FACTORS AFFECTING AUTOMOTIVE FUEL ECONOMY
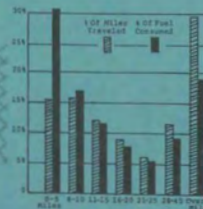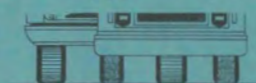
U.S. ENVIRONMENTAL PROTECTION AGENCY

OFFICE of AIR and WASTE MANAGEMENT
MOBILE SOURCE AIR POLLUTION CONTROL
Emission Control Technology Division

September 1975

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This is the third EPA report on the sub-
ject of automobile fuel economy. The
two previous reports were published in
November 1972 and October 1973.

The previous EPA reports have been studied
and commented upon by other government
agencies, the Congress, state and local
governments, private citizens, fleet
operators, motor vehicle manufacturers,
and fuel producers. This report is
intended for the same broad audience.

This report contains new information on
emission controls and tampering, and the
average fuel economy of the 1975 cars. It
also includes information on driving pat-
terns and their effect on fuel economy.
Thus it should aid drivers as well as car
buyers in making choices which can affect
their gas mileage.

I. INTRODUCTION

II. SUMMARY OF CONCLUSIONS

1. The most important vehicle design features affecting fuel economy are vehicle weight and engine displacement. A 10% change in either weight or displacement causes a fuel economy change of 3 to 6%. Since weight changes are usually accompanied by displacement changes, the fuel economy effect of both of these changes has sometimes been attributed to weight alone (Section V-C).

2. Vehicle size and weight and the use of power-consuming convenience devices have all been increasing steadily for more than 10 years. Parameters which affect engine efficiency have also been changing, sometimes in directions leading to lower efficiency (Section IV-C).

3. Driving habits and trip characteristics can have more effect on fuel economy than any vehicle design feature. A standard size car can get over 20 miles per gallon under favorable conditions; it can also get less than 2 miles per gallon under poor conditions (Section IV-D).

4. Travel habits in the U.S. lean heavily toward driving conditions which give poor fuel economy. U.S. autos accumulate about 15% of their mileage in trips of 5 miles or less; however, these trips consume more than 30% of the nation's automotive fuel, because autos operate so inefficiently in short trips (Section IV-D).

5. There is no simple or inherent relationship between fuel economy and the emissions standards that new cars are required to meet; especially misleading is the contention that fuel economy always becomes poorer as emissions standards are made more stringent. With the use of catalyst technology, the average fuel economy of 1975 cars is nearly 14% better than the 1974 models, although their emissions are lower than the 1974's. In fact, fuel economy of the 1975's is as good as cars built before emission controls were introduced (Section V-C).

6. Technology is under development in the laboratory to further reduce emissions without sacrifice in fuel economy from 1975 levels. Considerable engineering development remains before these new technologies are ready for production (Section V-A).

7. There is no guarantee of superior fuel economy through the use of catalytic converters. 1975 cars using catalysts can give excellent or poor fuel economy, depending on the manufacturer's overall design. Cars which do not use catalysts can also give excellent or poor economy, again depending on the overall design (Section V-C).

8. Emission control system tampering by garage mechanics is more likely to hurt fuel economy than to improve it. Such tampering virtually always makes emissions worse, and can cause deterioration in engine durability. Regular maintenance according to manufacturer specifications improves both emissions and fuel economy (Section V-B).

9. Of the many types of alternative engines developed and under development, three types are available in mass-produced 1975 vehicles. When compared to conventionally-powered 1975 cars with similar power-to-weight ratios, present rotary engines suffer a 30% penalty in fuel economy, CVCC engines give about the same economy, and Diesels provide a 35% improvement (Section V-E).

III. DATA BASE AND TEST PROCEDURES

The fuel economy data used in this report came from tests made by EPA, auto manufacturers, the Department of Transportation and other researchers. Each year, auto manufacturers demonstrate that their next model year's vehicles comply with Federal emission standards; they do this by running their own tests and also by submitting pre-production cars for testing by EPA.

In the EPA tests, two separate fuel economy values are determined for each car--one for city and one for highway driving, so each motorist can evaluate fuel economy potential according to his own mix of urban and highway travel. The average U.S. motorist travels 55% of his mileage under urban conditions and 45% on the highway.

The city test procedure is a 7.5 mile stop-and-go driving cycle with a speed range from zero to 57 MPH and an average speed of 20 MPH. The trip begins with a cold start,[1] takes 23 minutes, and has eighteen stops. 18% of the trip time is spent idling during these stops. The first 8-minute segment of the trip is then repeated from a hot start,[2] and test data are combined to represent a realistic mixture of hot and cold start urban driving.

The highway test procedure simulates a 10 mile non-stop trip with an average speed of 48 MPH. The trip begins with a hot start and lasts 13 minutes. Except for starting and finishing at a standstill, the speed range is 28 to 60 MPH.

The cars are tested indoors by professional drivers on a chassis dynamometer, a machine that reproduces the operation of a vehicle under various driving conditions. Use of a dynamometer, rather than road tests, allows the tests to be conducted in exactly the same way each time.

Fuel economy is calculated from measurements of the amount of fuel consumed during a test of known length (miles). This measurement can be done by before-and-after fuel weighing, by using flow meters in the fuel line, or by measuring the amount of carbon in the exhaust (since exhaust carbon originates in the gasoline, the amount of fuel used can be computed). When performed correctly, any of these techniques are acceptably accurate. EPA uses all three methods, but relies primarily on the carbon technique. (See Appendix A).

These test procedures compare well with driving patterns measured in actual traffic; they also compare well with gas mileage tests used by the auto industry. The fuel economy values from these tests are in reasonable agreement with statistics on national fuel consumption.

Two notes of caution:

(a) many of the fuel economy values in this report are average values for a number of vehicles in a given class: An individual car run through the same tests might give fuel economy results above or below the average for its class, depending on its engine, transmission, axle ratio, accessories, etc.

(b) reported test results are no guarantee of the fuel economy a motorist will get in actual driving. An individual car operated by its owner can deliver fuel economy different from the official test values if the type of driving he does differs significantly from the city and highway cycles used in the EPA tests.

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[1] Engine is started after vehicle has been parked overnight.

[2] Engine is started while still hot.

FIGURE 1   EFFECT OF CAR SIZE ON
POWER REQUIREMENTS

A.   40 MPH Cruise

Subcompact
Compact
Standard Car
Luxury Car

B. 70 MPH Cruise

Engine Horsepower

Rolling Friction   Aerodynamic Drag   Drive Train Losses   Accessories*
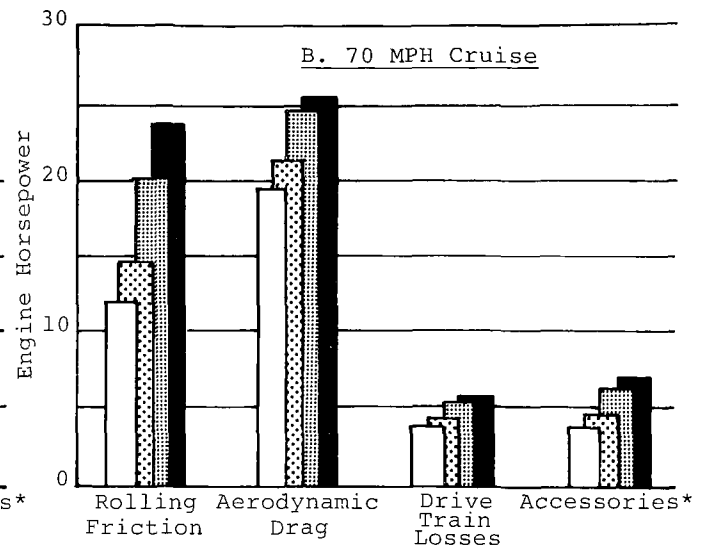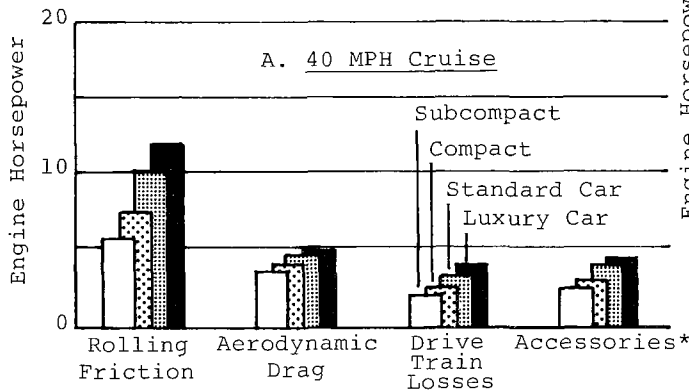
* Includes fan and alternator for all car sizes; includes power steering for two largest cars; does not include air conditioning.

IV. FACTORS AFFECTING AUTO FUEL ECONOMY

Fuel Economy, expressed in miles per gallon (MPG), is an index of the overall "effectiveness" achieved with a motor vehicle which consumes fuel. It measures what you get (miles traveled) versus what you put in (gallons of fuel). It is related to engine power load, vehicle speed, and engine efficiency. (See Appendix B for more detailed explanation.)

For a given speed and engine efficiency, fuel economy is high for low power requirements and decreases as power goes up. For a given speed and power load, economy is directly proportional to efficiency.

A.   FACTORS WHICH AFFECT ENGINE POWER LOAD

To move a car, an engine must provide power to overcome the following vehicle loads:

- Rolling friction
- Aerodynamic Drag
- Inertia (resistance to speed changes)
- Drive train losses
- Accessories

Figure 1 illustrates the relative contribution of these loads for several car sizes under steady speed cruise conditions (where there is no inertia effect).

Figure 2 shows the effect of cruise speed on these variables for a standard size car. Note that rolling friction predominates at low speed, while aerodynamic drag is the largest load at high speeds.

FIGURE 2   EFFECT OF
SPEED ON POWER
REQUIREMENTS

(STANDARD SIZE CAR)

Engine Load – Horsepower

Total
Engine HP
Required

Accessories
Drive Train
Aero Drag
Rolling
Friction

Speed – MPH
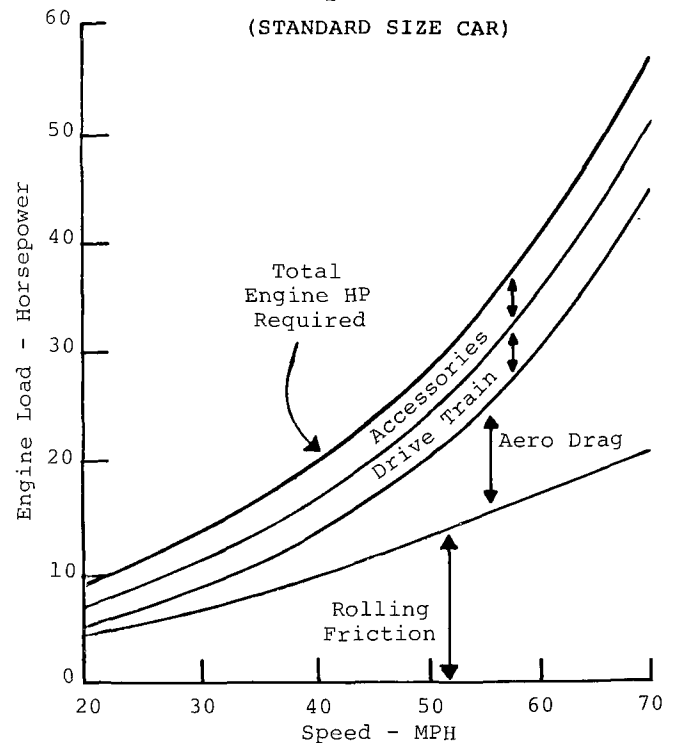
1. Rolling Friction

Rolling friction is the power lost in tires and bearings. It depends on vehicle weight, speed, and tire characteristics.

At any speed, doubling the weight will double the rolling friction. For any weight, doubling the speed will increase the friction a little more than double, as shown in figures 2 and 3.

FIGURE 3 - ROLLING FRICTION
FOR THREE TIRE TYPES
(STANDARD SIZE CAR)

As seen in figure 3, radial tires can have up to 20% less rolling friction than bias-belted tires when tested on typical road surfaces. Tire pressure can also affect rolling friction: higher pressures provide reduced friction. However, inflation of tires to pressures higher than the manufacturer's recommendations can cause increased tire wear as well as a harder ride and increased suspension system stresses.
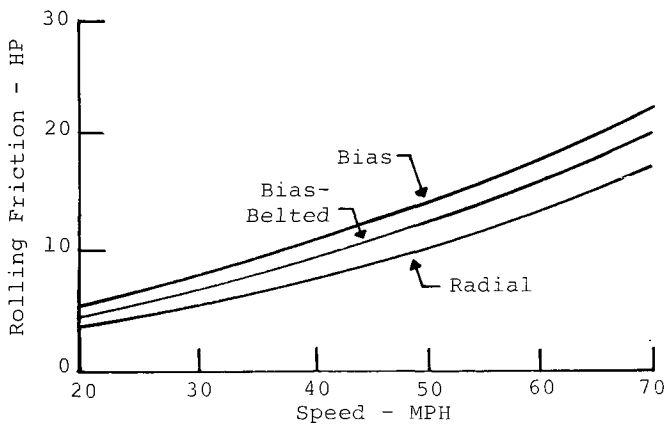
2. Aerodynamic Drag

The power needed to force an automobile through the air is a function of speed, and the size and shape of the vehicle. The effect of speed is quite pronounced, as shown in Figures 1 and 2. The most significant size factor is vehicle frontal area.[3] The frontal area of modern cars

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[3] The cross-section area of the car as veiwed from the front.

is not in direct proportion to weight, i.e. 5000 lb. cars do not have twice the frontal area of 2500 lb. cars. The four car sizes that were used to calculate the power requirements in Figure 1 show this effect:

Table 1

	Curb Weight, pounds	Frontal Area, Sq. Ft.
Subcompact	2500	17.5
Compact	3200	19.0
Standard	4400	21.5
Luxury	5300	22.5

The influence of vehicle shape is represented by a factor called "drag coefficient", which is lower for more streamlined shapes. The cars of the early 1930's, for example, had drag coefficients of about 0.70, which means the air drag on these cars was 70% of the drag on a rectangular box of the same overall dimensions. Today's cars generally have drag coefficients of less than 0.50.

