76-10 JLB

# Impact of Gasoline Characteristics on Fuel Economy and Its Measurement

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Technology Assessment and Evaluation Branch
Emission Control Technology Division
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## Background

The expanded role of the EPA in measuring and reporting motor vehicle fuel economy data, under the terms of the Energy Policy and Conservation Act, makes it necessary for the EPA to become very well informed on all technical factors which may influence the accuracy of fuel economy measurements. Also, the importance of achieving maximum conservation of fuel compels the investigation of all factors that may have an impact on this goal.

Consequently, the purpose of this report is to discuss the impact of the characteristics of gasoline on the fuel economy of motor vehicles and on the accuracy of its measurement. It also serves to help explain some of the differences that may be found between the results of the EPA fuel economy tests and the values observed by vehicle owners in normal service.

In principle, other factors such as vehicle weight, vehicle maintenance, etc., have a greater impact on fuel economy than the characteristics of gasoline; but a better knowledge of the impact of these fuel characteristics can contribute to fuel conservation and to the understanding of some of the variabilities in fuel economy measurements.

This report is based on the analysis of the available literature on the subject, as well as on the specific information submitted--upon request from the Emission Control Technology Division of the EPA--by companies engaged in petroleum refining, fuel additives production, and automobile manufacturing.

## Introduction

The composition of gasoline depends on the origin of the crude petroleum and on the refining process. Gasoline is principally a mixture of liquid hydrocarbons having from four to ten carbon atoms, small amounts of lighter and heavier hydrocarbons, and minute quantities of crude petroleum impurities such as sulfur and nitrogen. Also, very small quantities of certain additives are usually added to the gasoline in order to inhibit such undesirable conditions as knocking, surface ignition, spark plug fouling, rust, gum formation, and icing of the carburetor.

Apart from the effect of additives, the characteristics of a gasoline depend on its chemical composition. However, because a gasoline consists of a very large number of different hydrocarbons, its composition is usually expressed in terms of hydrocarbon types--saturates, olefins, and aromatics--rather than in terms of individual hydrocarbons.

The characteristics of gasoline which have the greatest impact on fuel economy are octane rating, density (as a measure of the heating value of the gasoline), volatility, viscosity, and cleanness. The effect of changes in these characteristics on fuel economy measurements* are presented summarily in the following sections. An additional section refers to the optimum octane ratings of gasoline. Details and complementary general information regarding the characteristics of gasoline are given in the Appendix.

The octane number requirements of given populations of motor vehicles depend basically on the design of their powertrain systems. Thus, such requirements are outside the specific area of concern of this report and are not dealt with here.

Except for a few comments, the report does not cover the impact of the characteristics of gasoline on the emission of air pollutants. This area of interest will be the subject of a separate or complementary report.

Impact of Gasoline Density

The fuel economy of motor vehicles is commonly expressed in miles per gallon (mpg). However, the mpg does not provide an accurate indication of the fuel economy of the vehicles unless the density of the gasoline is taken into consideration. This is because the heating value per unit volume of gasoline increases with its density. Of all the variations in gasoline characteristics which affect fuel economy, the variations in density are one of the more significant. For example, data indicates that in 1974 the density of some commercial gasolines ranged between 5.7 and 6.4 lb/gallon.[27] In the extreme case where tests of fuel economy are made using gasolines falling at the lowest and highest densities of this range, a difference in fuel economy of as large as 7% would be indicated if there is no correction made for gasoline density. Ordinarily, comparisons are not made involving the extreme cases of gasoline density and, consequently, the variations in the fuel economy of motor

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* To separate the effects of other variables, the impact of the characteristics of gasoline on fuel economy should be determined on the basis of the same test procedure (that is, for the same vehicle soak conditions, driving cycle, atmospheric conditions, etc.). Therefore, the report will distinguish between fuel economy differences measured using only the EPA test procedure and the differences observed when results from the EPA tests are compared with customer's measurements.

vehicles due to variations in gasoline density are much less than this figure. However, the corresponding differences in fuel economy can still be significant, and, therefore, should not be overlooked.*

Thus, for accurate evaluations or comparisons of fuel economy, the mpg should be measured using gasoline of a fixed density. Alternatively, the mpg should be corrected for density, to refer all the results to those of a fixed density of gasoline. In other words, the reported values of fuel economy should be:

$$mpg_o = mpg \times \text{Correction Factor.}^{**}$$

Impact of Differences in Volatility

As is indicated in Section IV of the Appendix, there is very little data regarding the effect of gasoline volatility on fuel economy. Also, there is the general belief that the impact of this variable on fuel economy is minor[29], for the soak conditions, ambient temperature, and driving cycle of the EPA test procedure. However, for other operating conditions the volatility of the gasoline may have a substantial impact on fuel economy. For instance, volatility greatly affects the engine starting and engine warm-up period, and these operating modes may have a very significant impact on the fuel economy of short trips, particularly at low ambient temperatures. In such an instance, the shorter the trip and the lower the ambient temperature and the volatility of the gasoline, the lower would be the fuel economy compared with the fuel economy measured during the EPA tests.

Impact of Differences in Octane Rating***

For a given motor vehicle, the impact of the octane ratings of different gasolines would be as follows. If the engine does not knock with either the fuel used in the EPA tests or the commercial fuel, the difference in octane ratings of the two fuels should not result in any variations in fuel economy. If the engine does not knock with the EPA test fuel but knocks with another fuel, the eventual difference in fuel economy due to

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* For the emission tests for certification of automobiles, Indolene HO III is used as fuel. In 1974 the density of this gasoline ranged between 6.10 and 6.22 lb/gallon.[27] The maximum variation in fuel economy which is possible for this change in density is approximately 1%.

** Section III in the Appendix indicates means for determining the correction factor.

*** This section refers only to the case of given vehicles, with fixed engine compression ratios and adjustments. The general relationship among octane rating, compression ratio, and engine efficiency is discussed in Section II of the Appendix.

the difference in octane ratings would depend on the level of knock. If the knock is sufficiently severe that spark timing must be retarded, fuel economy would suffer. Otherwise, the variations in fuel economy using the EPA test procedure would not be significant enough to be measurable since knock would occur only during a small fraction of the EPA driving cycle.

For a driving cycle and operating conditions different from those of the EPA test procedure, the impact of differences in octane rating on fuel economy would still be rather small, in general, but could become significant. If the engine knocks very lightly its fuel economy could be slightly better because of the small improvement in engine efficiency associated with faster combustion. On the other hand, if the level of knock in any cylinder is beyond its optimum level, the fuel economy could decrease because of the greater heat losses associated with knock. The magnitude of the fuel economy difference would depend on the intensity of knock and on the percentage of time operating under knock. The fuel economy variation could be very substantial for operation under severe knock.

Impact of Variations in Other Gasoline Parameters

There is no information to quantify what changes in fuel economy can result from changes in fuel metering caused by variations in the volatility, viscosity and surface tension of the gasoline. Within the constraints of the Federal Test Procedure the impact of these variations are believed to be minor. However, substantial departures from the conditions of the EPA test procedure--particularly regarding ambient temperature, because of its effects on viscosity and volatility--could possibly result in significant variations between the EPA and customer fuel economies.

As has been indicated above, changes in gasoline density have an impact on fuel economy, but this is not due to fuel metering effects. Although variations in density change the carburetor air-fuel ratio, such variations have a negligible or small effect on the air-fuel equivalence ratio of the mixture.

The use of unclean gasoline leads to deposits which may alter engine parameters and adjustments. This can result in significant differences between the fuel economies measured before and after the alterations caused by unclean gasoline.

## Optimum Octane Rating of Gasoline

With each succeeding new car model year the use of unleaded fuel is rapidly increasing. This is because the catalyst equipped new cars can only operate on unleaded fuel due to the deleterious effect of lead compounds on catalyst efficiency. The only other currently available antiknock additives can provide only a 2 octane boost or less. On the other hand, automobile manufacturers are striving to maximize engine compression ratios for optimum fuel economy within the constraints of the emission regulations, which retains the need to keep octane levels up. Thus in order to supply enough unleaded fuel at an octane level appropriate to satisfy the new vehicles with maximum conservation of petroleum, new refining techniques must be employed. Refining penalties for such an action would include the cost of new refining facilities.

Another factor which the petroleum companies must deal with is the widespread of octane requirements that their product must satisfy. Historically they have marketed two grades of leaded fuel with approximately two thirds of the customers using regular grade and the rest requiring premium fuel. One grade of unleaded fuel has more recently been added for use by the newer cars. However, because of the many factors which affect octane requirement, the vehicles designed for the available 91 RON unleaded fuel actually have requirements varying by about 10 octane numbers. The time is nearing when companies must decide whether to switch to two grades of unleaded fuel and retain only a single grade of leaded fuel. By going to two grades of unleaded fuel, one lower and the other higher than the present 91 RON, they could still satisfy the majority of their customers with minimal effect on their average marketed octane level.

In summary, each petroleum company is faced with a number of difficult decisions affecting day to day operations and long term planning regarding the optimum octane number of their products. The goal is to provide no more octane than is necessary to obtain the most transportation per barrel of crude.

## Conclusions Regarding the Impact of Gasoline Characteristics on Fuel Economy Measurements

1. For the EPA fuel economy tests, it appears that the effect of changes in fuel characteristics is minor. However, the available information permits an accurate assessment only of the impact due to changes in fuel density. The maximum variation in fuel economy due to changes in density of the EPA certification fuel was approximately 1% for the density range of Indolene HO III marketed in 1974.

2. For fuel economy tests carried out with the EPA procedure but using commercial gasolines, it is also believed that the impact of changes in the gasoline is usually small. A possible exception is the impact of changes in gasoline density. For extreme values of density of commercial gasolines a difference in fuel economy of as large as 7%* could be indicated if there is no correction made for gasoline density. Ordinarily, comparisons are not made involving the extreme cases of gasoline density and, consequently, the variations in the fuel economy of motor vehicles due to variations in gasoline density are much less than this figure. However, the corresponding differences in fuel economy can still be significant, and, therefore, should not be overlooked.

3. The variations in fuel economy due to changes in fuel density can be corrected by referring all the results to those of a fixed density of gasoline. The present EPA test procedure assumes a constant density and no such correction is made. Our records on Indolene fuel used for EPA certification indicate that the density has been held nearly constant for several years even though commercial fuels have varied on the average. In the event the density of the certification fuel should vary significantly, a correction factor can be applied as discussed in Section III of the Appendix.

4. Independently of the gasoline used, fuel economy measurements depend very significantly on the atmospheric conditions (particularly temperature), vehicle soak times, and driving cycle (particularly trip length, speeds, and rates of speed changes). In addition, the impact of certain characteristics of gasoline on fuel economy (mainly volatility and viscosity) depends on the very same variables. However, there are no data to quantify (for any given vehicle) the complex relationship among fuel economy, gasoline characteristics, atmospheric conditions, and driving cycle. Therefore, what can be said is that the more the driving cycle, soaking periods, atmospheric conditions, and characteristics of the gasoline for a vehicle in actual service differ from those of the EPA test procedure, the greater the differences that can be expected between the corresponding fuel economies.

5. For a better assessment of the relative impact of the different characteristics of gasoline on fuel economy, data are needed on the specific effects of the volatility, viscosity, and surface tension of gasoline. Likewise, data are needed to evaluate the impact on fuel economy of burning, in the engines, the evaporative emissions collected by their control equipment.

6. The available information does not indicate a need for varying the specifications[60] of the fuel for the EPA fuel economy tests.

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*For the density range of some gasolines in 1974.[27]

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# APPENDIX

APPENDIX

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## I. Insensitivity of the Thermal Efficiency of the Spark Ignition Engine with regard to the Hydrocarbon Composition of the Gasoline

The thermal efficiency of an engine is defined as the ratio of its work output to the heating value of the fuel consumed to yield this output:

$$\eta = \frac{\text{Work output}}{\text{Heating value of the fuel consumed}}.$$

Except for variations in gasoline composition which might affect its knocking resistance -- an aspect which is discussed in the following sections of the report -- the composition of the gasoline does not significantly affect the thermal efficiency of the spark ignition engine. That is, as long as: a) the engine has the same compression ratio, and b) the gasoline is vaporized and delivered to the cylinders at the same temperature and fuel-air equivalence ratio,* the thermal efficiency of the spark ignition engine is not affected perceptibly by the composition of the gasoline. In fact, it has been found that under these conditions the operation of the conventional spark ignition engine with any pure hydrocarbon fuel results in the same thermal efficiency to within less than 1 percent. Ricardo[1] was one of the first researchers to find experimentally this fundamental characteristic. Analytical results from other investigators corroborate this finding.[2,3]

This characteristic of gasoline can be explained basically as follows. The composition of hydrocarbon fuels affects the thermal efficiency of the engine mainly through its impact on the specific heats of $CO_2$ and $H_2O$, and on the dissociation of these gases. But it turns out that the influence of these factors tends to balance in such a way that neither carbon nor hydrogen is preferable as the main constituent of the fuel on the combined grounds of dissociation and change of specific heats. Therefore, the nature and chemical composition of the fuel, so long as it consists only of carbon and hydrocarbon, has no significance on the efficiency of an engine.

