas of vehicle safety and exhaust emissions. Today's automobile is a result of compromises, tradeoffs, and judgments by the vehicle designers as to what combination of vehicle parameters best suits the overall requirements. Those parameters which principally influence fuel economy are discussed in this report.

1. Weight

Vehicle weight is the single most important factor affecting passenger car fuel economy. Sub-compact cars in the lighter inertia weight [4/] classes (up to 2,500 pounds) generally achieve double the miles per gallon of full size cars in the heavier weight classes because a car's engine must do more work to move a heavy vehicle than a light vehicle. However, this is not the only reason lighter (smaller) cars achieved better fuel economy. Lighter cars have also, customarily, been designed to achieve good fuel economy by employing relatively smaller engines, manual transmissions and fewer accessories.

The difference in fuel economy between light and heavy vehicles has been increasing as emission controls have become more stringent. The fuel economy of light vehicles has not been significantly affected by emission controls, but heavy cars have realized significant penalties. Figure 1 and Table 1 illustrate this effect. The solid line shows that, on the average, the lighter uncontrolled (pre-1968) vehicles achieved much better fuel economy than the heavy uncontrolled vehicles. The dashed line, representing the 1973 vehicles, indicates the same trend but shows that the fuel economy of the heavy 1973 vehicles is poorer than the heavy uncontrolled vehicles while the light 1973 vehicles are slightly better than the light uncontrolled vehicles.

FIGURE 1
FUEL ECONOMY VS. INERTIA WEIGHT

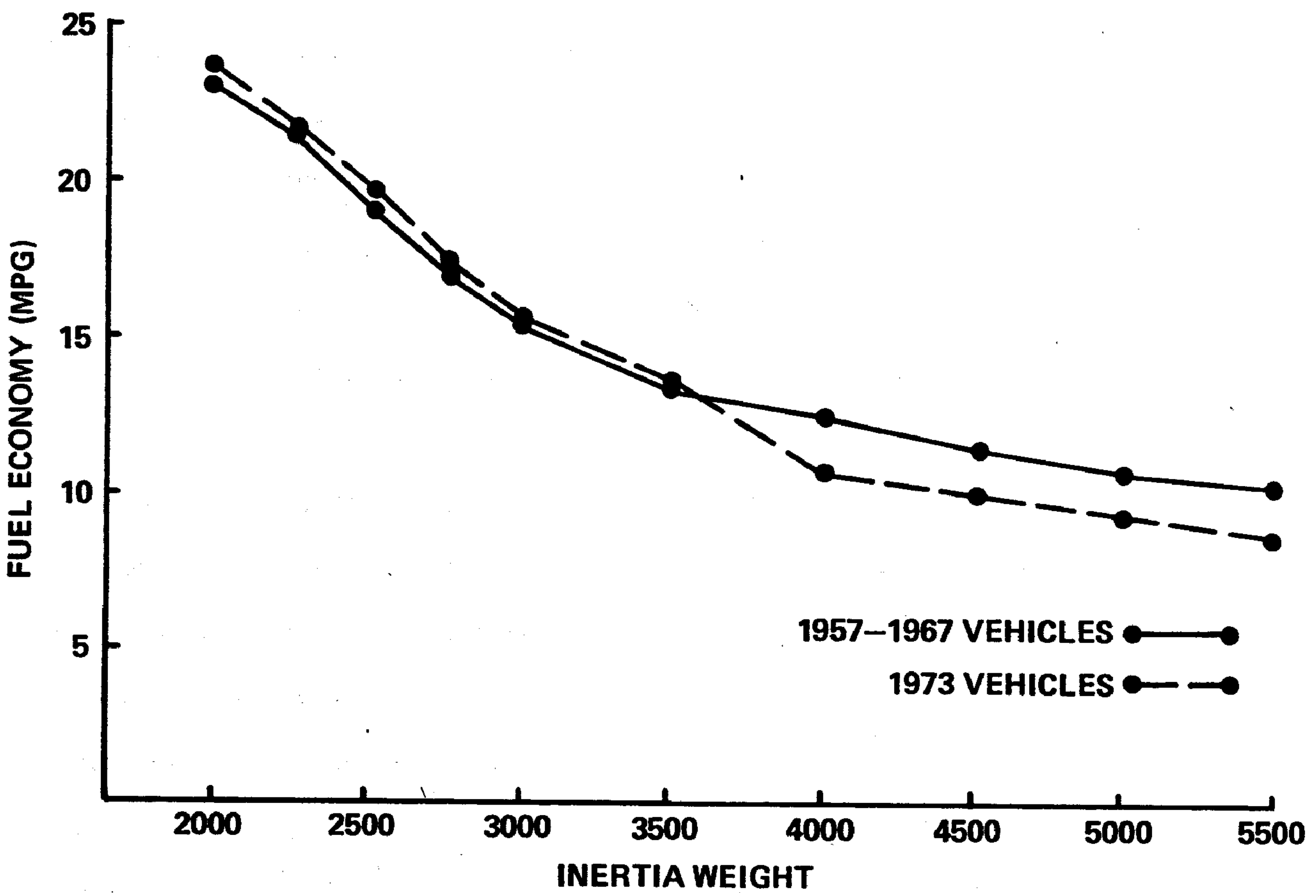
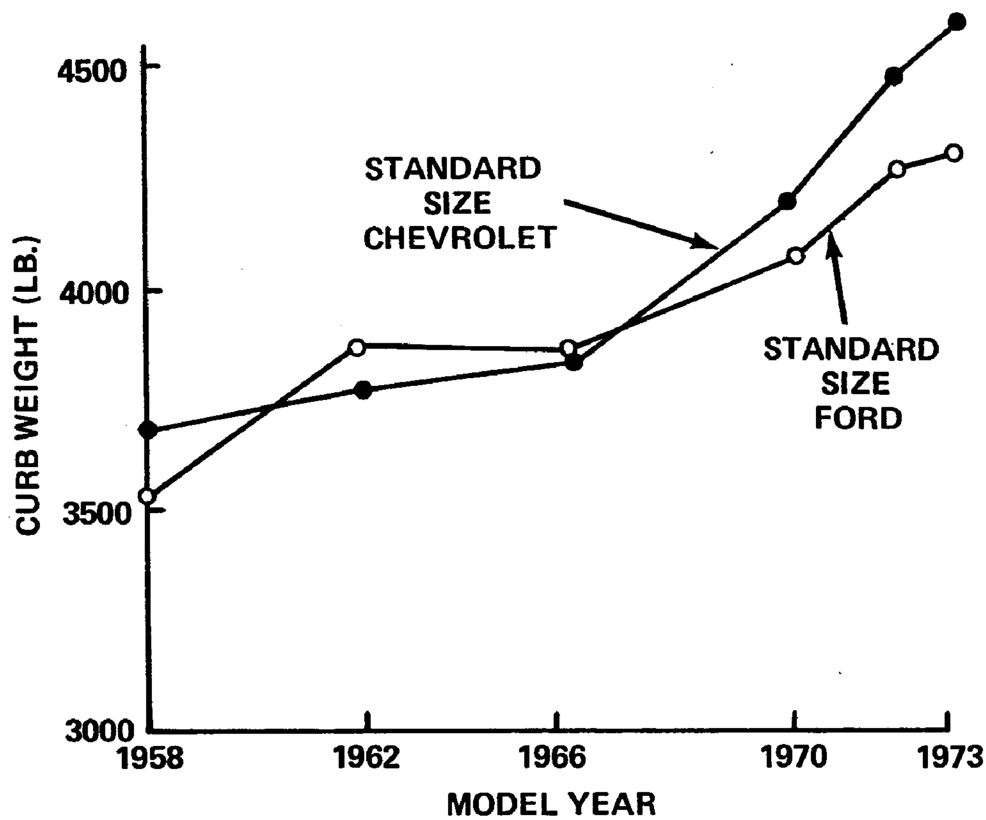