Surface irregularities such as outside mirrors, sun roofs, open windows, campers, etc. cause increased drag. In addition to depending on vehicle speed, air drag is a function of the direction and velocity of the surrounding air. Headwinds (and even crosswinds) increase air drag, and tailwinds tend to decrease it.

3. Inertia

When cruising at steady speed, the only forces acting on the car are rolling friction and aerodynamic drag, but if one wishes to accelerate, additional power must be provided to "push" the mass of the car to higher speeds.

Figure 4 shows this increase in power for a 2 MPH/Second acceleration. Even this mild acceleration can result in power requirements more than triple that of steady speed cruising.

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FIGURE 4 EFFECT OF
ACCELERATION ON POWER REQUIREMENTS
(STANDARD SIZE CAR)

5. Accessories

In this report, the term "accessories" is used to describe both necessary engine auxiliaries (fan, alternator) and convenience devices (power steering, air conditioning).

Accessories can add to vehicle power requirements in two ways: by consuming power themselves, and by adding weight.

For four particular accessories, power consumption outweighs the weight effect: these are the alternator, engine fan, power steering and air conditioning. This is illustrated in the table below for a 30 MPH cruise:

Table 3

| | Increase over 30 mph cruise HP* | |
	Due to Accessory Weight	Due to Accessory Power
Fan	0.1%	2%-3%
Alternator	0.2%	5%-20%
Power steering	0.3%	5%-9%
Air conditioning	1.2%	30%-50% (85°F)

* The % decrease in fuel economy is about 2/3 of the % increase in HP.

Power-consuming accessories are more prevalent in large cars than small ones, as shown in Figure 5.

4. Drive Train Losses

The power required to overcome rolling, aerodynamic, and inertial loads must be transmitted from the engine to the drive wheels by the drive train (transmission and differential/axle). Inefficiencies in the drive train components represent a power loss which must be made up by the engine.

The differential/axle and the transmission gear box each contribute about a 3% loss. Additional losses occur with automatic transmissions due to the torque converter and transmission oil pump. The total losses for automatic transmission drive trains are approximately as follows for a standard size car:

Table 2

	Wheel HP	Drive Train Loss, HP
20 MPH	4.97	1.24 (25%)
40 MPH	14.4	3.17 (22%)
60 MPH	31.7	5.09 (16%)
80 MPH	60.0	7.99 (13%)

FIGURE 5 - ACCESSORY INSTALLATION
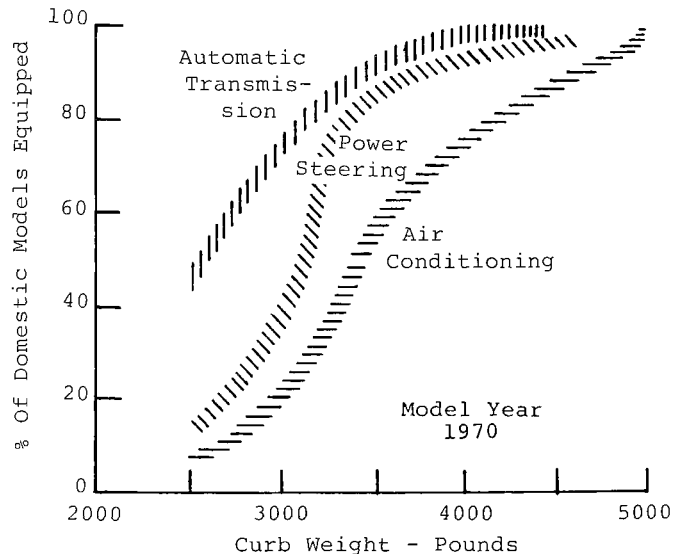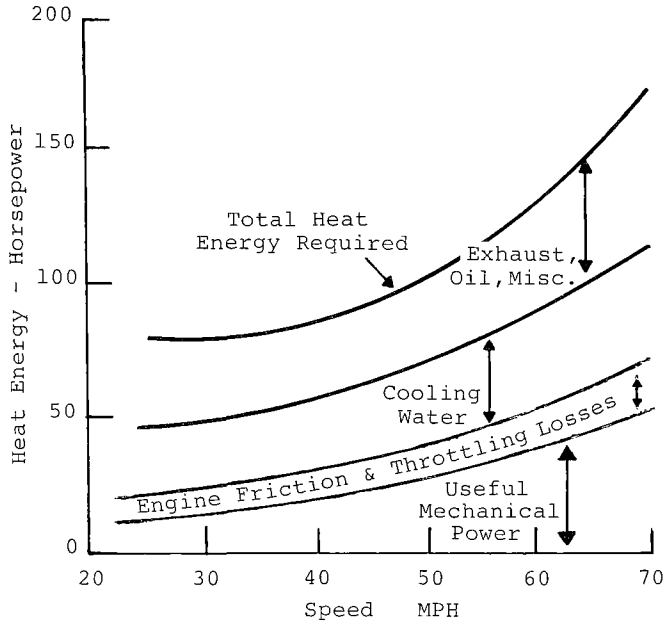VS. VEHICLE CURB WEIGHT

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FIGURE 6   HEAT ENERGY DISTRIB-
UTION, FULL SIZE AUTO ENGINE

Many other design features influence efficiency, such as number of cylinders, bore and stroke dimensions, number of rings, valve size, etc. but these are generally overshadowed by the above variables.

1.   Air-Fuel Ratio

Gasoline engines are usually most efficient at air-fuel ratios slightly above the stoichiometric (chemically balanced) value,[4] shown in Figure 7. In non-stoichiometric mixtures, there is either excess fuel (rich) or excess air (lean) present in the combustion chamber but not entering into the combustion reaction, and efficiency is lowered.

The peak of the efficiency curve can be shifted to leaner air/fuel ratios with engine modifications.

The figure also shows the effect of air-fuel ratio on emissions. HC and CO emissions generally decrease with leaner mixtures due to the increased availability of oxygen. NOx emissions peak where temperature and oxygen concentration are both relatively high. This is somewhat leaner than where peak temperature occurs (~13:1) and somewhat richer than the leanest mixtures attainable.

B.   FACTORS WHICH AFFECT ENGINE EFFICIENCY

As shown in the previous section, the mechanical output of an engine must overcome vehicle power loads such as rolling friction, aerodynamic drag, etc. But when fuel is burned in the cylinders of an engine, only part of the combustion heat energy is converted to mechanical power; the rest of the heat is carried away by the cooling water and the hot exhaust. Figure 6 shows how the total combustion energy splits between mechanical power and waste heat under cruise conditions.

The "efficiency" of an engine defines the fraction of the combustion heat which ends up as mechanical power output. Modern auto engines operate at efficiencies from about 10% to 30%, depending primarily on the following factors:

- Air-fuel ratio (carburetion)
- Compression ratio
- Engine load factor
- Engine speed (RPM)
- Spark timing

FIGURE 7 - EFFECT OF AIR-FUEL
RATIO ON EFFICIENCY AND EMISSIONS
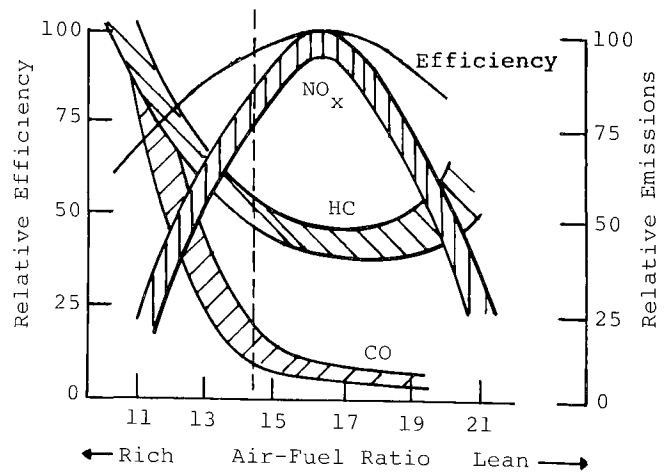
_____
(4)
   This value is a little less than 15 parts air to 1 part fuel, by weight.

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2. Compression Ratio

Higher compression ratios promote higher peak temperatures and lower exhaust temperatures, and hence greater conversion of the fuel's heat energy into mechanical work. The influence of compression ratio on efficiency varies with the engine's opera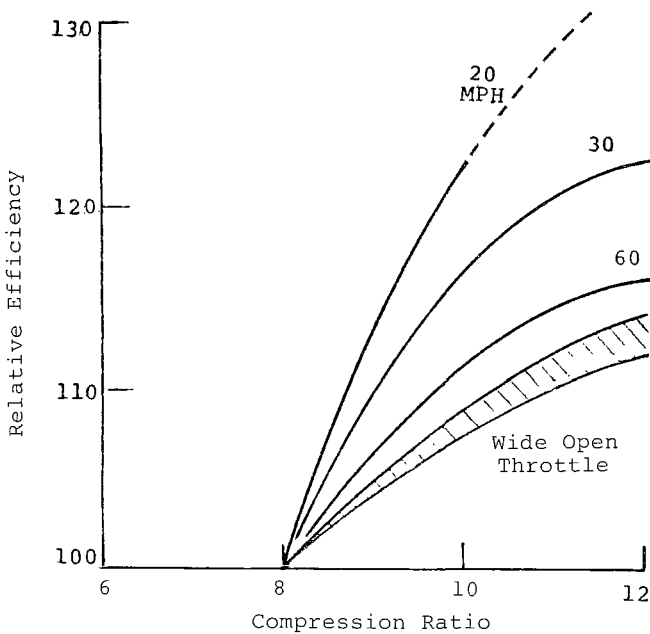ting condition. At low speeds, the compression ratio effect is more pronounced than at high speed, as shown in figure 8.

FIGURE 8 - EFFECT OF COMPRESSION
RATIO ON EFFICIENCY

Since higher compression ratios increase engine power capability, an additional efficiency benefit can be achieved by using a lower-displacement engine; this holds vehicle performance constant. Figure 8 includes this effect.

3. Engine Load Factor

As an engine's power level is reduced, it operates less efficiently, as seen in Figure 9. This occurs because a relatively closed throttle is a barrier in the intake, and the piston has to work harder to suck in the fuel and air

FIGURE 9 - EFFECT OF LOAD FACTOR
ON EFFICIENCY
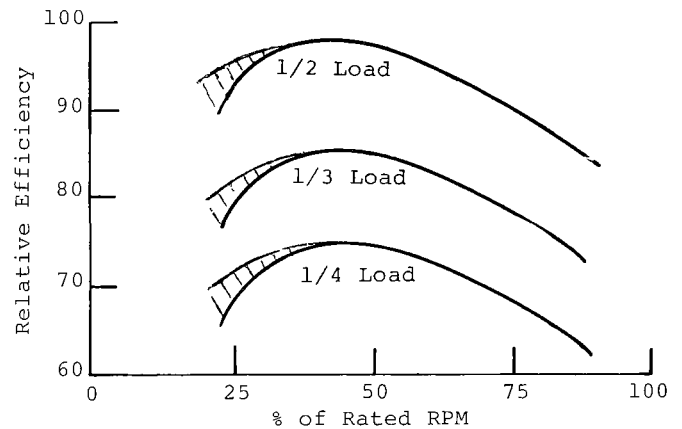
past this obstruction.

Also, when an engine is operated at low power, it wastes a higher fraction of its total power on internal friction, which is essentially constant for a given RPM.

Of course, running an engine at a higher power level will not produce better fuel economy, even though it may make it operate more efficiently; a power increase always overshadows the efficiency gain it produces. For a given speed and load, a small engine operating at a high load factor will have higher efficiency and better fuel economy than a larger engine running at a low load factor.

4. Engine Speed

Figure 9 showed that efficiency depends on engine RPM. This is more fully illustrated in Figure 10, which shows the effect of speed on efficiency for several fixed power levels.

A decrease in engine speed usually increases efficiency. This occurs because lower speeds give lower internal engine friction and lower throttling losses.

The fuel economy effect of this can be seen in actual practice when an engine is run slower by means of lower axle ratios and/or overdrives.

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FIGURE 10 - EFFECT OF ENGINE
SPEED ON EFFICIENCY

Relative Efficiency vs Engine Speed - RPM

60 HP, 40 HP, 20 HP curves

5. Spark Timing

An engine operates most efficiently
when peak combustion pressure is reached
just after the piston passes top dead
center (TDC) position. To achieve this,
the fuel-air mixture must be ignited
before TDC. The proper ignition time
is a function of the flame speed in the
combustible gas, and must be varied with
engine RPM and engine load. Spark timing
in today's engines is controlled by mani-
fold vacuum, an indication of load; and
by centrifugal advance, related to RPM.

Figure 11 shows that, for a given RPM,
there is a spark advance setting which
maximizes power output.

FIGURE 11 - EFFECT OF SPARK
TIMING ON POWER

Relative Horsepower vs Spark Advance - Degrees Before TDC

1500 RPM, 1200 RPM, 900 RPM curves

The effect of spark timing on efficiency
appears in Figure 12 for two cruise
speeds. As with power output, maximum
efficiency occurs at some particular
advance setting.