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* The fuel-air equivalence ratio $\emptyset$ is defined as:

$$\emptyset = \frac{\text{Mass rate of fuel}}{\text{Stoichiometric mass rate of fuel}} \equiv \frac{\text{Fuel-air ratio}}{\text{Stoichiometric fuel-air ratio}}$$

# II. Fundamentals Concerning the Octane Rating of Gasoline

## II.A. Relationship between Engine Efficiency and Compression Ratio

The efficiency of the spark ignition engine is related fundamentally to its compression ratio. The simplest thermodynamic model of this engine shows this. That is, the so called "air-cycle" efficiency of the spark ignition engine is:

$$\eta = 1 - (1/r)^{k-1} \qquad \text{(II.A.1)}$$

where r is the compression ratio of the engine, and k is the ratio $c_p/c_v$ of the specific heats of the air at constant pressure and constant volume.

Of course, the efficiency of an engine also depends on factors other than r and k -- such as engine design and operating load and speed -- and, therefore, the simple theoretical expression given by equation (II.A.1) is not appropriate for determining absolute values of the efficiency. But this simple expression can provide fairly close estimates of the variations in the relative efficiency with changes in the compression ratio. This is illustrated in figure II.A.1 (taken from reference 4) which compares the relative fuel economy based on equation (II.A.1) with those corresponding to actual data from nine different multi-cylinder engines having displacements from 85 to 413 cubic inches.

The theoretical advantage of having a compression ratio as high as possible is, in practice, limited by certain constraints. The most important of these constraints are discussed briefly in what follows.

One limitation on higher compression ratios is due to the fact that the actual, overall efficiency of the engine, the so called "brake thermal efficiency," starts to decrease beyond a certain value of the compression ratio. The equation (II.A.1) shown above corresponds to a thermodynamic process which does not consider the reduced flame speed and increased heat loss and engine friction, all of which appear to be associated with the higher compression ratios.[48,49] The highest value of compression ratio for optimum brake thermal efficiency depends on engine design and operating conditions, but in general the optimum compression ratio of the gasoline engine is probably not higher than around 16 or 17.

Another limitation occurs because as compression ratios increase beyond about 10, preignition may appear due to glowing of combustion chamber deposits. The so-called "rumble" is a low-pitched thud probably caused by early surface ignition raising the pressure greatly in the cylinders with consequent deflection of mechanical parts.

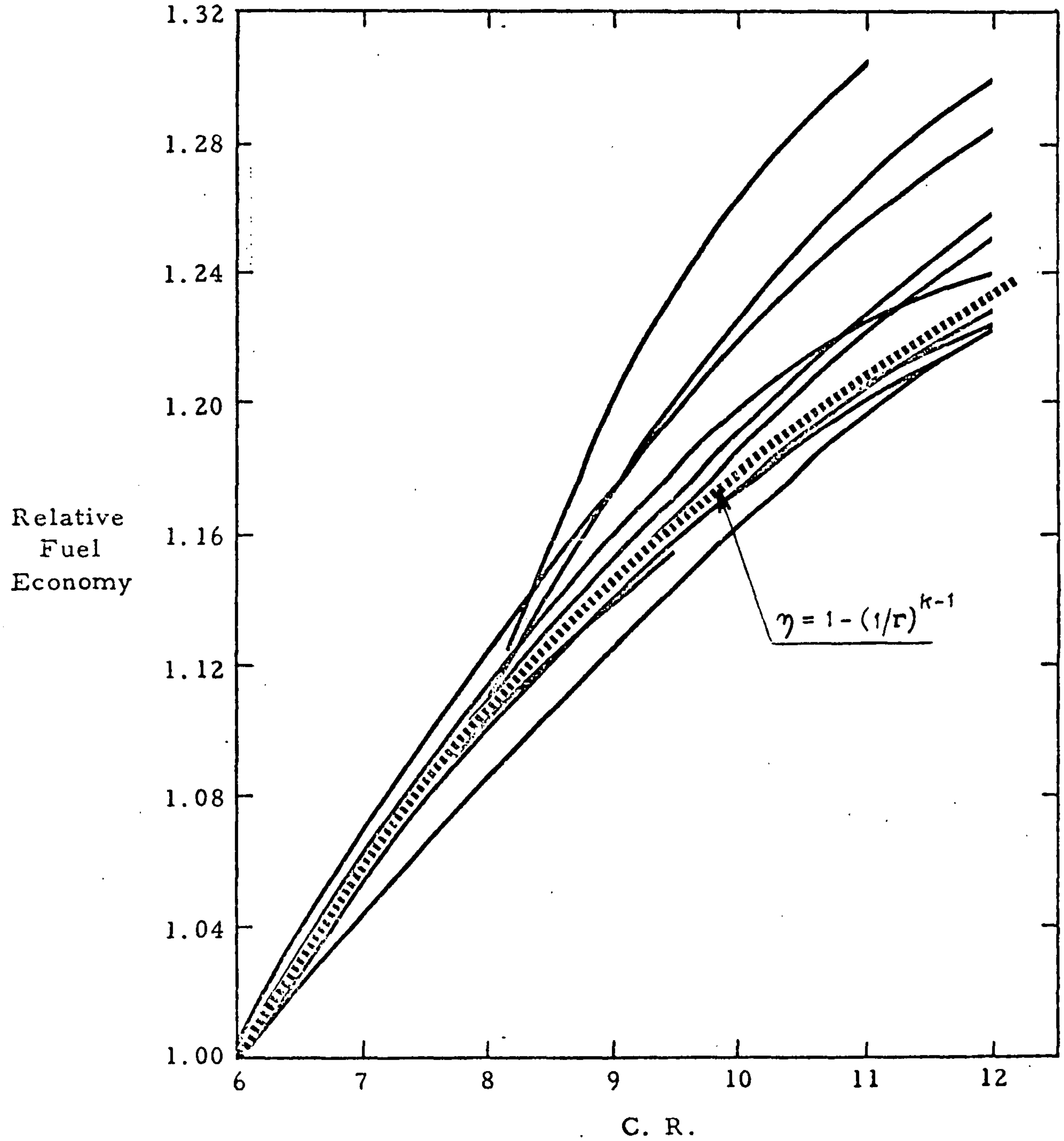


Figure II.A.1. Relative Fuel Economy vs. Compression Ratio

The limit on compression ratios due to these effects of brake thermal efficiency change or to surface ignition can be reached only if the spark ignition engine is operated with a non-knocking fuel. In practice, using commercial gasolines the compression ratio of the spark ignition engine is limited to lower values because of the appearance of knock.

Also, the control of some exhaust pollutants below certain values may pose another constraint on the compression ratio of the engine. Significant investigations have been and are being made regarding the relationship between engine compression ratio, exhaust emissions, and engine efficiency; but to assess this eventual limiation on the compression ratio due to emission constraints, there is a need for more comprehensive data -- which should include the effect of exhaust emission controls.

## II.B. Knock, the Variables which Affect It, and Its Effects on Engine Performance

Combustion in the spark ignition engine depends basically on engine design and fuel quality. Under normal conditions, the flame initiated at the spark plug spreads evenly across the combustion space until all the gasoline has been burnt. The spreading of the flame results in an increase in temperature and pressure in the "end gas," which is that part of the fuel-air mixture which the flame has not yet reached. This increase in temperature and pressure in the end gas causes the gas mixture to undergo preflame reactions. If the ignition delay -- i.e., the period which exists before a reaction becomes explosive -- of the end gas fully occurs before the flame arrives, "autoignition" takes place. With autoignition the combustion process becomes uncontrolled and an abrupt rise in pressure may occur. This local pressure rise may induce vibration of the walls of the combustion chamber or other parts of the engine, resulting in a knocking sound. Thus, "knock" in the spark ignition engine is due to sudden autoignition of the gas mixture near the end of the combustion period.

The most significant variables that control autoignition are the composition of the fuel and the following factors affecting the combustib mixture:

- Temperature
- Density
- Ignition delay
- Fuel-air ratio
- Homogeneity

Thus, because of the effects of these variables, knock in the spark ignition engine:

Increases with a lower octane rating of the fuel
Increases with the compression ratio
Increases with engine load
Increases with lower engine speed
Increases with inlet air temperature
Increases with engine coolant temperature
Increases with the supercharging of the inlet mixture
Decreases with spark retard
Decreases with higher inlet air humidity
Decreases with higher turbulence of the gas mixture
Decreases for either rich or lean mixtures
Decreases by stratifying the mixture (so that the end gas is less reactive)
Depends on the combustion chamber design.

Knock of high enough intensity can cause engine damage. The pressure waves associated with knock increase the rate of heat transfer to -- and hence the temperature of -- the susceptible parts, and this may result in local melting of the material or in its softening to such an extent that the high local pressure causes erosion. Most frequently, however, knock results in engine failure by causing pre-ignition. That is, knock of high enough intensity heats some part of the combustion chamber to the point that the fuel-air mixture is ignited before the ignition spark occurs. Then, pre-ignition, if not checked, gets progressively worse, culminating in engine failure.

Under knocking the gases in the combustion chamber vibrate with heat losses as a result, but at some level of light-knock the gain from the faster combustion associated with knock can be greater than the heat losses caused by the vibrating gases. Thus, data indicates that the maximum output and fuel economy of an engine are obtained under controlled light-knock conditions.*

It should be pointed out that advancing the ignition timing beyond its optimum setting results in deterioration of engine performance. In the case of optimum ignition timing under light-knock, advancing the ignition will not only decrease the power and the fuel economy but also increase the knock, and thus lead to engine failure. In the case of an engine operated under conditions such that its octane number requirement is below the octane number of the fuel, advancing the spark beyond the optimum timing will decrease the power and the fuel economy, and may or may not result in engine knock.

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*Supporting information is found in reference 5, pages 109 and 298. This data was originally presented in reference 43.

Whereas a certain level of light-knock* can be beneficial from the important viewpoint of fuel economy, there are some questions about the feasibility of extended use of light-knock operation. The first difficulty associated with permitting light-knock operation is rating the level of knock. Currently, the only practical method of measuring knock is by ear; therefore, the intensity of knock may vary according to the particular observer. Rating the level of knock is much more difficult than simply distinguishing the following cases included in the current CRC E-15** procedure for determining octane requirements:

1) no knock
2) borderline knock
3) above borderline knock.

Also, if some level of light knock is permitted within the normal ranges of speed, load, and weather, it must be considered that the knock will be higher under other conditions of operation which are more prone to induce knock.*** Furthermore, even if the knock would always be within a certain limit, there is a lack of information about the effect that this knock could have on engine durability and performance if it would occur for substantial periods of time. There are differences in opinion of whether the effects of such a substantial occurrence would be serious or not.

Therefore, it appears that to allow for the general use of light-knock operation with confidence that it will not cause serious hardship, two precautions should be taken. First, it would be necessary to establish a procedure to properly measure the level of light-knock. Second, it would be required to determine what level of light-knock would be permissible without penalizing performace or durability. However, the determination of a feasible level of light-knock is further complicated by the fact

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* The expression "light-knock" is used in this report to indicate the region of knock intensity immediately above the borderline of knock. Some literature uses expressions such as "audible knock" to refer to the first portion of the knock region beyond "trace" or "borderline knock".

** CRC E-15[52] refers to a direct method used for obtaining maximum octane requirements of cars under normal service. This method was developed by the Coordinating Research Council for use by all participants in its periodic new-car Octane Requirement Surveys. The maximum octane requirement of a car is given by the octane rating of the lowest octane fuel which is required to avoid knock of a level higher than border line during the complete CRC E-15 test. For most ordinary driving conditions,the octane requirement of a car may be substantially below its maximum octane requirement.

*** The calibration of engines for light-knock would decrease the margin of safety which may be needed to prevent engine damage from heavier knock under extreme conditions of operation. It is conceivable, however, that advanced developments in knock sensors and in ignition timing control technology could, at some future time, ensure that light-knock operation is maintained within the limits for engine safety and efficiency.

that different engines may be able to tolerate different levels of knock. Furthermore, the knock levels of cars of the same make and model may differ substantially (see section II.G).*

II.C. Knock Rating of Gasolines

The knock rating of a gasoline is found by comparing its knock response with that of a blend of "primary reference fuels" (PRF). These fuels are normal heptane with an "octane number" (ON) of 0, and isooctane (2, 2, 4 trimethyl pentane) with an octane number of 100. A blend containing x percent (by volume) isooctane is defined as an x octane primary reference fuel.**

Several methods of knock rating of gasoline are used. In each of these methods a special standard engine must be run under prescribed operating conditions (of speed, temperature, etc.). The octane rating of a gasoline may have different values for different tests. Some fuels are relatively insensitive to such changes while others are quite sensitive. The two most common octane rating tests are known as the Research and Motor methods, and their corresponding ratings are indicated as Research Octane Number (RON) and Motor Octane Number (MON). The difference between RON and MON is called the "sensitivity" of the fuel. Because of this sensitivity, the knocking characteristics of a gasoline*** cannot be determined specifically by a single octane number.