TABLE 1
FUEL ECONOMY VS.INERTIA WEIGHT
FOR UNCONTROLLED (1957–1967 AVERAGE) AND 1973 VEHICLES

	INERTIA WEIGHT									
	2000	2250	2500	2750	3000	3500	4000	4500	5000	5500
'57 – '67 MPG	23.2	21.7	19.1	17.1	15.4	13.5	12.6	11.7	10.9	10.5
'73 MPG	23.8	21.9	19.7	17.5	15.6	13.9	10.8	10.1	9.3	8.6

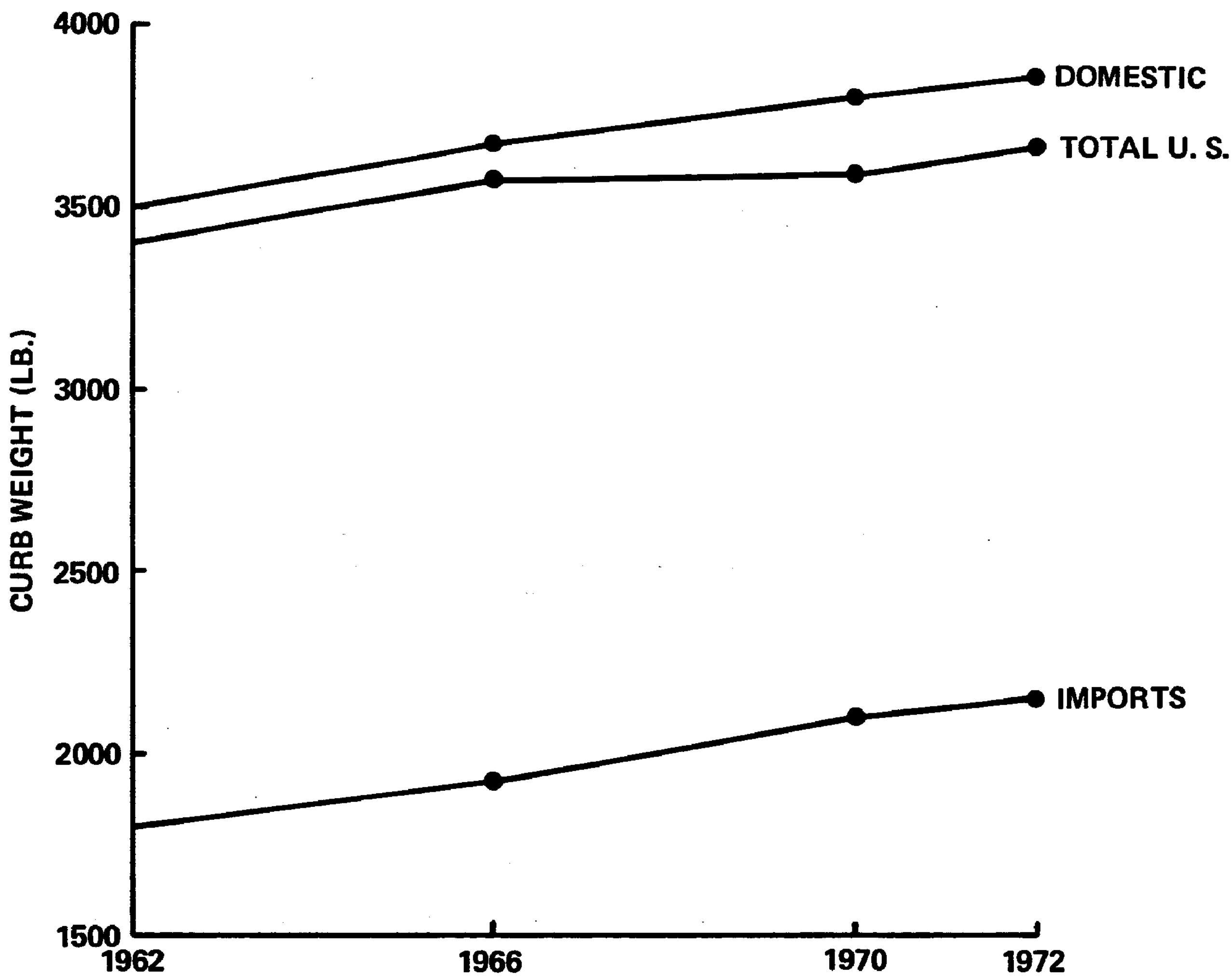
The weight of most model automobiles has been steadily increasing in recent years. As can be seen in Figure 2, the most popular standard size passenger cars have gained about 800 pounds from 1962 to 1973. This trend in increased weight has also been occurring among intermediate, compact, and sub-compacts. These weight increases alone have caused a significant drop in fuel economy of given model vehicles. However, the increased sales percentage in the lighter weight classes has held the "average" weight increase for all cars sold in the U.S. to about 25 pounds per year through 1972 as shown in Figure 3.

FIGURE 2
VEHICLE WEIGHT VS. MODEL YEAR
STANDARD SIZE CARS



The amount of increased sales percentage of light vehicles which will reverse the upward trend in weight and the resulting downward trend in fuel economy will depend on both the public's buying habits and the auto industry's ability to improve engine and vehicle efficiency. Increased sales of convenience devices (e.g., air conditioning, power steering) will continue to increase vehicle weight. Air conditioners for example, add approximately 100 pounds to the weight of a vehicle and cause a 1% to 2% fuel economy penalty [5/] (depending on type of system and vehicle weight) even when they are not used to cool the car. Styling can also affect vehicle weight. Vinyl tops, for example, add weight to the vehicle without performing any function other than styling. This trend is particularly important for the smaller cars, since it will lessen the significant fuel economy advantages these cars now have over larger vehicles which are already extensively equipped with these optional convenience devices. The techniques chosen by the manufacturers to meet future safety standards could also have significant impact on the trend in passenger car weight.

FIGURE 3
VEHICLE WEIGHT VS. MODEL YEAR
DOMESTIC, IMPORTS, AND TOTAL PASSENGER CAR SALES



2. Vehicle Size and Shape

The size and shape of the vehicle has an effect on fuel economy because the automobile has to be pushed through the air as it moves. At the low speeds experienced during city driving, this air drag effect is small, but on the highway, at higher speeds, it becomes important. Air drag is related to the cross-sectional area of the car when viewed from the front. This is approximately equal to the product of the height and width of the car. This cross-sectional area is often referred to as "frontal area". The shape of the car is also important. Even if the frontal areas of two automobiles are the same the one with the more streamlined shape will have less drag and use less fuel. It takes more fuel to push a flat faced box at a given speed than it does to push a streamlined shape, such as the body of a jet plane.

3. Rolling Resistance and Tires

Even if there were no air drag, it would still require power, and therefore fuel, to drive an automobile, because of rolling resistance. Rolling resistance is the name given to the resistance due to the tires, bearings, rear axle, and other rotating components. This resistance is more important to fuel economy during city driving than is air drag.

Since the rolling resistance due to tires has a significant effect on overall vehicle rolling resistance, and since the selection and care of tires are something over which the automobile owner has control, the effect of tires on fuel economy is important.

Two aspects of tires are most important to fuel economy--inflation pressure and type of construction. The correct amount of pressure in tires varies depending on the type of tire, automobile, and driving conditions. Information about correct inflation pressure can be found in the owner's manual for the automobile, and should be followed carefully. Incorrect inflation pressure can reduce fuel economy and tire life. An underinflated tire tends to wear out on the edges more quickly and results in a fuel economy loss. An overinflated tire while producing better fuel economy tends to wear out in the center faster.

The way in which the tire is made can also affect fuel economy. The type of tire construction that appears to have the most beneficial effect on fuel economy is the so-called radial tire. Use of radial tires results in about a 3% improvement in fuel economy when compared to normal bias ply tires.