The amount of advance shown for these
driving conditions should not be con-
fused with idle spark advance, which is
normally just a few degrees.

Spark timing is similar to compression
ratio: too much spark advance will cause
knocking unless higher octane fuel is used.

FIGURE 12 - EFFECT OF SPARK
TIMING ON EFFICIENCY

Relative Efficiency vs Spark Advance Degrees Before TDC

25 MPH, 55 MPH curves
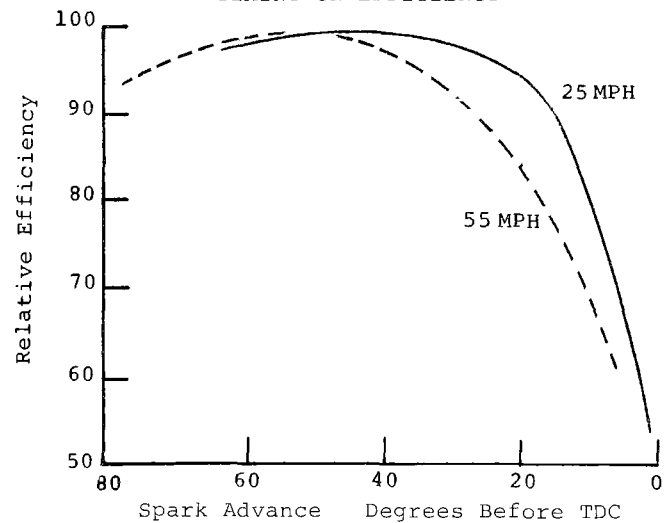
C. TRENDS IN CAR AND ENGINE DESIGN

Many vehicle design factors have changed
notably in the last several years. Many
of these changes have had adverse effects
on fuel economy. Fuel economy is not
ignored by car designers, but many changes
which reduce gas mileage have been made
in response to requirements (real or
anticipated) in other areas. Because
automobile design and development
decisions must be made several years
prior to actual production, the designer
has to guess far in advance what the
consumer, economic and government re-
quirements will be; the automobiles in
any particular model year are always the
result of compromises, tradeoffs, and
design judgments.

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1. Trends Affecting Power Requirements

In the past 15 years or so, most car lines have changed in ways which increase power requirements. The most obvious of these is vehicle weight. As shown in figure 13, vehicles offered for sale in the U.S. have been generally gaining weight at a rate of 50 to 100 pounds per year. The average weight of the compact and inter-

In every one of the eleven years from 1958 to 1968, the best-selling test weight class was 4000 pounds; in 1968 it jumped to 4500 pounds and for 1975 the projected best-selling class is 5000 pounds. Fortunately, average weight for the whole U.S. market has gained only about 25 pounds per year through 1973, because of the increased sales penetration of the light weight classes.

Car dimensions have been increasing too. Figures 14 and 15 illustrate the trends in wheelbase and length for the

FIGURE 13 - CURB WEIGHT TRENDS
BY MARKET CLASS, U.S. SALES

FIGURE 14 - TRENDS IN
AUTO WHEELBASE

FIGURE 15   TRENDS IN
AUTO LENGTH

mediate classes dipped in the early 1960's due to the introduction of new, lighter-weight models (Falcon, Corvair, Chevy II), but has increased steadily since then. The subcompact class was at its lightest in 1964 due to the high sales fraction of imports, but this class has grown in weight since the introduction in 1970 of heavier U.S. built models (Gremlin, Pinto, and Vega).

Note that 1973's subcompacts are nearly as heavy as 1962's compacts, 1973's compacts are as heavy as 1962's intermediates, etc.
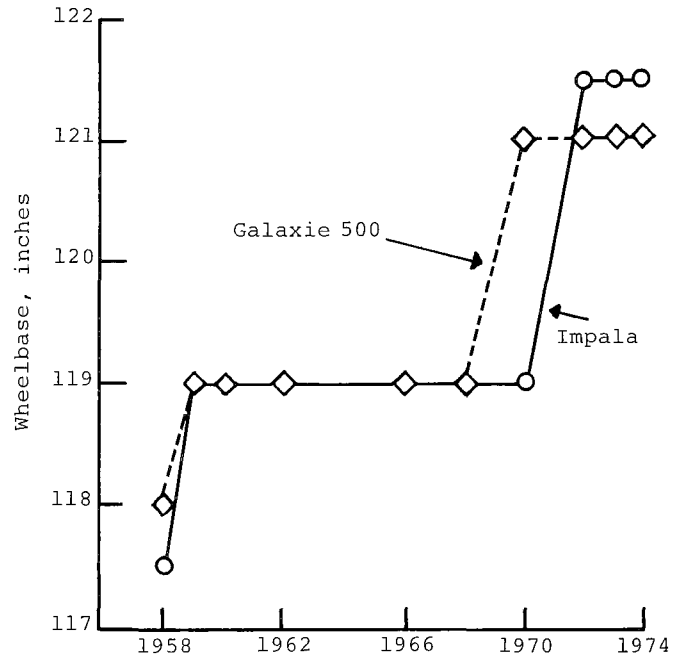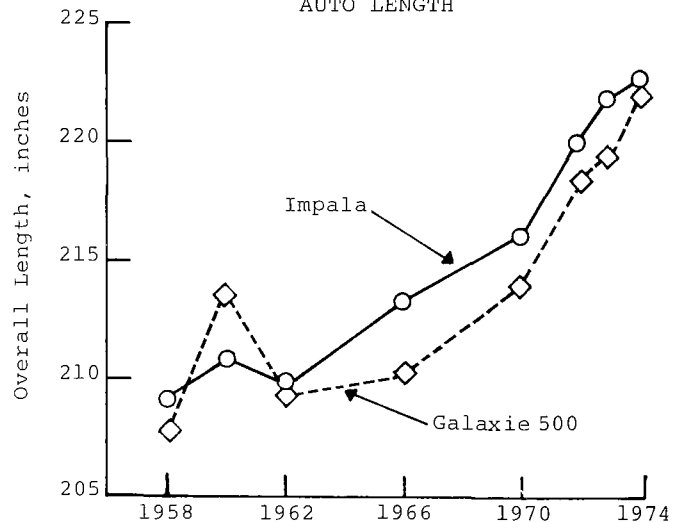
best-selling standard size cars. This rate of increase in dimensions is typical of all market classes.

Since some observers have linked growth in vehicle size to government safety regulations, note in figure 15 that these cars grew 14 to 15 inches longer from 1958 to 1972 - presumably due to styling choices - but they grew only 3 to 4 inches from 1972 to 1974 - when increased crashworthiness was first required in auto bumpers.

In addition to increases in car size, there has been a rising demand for convenience items which increase both vehicle weight and power consumption. Figure 16 shows this trend for those luxury items best known for their high power requirements.

FIGURE 16- INCREASES IN USE OF
CONVENIENCE ITEMS (DOMESTIC MODELS)
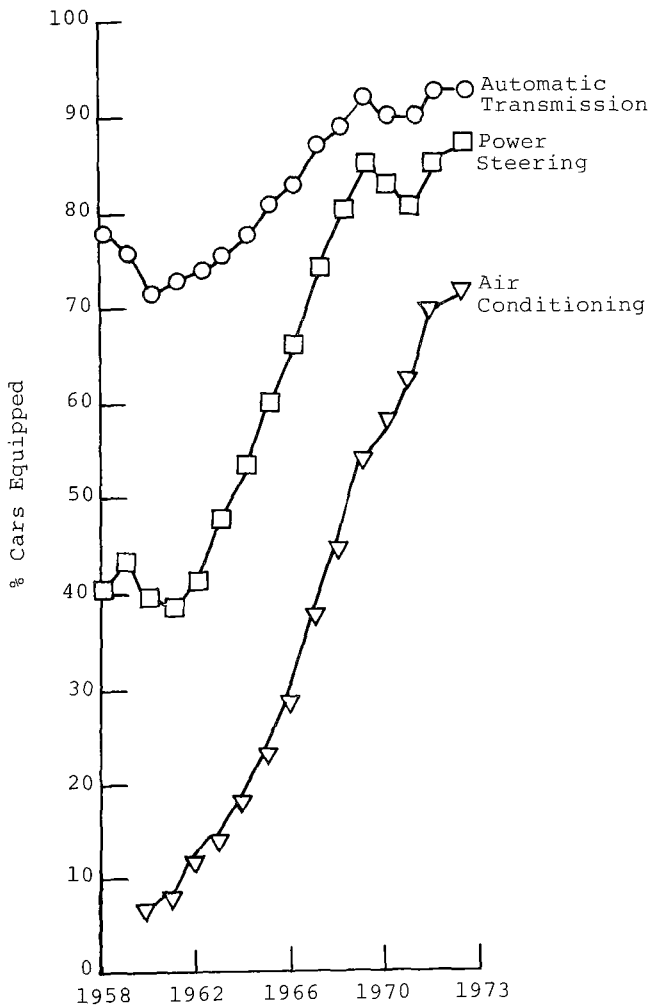
2. Trends Affecting Engine Efficiency

Figure 17 illustrates how average engine size has changed in the U.S. market since 1958. The drop in the early 1960's for

FIGURE 17 TRENDS IN
ENGINE DISPLACEMENT
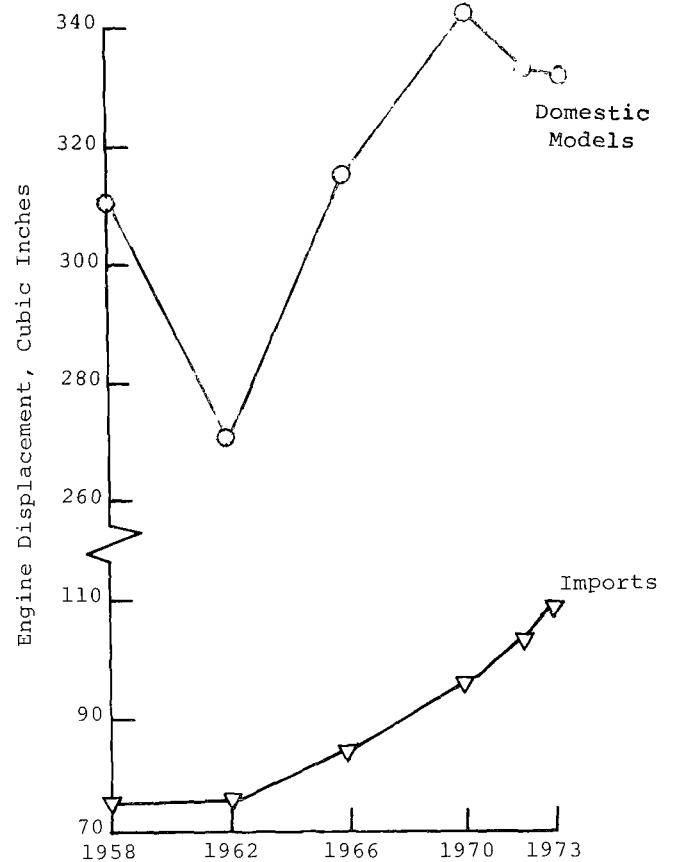
domestic models resulted from the introduction of new compacts and intermediates.

From 1962 to 1970, average engine displacement rose faster than average vehicle weight - a reflection of a general trend toward higher performance. Figure 18 shows that there is a large disparity between the way domestic cars are powered, compared with imports; this disparity has not changed much in 15 years.

Detailed engine design features have been changing also. As seen in figure 19, the average compression ratio of domestic cars declined due to high volume economy car sales, then rose sharply until the

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FIGURE 18 - TRENDS IN ENGINE
SIZE VS. VEHICLE WEIGHT
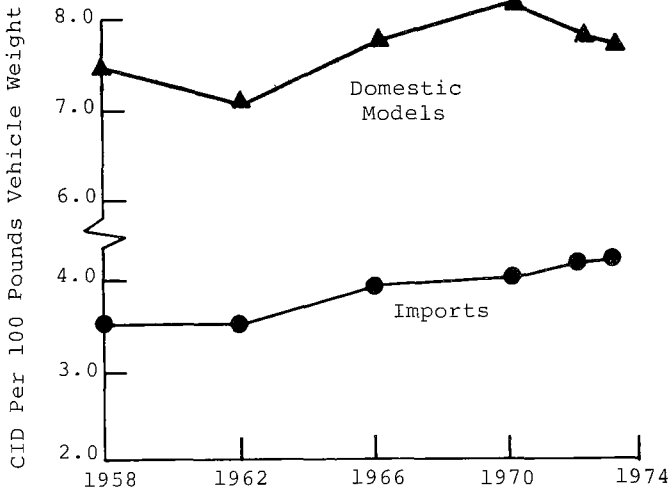
FIGURE 20 - TRENDS IN
ENGINE BORE AND STROKE
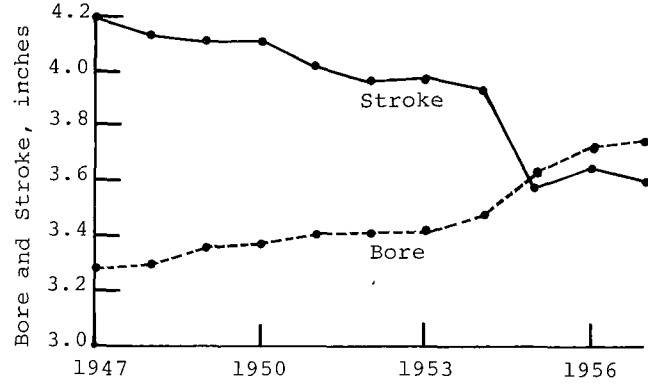
FIGURE 19 - TRENDS IN
COMPRESSION RATIO
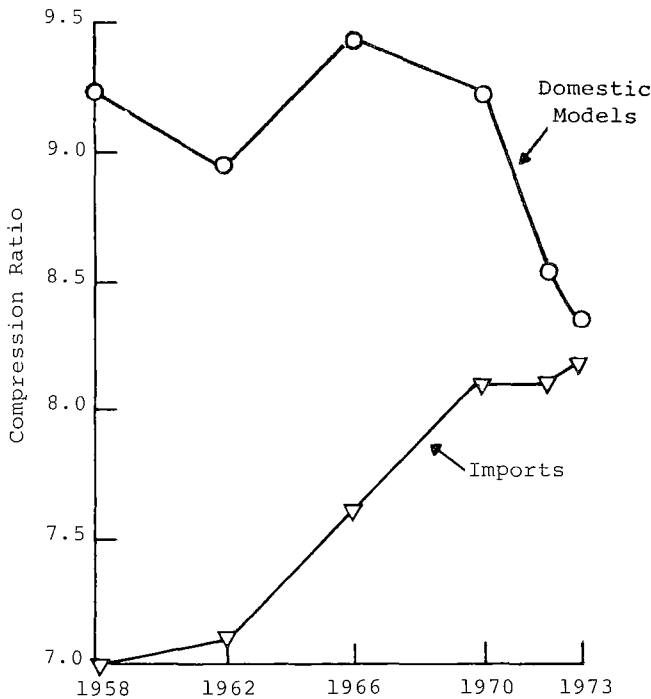
the sudden mid-50's change in the average
bore-to-stroke ratio for domestic engines.
The old long-strokers gave way to higher
RPM short-stroke machines, to provide
better breathing, less engine friction, and
snappier vehicle performance.