The knock rating of a gasoline depends on its chemical composition and on the structure of its molecules. The various types of the hydrocarbons that compose gasoline behave differently in their preflame reactions and, therefore, in their tendency to knock. Nevertheless, there is no precise relationship between chemical structure and anti-

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*Also, in multicylinder engines knock occurs first in the cylinder where conditions are more prone to induce it. Therefore, it would not be possible, with current engine technology, to have all cylinders operating at the level of light-knock for best efficiency.

**The rating of fuels with ON higher than 100 is made in terms of isooctane plus tetraethyl lead (TEL), and defined as the "performance number" (PN) of the fuel.[6] The relationship between ON and PN is such that ON (above 100) = 100 + (PN-100)/3.

***Due to differences between the standard engine for rating fuel and the engines installed in the vehicles, as well as to differences in operation, a thorough evaluation of knock for gasoline and engines is complex. The relationship involved is expressed by regressions of road octane rating versus Research and Motor octane numbers and variables reflecting the hydrocarbon composition of the gasoline. Details on these matters can be found in reference 53.

knock performance in an engine. Members of the same hydrocarbon series may have very different anti-knock characteristics; for example, normal heptane and normal pentane, both paraffins, have octane numbers of 0 and 62, respectively. In broad terms, however, it can be stated that aromatic hydrocarbons (e.g., benzene and toluene), and highly branched iso-paraffins (e.g., isooctane) and olefins (e.g., diisobutylene) have high knock resistance. In an intermediate position are iso-paraffins with little branching and hydrocarbons of the naphthene family (e.g., cyclohexane), while normal paraffins (e.g., normal heptane) have low anti-knock values. Also, in general, and always in the case of straight-chain paraffins, the knock resistance improves as the number of carbon atoms in the molecule decreases.

The anti-knock characteristics of a blend of two pure hydrocarbons is usually between those of the constituents. Generally, the knock rating of the mixture is somewhat lower than if there was a linear relationship between the knock ratings and the percentages of the two compounds. However, some hydrocarbons -- such as isooctane and di-isobutylene -- blend synergisticly, resulting in a knock rating higher than that expected from a linear relationship.

In automotive literature reference is made to "chemical" and "mechanical" octane numbers. The "chemical" octane numbers are those that have been covered in this section, and they refer specifically to the fuel and its additives. On the other hand, by "mechanical" octane numbers are meant those anti-knock gains associated with engine design (such as combustion chamber design, ignition control, etc.) and engine-transmission relationships.

## II.D. The Octane Requirement Increase (ORI)

As a new motor vehicle goes through its normal break-in process, deposits accumulate in the combustion chamber and eventually reach a stabilized level. The sources of these deposits are the fuel, the lubricant, and the air which enters the combustion chamber. The composition and the quantity of the deposits depend on: a) the physical and chemical natures of the fuel and the lubricant, b) the additives in the fuel and in the lubricant, c) the operating conditions of the engine (which are determined by the driving pattern of the vehicle), d) the weather and climate, e) the location in the combustion chamber, and f) the design of the powertrain system of the vehicle.

The deposits increase the octane requirements of the engine. Significant reasons for this increase are the higher end-gas temperatures caused by the insulating effect of the deposits, and the increase in the compression ratio caused by the volume of the deposits. The possibility of catalytic effects of the deposits has also been mentioned as another cause.

The "octane requirement increase" is defined as:

ORI = (octane requirement of engine with stabilized deposits) - (octane requirement of clean engine).

Data indicate that while cars operated with leaded fuel reached stabilized octane requirements before accumulating 5,000 miles, cars operated with unleaded fuel require more miles to reach stabilized requirements. Also, the ORI for cars operated with unleaded gasoline is higher than the ORI for leaded-fuel cars.[8,9,10,11,12] Unleaded gasolines result in combustion chamber deposits which have a composition with a higher carbon to metal ratio than the deposits from leaded gasolines. Since carbon is a good heat insulator and metals are good heat conductors, the increase in carbon to metal ratio of the deposits may be a basic reason for the higher ORI of the cars fueled with unleaded gasoline.[44] However, the available information regarding how large the differences are between the ORIs, and between their stabilization mileages, for cars operated with unleaded and leaded gasolines, is not conclusive. Furthermore, new ORI data must be obtained periodically to take into account the effect of changes in gasolines, lubricants, and their additives, and the effect of changes in powertrain system designs.[13,14,15,16,44]

The ORI is one of the important determinants of the octane requirements of motor vehicles.[17*] A better understanding of the mechanisms which produce the ORI and of the impact of the variables involved would lead to its decrease and, therefore, to a more efficient use of gasoline and engines.

## II.E. Octane Number Requirements versus Compression Ratio

Although the octane number requirements of engines depend very strongly on the compression ratio, there is no unique relationship between these two variables. This is due to the influence of the other variables (indicated in Section II.B) which affect engine knock. Thus, the correlations quoted in the literature vary somewhat, depending on the particular vehicles, fuels, and conditions of operation.

Figure II.E.1 presents the general trend of the octane number (MON) requirements for automobiles versus compression ratios -- for the model years 1956 through 1972 -- for different percentages of automobiles satisfied with a given octane number. This figure is taken from reference 18. It shows the results obtained by a regression analysis of the data accumulated by the Coordinating Research Council during its surveys for octane number requirements.

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* As indicated before, the octane number requirements of automobiles are normally determined using the CRC E-15 method. This method is currently under review for improving its reliability and accuracy.

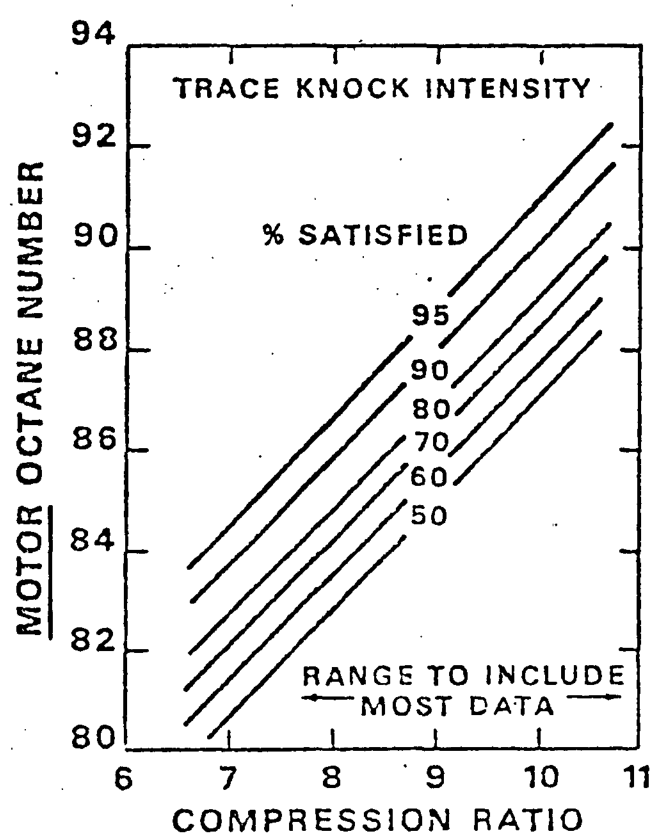


Figure II.E.1. Motor Octane Number vs. Compression Ratio--
General Trend for Automobiles

## II.F. Anti-Knock Additives

There are certain compounds soluble in gasoline which may decrease the tendency of the fuel-air mixture to autoignite. It is believed that the addition of these compounds results in a sufficient reduction of the chain reactions which produce the highly energized particles or radicals of pre-flame reactions. Thereby these additives delay the autoignition of the end gas and permit the normal flame to pass through it without combustion knock.

Ideally, anti-knock additives should have the following requirements:

a. Non-toxic.
b. Do not contribute to the formation of toxic substances.
c. No deposits left in the engine.
d. Relatively low boiling temperature to ensure good distribution in multicylinder engines.
e. Complete solubility.
f. Stable.
g. Low cost per unit increase in octane rating.

The most effective and extensively used anti-knock additives are certain lead compounds. Specifically, tetraethyl lead (TEL), $(C_2H_5)_4Pb$, is the primary commercial anti-knock additive. The burning of TEL results in lead compounds that condense readily and therefore must be removed to avoid increased deposits in the combustion chamber. To prevent these deposits, scavenging agents, mainly chlorine and bromine compounds, are blended with the TEL.

Another lead compound frequently used in gasoline is tetramethyl lead (TML), $(CH_3)_4Pb$. In general, this compound is less effective as an anti-knock agent than TEL. However, in some cases it can be more effective, primarily because it is more volatile than TEL and, therefore, can provide better distribution in some multicylinder engines. Likewise, a mixture of both (TEL-TML) may be more effective for some engines.

The lead-compound particulates which are exhausted into the atmosphere can result in health hazards. Therefore, the EPA has ruled that effective October 1, 1979, the maximum allowed average content of lead in motor gasoline will be 0.5 g/gallon.[59] Furthermore, the marketing of unleaded gasoline has become compulsory[57] for motor vehicles equipped with catalytic converters for the control of exhaust emissions. This is necessary because the lead compounds poison the catalysts.

Methylcyclopentadienyl manganese tricarbonyl (MMT), $CH_3(C_5H_4)Mn(CO)_3$, is an anti-knock agent which has been used to a limited extent in gasoline. This anti-knock agent is synergistic with TEL; that is, when a small amount is added to some leaded fuels the octane rating is raised more than when the same amount is added to the same fuels without lead.[19]

Since MMT does not contain lead it is being used in some of the unleaded gasolines. It has been reported that a concentration of 0.125 grams of manganese per gallon of gasoline is of greatest interest because an optimum combination of engine durability characteristics and economic anti-knock value is obtained at about this concentration. It has also been reported that the use of MMT in a concentration of 0.125 grams Mn/gallon would provide, on the average, an increase of about two road octane numbers. This increase could, compared to an equivalent increase in road octane numbers obtained through gasoline refining, represent about a 1% savings in crude oil.[20] Thus, although MMT is not as cost-competitive as lead anti-knock, it appears that its use can be economically attractive when compared with achieving anti-knock quality by processing, and can also offer significant savings in petroleum.

Reference 20 includes the following information regarding the use of MMT in unleaded gasoline for cars equipped with catalytic converters. The MMT does not lessen the effectiveness of exhaust catalysts in oxidizing unburnt hydrocarbons and carbon monoxide. When cars on the road were operated under extreme service conditions some plugging of monolithic exhaust catalysts occurred using MMT at the concentration of 0.125 grams Mn/gallon.*

Toxicologic evaluations of MMT have been undertaken by the National Environmental Research Center of the EPA. Researchers from that center have indicated in reference 21 that, "The most important factor that should be considered in determining the environmental impact of MMT is whether its usage will cause a significant increase in the ambient levels of Mn in highly populated areas with high traffic density. Further studies are needed to determine the lowest atmospheric Mn concentrations which will produce clinical Mn intoxication and the possible chronic effects of long term exposure to automotive exhaust containing Mn."

## II.G. Optimum Octane Rating of Gasoline

It has been explained in the previous sections that: 1) engine efficiency calls for the highest possible compression ratio, 2) compression ratios are limited by engine knock, and 3) engine knock is inversely related to the octane rating of the gasoline. Thus, from the viewpoint of having the maximum fuel economy for motor vehicles, gasoline should have the highest possible octane rating,** and the engines should be designed with the highest possible compression ratio compatible with this gasoline.

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*Investigations are currently being made by several organizations to evaluate the impact of MMT, for concentrations up to 0.125 g Mn/gallon, on emission controls and engine performance.

**The benefit of a gasoline with high octane rating is realized only if the design of the engine -- or its manufacture or condition -- calls for such a high octane rating. Use of gasolines of higher octane rating than the one required by the engine does not improve its efficiency, it is not economical, and may have negative effects -- such as increased combustion chamber deposits because of the probability of higher levels of lead or higher levels of aromatic hydrocarbons in the gasoline.

However, to optimize the conservation of petroleum it is necessary to consider not only the fuel economy of the vehicle but also the efficiency of the refining process of gasoline. This is because at the octane levels of interest the yield of gasoline per barrel of crude oil is in general inversely related to the octane number. This is particularly important in the case of unleaded fuels which do not have additives for raising their octane ratings.