4. Axle Ratio

One of the choices often available to the purchaser of a new automobile is that of axle ratio. This term refers to the number of times the driveshaft turns for each time the rear wheels turn. Numerically this number ranges from about 2.50 to over 4.00 for current automobiles. Generally, a numerically lower axle ratio will result in better fuel economy, compared to a higher value because, although it produces the same power, the engine runs slower for any given vehicle speed and therefore has less internal friction to overcome. Also, for a given power output (vehicle speed) the engine is operating more efficiently at the lower engine speed because of reduced throttling losses. For example, changing the axle ratio 10% (e.g. from about 3.0 to 2.7) can improve fuel economy by about 2% to 5%.

Another way to obtain the benefits of making the engine run slower for a given vehicle is the overdrive feature with which some automobiles are equipped. In essence this is another gear to shift into once the vehicle is up to cruising speed on the road, reducing engine speed and improving economy. Fuel economy gains of more than 10% during cruising conditions are possible with overdrives. However, despite its merits, overdrive has fallen into disuse. This may be due in part to increased driving in urban areas where overdrive is not used, the greater initial cost, and greater use of automatic transmissions.

5. Convenience Devices

Of the many convenience devices available to the new car buyer, the following can have a negative effect on fuel economy.

1. air conditioning
2. automatic transmission
3. power steering
4. power brakes
5. power seats
6. power windows
7. power sunroof

All of these devices can cause fuel economy penalties in as much as they all add to the vehicle weight. In addition, some of the devices consume significant amounts of energy directly during use. Two of the more important devices, air conditioning and automatic transmissions, are discussed below.

Air conditioning has a two-fold effect on fuel economy. As discussed earlier, the addition of the approximate 100 pounds weight of the system causes a 1% to 2% penalty. A much larger penalty is suffered when the air conditioner is actually running, since the engine is required to produce additional power to drive the compressor. The effect on fuel economy will vary depending on the ambient temperature and the type of driving. Stop-and-go driving in hot weather can result in a 20% penalty if the air conditioning system is turned on. An "average" loss associated with the use of air conditioning is about 9%. Obviously, this loss in fuel economy and the resultant increased gasoline consumption tends to occur during the summer months, when recent fuel shortages were most critical.

The automatic transmission has often been associated with significant fuel economy penalties. When other aspects of vehicle design remain constant, the use of an automatic transmission can result in a fuel economy loss of up to 15%. However, the data in the earlier EPA report and in other studies failed to fully consider the impact of transmission type on exhaust emission controls. Vehicles with manual transmissions sometimes require more severe (e.g. more spark retard) engine calibration to meet a given level of emission control than do vehicles with automatic transmissions, since the throttle movement required during the shifting of a manual transmission equipped vehicle tends to increase HC emissions.

Analysis of the fuel economy data from vehicles designed to meet the 1973 Federal emission standards shows that, on the average, automatic transmission equipped vehicles show only slightly worse fuel economy (2% loss) than vehicles equipped with manual transmissions. Greater fuel economy advantage (6%) is seen for the manual transmission in the lighter weight classes. This may be due in part to the use of less sophisticated automatic transmissions in these light weight categories and the increased use of the energy consuming torque converter in these vehicles which tend to have low power- to-weight ratios.

6. Engine Design

The design of a vehicle's engine can have a significant effect on fuel economy. This is particularly true in view of the different techniques various manufacturers have chosen to reduce manufacturing cost, meet emission standards, reduce octane requirements and produce additional power.

One manufacturer may choose to meet emission standards by the use of control techniques such as ignition spark retard, which will reduce fuel economy; another manufacturer may use fuel injection to meet the same standards with a fuel economy improvement. The manufacturing cost of emission control systems which do not reduce fuel economy is, however, generally higher than the cost of systems which sacrifice fuel economy for low emissions, hence fuel economy tends to be sacrificed by automobile manufacturers in favor of lower vehicle sale prices.

Many passenger cars currently sold in the U.S. have lower compression ratios now than prior to 1971. This trend has tended to reduce fuel economy somewhat. The reduction in average compression ratio from approximately 9.3:1 to 8.3:1 has reduced fuel economy about 3.5%. This change, however, has also reduced the octane requirements of engines from 94 octane (regular leaded fuel) to 91 octane (presently low lead). The customer can usually purchase these low lead fuels for one cent per gallon less than "regular gasoline". This can result in approximately a 2.5% fuel cost savings which makes up most of the cost penalty associated with the compression ratio reduction, although the fuel economy penalty (and the associated increased consumption of petroleum) is still present.

Techniques to increase compression ratio without increasing the engine octane requirements could result in significant fuel economy improvements without increasing fuel costs. Such techniques involving the use of proportional exhaust gas recirculation systems and high swirl combustion chambers have been investigated by the industry and may be available to the public in the future.

The size (horsepower or displacement, which are directly related for most conventional engines) of the engine can also have a significant effect on fuel economy. When two vehicles are identical in all other respects, the vehicle with the smaller engine will usually show better fuel economy. This is because spark ignition engines tend to be more efficient when operated at a higher percentage of full load power. For a given driving condition, two vehicles which are identical except for their engines will have equal horsepower requirements. The vehicle with the smaller engine, however, will have to operate <u>nearer</u> full load than the vehicle with the larger engine, thus delivering better fuel economy. But when the power required to drive the vehicles is so large, or the engine's maximum available power is so low, that the engine in one of the vehicles is operating <u>at</u> full load, then the larger engine may deliver better fuel economy. This is because most engines are inefficient when operated <u>at</u> full load, where some fuel is intentionally wasted in order to obtain maximum utilization of the air passing through the engine. The optimum load for a given engine depends on many engine parameters (ignition timing, carburetor calibration, etc.) and cannot be generalized.

7. Control of Vehicle/Engine Design Parameters to Achieve Improved Fuel Economy

While engine displacement and horsepower are directly related for most passenger car engines today, this does not have to be the case. Several different techniques are available to increase the horsepower of an engine by making high pressure intake air available. This can be done with turbochargers and superchargers. Efforts to improve fuel economy by restricting the allowable horsepower could prevent the development of engine concepts which result in good fuel economy and higher horsepower simultaneously.

Controlling the displacement allowable for passenger cars would be a more logical approach; however, even that would be unfair to manufacturers who have the talent to develop engines that are highly efficient without being small. The most obvious example of how different engine designs can cause different efficiency for a given displacement can be seen in the case of the Mercedes 220 series automobiles.

Mercedes builds two 1973 models that fall in the same weight class and have the same size engines. Yet one model, the 220D, delivers 24 mpg in urban/surburban driving while the other model, the 220 gasoline, delivers only 13 mpg. Although these two models were tested at the same weight and with the same transmission type, the fuel economy of one is 85% better than the other. The 220D model uses a Diesel engine which delivers much better fuel economy than conventional gasoline engines of equivalent displacement.

The use of non-conventional engines in the market place will essentially eliminate the correlation between horsepower and fuel economy or displacement and fuel economy. Differences in engine design also make impractical the use of weight as a possible control variable. Some 2,750 pound vehicles powered by rotary engines deliver worse fuel economy than many 4,000 pound vehicles with conventional engines.

Because design differences in engines can have such a pronounced effect on fuel economy, there is no simple and equitable way to improve fuel economy of passenger cars by restricting the design (e.g. horsepower limit, displacement limit, weight limit) of the vehicle. Any control measure, to achieve its objective in the least limiting way in terms of stifling innovation, should be based directly on the fuel economy achieved, in terms of fuel required for miles driven on a standardized test.

8. Alternative Engines

Alternatives to the conventional gasoline engine may be produced in large numbers in the future and the use of alternative engines could have a significant impact on fuel economy. However, just because an engine is different than a conventional engine does not mean its fuel economy will be better. While the development of alternate engines is continuing and progress in the area of fuel economy will probably be made, the same is also true for the conventional engine. As shown in Table 2, as of today, some alternate engines have demonstrated improved fuel economy over the conventional engine, some demonstrate equivalent fuel economy, and some demonstate inferior fuel economy.