D.   EFFECTS OF VEHICLE OPERATION

The foregoing section discussed separately
the variables affecting load and efficiency;
it is useful now to examine vehicle
operating situations wherein power level
and efficiency interact. Consider a car
cruising at constant speed versus
accelerating through the same speed:

Table 4

	Cruise	Accelerating 20→25 MPH	
	22.5 MPH	2 MPH/Sec	4 MPH/Sec
	(3rd Gear)	(3rd Gear)	(2nd Gear)
Avg. MPH	22.5	22.5	22.5
Avg. RPM	1100	1100	1650
Avg. HP	8.5	40.5	67.9
Efficiency	16%	27%	27%
MPG	20.0	6.9	4.0

desirability of operating with lower
octane gasolines turned it back downward.
Compression ratios of the imports, for a
long time lower than the domestics, have
now risen to comparable values.

As an illustration that auto engine
design changes have been going on for
years, consider figure 20 which shows

This example shows how a large power in-
crease can significantly diminish fuel
economy, although engine efficiency nearly
doubles. It also shows how much accelera-
tion rate can affect fuel economy.

The example in Appendix B   comparing a
50 MPH cruise and a 70 MPH cruise also

illustrates the tradeoff between power
and efficiency, with the higher power
case again coming out second best
in fuel economy.

Since the way a car is driven can make
such differences in fuel economy, it is
worthwhile to look at the driving patterns
actually used by motorists in the U.S.

1. Characteristics of Trip Patterns

Trip patterns have been studied exten-
sively by the U.S. Department of Trans-
portation, the Environmental Protection
Agency, auto manufacturers, the Society
of Automotive Engineers, and others.
These studies have found that trip length
has a large effect on average trip speed,
as shown in figure 21.

This occurs because most long trips are
usually taken on the highway while shorter
trips tend to involve more urban travel,
with a higher frequency of stops.

FIGURE 21 - AVERAGE TRIP SPEED
VS. TRIP DISTANCE
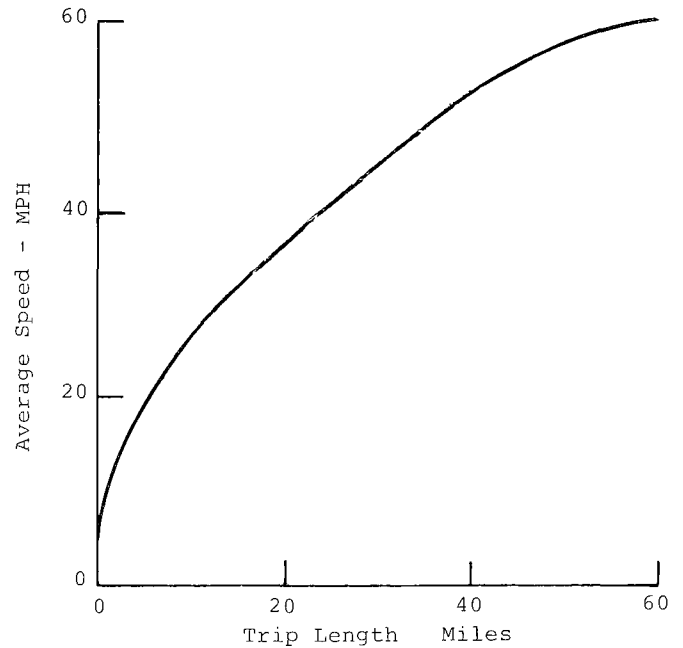
In fact, there is a direct correlation
between frequency of stops and the
average speed of the trip, as illustrated
in figure 22. The line in this figure comes
from measurements taken in actual traffic.
The figure also shows the average speed
and stop frequencies for test procedures
developed by EPA, the SAE, and a major
auto manufacturer. While the average
speeds of these procedures vary, they
all correlate well with the traffic
measurements.
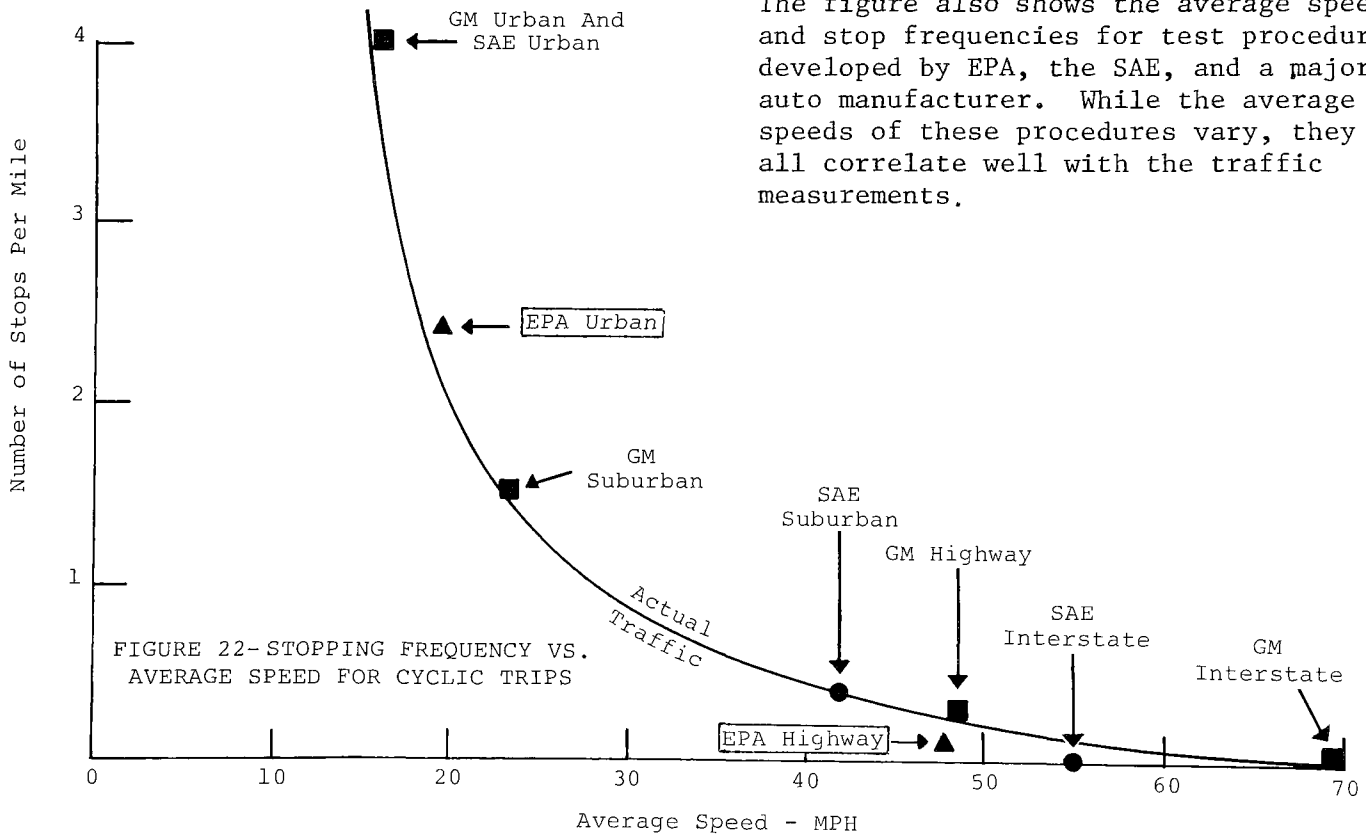
FIGURE 22- STOPPING FREQUENCY VS.
AVERAGE SPEED FOR CYCLIC TRIPS

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FIGURE 23 - INFLUENCE OF DRIVING PATTERN ON FUEL ECONOMY

Standard Size Car

Compact Car
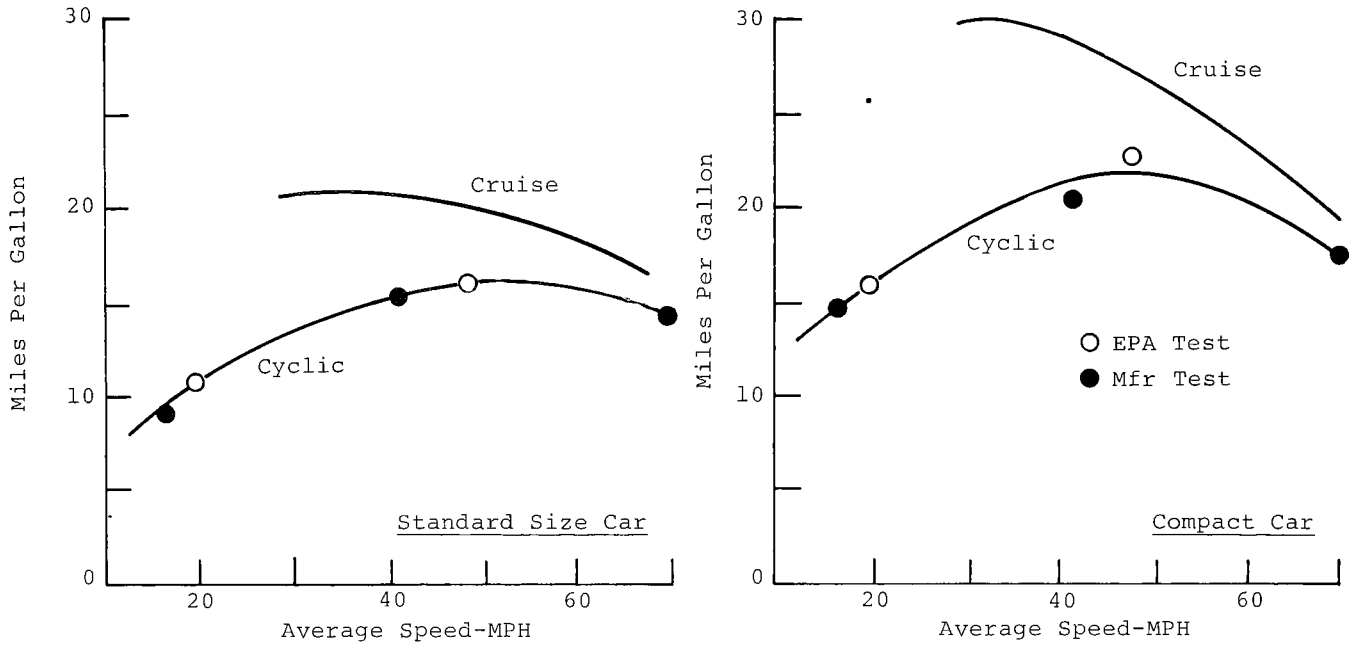
The fuel economy effects of these varying trip characteristics appear in figure 23, for a standard size car and a compact. Economy under cruise conditions for the same cars is also shown for comparison. Low speed cyclic (stop-and-go) driving gives lower economy than steady speed driving, because of all the accelerations in these driving patterns. At higher speed, the cyclic MPG is closer to the cruise MPG, but still drops off because high speeds give lower economy than lower speeds.