Studies have been made for estimating the optimum octane number of unleaded gasoline for maximum conservation of petroleum considering both the efficiency of the refining process of gasoline and the fuel economy of automobiles. The estimates vary, ranging between 93 RON and 97 RON (approximately between 85 and 87 MON for the prevailing gasoline sensitivities).[18,22,23,24,50] It has also been estimated that the saving in crude oil corresponding to the optimum octane rating, compared with the current minimum rating of 91 RON/83 MON for unleaded motor gasoline, would be approximately 1 to 3 percent.*

It should be indicated that some of these studies for optimum octane rating have considered availability of more than one grade of unleaded gasoline.** Such consideration is based on the fact that the distribution of octane number requirements of motor vehicles is rather wide. Because of the many factors which affect the octane number requirements, even identical cars may have large differences in octane requirements. Typically, the distribution of octane number requirements of identical cars show (when operated with full boiling range unleaded fuels) a variation of about 10 research octane units, between the 5 and 95 percentiles. The variability of the octane requirements for the whole car population of a given model year is even higher. Accordingly, availability of unleaded gasoline with octane rating higher than 91 RON/83 MON is needed for optimizing petroleum conservation, but availability of unleaded gasoline of lower than 91 RON/83 MON would also aid petroleum saving.

Thus, it appears that there is some potential for maximizing the conservation of petroleum by optimizing the octane ratings of unleaded gasoline. However, some of the studies on optimum octane number have pointed out constraints against raising the octane rating of the unleaded gasoline beyond the current minimum rating of 91 RON/83 MON.

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*The actual saving would be somewhat smaller since the average octane rating for unleaded gasoline is higher than the minimum 91 RON/83 MON. The last survey reported by ERDA indicates a national average of 92.1 RON/83.9 MON in summer 1975, and 92.3 RON/84 MON in winter 1975-76.[51]

**Reference 50 has considered up to a three grade system which would have grades of 80 MON, 83 MON, and 88 MON.

Specifically, it has been indicated that in order to raise the octane rating the petroleum industry would have to construct additional processing facilities, and that this would take time and require large capital investments. Supposedly, these constraints justify the current octane rating. But considering the scarcity of petroleum, the optimization of octane ratings should be pursued. Unless a thorough analysis demonstrates the impossibility or secondary importance of changing it -- or that the necessary capital investment cannot be made available, or would be better spent in other projects for increasing the availability of energy -- the current rating of 91 RON/83 MON for unleaded gasoline does not appear strictly appropriate on a permanent basis. In particular, a reevaluation of the optimum octane ratings of the gasolines of the future should consider the nationwide marketing of at least two different grades of unleaded gasoline, to efficiently match the wide variation in octane requirements of motor vehicles.

In reevaluating future octane ratings of gasoline, an additional consideration should be taken into account. As has been indicated in section II.A, the control of some exhaust pollutants below certain values may pose a limitation on the compression ratio of the engines. Since a compression ratio constraint would limit the maximum octane requirement for gasoline, a reevaluation of the optimum octane ratings should also research thoroughly whether such a constraint on the compression ratio might occur.

## III. Density

Because the densities of the various hydrocarbon compounds are different, the density of a gasoline varies according to its composition. For example, since aromatics are heavier than paraffins and olefins, the density of gasoline increases with its percentage of aromatics.

The fuel economy of motor vehicles is commonly expressed in miles per gallon (mpg). However, the mpg does not provide an accurate indication of the fuel economy of the vehicles unless the density of the gasoline is taken into consideration. This is because the density of the gasoline affects the mpg of a vehicle. The explanation is that the heating value per unit volume of gasoline increases with its density.* Thus, higher mpg values are achieved using heavier gasolines. However, this is not due to a variation of the efficiency of the vehicles, but rather to the change in gasoline density. In other words, there are fuel economy variations which are due to changes in fuel density, and therefore, should not be attributed to the vehicle, but only to the gasoline. As explained before in Section I, the composition of the gasoline does not significantly affect the thermal efficiency of the engine. If the fuel economy of motor vehicles was measured in miles per pound of gasoline instead of miles per gallon, the heavier gasolines would result in lower mileages per pound of fuel because the heating value per unit of mass of gasoline decreases when its density increases.

Given the same vehicle, driving cycle, and atmospheric conditions, the relationship between the miles** per gallon and the densities of gasoline can be expressed as:

$$\frac{mpg_o}{mpg} = \frac{\rho_o \cdot HV_o}{\rho \cdot HV} \qquad \text{(III.2)}$$

where HV stands for the heating value of the gasoline per unit mass, $\rho$ is the density of the gasoline, and the subscript o refers to the values corresponding to any particular gasoline used for reference.

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* A correlation of the heating value of commercial full-boiling range gasolines with density indicates that the

$$\text{Low Heating Value } |\text{Btu/gal}| \approx 47{,}400 + 10{,}960 \cdot \rho \qquad \text{(III.1)}$$

where $\rho$ is the density in lb/gal.[25]

** The derivation of this relationship is given at the end of this section. Also, since the HV is practically a function of $\rho$ only, for the given conditions the ratio $mpg_o/mpg$ can be considered a function of $\rho$ only. If consideration of secondary effects (such as the effect of variations is distillation temperatures) would be desired, it would then be necessary to expand the function HV to include the additional variables.

Thus, for accurate evaluations or comparisons of fuel economy, the mpg should be measured using gasoline of a fixed density. Alternatively, the mpg should be corrected for density, to refer all the results to those of a fixed density of gasoline. In other words, the reported values of fuel economy should be:

$$mpg_o = mpg \times \text{Correction Factor}.$$

The correction factor determined analytically according to equations (III.1) and (III.2) is shown in Figure III.1, as a function of $\rho$ (taking for reference a gasoline with $\rho_o$ = 6.14 lb/gal.) The SAE* correction factor for density, which has been found to correlate well with large volumes of actual fuel economy data, has also been plotted in the same figure. The two correction factor curves are practically the same.

The densities of the gasolines in the market vary significantly. Data indicates that in 1974 the density of some commercial gasolines ranged between 5.7 and 6.4 lb/gallon.[27] In the extreme case where tests of fuel economy are made using gasolines falling at the lowest and highest densities of this range, a difference in fuel economy of as large as 7% would be indicated if there is no correction made for gasoline density. Ordinarily, comparisons are not made for the extreme cases of gasoline density and, consequently, the variations in the fuel economy of motor vehicles due to variations in gasoline density are much less than this figure. However, the corresponding differences in fuel economy can still be significant, and, therefore, should not be overlooked.**

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* "Fuel Economy Measurement Road Test Procedure - SAE J1082".[26]

** For the emission tests for certification of automobiles, Indolene HO III is used as fuel. In 1974 the density of this gasoline ranged between 6.10 and 6.22 lb/gal.[27] The maximum variation in fuel economy which is possible for this change in density is approximately 1%.

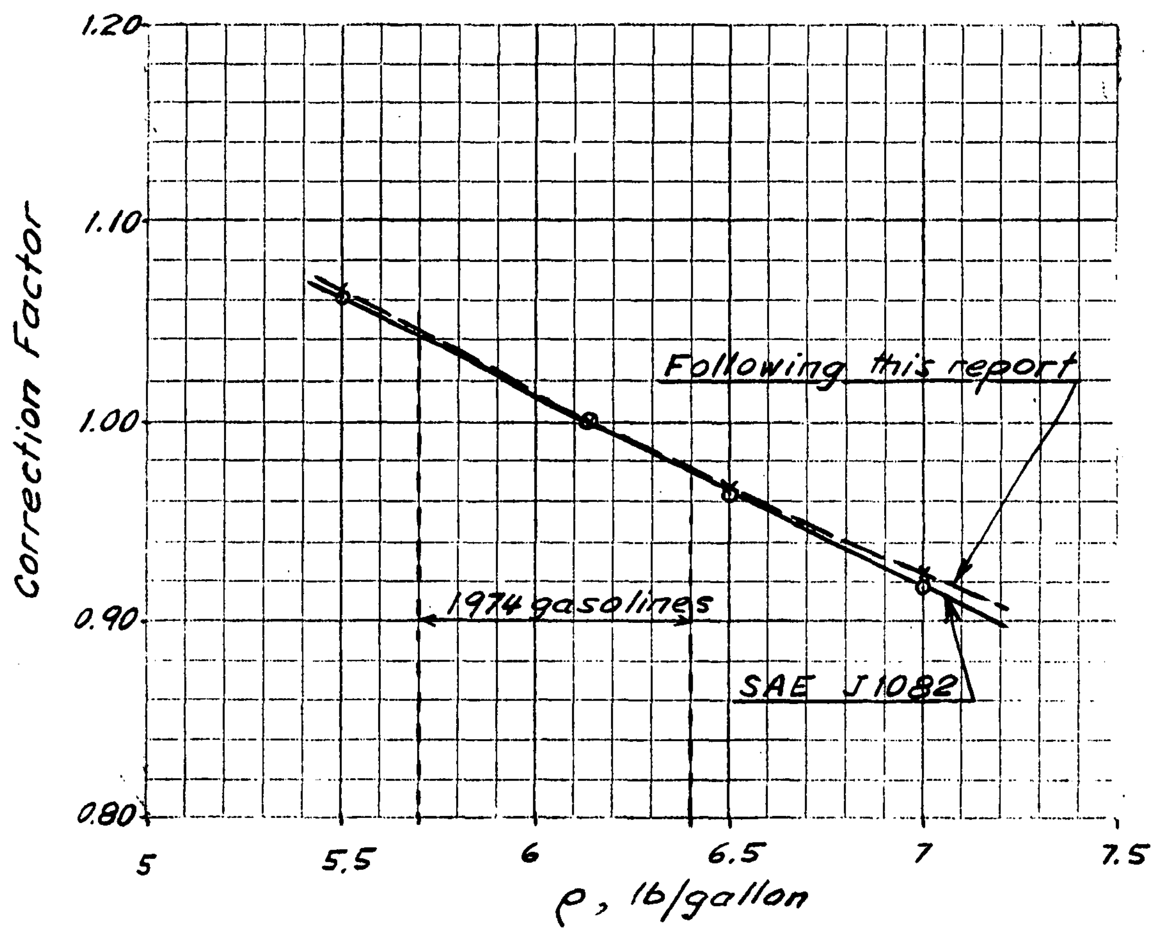


Figure III.1 Correction Factor for Gasoline Density

Analytical Derivation of the Correction Factor for Gasoline Density

Consider an arbitrary -- but fixed -- driving cycle, and a given vehicle and atmospheric conditions.

Let:

L = length of the driving cycle, |miles/cycle|.

W = work produced by the engine during a cycle, |Btu/cycle|.

$\bar{F}$ = average force during the cycle, |Btu/mile|, such that $W = \bar{F}.L$.

HV = heating value of the gasoline per unit mass, |Btu/lb|.

HV' = heating value of the gasoline consumed per cycle, |Btu/cycle|.

mpg = fuel economy.

v = volume of gasoline consumed per cycle, |gal/cycle|.

$\rho$ = density of the gasoline, |lb/gal| .

$\eta$ = engine efficiency for the given conditions.

o as the subscript to indicate values corresponding to any particular gasoline used for reference.

As indicated in section I, the thermal efficiency of the engine is practically independent of the composition of the gasoline. Therefore, it can be written:

$$\eta = \frac{W}{HV'} = \frac{W}{HV'_o} \quad . \qquad \text{(III.3)}$$

Now, since

$$V = \bar{F}.L,$$
$$HV' = v.\rho.HV, \text{ and}$$
$$HV'_o = v_o . \rho_o . HV_o,$$

substituting in equation (III.3) :

$$\frac{\bar{F}.L}{v.\rho.HV} = \frac{\bar{F}.L}{v_o.\rho_o.HV_o} ,$$

or

$$\frac{L}{v.\rho.HV} = \frac{L}{v_o.\rho_o.HV_o} . \qquad \text{(III.4)}$$

Furthermore,

$L/v = mpg$, and $L/v_o = mpg_o$;

therefore, substituting in equation (III.4):

$$\frac{mpg}{\rho \cdot HV} = \frac{mpg_o}{\rho_o \cdot HV_o},$$

or

$$\frac{mpg_o}{mpg} = \frac{\rho_o \cdot HV_o}{\rho \cdot HV} \qquad \text{(III.5)}$$

which is the equation (III.2) indicated at the beginning of this Section III.

Accordingly, the reported values of fuel economy should be

$mpg_o = mpg \times \text{Correction Factor}$

where the Correction Factor $= \frac{\rho_o \cdot HV_o}{\rho \cdot HV}$. (III.6)

If the correlation of the heating value of commercial full-boiling range gasolines with density

Low Heating Value $|Btu/gal| = 47{,}400 + 10{,}960 \cdot \rho$

(from reference 25) is used, we can write

$HV|Btu/lb| = 10{,}960 + 47{,}400/\rho$. (III.7)

Therefore, substituting equation (III.7) into equation (III.6):

$$\text{Correction Factor} = \frac{10{,}960 \cdot \rho_o + 47{,}400}{10{,}960 \cdot \rho + 47{,}400}. \qquad \text{(III.8)}$$

The SAE, in its "Fuel Economy Measurement Road Test Procedure - SAE J1082"[26], provides the following correction factor (using a reference gasoline with specific gravity of 0.737, i.e., $\rho_o = 6.14$ lb/gal):

Correction Factor = 1 + 0.8 (0.737 - Specific Gravity). (III.9)

The correction factors for both equations, (III.8) and (III.9), are plotted in Figure III.1. It is seen that both methods provide practically the same values.