Of the available alternatives, the diesel engine offers the maximum potential for improved vehicle fuel economy. Although it has been in commercial production for over 50 years, it is imported into this country in very small quantities, and no domestic manufacturer has indicated an intention of producing a diesel-powered vehicle for domestic sales. However, a second foreign manufacturer has indicated that he will import a diesel-powered vehicle beginning in 1974.

TABLE 2
FUEL ECONOMY OF VEHICLES EQUIPPED WITH ALTERNATIVE ENGINES EXPECTED TO BE IN USE IN THE NEAR FUTURE.
% CHANGE COMPARED TO AVERAGE 1973 VEHICLE OF SAME WEIGHT

WORSE	EQUIVALENT	BETTER
1. ROTARY: 35% LOSS	1. PRE-CHAMBER STRATIFIED CHARGE (HONDA CVCC)	1. DIESEL: 40% TO 70% GAIN
		2. CONVENTIONAL ENGINE EQUIPPED WITH CATALYST: 0% TO 15% GAIN
		3. OPEN CHAMBER STRATIFIED CHARGE (PROCO): 12% GAIN

9. Emission Controls

Fuel economy penalties brought about by emission control devices have been reported by many different sources. The idea expressed in many reports is that "everyone knows" fuel economy has suffered because of emission control. Usually a percent penalty, one number, is given as "the penalty". Such reports are, however, generally not supported by a statistically significant data base.

EPA studies involving several thousand tests of both uncontrolled (pre-1968) and controlled cars indicate that the effect of emission controls on fuel economy has not been the same for all cars. Some models have realized severe penalties, but other models have realized improvements. A definite trend can be seen from the data. Figure 4 shows that the change in fuel economy between 1973 cars and uncontrolled cars is strongly dependent on the weight of the car. 1973 vehicles in the lighter inertia weight categories (up to 3,500 pounds) show slightly better fuel economy than uncontrolled cars, but vehicles in the heavier categories (4,000 pounds and above) have demonstrated significant penalties, as much as 18% for the heaviest weight class. These figures include the impact of changes in compression ratio.

FIGURE 4
CHANGE IN FUEL ECONOMY
BETWEEN '57-'67 AVE. AND '73 BY INERTIA WEIGHT CLASS

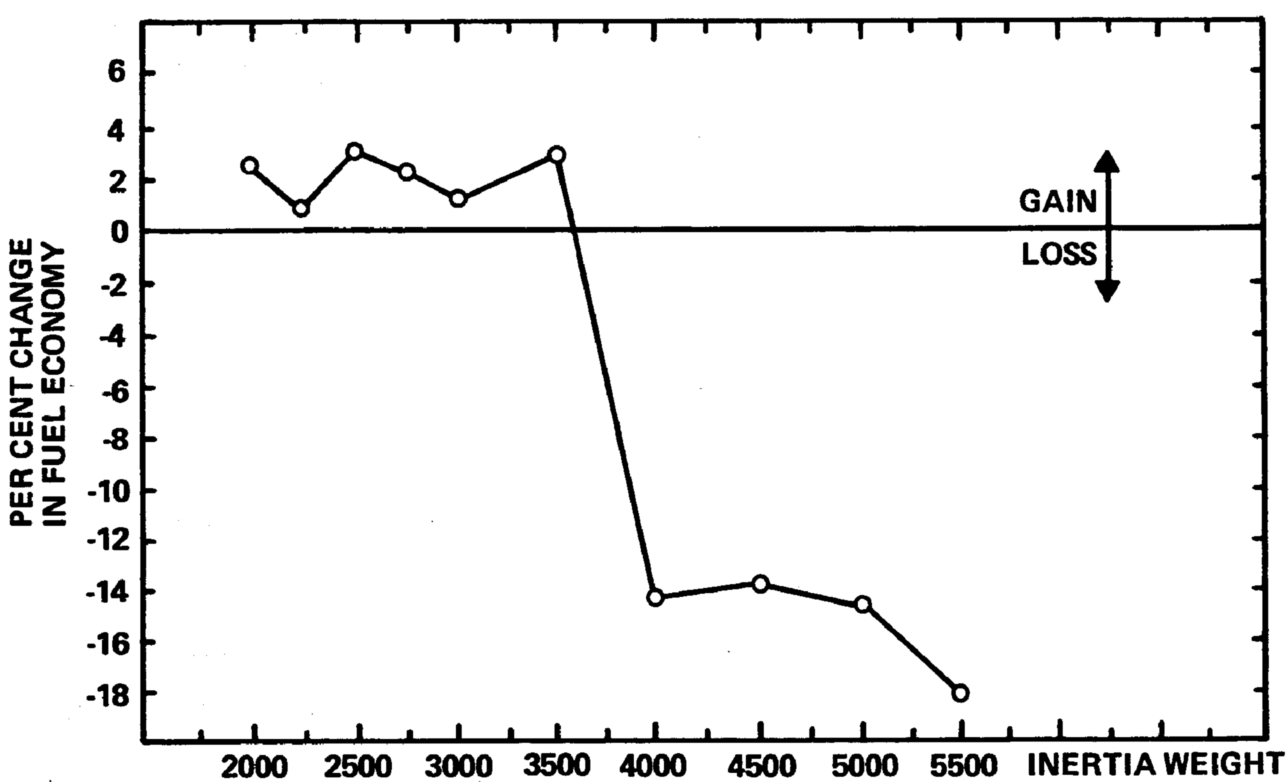


Table 3 presents the same information shown in Figure 4 in the tabular form. The percent change shown for each weight class was determined from the average fuel economy of all cars tested in that class. Trends may have been different for individual models.

TABLE 3
CHANGE IN FUEL ECONOMY DUE TO EMISSION CONTROLS
1973 VEHICLES COMPARED TO UNCONTROLLED VEHICLES

INERTIA WEIGHT CLASS	% CHANGE
2000	+ 2.6
2250	+ .9
2500	+ 3.1
2750	+ 2.3
3000	+ 1.3
3500	+ 3.0
4000	−14.3
4500	−13.7
5000	−14.7
5500	−18.1

The reason for the dramatic difference in fuel economy change between the light and heavy passenger cars appears to be due in part to the difference in the degree of control required to meet the 1973 oxides of nitrogen (NOx) exhaust emission standard, 3.0 grams per mile. The lighter cars need less control to meet this standard than do the heavy cars because their smaller power requirement results in a lower volume flow of their exhaust gas and therefore lower mass emissions. Thus, while techniques used by the industry to control NOx (e.g. spark retard and non-proportional exhaust gas recirculation, EGR) have adversely affected fuel economy, many light cars need little or no NOx control to meet the standard and therefore they have not realized this fuel economy penalty. In fact, since many light cars use emission control techniques (e.g. mixture enleanment or more precise fuel management through the use of fuel injection) which can reduce HC and CO emissions while improving fuel economy and need little additional NOx control, slight improvements in fuel economy are found in the lighter weight classes. However, the step-change between the 3,500 and 4,000 pound weight classes is not fully understood at this time since the same change is demonstrated for other model years as well. The EPA will continue to investigate this difference.

Because of this difference in fuel economy penalty, the average penalty realized by the driving public will depend on which cars the public buys. If more heavy cars are sold the penalty will be severe (up to 15%). This penalty coupled with the already poorer fuel economy of heavy cars would result in a drastic increase in gasoline demand. If, however, more light cars are sold there will be less penalty associated with emission controls, and gasoline demand would be sharply reduced since light cars also get better fuel economy than heavy cars. If the public buys light and heavy cars in the same proportions as they bought them in 1972 then the "average" penalty for the 1973 models will be 10.1%, [6/] including the 3.5% loss due to compression ratio changes discussed earlier.