Another trip characteristic which influences fuel economy is the warmup effect illustrated in figure 24. The data were taken by driving over the same 1-mile road course for varying distances, each run being made from a cold start. Economy
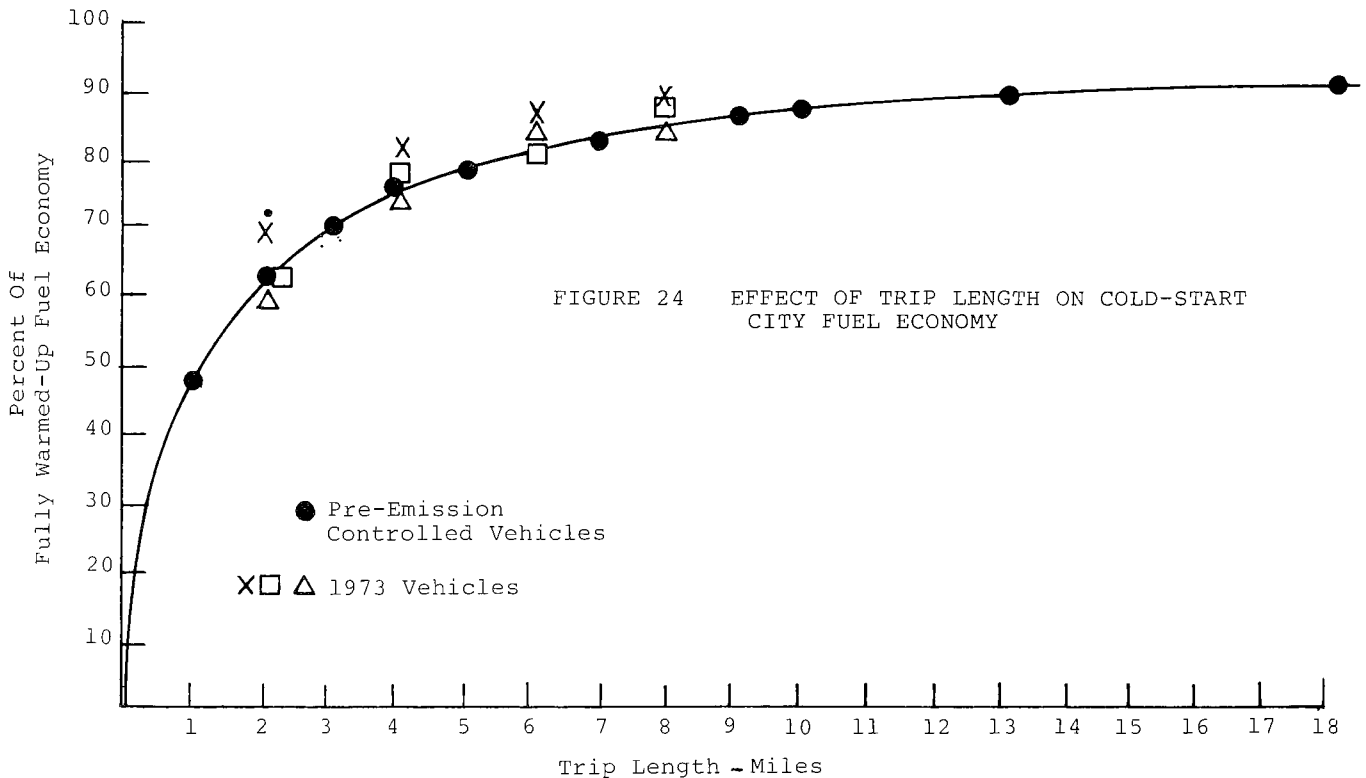
FIGURE 24   EFFECT OF TRIP LENGTH ON COLD-START CITY FUEL ECONOMY

% Of
Total Trips
1 Division = 2.5%
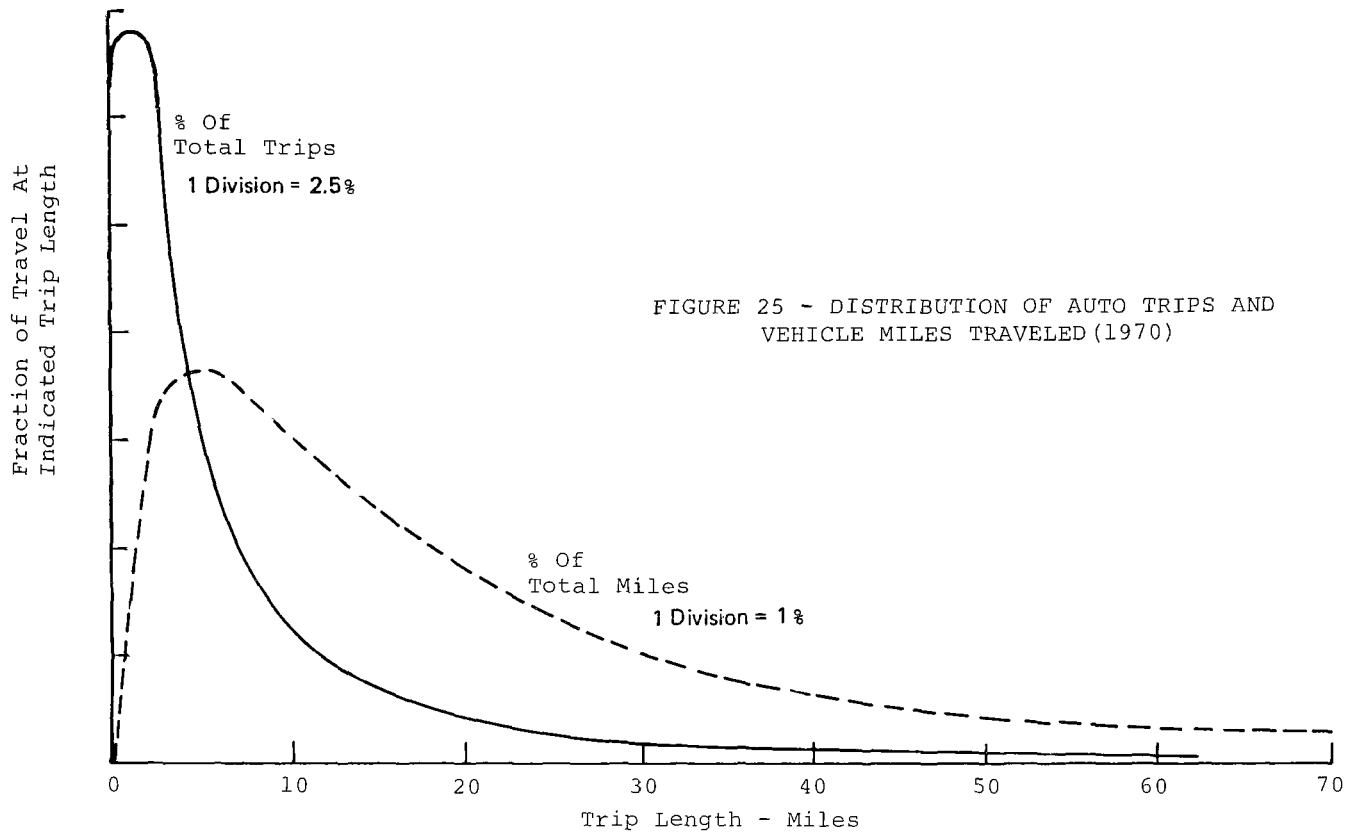
FIGURE 25 - DISTRIBUTION OF AUTO TRIPS AND
VEHICLE MILES TRAVELED (1970)

% Of
Total Miles
1 Division = 1%

Fraction of Travel At
Indicated Trip Length

Trip Length - Miles

improves with distance traveled because:

(a) rolling friction decreases as tires warm up and inflation pressures rise;

(b) lubricants warm up and friction decreases in the engine and transmission;

(c) carburetion gets leaner (less choke) as the engine becomes hotter; and

(d) less combustion heat is lost to the combustion chamber walls and coolant after they warm up.

2. U.S. Travel Habits

In figure 25 we see the results of some of the trip pattern studies mentioned earlier. Short trips overwhelmingly out-number long ones; the most frequently made car trip is about one mile long. Because the most frequent trips are so short, the distribution of miles traveled peaks at a higher trip distance (5 miles) than the trip distribution, as shown by the dashed curve. This means that more total mileage is accumulated with 5-mile trips although twice as many 1-mile trips are taken.

Applying the data on economy vs. speed and trip length to the distribution of

trips, we find that a significant amount of travel in the U.S. is made under poor fuel economy conditions.

The mileage and fuel consumption effects of this are summarized in figure 26, which shows that trips of 5 miles or less make up 15% of miles driven but consume more than 30% of all auto fuel.
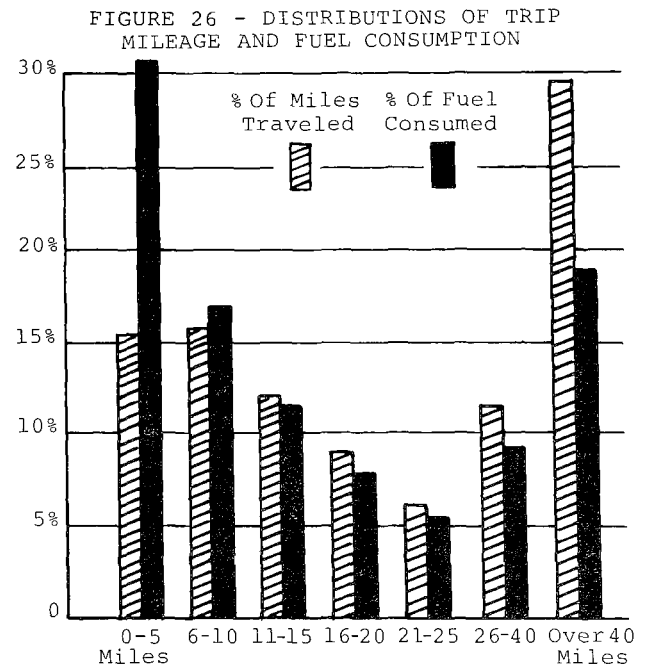
FIGURE 26 - DISTRIBUTIONS OF TRIP
MILEAGE AND FUEL CONSUMPTION

% Of Miles   % Of Fuel
Traveled   Consumed

0-5   6-10   11-15 16-20 21-25 26-40 Over 40
Miles   Miles

15

3. Cost to the Individual Motorist

Due to the fuel economy effects of trip length, a typical family car can take the following trips on 25 gallons of gas:

> Ten 40-mile trips, or
>
> Sixty 4-mile trips, or
>
> Ninety 2-mile trips, or
>
> One hundred 1-mile trips.

At 75¢ per gallon, the fuel costs would be:

> 4.7¢ per mile on 40-mile trips, or
>
> 7.8¢ per mile on 4-mile trips, or
>
> 10.4¢ per mile on 2-mile trips, or
>
> 18.8¢ per mile on 1-mile trips.

4. Weather and Road Conditions

The section on engine power loads mentioned how wind conditions affect vehicle power requirements by changing air drag. Other conditions which can influence fuel economy are listed in the table, with their economy penalties based on steady speed cruising at about 50 MPH.

Road Conditions:	MPG loss
Broken & patched asphalt. . .	15%
Gravel.	35%
Dry sand.	45%
3% Grade.	32%
7% Grade.	55%

Environment:

18 MPH tailwind . .(19% gain)	
18 MPH crosswind.	2%
18 MPH headwind	17%
50°F ambient temperature. . .	5%
20°F ambient temperature. . .	11%
Altitude (4000 ft).	15%

State of Vehicle Maintenance:

One plug misfiring 50% of time.	7%
Tires underinflated 35% . . .	7%
Front wheels 1/4 inch out of alignment.	2%

V. COMBINING THE INFLUENCING FACTORS

Power loads ... Efficiency ... Driving patterns ... these are the ingredients of which fuel economy is made. This section will discuss the results of the ways these ingredients have been combined.

Figure 27 illustrates fuel economy trends observed over the last quarter century.

FIGURE 27 - TRENDS IN FUEL ECONOMY - ALL U.S. CARS
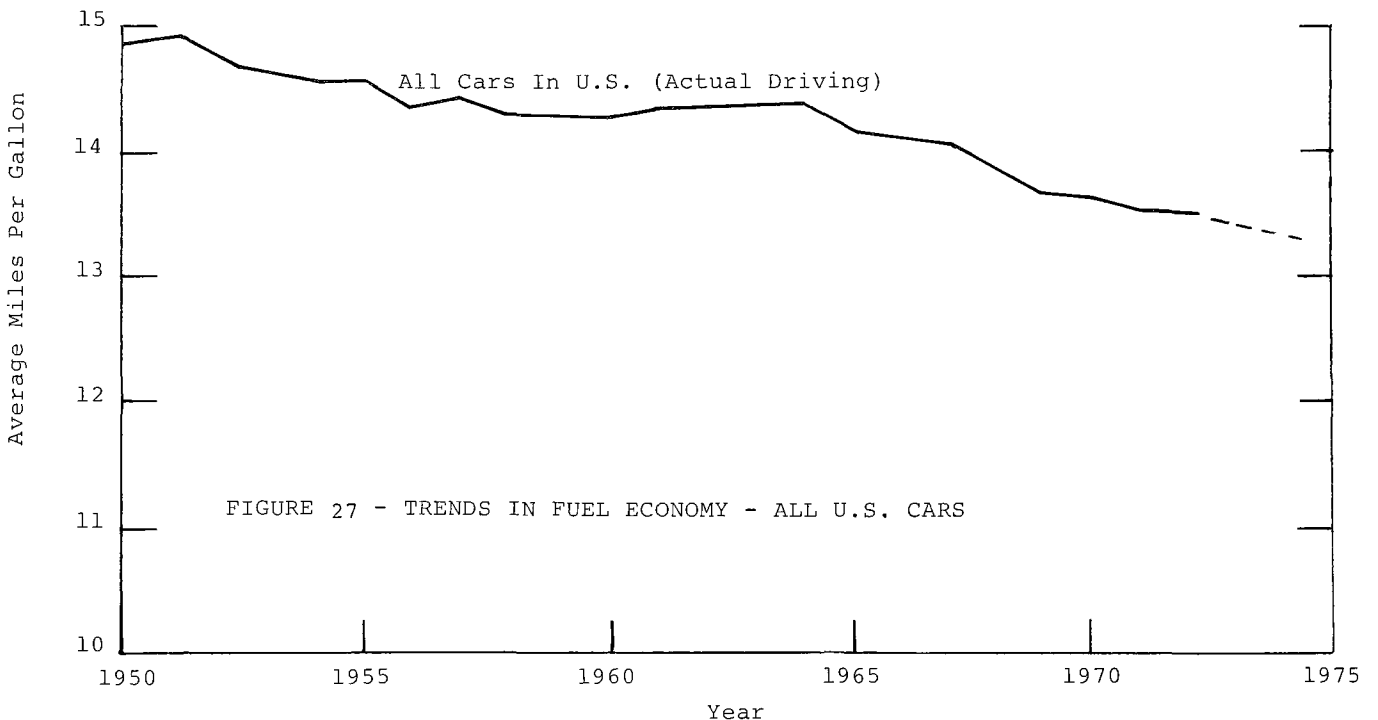
The solid curve shows the Federal Highway Administration's estimate of total miles driven by U.S. autos, divided by the total fuel they consumed. Thus the "actual driving" curve includes the fuel consumption of all the old and new cars on the road, and all the driving conditions they encounter: city and highway trips, weather and road conditions, etc. National gas mileage dropped about 9.4% in the 22 years shown.