## IV. Volatility

The volatility of a gasoline, that is, its readiness to become vaporized, affects the performance of motor vehicles in different ways. Specifically, volatility has an impact on the various aspects of the driveability of the vehicle -- starting, warm-up, acceleration, power, vapor lock, and carburetor icing. Volatility also affects the fuel economy, and the dilution of the lubricant oil of the engine. These effects of volatility are discussed in the corresponding subsections that follow.

### IV.A. Common Ways of Identifying the Volatility of Gasoline

The hydrocarbons that compose a gasoline have widely divergent boiling points. Accordingly, gasoline evaporates over a range of temperatures depending upon the types and amounts of hydrocarbons used in blending the gasoline. Its boiling range may extend from about 80°F to about 430°F.

The volatility of gasoline is normally assessed by a standard distillation test (ASTM D86[28]) which indicates the percentage of gasoline evaporated along its temperature boiling range. The temperatures at which 10, 50, and 90 percent have evaporated are commonly used to characterize the volatility of automotive gasolines. A typical gasoline distillation curve is shown in Figure IV.A.1. In general, each of the vehicle performance parameters affected by gasoline volatility depends particularly upon certain portions of the distillation curve. Therefore, to facilitate discussions related to volatility, the distillation curve is usually divided into three major regions. These regions are referred to as the Front-End, Mid-Range, and Tail-End, and they cover the lowest, middle, and highest boiling temperatures, respectively.

Determining the vapor pressure is another means for assessing the volatility of a gasoline, particularly its tendency towards vapor locking. The vapor pressure of gasoline is normally measured by the Reid Method (ASTM D323[28]), at a temperature of 100°F, in a closed apparatus at the standard but arbitrary condition of 4/1 ratio of vapor to liquid. However, due to the variable composition of gasoline the Reid vapor pressure is not a conclusive criterion of the vapor locking tendency. A more reliable indication of the vapor lock propensity is a set of values showing the relationship between V/L (the ratio of the equilibrium volumes of the vapor fuel and the liquid fuel) and temperature, at a given pressure (ASTM D2533[28]). Other expressions for assessing vapor lock performance of gasolines can be found in reference 55.

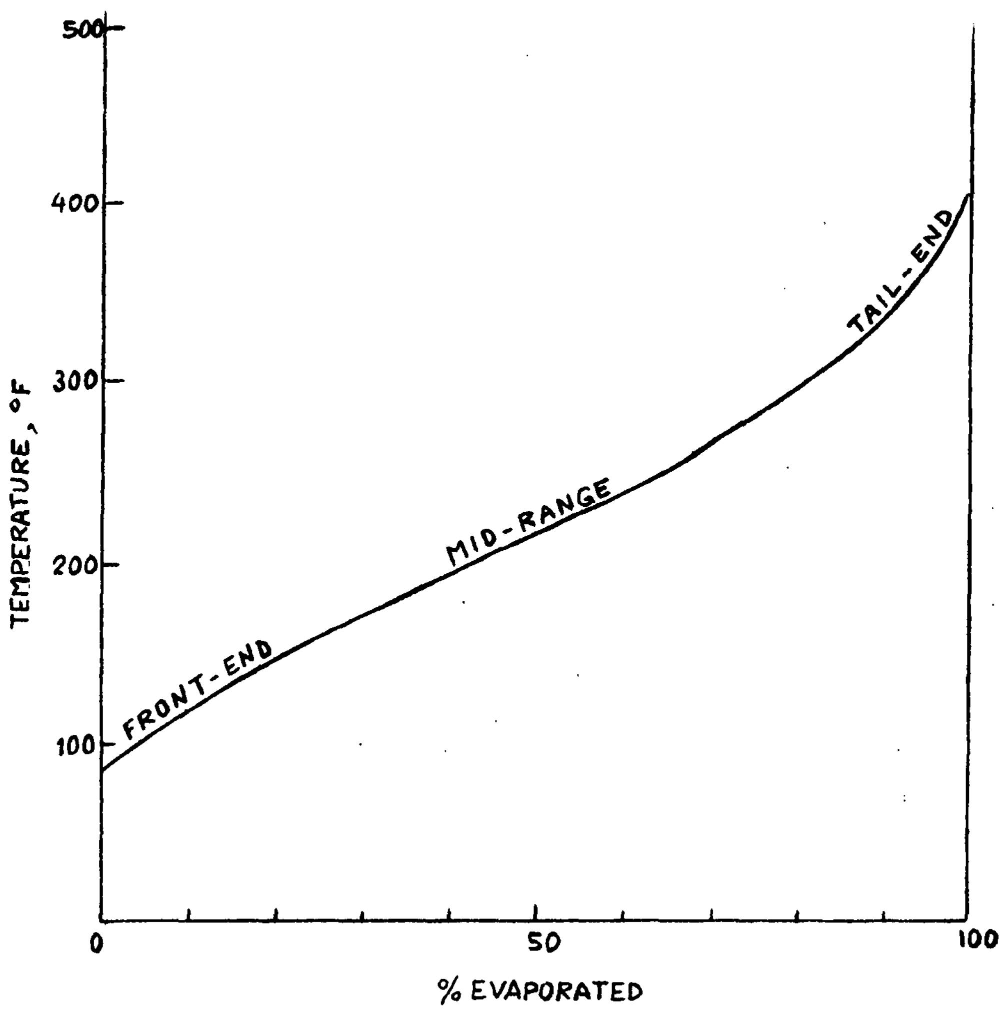


Figure IV.A.1. Typical Distillation Curve for Gasoline

## IV.B. Volatility versus Cold Starting, Hot Starting, and Vapor-Lock

Under cold engine conditions -- particularly at low ambient temperatures -- normal carburetor operation would evaporate only a small percentage of the gasoline supplied through the carburetor, and this would result in a fuel-air mixture too lean for ignition. It is for this reason that carburetors are equipped with chokes which increase the amount of fuel going into the engine and result in ignitable fuel-air mixtures for cold starting. Thus, from a fuel standpoint the problem of cold starting is mainly one of getting sufficient evaporation of fuel. Accordingly, a low front-end distillation curve is important for cold starting.

Hot starting presents an opposite requirement. If the front-end of the distillation curve is made excessively low to provide good cold starting, then the fuel evaporates out of the carburetor bowl when a hot engine is turned off. If there are no evaporative control devices this evaporated fuel goes into the intake manifold forming a mixture which is too rich to burn and results in hard starting. If the vehicles have evaporative control devices, excessive volatility of the fuel may pose problems to these devices with regard to capacity for storing the vapor and control of its disposal.

Also, gasolines with excessive front-end volatility enhance vapor-lock. This is a condition in which partial or complete interruption occurs in the liquid fuel flow because of vaporization of the fuel. Vapor-lock problems can be reduced by proper attention to the design and location of fuel-system components -- keeping fuel lines away from hot engine parts, avoiding sharp turns and restrictions in fuel lines, etc., and maintaining the fuel under pressure. But to prevent these problems, as well as hot starting problems, the front end volatility should be maintained as low as permitted by opposite requirements. Cold starting, conservation of crude oil, and gasoline manufacturing favor a high front-end volatility.

## IV.C. Carburetor Icing

Under certain ambient and operating conditions, ice can be formed in the carburetor. The ice upsets carburetion and results in poor vehicle performance. Throttle plate icing originates from water in the air. Ice in the carburetor and in the fuel lines may also be formed from water in the gasoline.

The formation of the ice in the carburetor is dependent upon the cooling effect of fuel evaporation. A fuel which evaporates more rapidly exerts more cooling effect, and therefore is more prone to result in carburetor icing. Lowering the volatility of the gasoline decreases the evaporation rate and aids in preventing carburetor icing. However, carburetor icing can also be controlled by adding to the gasoline surface-active agents and freezing point depressants. Also, the recent practice -- due to emission control needs -- to heat the inlet air has greatly diminished carburetor icing tendencies.

## IV.D. Impact of Volatility on Warm-up and Normal Operation of the Engine

The warm-up period of an engine is related very significantly to the mid-range portion of the distillation curve. This portion includes a considerable amount of the total quantity of fuel; therefore, it must be volatile enough to provide appropriate fuel-air ratios under a variety of operating conditions if operational flexibility is to be achieved. For long trips the impact of the warm-up period on the overall fuel economy should be small or negligible because for these trips the warm-up period represents only a small fraction of the total driving. However, the impact of the* warm-up period on fuel economy may be very significant in short trips. Thus, keeping the warm-up period to a minimum by having a gasoline which is relatively volatile in the mid-range section permits better driveability and fuel economy.

Furthermore, to obtain optimum acceleration, power, smoothness of operation, and engine efficiency, it is important that the appropriate fuel-air ratio be delivered to all the cylinders, both during warm-up and during normal operation of the engine. Consequently, since high volatility aids good mixture distribution, keeping the mid-range and tail-end portions of the distillation curve as low as practical** will favor good performance and vehicle fuel economy.

Because hydrocarbons with higher boiling points are generally heavier than the more volatile ones, and because hydrocarbons of higher density have higher energy content per gallon, it can be stated that gasolines with the lowest possible volatility in the mid-range and tail-end of their distillation ranges increase the mileage. However, as was explained in section III, this is not due to an increase in the efficiency of the vehicle. This impact (of higher density due to lower volatility) on the miles per gallon does not appear when the fuel economy is corrected for the density of gasoline.

## IV.E. Effects relative to the Tail-End of the Distillation Curve

High boiling temperatures at the tail-end portion of the distillation curve have some undesirable characteristics other than being a possible cause for poor mixture distribution among the cylinders. Fuel that does not vaporize may pass the piston rings into the crankcase of the engine where it dilutes the oil and decreases its viscosity. Crankcase dilution is intensified under the low engine temperatures encountered in cold weather, particularly for short trip driving patterns. Thus, the degree of crankcase-oil dilution is inversely related to the tail-end volatility.

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* Also, motor vehicles are designed to achieve optimum performance when their powertrain systems are at normal operating temperatures. Consequently, before reaching this normal operating condition, the fuel economies of motor vehicles are below optimum.

**In particular, certain refineries have problems in manufacturing gasolines with high mid and tail-end volatility.

Also, lowering the tail-end of the distillation curve of gasoline eliminates some of the hydrocarbons with high boiling points which contribute to combustion chamber deposits and to varnish and sludge deposition inside the engine. This deposition can cause piston ring plugging and sticking, and valve sticking, resulting in poor operation and poor fuel economy. Likewise, less spark plug fouling is usually experienced with gasolines with high tail-end volatility.

Conversely, there are reasons that preclude raising the tail-end volatility. For one thing, economic considerations require including relatively heavy fractions in the gasoline. In addition, removal of the heavy fractions would also eliminate high anti-knock components which the gasoline gains by catalytic reforming.

## IV.F. Optimum Volatility, and Impact of Volatility on Fuel Economy

The foregoing discussion indicates that there are conflicting requirements for gasoline volatility, with some performance features requiring a more volatile fuel while others demand less volatility. Consequently, the volatility characteristics of the finished fuels must be a compromise for best overall performance and fuel economy. Optimum satisfaction can be approached by distinguishing seasons and geographical areas and distributing gasolines with different volatilities. In this way the volatility of the gasoline can be consistent with the altitude and prevailing temperatures in each of these areas.*

Due to the multiplicity of factors which affect the influence of the volatility of gasoline, it is very difficult to isolate the impact of volatility on fuel economy. In previous paragraphs it has been indicated that the volatility of the fuel affects the starting, the warm-up and the normal operation of the engine. But the impact of volatility on the fuel economy is coupled to the effect of other variables. Thus, during starting and warm-up operation, the impact of volatility is affected by:

a. Atmospheric conditions (particularly temperature)
b. Choke type**
c. Carburetor design and adjustment
d. Inlet manifold design and heating**
e. Engine cooling
f. Driving pattern.

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* Gasoline volatility classes and a schedule of seasonal and geographic volatility classes are included in the "Standard Specifications for Automotive Gasoline," ASTM D439.[54]

**The rate at which an automatic choke begins to open is one of the most critical factors affecting warm-up performance. Fast-opening chokes improve fuel economy -- and CO and HC emissions -- but deteriorate vehicle driveability. However, an appropriate combination of manifold heating (which improves fuel distribution and warm-up operation) with a fast-opening automatic choke should provide the best fuel economy.

Similarly, when the powertrain system of the vehicle has reached its normal operating temperatures, the impact of volatility on fuel economy also depends on engine design and on the driving pattern.