The effect of future emission standards on fuel economy has been considered by EPA in making decisions on the feasibility of the future standards. While there can be disagreement on this issue, it appears that the changes in engine/vehicle design required to meet the HC and CO levels will result in improved fuel economy. Much of this improvement will be due to the rapid release of the choke which will be made possible through the use of quick heat intake manifolds and higher energy ignition systems. When a vehicle is operated with the choke on, the fuel economy is poor because the mixture delivered to the engine is richer then required for optimum economy. The choke is necessary only when the vehicle is being started and warmed up. When choking requirements are reduced, fuel economy is improved during vehicle warm-up.

Some of the improvements expected on vehicles designed to meet future standards will also be due to the use of improved EGR systems and optimized ignition timing which will allow heavy cars to gain back some of the economy lost in 1973. General Motors data on prototype vehicles indicates that the fuel economy of their vehicles designed to meet the 1975 and 1976 interim standards will be up to 15% better than 1973 vehicles.

B. Vehicle Operation and Use

The manner in which a vehicle is used has a significant effect on vehicle fuel economy. This effect can be as, or more, important than the design of the vehicle and engine itself. It is also one aspect of vehicle fuel economy over which the vehicle operator has control throughout the vehicle's life and not only at the time of purchase.

1. Vehicle Speed and Trip Length

Vehicle speed has a significant effect on fuel economy. The energy required to drive a vehicle a given distance goes up as speed increases. The impact of air drag and rolling resistance on fuel economy, plus the way in which the engine efficiency varies with speed and load, combine to produce the results for a typical domestic automobile shown in Figure 5 and Table 4.

FIGURE 5

FUEL ECONOMY VS. VEHICLE SPEED

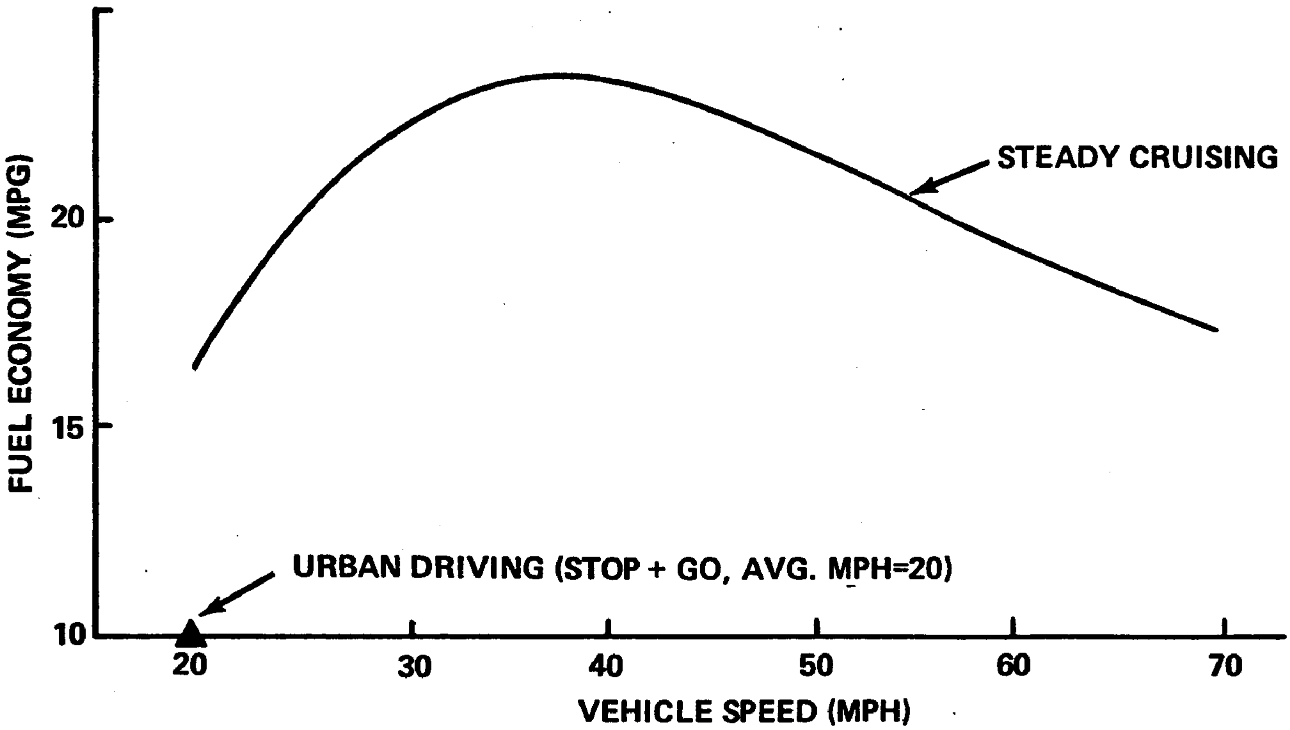


TABLE 4
FUEL ECONOMY VS.VEHICLE SPEED

	SPEED	FUEL ECONOMY
URBAN DRIVING	20 MPH	10 MPG
CRUISE	20 MPH	16.5 MPG
	30 MPH	22.0 MPG
	40 MPH	22.5 MPG
	50 MPH	21.5 MPG
	60 MPH	19.5 MPG
	70 MPH	17.3 MPG

This figure and table show how fuel economy is affected by the steady cruise speed [7]. Two things can be seen from this information. The best fuel economy occurs at a steady speed of between 30 and 40 miles per hour. While interesting, it is not of much practical value because few trips are made at a constant speed between 30 and 40 miles per hour. The most important knowledge to be gained from this information is the effect of high speeds. At a cruise speed of 70 miles per hour, the fuel economy is significantly worse than at 60 or 50. Cruising at 60 instead of 70 miles per hour improves economy about 15%. Cruising at 50 instead of 70 miles per hour increases the savings to about 25%.

Trip length also has a significant effect on fuel economy. Figure 6 shows that the fuel economy achieved during an urban trip is strongly dependent on the length of the trip. Short trips result in poor fuel economy. The engine is less efficient while it is warming-up, due primarily to fuel enrichment (choking needed during start-up) and engine and driveline friction which are higher when the vehicle is cold.