Figure 28 shows the city fuel economy of new cars for the last nine model years, as determined from EPA city mileage tests. From 1967 to 1974, new cars lost 11.2% in economy, while average new-car weight climbed (7% for domestics, 17% for imports), displacement rose (domestics 6%, imports 29%), air conditioning usage increased sharply (38% of domestic 1967's vs. 70% of 1974's), and emission standards were legislated by Congress. More often than not, the fuel economy loss has been attributed to the emission standards. Indeed, the economy trend seemed to parallel the gradually-tightening emission standards, as shown in Figure 28.

But in 1975 the pattern was broken; the 1975 emission standards are the toughest ever, but fuel economy has never been better.

This calls for a closer look at recent developments related to emissions and fuel economy.

A. EMISSION CONTROLS

While much has been said about the effect of emission controls on automobile fuel economy, a review of the available control techniques shows that some can improve economy, some can degrade it, and some have no effect. Whenever fuel-efficient techniques are chosen, emission control need not result in fuel economy losses.

There are three types of automotive emissions:

(a) Evaporative losses – consisting of raw fuel vapor escaping from the fuel tank, carburetor, and any leaks in the fuel system;

(b) Crankcase vent gases – consisting of blow-by combustion gases escaping past the piston rings into the crankcase.

(c) Exhaust pollutants – consisting of unburned hydrocarbons (HC), carbon monodixe (CO), and nitrogen oxides (NOx), along with a host of other compounds emitted in smaller amounts.

FIGURE 28
FUEL ECONOMY VS MODEL YEAR
(FIXED MODEL MIX, SALES WEIGHTED)
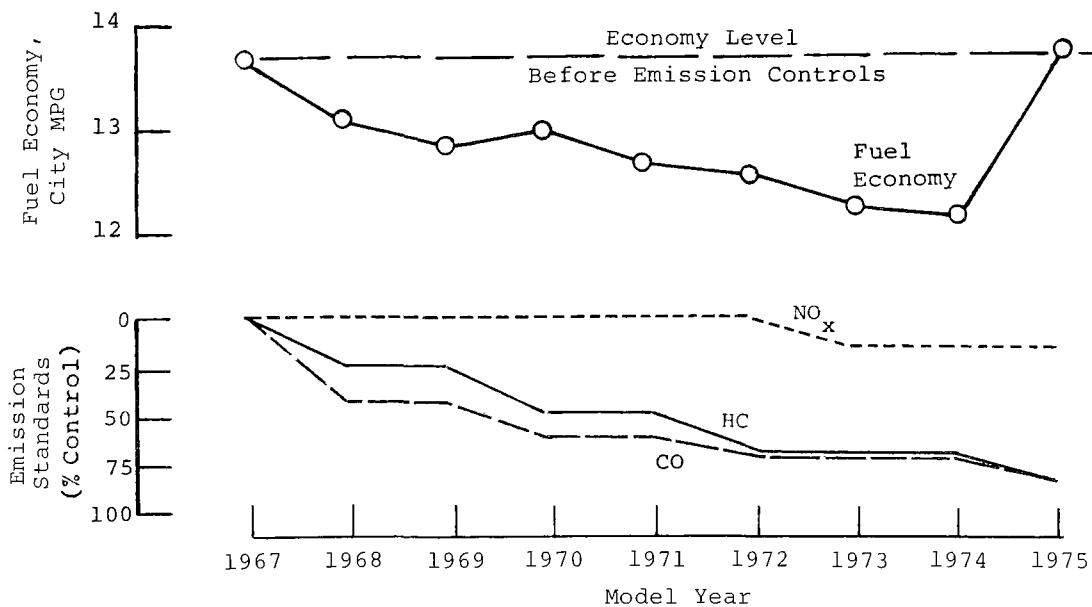
1. Evaporative and Crankcase Emissions

Evaporative emissions have been controlled since 1971[5] through the use of modified gas tanks, sealed gas tank caps, and activated charcoal canisters which store fuel vapor during engine shutdown and release it into the air cleaner for combustion when the engine is operating.

Crankcase ventilation has always been required in internal combustion engines, to relieve pressure build-up in the crankcase and reduce the sludge-forming and oil dilution effects by blow-by gases, water vapor, and unburned fuel vapor.

Since the early 1960's, all new cars use Positive Crankcase Ventilation (PCV) systems which route crankcase vapors into the engine's intake manifold.

2. Exhaust Emissions

A variety of techniques are available for controlling exhaust emissions. Modifications in the fuel and air intake systems and within the combustion chamber reduce the formation of pollutants in the combustion process. Other techniques function in the exhaust to clean up pollutants which remain after combustion. The most common of these techniques are discussed below.

(a) Fuel/Air Induction Modifications

Techniques frequently used upstream of the combustion chamber include intake manifold modifications to promote better fuel/air distribution, intake air heating, early fuel evaporation, improved chokes, improved carburetion, and exhaust gas recirculation (EGR). The first five are usually combined to permit leaner combustion, which decreases HC and CO emissions. Up to a point (Figure 7), lean combustion also increases fuel economy.

---

[5] Standards for controlling evaporative emissions were first put into effect in 1970 in California and 1971 nationwide.

Exhaust gas recirculation decreases NOx formation by lowering peak flame temperature during combustion. EGR can either improve or degrade fuel economy: if excessive exhaust gas is recycled at light loads, flame speed slows down and engine efficiency is impaired; misfire can also result. On the other hand, properly controlled EGR systems can maintain or even improve fuel economy by reducing throttling and allowing higher compression ratios and/or increased spark advance with no change in fuel octane.

(b) Combustion Modifications

Emission control techniques used in the combustion chamber include revised chamber shapes and lower compression ratios. The latter permits use of lower octane, low-lead or no-lead fuels; the resulting lower peak flame temperatures and higher exhaust temperatures reduce HC and NOx emissions, but efficiency suffers.

Spark retard is often used to control emissions. Late combustion reduces peak temperatures, and hence NOx formation, and increases exhaust temperature. The hotter exhaust promotes oxidation of HC and CO downstream of the cylinders. As with lower compression ratios, less mechanical work is extracted and efficiency drops. A well-controlled spark retard system can cut the fuel economy loss by operating only during speed changes or when driving in the lower transmission gears. This reduces the economy loss in the city and eliminates the loss on the highway.

High-energy ignition has no direct economy effect, but can promote leaner A/F ratios and improve engine reliability.

(c) Post-Combustion Chamber Modifications

Techniques used downstream of the combustion chamber include enlarged exhaust manifolds, thermal reactors, catalytic converters, and air injection. All of these techniques promote chemical con-

version of exhaust pollutants to relatively harmless compounds; the devices themselves do not affect fuel economy.

Revised manifolds and thermal reactors both provide increased residence time of the hot exhaust gases, promoting further oxidation of the HC and CO leaving the combustion chambers.

Because excess oxygen is required, systems with thermal reaction manifolds use either lean combustion or rich combustion plus air injection. Since thermal reaction efficiency depends on temperature, timing and carburetion calibrations may be used to get high exhaust temperatures, and the fuel economy effects of these may show up in connection with thermal reaction emission controls.

Catalytic converters can be used to reduce HC and CO emissions (oxidation catalysts), NOx emissions (reduction catalysts), or all three (dual catalysts or 3-way catalysts). Oxidation catalysts are the only ones with proven durability sufficient for incorporation in 1975 cars.

Unlike thermal reactors, oxidation catalysts can reduce HC and CO emissions effectively at normal exhaust temperatures. These catalysts can make emission control relatively independent from engine operation, and permit tuning of the engine for better efficiency.

There is no simple relation between fuel economy and the emission levels that cars are designed for.

It is possible to utilize any given combination of emission control techniques and engine design specifications over a broad range of emission levels, through adjustment of design features and operating conditions (e.g. spark timing and carburetor adjustments). Fuel economy will also vary with the adjustments made for emissions control.

Unfortunately the optimum fuel economy is usually reached before the full emissions control potential of the technology is realized, so that pushing a given technology to its ultimate emissions control potential will result in a fuel economy lower than optimum. For example, prior to 1975, auto manufacturers controlled emissions mainly through engine modifications. This resulted in a reduction in fuel economy--especially for large cars--from the optimum fuel economy achievable with that particular technology.

However, with the effective use of 1975 catalytic emission control technology, fuel economy can be at its optimum for the 1975 Federal emission levels; hence a roll-back of emission standards to pre-1975 Federal levels would not improve fuel economy. At best, it might make it easier (or cheaper) for those manufacturers with lower-than-average economy to come up to par.

To achieve emission levels significantly lower than the 1975 Federal standards, fuel economy penalties can be incurred if only the present technology is used; preservation of current optimum fuel economy levels requires the use of improved technology.

Many suitable technologies have been demonstrated in the laboratory, but require further development to assure adequate durability and reliability, and to permit production application of these technologies to the many different types of vehicles and engines that are produced. Some of these technologies have fuel economy potential that is at least as good as provided by the best 1975 emission control technology.

B. EFFECTS OF TAMPERING WITH EMISSION CONTROL SYSTEMS

It is widely believed that fuel economy can be improved by tampering with emission controls on today's engines.

A research project was conducted to test this theory in actual practice; A number of 1973 and 1974 cars[6] were subjected to the following test sequence:

(a) Tune to manufacturer's specifications and test for emissions and fuel economy;

(b) Consign to a private service garage with a request to "do whatever they could to improve fuel economy".

(Note: emission control system tampering is illegal in more than half the states, but not as yet in Michigan; all modifications in this project were performed by Michigan garages.)

(c) Test for changes in fuel economy and emissions resulting from the garage tampering.

_____

[6]Subcompact, compact, intermediate, and full-size cars were included.

(d) Restore to manufacturer's specifications.

The garage modifications were performed by a variety of shops, including service stations, neighborhood garages, "speed shops", nationally-franchised tune-up centers, and foreign car specialists.

The main result of the project was that both emissions and fuel economy were made worse by the garage modifications, as illustrated in figure 29.

About 2/3 of the cars lost fuel economy and increased in emissions. Less than 10% improved in both emissions and economy.

It is interesting that no modification which improved emissions resulted in poorer fuel economy.

The effectiveness of the garage modifications did not vary much from shop to shop. Of those shops which modified only one car, two out of every three made fuel economy worse; of those shops performing more than one modification, every one degraded the fuel economy of at least one of the cars it worked on.

FIGURE 29 - EFFECTS OF PRIVATE GARAGE TAMPERING

(% Of Cars Modified)

Fleet Emissions
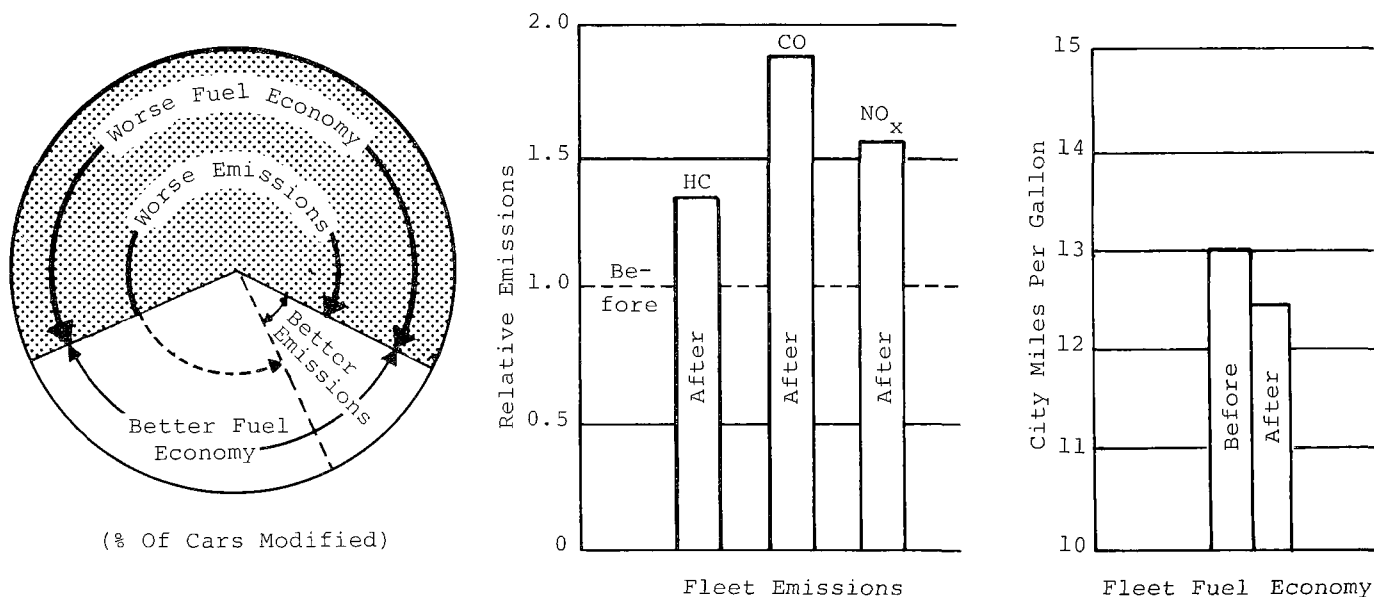
Fleet Fuel Economy

The results of the project lead to the following conclusions:

(a) An attempt to improve fuel economy by tampering with emission controls is more likely to fail than to succeed. Few mechanics, even skilled ones, have the information necessary to fully understand emission control systems. (Even highly - skilled engineers trained in emission control technology and equipped with sophisticated instruments sometimes make fuel economy worse when they attempt to modify those parts that are adjustable.)