The difficulty of isolating the specific impact of gasoline volatility on fuel economy, and also the general belief that this impact is minor compared with the impact of other variables, have resulted in a very limited investigation of this point.[29] Consequently, the availability of data regarding the impact of volatility on fuel economy is very scarce.

An indication of the change in fuel economy caused by a change in gasoline volatility can be estimated from the results given in reference 30. These results were obtained for one 1973 and three 1974 model year automobiles, having engines of 455, 258, 360, and 400 cubic inches of displacement, respectively. The fuel economy of these vehicles was measured for eight different gasolines -- using the cold start 1972 Federal Test Procedure -- and the results were correlated by a regression analysis. From the regression equation, it is estimated* that for the given test procedure and model year cars, an increase of $20^{o}F$** in the mid-range of the distillation curve -- maintaining the same fuel density -- would result in about 1% deterioriation in the fuel economy (but the statistical significance of this is unknown).

Another item associated with the volatility of gasoline is the one referring to "fuel evaporative emissions". These evaporative emissions from the fuel system of a motor vehicle depend on the front-end and mid-range volatility of the gasoline. Distinction is made between the "running", "diurnal breathing" and "hot soak" portions of these fuel evaporations. They are, respectively, the fuel evaporative emissions that occur during the operation of the vehicle, those resulting from the daily range in temperature to which the fuel system is exposed, and those that occur during the hot soak periods which begin immediately after the engine is turned off.

In motor vehicles equipped with evaporative emission controls (and in older cars with internally vented carburetors), the running evaporative emissions are fed into the intake of the engine and are not a loss. Also, the evaporative emission controls collect nearly all of the diurnal breathing and hot soak evaporations, which later are drawn in and burned by the engine when it is operated. Thus, the diurnal breathing and hot

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* As shown in IV.G.

** For comparison, in 1974 the average difference between the distillation temperatures at the 50% evaporative point of the summer and winter gasolines was about $10^{o}F$.

soak evaporations are kept from polluting the atmosphere; however, these evaporations may still result in some loss, as far as fuel saving is concerned. This loss may occur because of the difficulty in optimizing the fuel-air ratio of the intake* mixture under the transient purging of the evaporative control system.

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* There is no available data about the magnitude of this possible loss. A very rough estimate of an upper limit for this eventual loss can be determined on the assumption that: a) all the evaporative emissions are burnt, but without changing the work released by the engine, b) the average evaporative emissions are 100 g/day per car[31], c) the average car travels 10,000 miles/year, and d) the average car has a fuel economy of 16 mpg. For these assumptions, it is found that the evaporative losses could be up to 2% of the gasoline supplied to the vehicle. However, if the burning of the evaporative emissions results in a relatively significant addition of released work, the actual fuel loss should be well below 2% for the average automobile equipped with an adequate evaporative control system. Of course, any burning of evaporative emissions which yields additional released work results in a saving of fuel compared to the case of cars without evaporative emission controls.

## IV.G. An Estimate of the Impact of Gasoline Volatility on Fuel Economy

Reference 30 indicates a correlation of fuel economy with gasoline volatility and density*. The data was taken for one 1973 and three 1974 model year automobiles (having engines of 455, 258, 360, and 400 cubic inches of displacement, respectively), using the cold start 1972 Federal Test Procedure, and with eight different gasolines (having the properties shown in the attached table). The correlation yielded the following equation (with a multiple correlation coefficient of 0.952):

$$\text{mpg} = 0.142\rho^2 - 0.007\rho\,(0.093\,T_{50} + 0.029\,T_{90}) + 0.811 \qquad \text{(IV.G.1)}$$

where $\rho$ is the density of the gasoline in lb/gal, and $T_{50}$ and $T_{90}$ are the temperatures, in $^{\circ}$F, at the 50% and 90% distillation points, respectively.

The regression equation (IV.G.1) can be used to estimate the impact of changes in volatility on fuel economy. First, to simplify (noticing that the data shows, on the average, that $T_{90} \approx 1.5\,T_{50}$), we eliminate $T_{90}$ from the equation, leaving only one distillation variable. That is, we write equation (IV.G.1) as

$$\text{mpg} \approx 0.142\rho^2 - 0.007\rho\,(0.093\,T_{50} + 0.029 \times 1.5\,T_{50}) + 0.811$$

or, $$\text{mpg} \approx 0.142\rho^2 - 0.00095\rho\,T_{50} + 0.811\,. \qquad \text{(IV.G.2)}$$

Then, differentiating with respect to $T_{50}$:

$$\frac{\partial\,\text{mpg}}{\partial T_{50}} \approx -0.00095\,\rho\,. \qquad \text{(IV.G.3)}$$

Accordingly, for constant $\rho$, $\Delta\text{mpg} \approx -0.00095\,\rho\,.\,\Delta T_{50}$.

Therefore, the percentage variation in fuel economy, due to a variation in distillation temperature, is

$$\Delta\text{mpg} \times 100/\text{mpg} \approx -0.095\,\rho\,.\,\Delta T_{50}/\text{mpg}. \qquad \text{(IV.G.4)}$$

For the given data, the average $\rho$ and fuel economy were 6.38 lb/gal and 12.51 mpg. Therefore, for the given test procedure and model year cars, an increase of 20$^{\circ}$F (for example) in the mid-range of the distillation curve -- maintaining the same fuel density -- would result in

$0.095 \times 6.38 \times 20/12.51 \approx 1\%$ deterioration in the fuel economy (but the statistical significance of this is unknown).

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*The correlation does not consider the effect of gasoline viscosity. However, as shown in Section V.C, gasoline viscosity may have a significant impact on fuel economy.

TABLE IV.G.1
FUEL VOLATILITY CHARACTERISTICS

| Distillation, D86°C (°F) | Fuel No. 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Over | 43 (109) | 29 (84) | 39 (102) | 24 (76) | 37 (99) | 35 (95) | 28 (82) | 35 (95) |
| End | 180 (356) | 219 (427) | 208 (407) | 165 (329) | 180 (356) | 207 (404) | 213 (416) | 209 (409) |
| % Evap. At: | | | | | | | | |
| 10 | 57 (135) | 45 (113) | 63 (145) | 37 (98) | 63 (146) | 61 (142) | 38 (101) | 62 (143) |
| 20 | 64 (148) | 56 (132) | 71 (160) | 49 (120) | 80 (176) | 76 (169) | 48 (118) | 79 (174) |
| 30 | 72 (161) | 67 (152) | 77 (170) | 62 (143) | 94 (202) | 89 (193) | 59 (138) | 93 (200) |
| 40 | 78 (173) | 78 (172) | 81 (178) | 82 (180) | 106 (223) | 103 (217) | 81 (178) | 107 (225) |
| 50 | 87 (189) | 92 (198) | 86 (186) | 114 (237) | 114 (237) | 114 (237) | 114 (237) | 120 (248) |
| 60 | 98 (208) | 109 (228) | 90 (194) | 131 (267) | 122 (251) | 126 (259) | 132 (269) | 133 (271) |
| 70 | 111 (231) | 135 (275) | 99 (211) | 136 (277) | 128 (262) | 139 (282) | 149 (300) | 148 (298) |
| 80 | 127 (261) | 163 (325) | 122 (252) | 139 (283) | 134 (273) | 156 (312) | 164 (327) | 168 (334) |
| 90 | 145 (293) | 185 (365) | 180 (356) | 144 (292) | 143 (289) | 180 (356) | 186 (366) | 189 (372) |
| Driveability Index ($0.093\ T_{50} + 0.029\ T_{90}$) | 26.1 | 29.0 | 27.6 | 30.5 | 30.4 | 32.4 | 32.7 | 33.9 |
| Fuel Density, $kg/dm^3$ (lb/gal) | 0.73 (6.09) | 0.73 (6.06) | 0.80 (6.64) | 0.77 (6.40) | 0.79 (6.58) | 0.77 (6.39) | 0.75 (6.25) | 0.79 (6.62) |

## V. Relationship Between Fuel Characteristics, Fuel Metering, and Fuel Economy

Automotive engines are designed taking into consideration the characteristics of the gasoline that will be used. Ordinarily, the engine parameters related to the fuel are optimized during the development of the engine for the average characteristics of the gasoline that will be consumed. Consequently, the engines will have during their commercial use performances and efficiencies which will be affected somewhat by the variations of the characteristics of the gasolines used.

As explained below, one of the most important parameters affecting fuel economy is the strength of the fuel-air mixture supplied to the cylinders of the engine. Therefore, it is pertinent to investigate what fuel metering changes may occur in the carburetor as a consequence of the changes in the characteristics of gasoline. Accordingly, this section is devoted specifically to these matters.

### V.A. Impact of Fuel-Air Mixture Strength on Engine Efficiency

Theoretical and experimental work indicate that the efficiency of the gasoline engine is highly dependent on the strength of the mixture supplied to the cylinders. The efficiency of the engine increases with leaner air-fuel ratios up to the point where a too lean mixture would result in misfiring or in a combustion process which is too slow. A typical plot of fuel consumption versus mixture strength is shown in Figure V.A.1.

The leaner mixtures provide higher engine efficiencies because the excess of air decreases the temperatures of combustion. The lower temperatures have such an effect because:

a. The ratio of the specific heats of the gases, $k = c_p/c_v$, increases for decreasing temperatures. This effect is shown in the constant volume air cycle efficiency,

$$\eta = 1 - (1/r)^{k-1}*.$$

b. Dissociation of the gases decreases as the temperature decreases.

c. Heat losses decrease as the temperatures decrease.

Also, operation with leaner mixtures reduces carburetor throttling resulting in reduced pumping losses and, therefore, in increased engine efficiency.

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* This is the same equation shown before in section II.A.

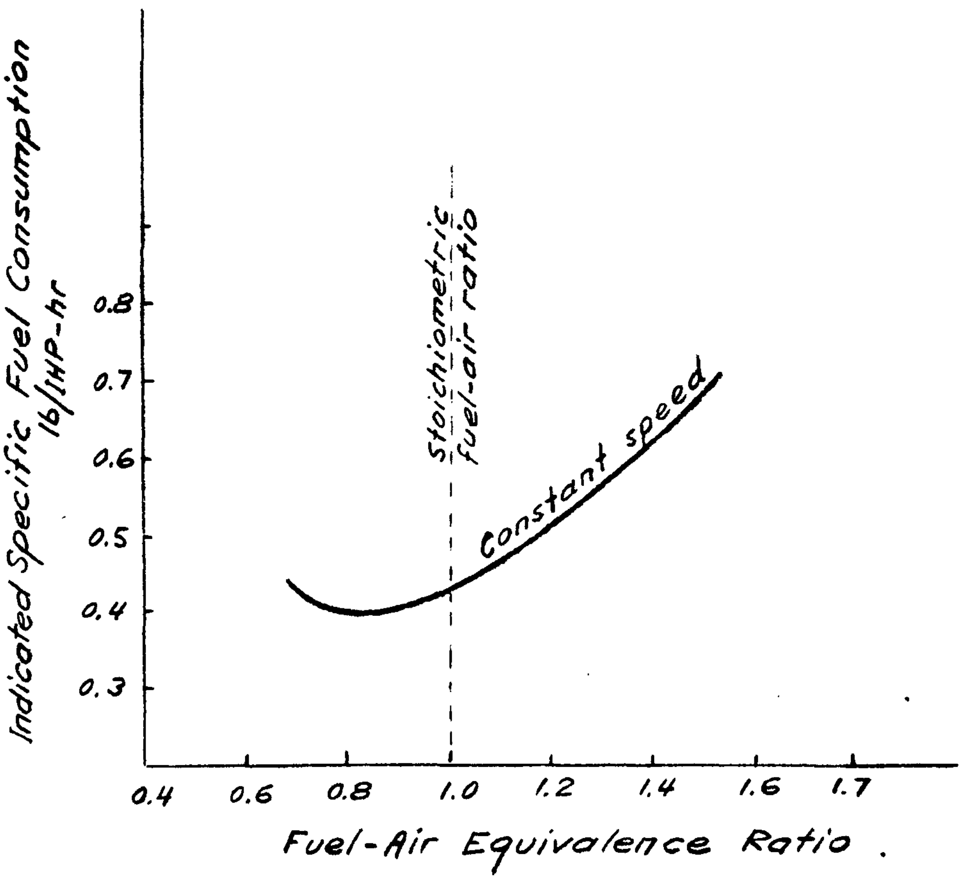


Figure V.A.1. Typical Plot of Engine Fuel Consumption vs. Mixture Strength

Gasolines have chemical and physical characteristics which affect the carburetion of the mixture supplied to the cylinders of an engine. For fuel metering requirements, the chemical properties of interest are those which determine the stoichiometric ratio of fuel to air. The physical properties which can directly influence the metering process are density, viscosity, volatility, and surface tension.