FIGURE 6
FUEL ECONOMY VS. TRIP LENGTH

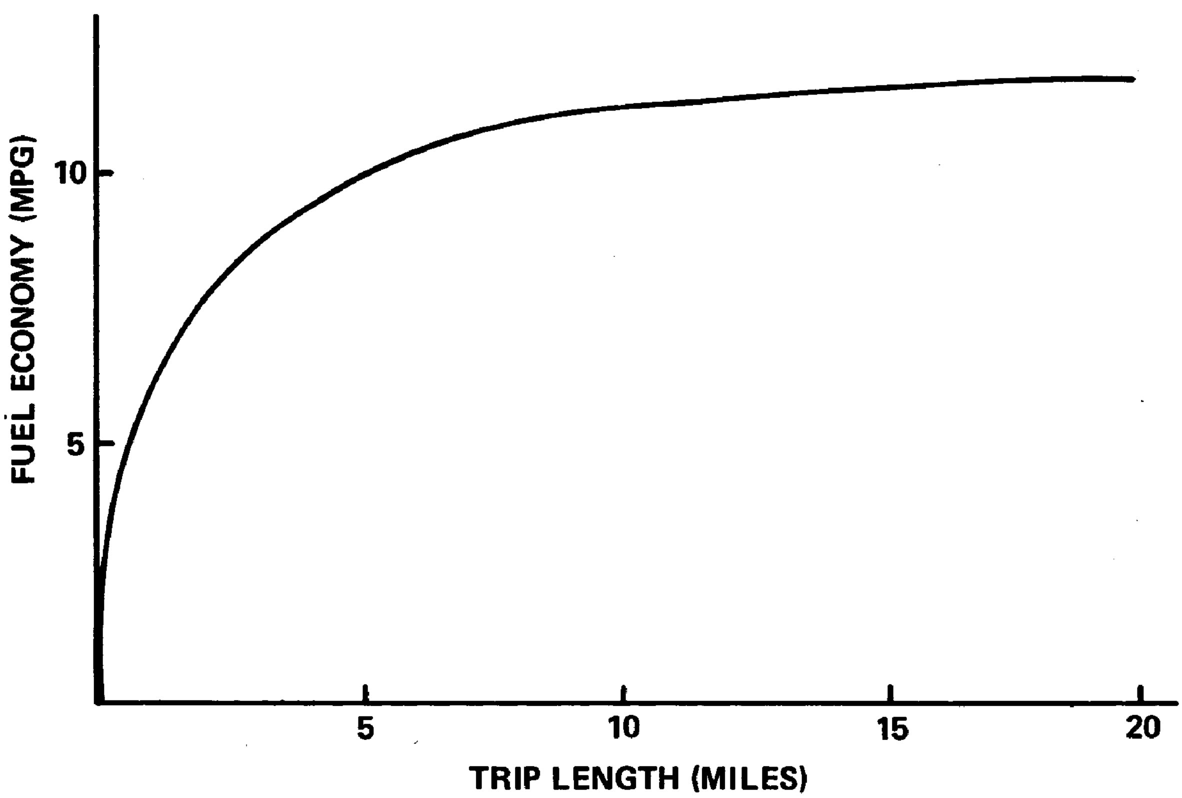


Figure 6 shows that the difference in fuel economy between short trips and long trips is dramatic. The vehicle used to develop this data had a fully warmed-up fuel economy of 13.5 mpg under the same driving conditions. Driven on a ten-mile trip the economy would drop to about 11 mpg and driven on a one-half-mile trip the economy would be only 5 mpg.

Figure 6 applies only to trips that are started with a "cold" engine. The engine can be considered "cold" if the vehicle has been parked overnight or all day long. The same trend would also apply to engines which are warm when the trip is started, but the fuel economy for a short trip would be much better than had the engine been cold at the beginning of the trip.

Figure 6 must be interpreted carefully. The graph indicates that a driver could get better fuel economy by taking a longer route to his designation. This is true but this is also false economy. The mpg value would be higher but the total fuel consumed would also be higher. The total amount of fuel consumed in going from point A to point B is obviously more important than the mpg value obtained between points A and B.

2. Other Driving and Maintenance Habits

The manner in which an automobile is driven can influence its fuel economy. The driver who habitually accelerates away from a stop as fast as he can uses up to 15% more fuel, compared to a driver who uses a moderate acceleration. Other driving habits that can help fuel economy are anticipating stoplights and slowing down gradually, driving smoothly and making as few as possible unnecessary speedups and slowdowns, and keeping idle time to a minimum. At a speed of 50 mph, one speed change per mile can result in up to a 25% increase in fuel consumption. Prolonged periods of idle should also be avoided since an idling automobile delivers zero miles per gallon fuel economy.

Automobiles, like other machines, require maintenance to operate properly. Lack of, or improper, maintenance can hurt fuel economy. The proper maintenance items and frequency are described in the owner's manual and should be followed carefully. Areas requiring periodic maintenance that can affect fuel economy are: air filters, the ignition system (spark plugs, distributor points, and ignition timing), carburetor and proper air-fuel mixing, cylinder compression, and lubrication. If any or all of these areas are not in proper working order or the correct part is not used, fuel economy will suffer. Keeping an automobile tuned up can on the average improve fuel economy 6%, compared to an untuned automobile. However, an individual vehicle which is grossly maladjusted or unmaintained (e.g., spark plug misfiring, clogged air filters, improper carburetor adjustment) can suffer a significantly worse fuel economy penalty of more than 20%.

3. Weather and Road Conditions

The weather in which an automobile is operated can have an effect on fuel economy. Generally, the colder the temperature the worse the fuel economy. This is due to two effects. When it is cold, it takes longer for the engine and drivetrain to warm up, thus hurting fuel economy. However, even when the engine and drivetrain are warm, colder weather generally tends to reduce fuel economy. This effect is about a 2% loss in fuel economy in each 10°F drop in temperature at 50 miles per hour. Many current automobiles, because of emission control requirements, have provisions for heating the intake air. This helps to reduce the adverse effect of low temperature on fuel economy.

The wind can also have an effect on fuel economy. Cruising at 50 miles an hour into a 20 miles per hour headwind results in fuel economy much closer to what would be obtained cruising at 70 miles per hour with no wind. This is because of the increased air drag due to the wind.

The elevation at which an automobile is operated will also affect fuel economy. At high altitudes, current design carburetors get "fooled" and deliver more fuel to the engine, compared to the amount of air, than they should. The vacuum advance feature of the ignition system also fails to function properly at high altitude. This can reduce fuel economy up to 15% at 4000 feet elevation. Modifications to carburetors and ignition systems can eliminate the high altitude fuel economy penalty but the vehicle will then drive poorly at low altitude. Altitude compensated carburetors and ignition systems are currently being developed by several automobile manufacturers. If these systems are put into production in the future, fuel economy penalties will not be experienced at high altitudes. Most vehicles currently equipped with fuel injection already provide some compensation for altitude which reduces the penalty.

The type of road surface and the grade of the road have an effect on fuel economy. The poorer the road, the worse the fuel economy. At 40 miles per hour cruise, badly broken and patched asphalt causes about a 15% fuel economy penalty, compared to a good smooth road. Gravel causes a 35% penalty, and dry sand has a 45% penalty. Dirt roads probably fall somewhere between the bad asphalt and the gravel.

Going uphill reduces fuel economy because the engine has to supply power not only to move the automobile along the road, but also to lift it to the top of the hill. The "grade" of a road is a measure of how steep it is. The maximum grade on most interstate highways is about 5 to 7 percent. Going 50 miles per hour up a 7% grade results in a fuel economy penalty of 55%, compared to going 50 mph on a flat road. On a 3% grade this penalty is about 32%.

V. TRENDS IN AUTOMOBILE FUEL ECONOMY

Year-to-year trends in fuel economy are the combined effects of trends in all of the parameters which affect fuel economy. For any given model year the average fuel economy will depend on the design characteristic of vehicles that are sold, which in turn depends, in part, on what emission and safety standards are in effect and on consumer preference as expressed through buying habits.

By using sales and weight data from vehicle registration lists and fuel economy data from the EPA Federal Test Procedure, a "sales-weighted" average fuel economy [8/] for the model years 1957 through 1973 has been calculated. Figure 7 shows the trend in sales-weighted fuel economy. The same data are presented in Table 5. While market changes (e.g. the penetration of the subcompact car in the early '60's) have had significant effects on individual model years, the general trend has been toward poorer fuel economy. It can be seen from Figure 7 that the loss in average fuel economy during the last 12 years (1962-1973) has been about 16%. Prior to 1968 and the imposition of Federal emission standards, this loss was due largely to vehicle weight increases and the associated changes in engine size, and the increased usage of convenience devices. This trend towards worse fuel economy is slightly greater for the model years after 1967 which were subject to exhaust emission standards, and during which there was an even greater rate of increase in the usage of convenience devices and the trend toward higher vehicle weight. However, the increase in average vehicle weight (more than 350 pounds) and the associated changes in engine size over the total 12 year period alone have accounted for about 1/2 of the total loss.