(b) Any massive effort to remove or modify emission controls on existing cars would result in no net gain, and probably some deterioration, in nation-wide fuel economy. The only certain result of such an effort would be a major increase in motor vehicle emissions.

In addition to the specific conclusions above, these factors must be kept in mind:

• Today's auto engines have undergone changes in design to incorporate emission control systems. These changes are not readily reversible on existing engines.

• Where emission reductions have been achieved with specific devices or calibrations which could be "reversed", these modifications are so closely related to the basic changes in engine design that they cannot be varied independently.

• Some emission control systems and adjustments used on late-model engines improve fuel economy; removal or readjustment of such items can only result in simultaneous degradation of both emissions and economy.

• Carburetor settings, ignition timing, compression ratio, and exhaust gas recirculation all affect engine durability. Changes in these parameters to specifications other than those the engine was designed for can result in mechanical durability problems, performance problems, or both.

Benefits of Regular Tuneups

The discussion above dealt with the pre-dominantly unfavorable results of tampering with properly-tuned engines. The other side of the coin involves the effects of performing manufacturer-recommended tuneups on as-received vehicles.

The tampering study also evaluated this aspect of engine adjustment on a small sample of cars. The results are shown below:

	Garage Tune-up
Emissions	Improved 9%
Fuel Economy	Improved 8%

Thus, it appears on the whole that well-tuned cars are more likely to consume less fuel and emit less pollution than either untuned cars or cars with their emission controls deactivated.

C.   FUEL ECONOMY OF 1975 AUTOS

As discussed in earlier sections of this report, fuel economy is determined by many factors. This section will illustrate 1975 fuel economy as a function of vehicle test weight class. Remember that vehicles in these weight classes differ from each other in more ways than weight: the heavier cars are larger in size, they use larger engines, and more of them use power-consuming accessories. So weight is not the only factor which causes the fuel economy differences between weight classes.

Figure 30 shows 1975 EPA city and highway fuel economy versus vehicle test weight. The values for each weight class are averaged in proportion to projected sales.

The average highway MPG for all weight classes is nearly 50% higher than the city mpg. This is consistent with the experience of many motorists in actual driving.

FIGURE 30 - FUEL ECONOMY OF 1975 MODELS
BY TEST WEIGHT CLASS
(SALES WEIGHTED)

Highway
MPG

(1.5 x City MPG)

City
MPG

Fuel Economy - MPG

Vehicle Weight   Pounds

The composite MPG in figure 31 was cal-
culated for 55% city and 45% highway
driving. (See Appendix C.)

For each engine size, the RPM character-
istics as   determined by axle ratio and
tire size are held constant over the
vehicle weight range used for that engine.

Since the 1975 emission standards (and
control technologies used to meet the
standards) are different from previous
years, the difference in fuel economy
between 1975 cars and earlier models is
of considerable interest.
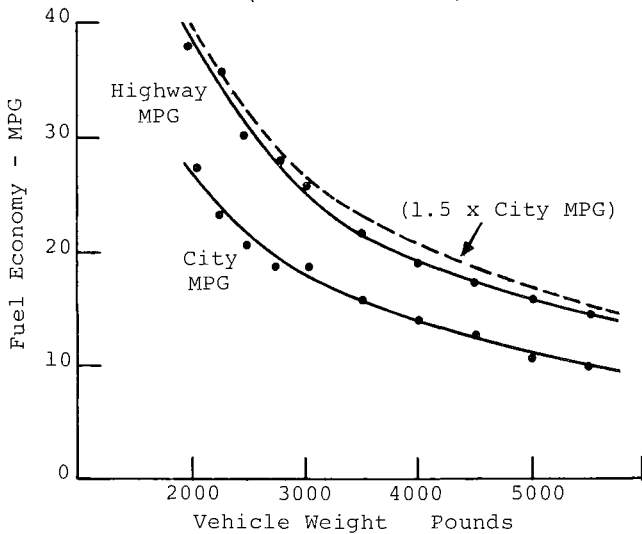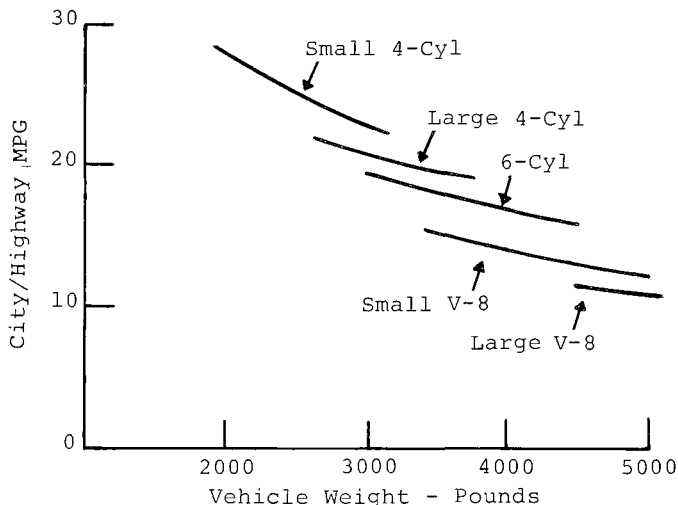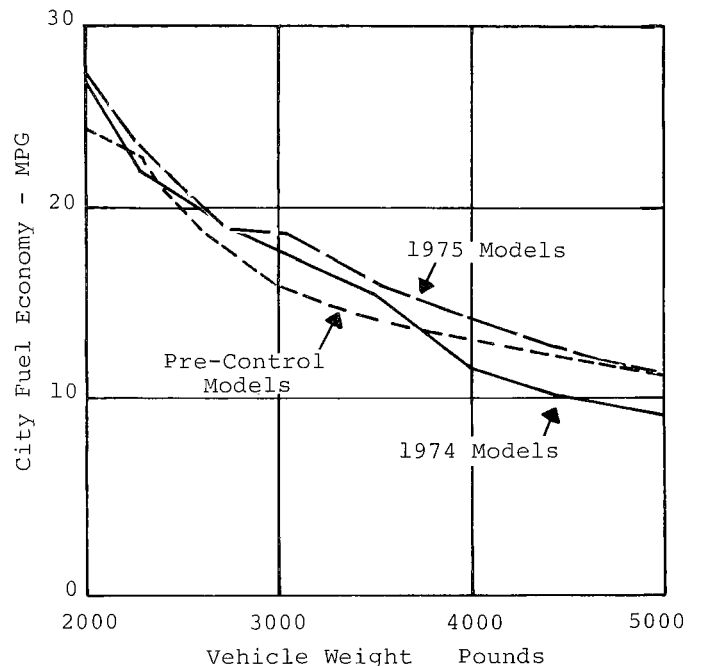
Figure 32 shows this comparison.

Figure 31 shows the separate influences
of weight and engine size, when both
are varied independently.

A change to a lower engine size in the
same car can give a bigger fuel economy
improvement than a 25% weight reduction
with the same engine; a conservatively-
powered standard size car can have fuel
economy as good as, or better than, a
high-performance compact car.

FIGURE 32 - LATE MODELS' ECONOMY COMPARED TO
PRE-EMISSION CONTROL MODELS

1975 Models

Pre-Control
Models

1974 Models

City Fuel Economy - MPG

Vehicle Weight   Pounds

It is clear from the figure that 1975
fuel economy is better than both pre-
control and 1974 models.

FIGURE 31 - THE SEPARATE EFFECTS OF
VEHICLE WEIGHT AND ENGINE SIZE
ON 1975 VEHICLES' FUEL ECONOMY

Small 4-Cyl

Large 4-Cyl

6-Cyl

Small V-8

Large V-8

City/Highway MPG

Vehicle Weight - Pounds

Figure 32 is based on the economy of
individual makes and models averaged in
proportion to projected sales. Changes
from 1974 to 1975 are not the same for all
manufacturers: some automakers have
achieved large gains in economy, while
others have lost ground. Since the
"gainers" outnumber the "losers" in
sales, the overall average has never-

22

theless increased. Table 5 lists the 1974 to 1975 gains and losses for ten individual manufacturers, as of October 1974.

Table 5
Overall Fuel Economy Change from 1974

| Manufacturer	% Change in City MPG 1974 to 1975
Volkswagen	up 4%
Nissan	up 8%
Saab	up 24%
Peugeot	up 10%
American Motors	up 21%
Volvo	down 6%
BMW	down 11%
Chrysler	up 12%
General Motors	up 28%
Ford	down 2%
All Mfrs. together (Sales weighted)	up 13.8%

If the data is subdivided according to the emission control approach used, it seems that catalyst-equipped cars, as a group, deliver better-fuel economy than cars which use other control techniques, as depicted in figure 33.

FIGURE 33   FUEL ECONOMY OF 1975 CATALYST AND NON-CATALYST CARS
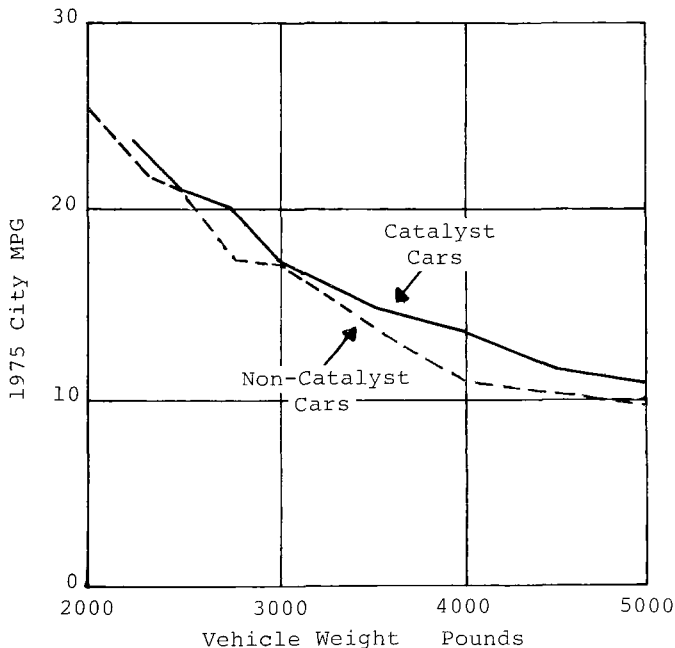
However, the mere presence of catalysts in a car line does not guarantee good fuel economy: As shown in figure 34, the average of the best economy 1975 catalyst cars is significantly higher than the average of the worst-economy catalyst cars.

FIGURE 34 - VARIATIONS IN FUEL ECONOMY WITH 1975 CATALYST TECHNOLOGY
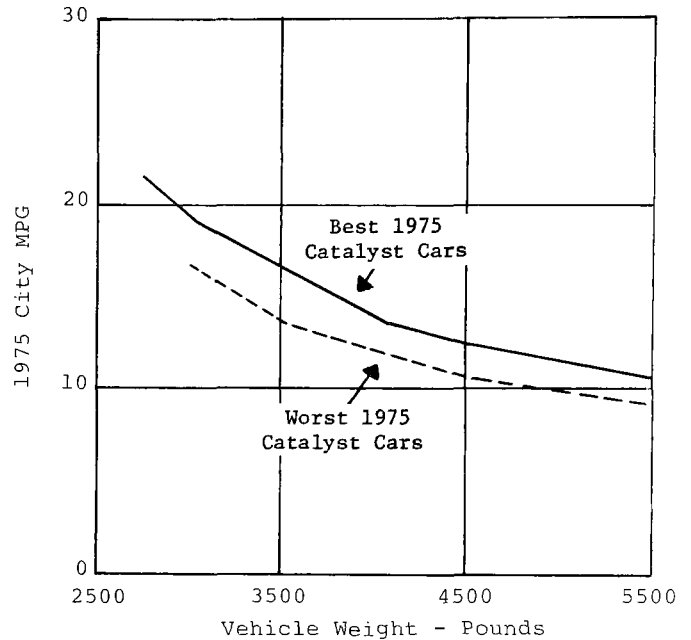
Conversely, the absence of catalyst usage does not necessarily mean poor fuel economy: many of the better-fuel economy 1975 models (particularly in the lighter weight classes) achieved their optimum fuel economy without catalysts.

Table 6 compares the relative fuel economy and emission control approach for the same manufacturers listed earlier.

Table 6
Relative 1975 Fuel Economy

Manufacturer	1975 MPG Relative to Similar Cars	Overall Car Line Emission Control
General Motors	High	100% Catalyst
Saab	High	Engine Mods
American Motors	High	15% Catalyst
Peugeot	High	Thermal Reactor
Nissan	High	50% Catalyst
Chrysler	Average	95% Catalyst
Volkswagen	Average	65% Catalyst
Ford	Low	75% Catalyst
Volvo	Low	15% Catalyst
BMW	Low	Thermal Reactor

(Tables 5 and 6 are based on data that reflect fuel economy as of the date of the introduction of the 1975 models. These data can be expected to change as the manufacturers make technology improvements during the 1975 and subsequent model years.)