The stoichiometric ratio of a fuel-air mixture is determined by the H/C atom ratio of the fuel, i.e., by the hydrocarbon composition of the fuel. Of importance are the relative amounts of the paraffin, olefin, and aromatic series, as well as the percentages of each hydrocarbon compound in a given series. Thus, different gasolines may have different stoichiometric fuel-air ratios. Consequently, since there is no one unique stoichiometric fuel-air ratio for gasolines, and since engine efficiency -- and exhaust emissions --depend on the strength of the fuel-air charge, the significant factor is the fuel-air equivalence ratio*, $\phi$, rather than the fuel-air ratio itself.

## V.B. Impact of Changes in Fuel Density on Fuel Metering

Theoretical analyses indicate that the fuel-air ratio of the mixtures supplied by the conventional carburetors increases with fuel density**. This is confirmed by experimental results. However, it is important to note that in general the stoichiometric fuel-air ratio of gasoline also increases with fuel density. Thus, the net effect on the fuel-air equivalence ratio changes caused by variations in fuel density is usually negligible or small. Accordingly, the effect of these density variations on fuel economy -- due to their impact on fuel metering -- should also be negligible or small***.

Some data regarding the effect of fuel density on the fuel metering of carburetors is presented in the following Figures V.B.1 and V.B.2.

Figure V.B.1 (from reference 33) shows the results of flow-stand tests for two different carburetors. It is seen that for the given Carter carburetor, the fuel-air ratio increased approximately from 0.069 to 0.076 (i.e., about 10%) when the specific gravity of the fuel changed from 0.69 (80 ON primary reference fuel) to 0.86 (toluene). However, the corresponding fuel-air equivalence ratios were 1.04 and 1.03 respectively. Similarly, for the same change in fuel density with the Holley carburetor the fuel-air ratio changed approximately from 0.074 to 0.082 (i.e., about 10%), and the fuel-air equivalence ratio changed from 1.13 to 1.10. These results indicate, in fact, that the stoichiometric change associated with the increase in density overcompensated, slightly, the associated increase in fuel-air ratio.

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* The definition of $\phi$ was presented earlier in section I.

** See reference 32, p. 423-428 for example.

*** As indicated before in section III, the changes in gasoline density may have a significant impact on fuel economy, but this is not due to fuel metering effects.

| Fuel | Specific Gravity, °API | Viscosity, Centistokes |
|---|---|---|
| 80 O.N. Primary Reference Fuel | 71.9 | 0.690 |
| Insensitive Straightrun | 66.3 | 0.749 |
| SR-10 | 64.5 | 0.739 |
| Michigan Reformed | 63.6 | 0.609 |
| Dynafuel | 61.3 | 0.601 |
| RE-9A | 57.3 | 0.618 |
| Cat. Cracked | 55.4 | 0.643 |
| Balanced Fuel | 54.3 | 0.760 |
| 50% Toluene + 50% 80 O.N. PRF | 49.7 | 0.633 |
| Toluene | 31.6 | 0.679 |

Carburetors

1. 1948 Carter 664S

   Dual throat, downdraft, $1\frac{1}{4}$" throat, metering rod jet. Accelerating pump jet plugged during test.

2. 1949 Holley AA-1

   Dual throat, downdraft, 1-1/16" throat, fixed jet.

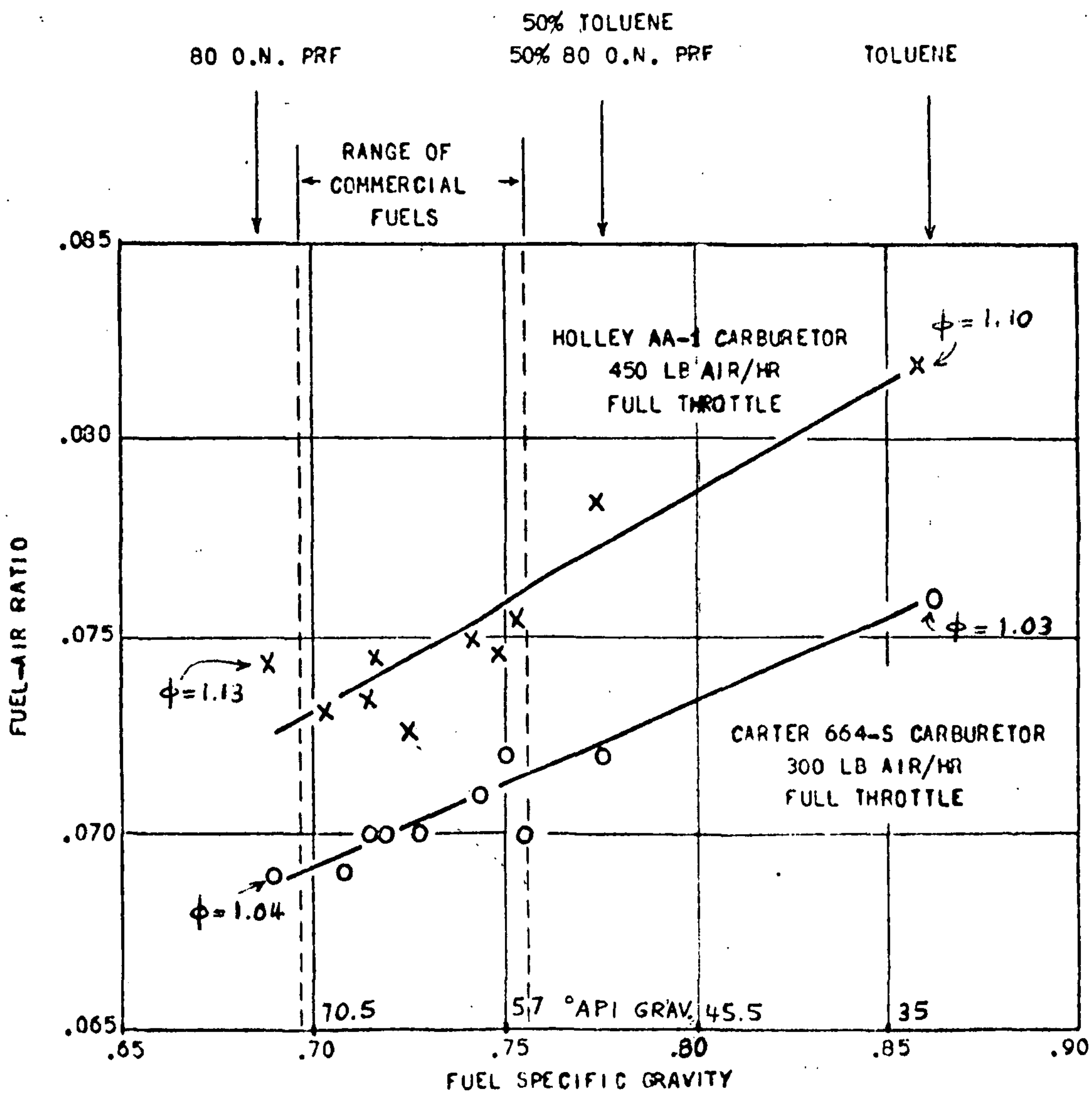


Figure V.B.1. Impact of Fuel Density on Fuel Metering. Flow Stand Tests

| Fuel | Viscosity D445, cs, 77°F | API Gravity | Distillation, D86, °F 10% | 50% | 90% | Carbon Percent |
|---|---|---|---|---|---|---|
| 1 | .65 | 53.6 | 151 | 227 | 302 | 87.30 |
| 2 | .68 | 60.4 | 146 | 224 | 319 | 86.00 |
| 3 | .65 | 69.7 | 153 | 223 | 266 | 84.26 |

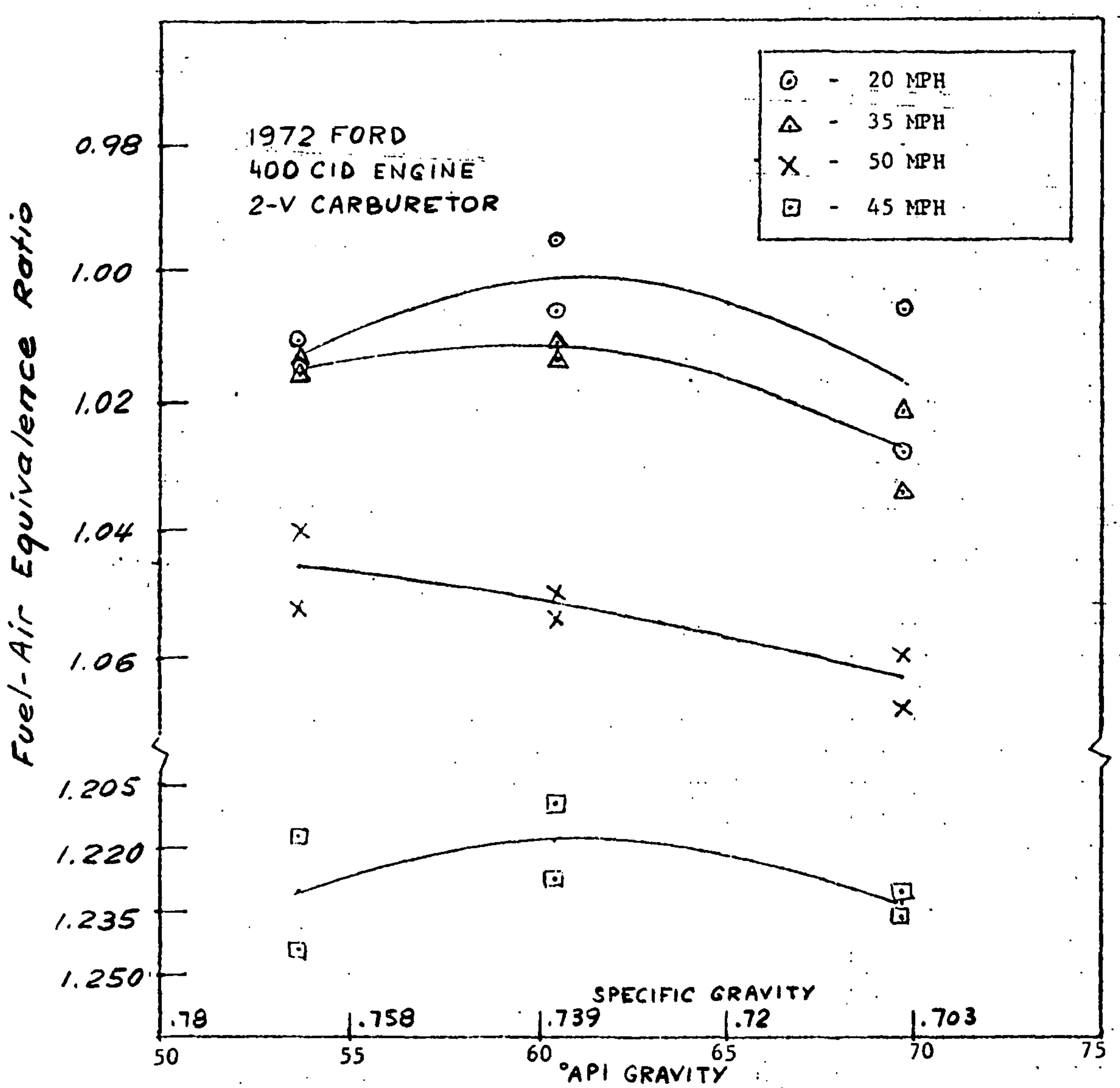


Figure V.B.2. Impact of Fuel Density on Fuel Metering. Chassis Dynamometer Test

Figure V.B.2 (from reference 30) shows the results for a carburetor installed in a car. The tests were conducted on a chassis dynamometer at constant ambient temperature. Three different gasolines having substantially different densities but similar viscosities and volatilities were used. The changes in fuel density changed the fuel-air ratios significantly but, again, on an equivalence ratio basis the corresponding changes in stoichiometry served to compensate for the changes in fuel-air ratio. Varying the specific gravity of the gasoline over the range from 0.70 to 0.76 resulted in a relatively small effect on the fuel-air equivalence ratios.

## V.C. Impact of Variations in Fuel Viscosity

Variations in the viscosity of gasoline affect the metering of the fuel by changing the Reynolds number of the fuel flow. This change in $R_e$ generally results in variations in the coefficients of discharge of the fuel orifices. However, the fuel-air ratio changes resulting from variations in fuel viscosity depend on the particular channel geometry and operating points of the carburetor. Accordingly, different carburetors can be affected differently by the changes in fuel viscosity.

The data regarding the effects of viscosity change on fuel metering is scarce and inconclusive. During the carburetor flow-stand tests quoted above in section V.B., from reference 33, the kinematic viscosity of the fuel ranged from 0.60 to 0.76 centistokes, but no apparent effect on carburetion was found. On the other hand, the results from reference 30 indicate a definite effect of the variations in viscosity although the impact changed with the operating mode of the carburetor. The fuel-air equivalence ratios decreased with increasing viscosity, which is consistent with the reasoning that increased viscosity should decrease fuel flow.