FIGURE 7
SALES WEIGHTED FUEL ECONOMY
VS. MODEL YEAR

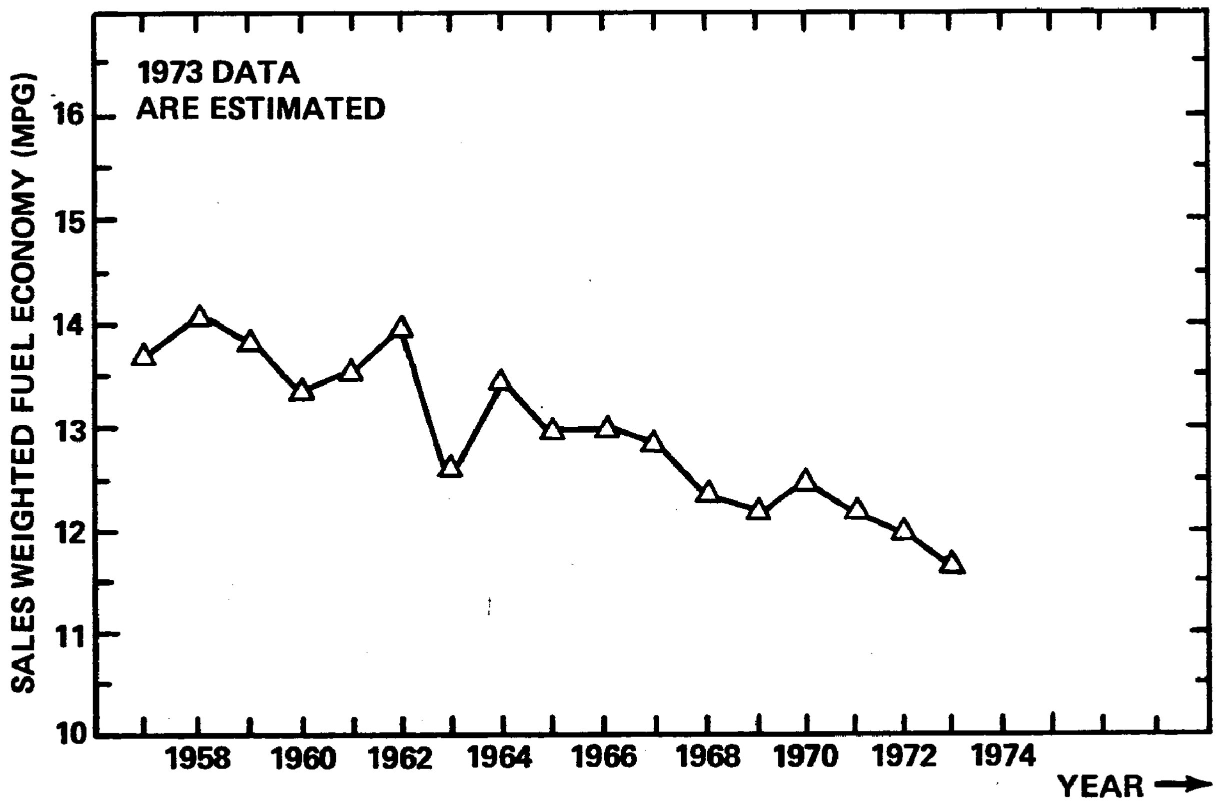
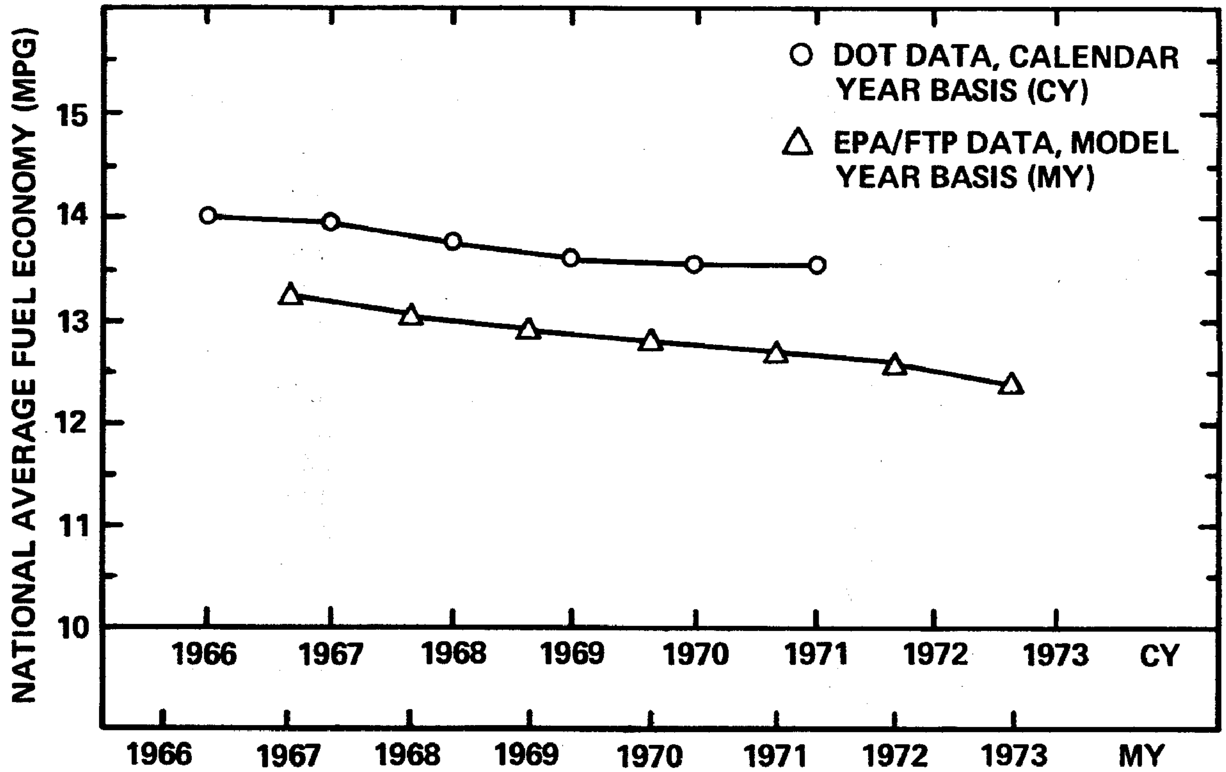


TABLE 5
SALES WEIGHTED FUEL ECONOMY BY MODEL YEAR

MODEL YEAR	SALES WEIGHTED MILES PER GALLON
1957	13.67
1958	14.07
1959	13.85
1960	13.36
1961	13.55
1962	13.96
1963	12.62
1964	13.49
1965	12.98
1966	12.95
1967	12.86
1968	12.44
1969	12.21
1970	12.51
1971	12.21
1972	12.03
1973	11.67
74	13.9
75	15.6
76	17.6

Another way to consider fuel economy trends, that relates more directly to total fuel consumption, is to examine the fuel economy for all cars on the road, not just the new models. This is the basis of the true national average fuel economy figures which are reported annually by the Department of Transportation. DOT's values are calculated from total miles travelled by passenger cars and total gallons of fuel sold to passenger cars in each calendar year. This is shown as the upper curve in Figure 8. The nationwide average fuel economy for all cars on the road can also be determined using the EPA test results, if the make-up of the total passenger car population in any one calender year is known. Using registration data, annual vehicle mileage as a function of age, and vehicle attrition rate information, a "national average" fuel economy has been calculated for several calender years. The trend in national average fuel economy as determined by this method is shown in the lower curve in Figure 8.

FIGURE 8
NATIONAL AVERAGE FUEL ECONOMY
VS. CALENDAR YEAR



Both sets of data show the same trend, a downward shift in national average fuel economy of from 3% to 6% depending on the years chosen for comparison. In addition to showing the same trend, it can be seen that the fuel economy values based on the 1972 Federal Test Procedure results correlate closely with the absolute value of the DOT results, indicating the driving cycle used for the Federal emission test is a good representation of customer average driving. A modification (the inclusion of a hot start and about three additional miles of operation) being made to the Federal Driving Cycle for the 1975 and later model years results in nearly perfect correlation with DOT's values.

Footnotes:

1/ A more detailed discussion of the derivation and use of the equation can be found in Appendix A.

2/ Suppose a motorist took a trip of 600 miles and used three tanks of gasoline. For the first 200 mile segment he used 10 gallons, in the second 200 mile segment he used 20 gallons, and for the third 200 mile segment he used 18 gallons. If he just averages the individual mpg results he gets the wrong answer. The individual fuel economy values for the three segments are 20 mpg (200/10), 10 mpg (200/20) and 11.1 mpg (200/18). The simple average is (20 + 10 + 11.1)/3 = 13.7 mpg. But the trip was 600 miles long and 10 + 20 + 18 = 48 gallons were used, so the trip fuel economy was 600/48 = 12.5 mpg, not 13.7.