From table 6 and figure 34 it is clear
that a manufacturer's ingenuity in optimi-
zing his overall engine system has more
effect on fuel economy than the building
blocks he chooses.

The data base was also divided into
"California" and "49-states" groups.
Many manufacturers produce two versions
of their models: one version for sale
in California, which has stricter 1975
emission standards, and another version
for sale elsewhere in the U.S. Figure 35
shows the comparison between these groups.

Table 7 presents the California com-
parison by manufacturer. Again, the 1975
California versions tend toward lower
economy than the 1975 49-states versions,
but seven of the firms' 1975 California
cars were as good or better than their
1974's.

FIGURE 35 - ECONOMY OF 49-STATES
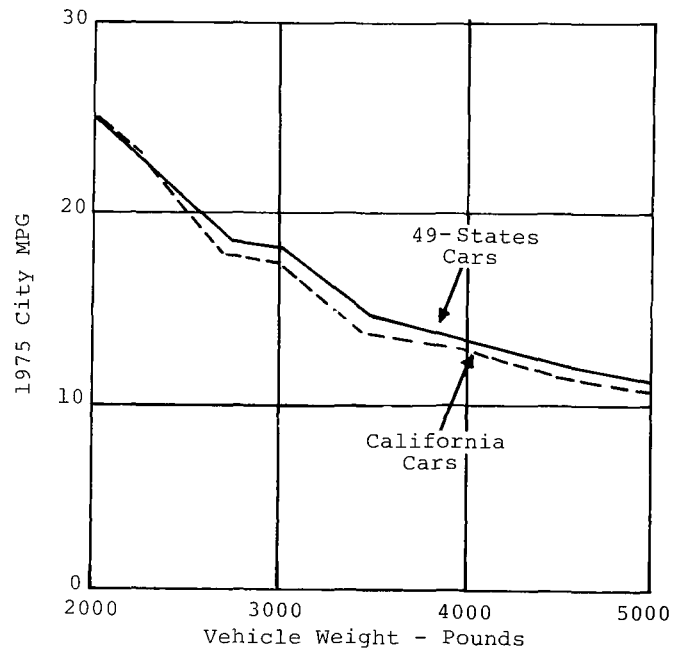MODELS VS. CALIFORNIA MODELS

Table 7

Economy of California Models
vs. 49-States Models

Manufacturer	1975 MPG, California vs. 49-States
Saab	Calif. Higher*
Volkswagen	Calif. Higher
Volvo	Calif. Higher
Ford	No Difference
Nissan	Calif. Lower*
Peugeot	Calif. Lower*
Chrysler	Calif. Lower*
General Motors	Calif. Lower*
American Motors	Calif. Lower*

* '75 Calif. higher than '74 49-states.

D.   FOR INFORMATION ON SPECIFIC MODELS

Since the 1974 model year, EPA has
sponsored a voluntary fuel economy
labeling program, wherein manufacturers
post on each new car the EPA-determined
fuel economy of that model. Figure 36
is a typical fuel economy label. Most
manufacturers are participating in the
labeling program, and are using EPA fuel
economy test results in advertising as
well.

In addition, EPA and the Federal Energy
Administration jointly publish each model
year a Gas Mileage Guide for New Car
Buyers which lists the fuel economy of
each model of passenger cars and light
duty trucks eligible for sale in the U.S.

A separate guide is published for Cali-
fornia models.

For a copy of the Mileage Guide, write to:

Fuel Economy
Pueblo, Colorado 81009

E.   ALTERNATIVE ENGINES

The conventional internal combustion
gasoline engine must feel like the pro-
verbial mousetrap: researchers are
always trying to replace it with a
better one.

Each proposed alternative engine concept
has its own advantages and its own parti-
cular disadvantages. Depending on the
type of alternative engine, fuel economy
can be "good" or "bad", compared to the
conventional engine.

24

Based on the results of tests conducted
or certified by the U.S. ENVIRONMENTAL
PROTECTION AGENCY, the typical gas
mileage of this car is estimated to be:

Vehicle: Aardvark, 10 cylinder, 436 cubic inch displacement, 5 barrel
carburetor, automatic transmission, catalyst equipped,
air conditioning equipped.

10 MILES PER GALLON FOR CITY DRIVING

and

16 MILES PER GALLON FOR HIGHWAY DRIVING

These estimates are based on tests of vehicles equipped with frequently
purchased optional equipment.

Reminder: The actual fuel economy of this car will vary depending on
the type of driving you do, your driving habits, how well you maintain
your car, optional equipment installed, and road and weather conditions.
The use of overdrive provides approximately a 3% highway fuel economy
improvement.

To compare the fuel economy of this car with other 1976 cars, and to
learn how the tests were conducted, write for the EPA/FEA 1976 Gas
Mileage Guide for New Car Buyers, to Fuel Economy, Pueblo, Colorado 81009.

FIGURE 36 - TYPICAL FUEL ECONOMY LABEL

Three such engines are available in today's production automobiles: the rotary (Wankel), the CVCC stratified charge, and the Diesel. The fuel economy of these engines is compared with conventionally-powered cars' economy in figure 37, which shows that the rotary's fuel economy is worse, the CVCC's is about the same, and the Diesel's is better.

For these engines, the comparison at equivalent power-to-weight ratios is valid for either city or highway MPG's.

Other alternative engines being developed are: advanced versions of the stratified charge engine , and "continuous combustion" engines including the Rankine (vapor cycle) engine, gas turbines, Stirling engines, and others. Early experimental versions of these have frequently shown inferior fuel economy test results, but their proponents believe that further development will significantly improve these engines' fuel economy capabilities.

It is too early to reach firm conclusions about the feasibility of mass production of cars powered by these advanced alternative engines; the only certainty is that such engines will not see widespread use before the 1980's.

FIGURE 37 - RELATIVE FUEL ECONOMY OF
1975 ALTERNATIVE ENGINES
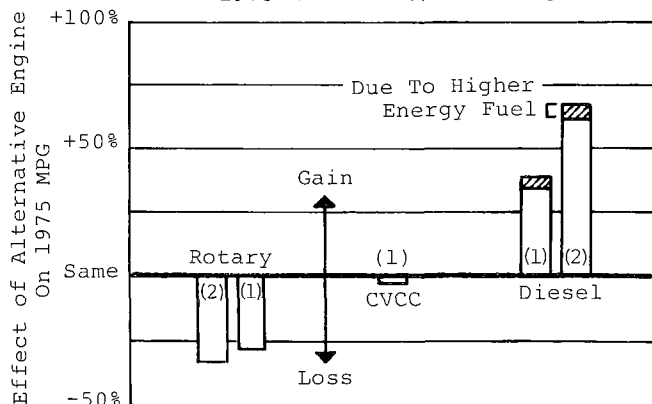
(1) Compared To Conventionally Powered Cars With Equivalent Power-To-Weight Ratio
(2) Compared To Cars With Different Power-To-Weight Ratio

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To calculate fuel economy, in miles per gallon (MPG), from an emission test, the following equation applies:

$$\frac{Miles}{Gallon} = \frac{gms\ carbon/gal\ of\ fuel}{gms\ carbon\ in\ exhaust/mile} \quad (A-1)$$

The carbon in the fuel is:

$$grams\ C_{fuel} = \frac{grams\ fuel}{gallon} \times \frac{molecular\ wt.\ C}{molecular\ wt.\ fuel} \quad (A-2)$$

$$= (2798) \times (.866)$$

$$= 2423$$

where:

2798 is the mean density of EPA test gasoline, in grams/gallon; and

.866 is the weight fraction of carbon in the fuel.

The carbon in the exhaust is contained in the unburned fuel hydrocarbons (HC), carbon monoxide (CO), and carbon dioxide (CO_2), as follows:

$$grams\ C_{HC} = gm\ HC \times \frac{mol.\ wt.\ C}{mol.\ wt.\ HC} \quad (A-3)$$

$$= gm\ HC \times (.866)$$

$$grams\ C_{CO} = gm\ CO \times \frac{mol.\ wt.\ C}{mol.\ wt.\ CO} \quad (A-4)$$

$$= gm\ CO \times (.429)$$

$$grams\ C_{CO_2} = gm\ CO_2 \times \frac{mol.\ wt.\ C}{mol.\ wt.\ CO_2} \quad (A-5)$$

$$= gm\ CO_2 \times (.273)$$

So we have:

$$\frac{Miles}{Gallon} = \frac{2423}{(.866gmHC+.429gmCO+.273gmCO_2)/miles}$$

or

$$MPG = \frac{2423 \times miles\ traveled}{.866gmHC+.429gmCO+.273gmCO_2} \quad (A-6)$$

Example: In a 10-mile test, a car's exhaust emission measurements show the following amounts of carbon compounds:

HC – 9 grams
CO 124 grams
CO_2 3641 grams

Using equation A-6, the fuel economy is:

$$MPG = \frac{2423 \times 10}{.866(9)+.429(124)+.273(3641)}$$

$$= \frac{24,230}{7.8 + 53.1 + 993.7} = \underline{\underline{23.0\ MPG}}$$

Fuel economy can be expressed in terms of speed and fuel consumption rate, as follows:

$$\frac{Miles}{Gallon} = \frac{Miles/Hour}{Gallons/Hour} \quad (B-1)$$

But fuel consumption rate is related to the engine power output (not the power rating) by the expression:

$$\frac{Gallons}{Hour} = HP \times \frac{lbs(fuel)}{HP-Hr} \times \frac{Gals}{lb} \quad (B-2)$$

So fuel economy is:

$$\frac{Miles}{Gallon} = \frac{(Mi/Hr) \times (lbs/gal)}{(HP) \times (lb/HP-Hr)}$$

or

$$MPG = \frac{MPH \times Df}{HP \times SFC} \quad (B-3)$$

Where Df = fuel density, pounds per gallon (approximately 6.2 for gasoline); and

SFC = specific fuel consumption, pounds per hour per horsepower output.

SFC is a commonly-used engineering term directly related to engine efficiency. The more efficient an engine is, the less fuel it needs to deliver a given power output. For a typical gasoline fuel, the relationship between SFC and engine efficiency is:

$$SFC = \frac{13.5}{Efficiency} \quad (B-4)$$

(An efficiency of 13.5% corresponds to an SFC of 1.0 lb/HP-Hr)

Substituting equation B-4 into B-3,

$$MPG = \frac{MPH \times Df}{HP \times 13.5/Eff.} = \frac{MPH \times 6.2 \times Eff.}{HP \times 13.5} \quad (B-5)$$

So we see that fuel economy is a function of speed (MPH), engine load (HP), and engine efficiency according to:

$$MPG = .46 \frac{MPH}{HP} \times Efficiency \quad (B-6)$$

for a typical gasoline fuel.

Example: An intermediate size car requires an engine output of 26 HP to cruise at 50 MPH. The engine efficiency for this condition is 22.0% (SFC = 0.614) Using equation B-6, the fuel economy is:

$$MPG = .46 \times \frac{50}{26} \times 22.0 = \underline{\underline{19.5\ MPG}}$$

To cruise at 70 MPH, the same car requires 51 HP, and the engine efficiency is 25.4% (SFC = 0.532). The fuel economy is:

$$MPG = .46 \times \frac{70}{51} \times 25.4 = \underline{\underline{16.0\ MPG}}$$

Suppose a motorist takes the following trips:

200 miles, using 15.0 gallons;
100 miles, using 9.4 gallons;
140 miles, using 11.8 gallons.

The fuel economies of these trips are:

$$\frac{200\ miles}{15.0\ gal.} = 13.3\ MPG;$$

$$\frac{100\ miles}{9.4\ gal.} = 10.6\ MPG;$$

$$\frac{140\ miles}{11.8\ gal.} = 11.9\ MPG.$$

If he merely averages the trip MPG's, he gets:

$$(13.3 + 10.6 + 11.9) \div 3 = \underline{11.9\ MPG}$$

But this is incorrect. The motorist traveled 440 miles and used 36.2 gallons, so his overall fuel economy was:

$$440 \div 36.2 = \underline{12.2\ MPG}$$

To get the correct fuel economy for multiple trips, the following equation must be used:

$$\frac{Miles}{Gallon} = \frac{total\ miles\ traveled}{total\ gallons\ used} \quad (C-1)$$

If the individual trip lengths and fuel economy values are known, but the gallons used are not known, the proper equation is:

$$MPG = \frac{miles_1 + miles_2 + ... + miles_N}{\frac{miles_1}{MPG_1} + \frac{miles_2}{MPG_2} + ... + \frac{miles_N}{MPG_N}} \quad (C-2)$$

where $miles_x$ = length of trip "x";
MPG_x = gas mileage for trip "x"; and
N = number of trips.

For a number of test trips of the same length, equation C-2 is equivalent to:

$$MPG = \frac{miles_t \times N}{miles_t \left(\frac{1}{MPG_1} + \frac{1}{MPG_2} + ... + \frac{1}{MPG_N}\right)} \quad (C-3)$$

where $miles_t$ = the standard test length and
N = the number of tests.

Equation C-3 simplifies to:

$$MPG = N \div \sum_N \left(\frac{1}{MPG_N}\right) \quad (C-4)$$

which is the "harmonic average" of the MPG's from the tests.

To calculate the composite MPG from known city and highway MPG's, the apportionment of total mileage between city and highway driving must be used. If a motorist drives 55% of his mileage in the city and 45% on the highway, his composite fuel economy is:

$$MPG = \frac{total\ miles}{\frac{.55(total\ miles)}{City\ MPG} + \frac{.45(total\ miles)}{Highway\ MPG}}$$

$$= \frac{1}{\frac{.55}{MPG_C} + \frac{.45}{MPG_H}} \quad (C-5)$$