3/ Fuel economy should not be confused with fuel consumption which is expressed in terms of gallons of fuel consumed per mile. One is the inverse of the other. A certain percentage increase or decrease in fuel economy <u>does not equal</u> the same percentage decrease or increase in fuel consumption. For example, one car getting 20 MPG has 33% better fuel economy than one with 15 MPG. However its fuel consumption is 25% less. The two terms cannot be used interchangeably.

4/ The term "inertia weight" refers to the test weight of the vehicle that was simulated on the chassis dynamometer during the emission tests. Inertia weight corresponds to the weight of the automobile with a full tank of fuel and two passengers. These classes range from 1750 to 5500 pounds for cars tested by EPA.

5/ Unless otherwise noted, the losses and gains in fuel economy discussed in this report refer to urban/suburban driving and not to steady cruise driving. However, changes in vehicle design or operation which affect urban/suburban fuel economy will have the same relative effect on steady cruise fuel economy.

6/ The calculation of the sales weighted average fuel economy loss due to emissions controls assumes the same market share for the various weight classes for both 1973 and pre-1968. This is done to avoid the possible confounding effects of fuel economy changes due solely to shifts towards heavier or lighter cars being attributed to emission controls. The loss was calculated based on the harmonic means of the fuel economy data or, in other words, based on average fuel consumption data. If the calculations had been based on the average of the fuel economy data, the loss due to emission controls would have been shown to be significantly less.

7/ The steady cruise fuel economy at a given speed should not be confused with the fuel economy obtained during stop and go driving but at the same average speed. This difference is shown in Figure 5. The fuel economy achieved during actual "cruising" will be less (relative to urban driving) than that indicated by Figure 5 because of the many speed changes made (passing other cars), wind conditions, hills, etc.

8/ Sales weighted average fuel economy is the average fuel economy of all cars sold in a given model year, taking into account the number of cars sold in a given weight class.

Appendix A

The equation used to calculate the fuel economy of a vehicle, in miles per gallon (mpg), from data gathered during a 1972 Federal Emission Test is of the following form:

$$\text{mpg} = \frac{\text{grams of carbon/gallon of fuel}}{\text{grams of carbon in exhaust/mile}} \qquad \text{(A-1)}$$

$$\text{mpg} = \frac{(K_1)\ \text{(grams/gallon)}}{(K_1)\ \text{(grams HC/mi)} + (K_2)\ \text{(grams CO/mi)} + (K_3)\ \text{(grams } CO_2\text{/mi)}} \qquad \text{(A-2)}$$

where:

K1 = carbon weight fraction of gasoline or unburned HC (mol. wt. C) / (mol. wt. $CH_{1.85}$) = .866

K2 = carbon weight fraction of CO, (mol. wt. C) / (mol. wt. CO) = .429

K3 = carbon weight fraction of CO2, (mol. wt. C) / (mol. wt. CO2) = .273

grams/gallon = mean density of Indolene 30 test fuel = 2798

substituting:

$$\text{mpg} = \frac{.866\ (2798)}{.866\ \text{(gpm HC)} + .429\ \text{(gpm CO)} + .273\ \text{(gpm CO2)}} \qquad \text{(A-3)}$$

$$\text{mpg} = \frac{2423}{.866\ \text{(gpm HC)} + .429\ \text{(gpm CO)} + .273\ \text{(gpm CO2)}} \qquad \text{(A-4)}$$

Appendix B

Fuel Economy in Miles per Gallon for Various
Model Years and Inertia Weight Categories
(—indicates no data)

Model Year	Inertia Weight 1750	2000	2250	2500	2750	3000	3500	4000	4500	5000	5500
57	—	26.4	—	—	—	—	14.7	13.0	—	—	12.5
58	—	25.3	18.2	—	13.2	—	13.6	15.2	12.5	8.6	—
59	—	28.6	—	—	—	15.2	15.0	13.2	12.7	13.8	—
60	—	20.4	—	22.3	24.5	—	15.7	12.4	10.8	10.9	—
61	—	29.4	—	20.9	16.3	17.2	11.4	14.0	10.5	10.6	—
62	—	25.8	—	—	18.0	16.3	13.0	13.8	12.6	10.8	—
63	—	23.2	19.5	—	16.1	14.7	12.6	12.0	11.1	10.6	—
64	—	22.8	—	—	17.3	16.2	13.7	12.9	11.4	11.0	—
65	—	23.8	—	—	18.3	15.2	13.7	12.3	11.7	10.3	—
66	—	20.9	—	12.7	14.9	14.6	13.9	12.3	12.1	11.3	9.3
67	—	22.6	25.7	—	18.7	15.9	13.1	12.1	11.6	11.2	10.3
68	—	19.3	20.5	18.5	19.7	15.6	13.3	12.0	11.3	9.5	—
69	—	22.2	20.3	18.8	—	15.4	13.3	11.9	11.3	9.1	10.8
70	—	23.4	19.3	17.5	18.5	15.9	13.3	12.0	10.9	10.1	9.9
71	27.2	22.6	21.4	19.3	18.3	14.8	12.2	11.7	10.7	9.6	10.9
72	—	23.0	21.9	19.6	20.0	14.4	13.3	11.1	10.7	9.6	9.3
73	24.8	23.8	21.9	19.7	17.5	15.6	13.9	10.8	10.1	9.3	8.6
74	—	24.1	21.4	18.7	17.7	14.8	13.7	10.8	9.6	9.1	8.2
75	—	—	20.1	17.4	16.6	—	14.3	—	10.1	9.6	8.4
57-67 Aver.	—	23.2	21.7	19.1	17.1	15.4	13.5	12.6	11.7	10.9	10.5

Appendix C

ANONTATED BIBLIOGRAPHY

Further information about automobile fuel economy can be found in the following references:

1. C. E. Schffler and G.W. Niepoth, "Customer Fuel Economy Estimated from Engineering Tests", SAE paper 650861, November 1965.

This paper discusses some of the factors that influence fuel economy. Among the specific factors treated are the effect of how "hard" the vehicle is driven, and the significant effect that short trips, cold engines have on fuel economy.

2. "Weight Trends of Passenger Vehicles", The Aerospace Corporation, El Segunda, California, October, 1973.

This report contains information about the trends in vehicle weight over the time period 1958 through 1972. Data are presented on the average (sales weighted) weight during the 1958-1972 time period, weight trends of specific automobile types, such as subcompact cars, compact cars, intermediate cars and standard cars, weight trends of certain specific model automobiles, and trends in in accessory and convenience device installation.

3. Paul J. Claffey "Running Costs of Motor Vehicles as Affected by Road Design and Traffic", National Cooperative Highway Research Program Report 111 , 1971.

This report includes data on how road type, grade, curvature, traffic density and vehicle speed affect fuel economy. This report also discusses the fuel economy of trucks and contains information concerning some of the other operating costs of motor vehicles, such as oil consumption.

4. G. J. Huebner Jr. "General Factors Affecting Vehicle Fuel Consumption", SAE paper, May 1973.

This paper contains information about the effect of some vehicle parameters, such as axle ratio, compression ratio, and engine size on,fuel economy. Also presented are some data on the steady state fuel economy of three different kinds (size and weight) of vehicles as a function of speed. The effect of tire type is also discussed in this paper.

5. T. C. Austin and K. H. Hellman "Passenger Car Fuel Economy - Trends and Influencing Factors", SAE paper 730790, September 1973.

This paper contains information on trends in fuel economy from 1957 to 1973. Fuel economy data are presented on the basis of the 1972 Federal Test Procedure. Sales weighted fuel economy and national average fuel economy are presented and compared to other references. The effect of various engine and vehicle parameters are quantified by use of a regression analysis. The effect of emissions controls on fuel economy is also discussed. Much of the information in this paper was used in the preparation of this EPA report on automobile fuel economy.