These results from reference 30 were obtained by isolating the effects of viscosity (from the effects of density and volatility) by proper fuel design and careful testing -- which included dynamometer operation at a constant temperature of 75°F.* The results are plotted in Figure V.C.1 . The maximum variation in the fuel-air equivalence ratios for these tests -- which covered a range from 0.56 to 0.69 centistokes** -- was about 3.5%. Thus, these particular results indicate that viscosity variations may cause significant changes in fuel economy*** However, these results cannot be considered typical since only one car with only one type of carburetor was used for the tests. Furthermore, all carburetors do not respond to fuel property changes in the same manner, even at the same operating point.

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*Gasoline viscosity undergoes large changes with temperature variance; therefore, the impact of viscosity variations must be determined under controlled temperature.

**For comparison, some measurements of the viscosity of commercial gasolines have shown differences of 0.17 cs at 0°F, and 0.06 cs at 100°F.[34]

***In a first approximation, for rich fuel-air mixtures, the percentage variation in fuel economy can be taken as roughly equal -- although opposite in direction -- to the percentage variation in fuel-air equivalence ratio.

| Fuel | Viscosity D445, cs, 77°F | API Gravity | Distillation, D86, °F 10% | 50% | 90% | Carbon Percent |
|---|---|---|---|---|---|---|
| 1 | .56 | 61.3 | 129 | 221 | 323 | 85.96 |
| 2 | .60 | 61.3 | 130 | 221 | 319 | 85.96 |
| 3 | .64 | 61.0 | 129 | 221 | 318 | 86.06 |
| 4 | .69 | 60.9 | 125 | 219 | 319 | 86.02 |

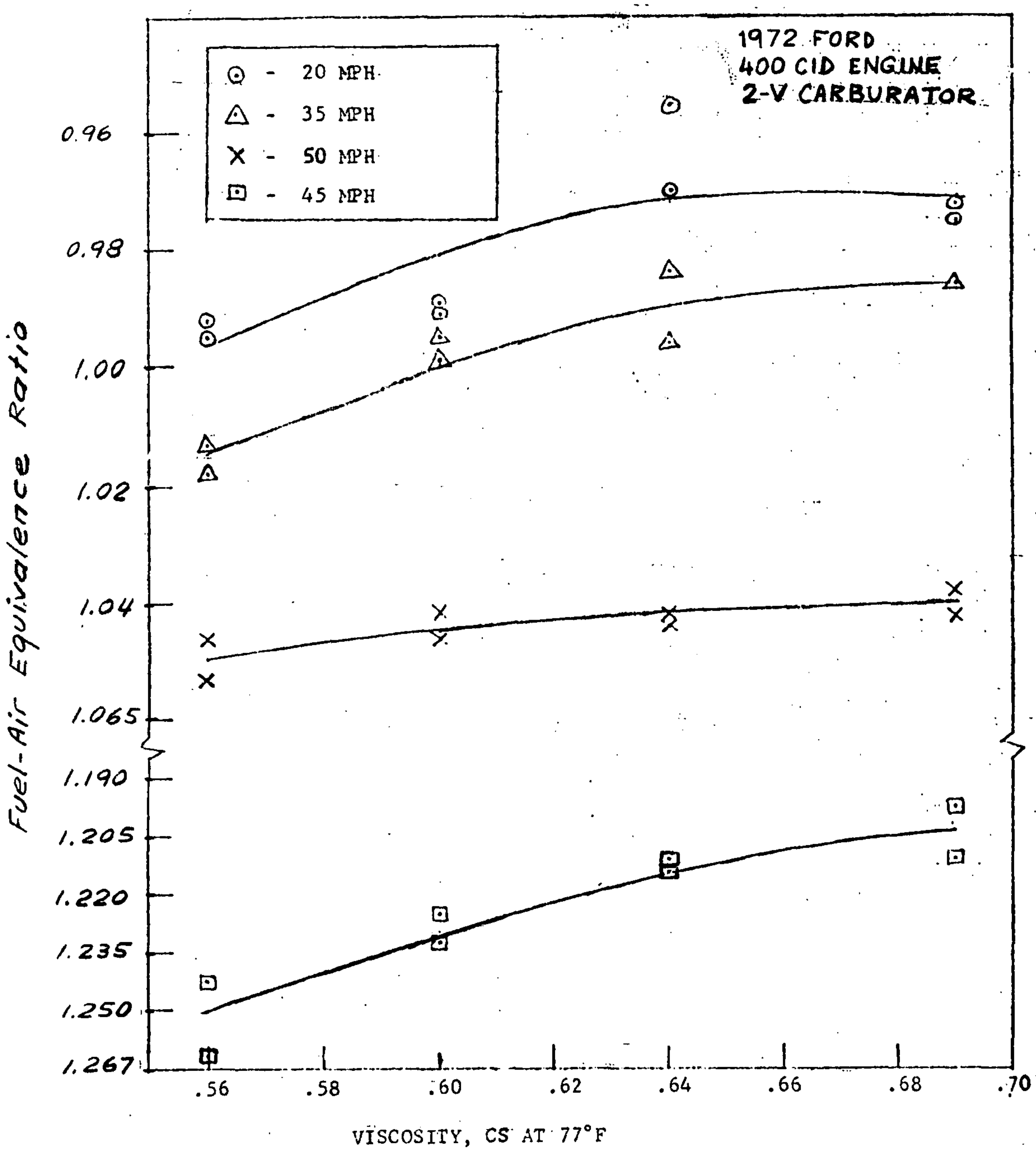


Figure V.C.1. Impact of Fuel Viscosity on Fuel Metering. Chassis Dynamometer Tests

## V.D. Impact of Variations in Fuel Volatility and Surface Tension on Fuel Metering

The volatility of the gasoline may have a noticeable effect on fuel metering. The higher the volatility, the higher the amount of fuel vaporized in the fuel passages of the carburetor. This tends to decrease the fuel-air ratio delivered by the carburetor. On the other hand, an increase in fuel volatility increases float bowl evaporation, and this evaporation vented into the intake system tends to increase the fuel-air ratio. Therefore, the overall effect of changes in fuel volatility on fuel metering depends on the carburetor design, carburetor temperature, and carburetor operating point.

As was indicated in section IV.F above, there is very little data referring to the impact of gasoline volatility on fuel economy. In particular, there is no data available regarding the impact on fuel economy that is due exclusively to the changes in fuel metering caused by variations in fuel volatility.

The surface tension of the gasoline affects fuel metering because of its effects on orifice flow. The venturi suction required at the discharge nozzles depends on the surface tension of the fuel. A primary metering effect of surface tension is its influence on determining at what air flow the main system fuel-flow is initiated. Likewise, the minimum pressure differential necessary to initiate flow in the air bleeding channels is also dependent on the surface tension of the fuel. However, there is no available information regarding the impact that the changes in surface tension may have on fuel metering and fuel economy. There is a general belief that the impact of fuel surface tension on fuel economy is minimal, and, apparently, no specific efforts have been devoted to measure this impact.

## VI. Gasoline Cleanness and Additives

Cleanness as applied to gasoline refers to foreign material which gets into the fuel as well as to the original impurities in the fuel, and to the fuel's tendencies to promote deposit formation in engines. Cleanness is an important property of gasoline because foreign material and fuel deposits alter engine parameters and adjustments and result in poor engine performance, lower fuel economy, and higher emission of air pollutants.

The following paragraphs point out important factors in gasoline cleanness and indicate those additives which are usually added to gasoline for preserving its cleanness or to inhibit undesirable performances.

Foreign particulate matter. Substances such as rust, sand, and fibers must be excluded from gasoline insofar as possible. These materials interfere with proper operation of fuel pumps and carburetors and will plug gasoline filters.

Liquid impurities. Contamination with liquids such as diesel fuels and water must also be avoided. Diesel fuel lowers the anti-knock quality of gasoline, and it also increases crankcase dilution due to its high boiling point. Water promotes deterioration of the fuel system and can cause filter clogging.

Anti-rust additives. To prevent the rusting that might be caused by traces of water in the gasoline--and also the corrosion arising from contact with air--anti-rust agents are added to the gasoline (such as fatty-acid amines, in amounts ranging from 1 to 15 lb/1,000 bbl).

Sulfur. Sulfur or sulfur compounds in the gasoline are objectionable for various reasons. In some forms, mainly free sulfur and hydrogen sulfide, it is corrosive and can attack fuel lines, carburetors, and injection pumps. In all forms, the sulfur will unite with oxygen to form sulfur dioxide, which in the presence of water may form sulfurous acid. Also, the anti-knock effect of the lead alkyl compounds added to gasolines is reduced by the presence of sulfur.[46,47] Presently, sulfur contents of less than 0.1 percent, by weight, are specified for most gasolines.

The sulfur emissions emitted by motor vehicles also have an impact on air quality. In particular, concern has been voiced regarding the increase in sulfur emissions (mainly sulfur trioxide, sulfuric acid, and sulfates) from automobiles equipped with catalyst systems for controlling carbon monoxide and unburned hydrocarbons. In the presence of a catalyst, the sulfur dioxide oxidizes into sulfur trioxide which is a corrosive gas and which combines vigorously with water to form sulfuric acid. Work is currently underway to improve the techniques for measuring sulfur emissions and to determine the actual impact of these emissions from catalyst-equipped cars on air quality.

Anti-knock additives. Currently, most commercial gasolines contain lead alkyl compounds. A general account of anti-knock additives has been included in Section II.F.

Lead, phosphorus. The introduction of catalyst-equipped automobiles with the 1975 model year resulted in the promulgation of regulations which require the availability of a grade of gasoline with not more than 0.05 g of lead per gallon and 0.005 g of phosphorus per gallon. This fuel is required because catalysts have been shown to be poisoned by both lead and phosphorus.[58] Further, in late 1973, the EPA promulgated regulations requiring the gradual phase-down of lead levels in the remaining gasoline grades. These regulations to phase-down lead were based on the Agency's concern regarding the public health consequences of lead contained in the exhaust gases from motor vehicles. These regulations were overturned by the courts, but the U.S. Court of Appeals has ruled that the EPA has the authority to regulate the use of lead in gasoline. The U.S. Supreme Court has declined to review the ruling, and the EPA has resumed enforcement of the regulations. However, to ensure that refiners have sufficient lead time to modify the manufacturing process of the gasoline without resulting in any gasoline shortage, the EPA has amended the schedule of the regulations. The definitive regulations limit the average content of lead in motor gasoline to 0.8 g/gallon, effective January 1, 1978*, and to 0.5 g/gallon, effective October 1, 1979.[59]

"Gum". Unsaturated hydrocarbons and impurities in the fuel have a tendency to oxidize and polymerize, resulting in viscous liquids and solids which are described as "gum." Gum formation appears to be due to some reaction initiated by the formation of peroxides and catalyzed by the presence of metals, particularly copper, which may have been picked up during refining and handling operations. The pure stable hydrocarbons of the paraffin, naphthene, and aromatic families form little gum, while cracked gasolines have the highest tendency to form gum. A gasoline with high gum content will cause operating difficulties, such as sticking valves and piston rings, gum deposits in the inlet manifold, clogging of carburetor jets, and lacquering of the valve stems, cylinders, and pistons.

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*"Suspension of the 0.8 g/gallon standard is conditioned on a showing by a refiner that he has prior to that time taken and is continuing to take sufficient actions in procuring and installing equipment or arranging process and exchange agreements, or both, to insure compliance with the 0.8 g/gallon standard at the earliest practical date, and 0.5 g/gallon no later than October 1, 1979".[59]

Freshly manufactured gasoline normally has an insignificant gum content but upon aging varying amounts of gum may be formed. In storage gasoline will increase its gum with increased concentrations of oxygen, with a rise in temperature, with exposure to sunlight, and also on contact with metals. Thus, distinction must be made between the actual or preformed gum existing in the gasoline at a particular time and the potential gum that may be present at some future time. The actual gum content is no guarantee of the stability of the gasoline against future gum formation.

Anti-oxidant and Metal Deactivator additives. To ensure storage stability, anti-oxidant additives known as "inhibitors" are commonly added to the gasoline (such as phenols or amine compounds, in amounts ranging from 1 to 15 lb/1,000 bbl.). Such inhibitors react with the chain carrying free radicals that propagate the auto-oxidation of gasoline.[45] Other types of additives used to ensure stability are "metal deactivators" (amine derivatives, in amounts of up to 1 lb/1,000 bbl) which destroy the catalytic activity of traces of copper.

Detergents. Deposits in the induction system of the engine may come from air-borne contaminants, preformed gum in the gasoline, and gum formed in the induction system. Incomplete combustion products and crankcase vapors have been found to be major contributors to these deposits. Positive crankcase ventilation and exhaust gas recirculation increase their formation. Some deposits form in throttle bodies when the incoming flow strikes the throttle and impacts against the throttle walls. These deposits restrict the flow of air past the throttle plate in the idle position and through the idle air bleed and vacuum advance ports, causing rough idling and stalling. The fuel-air ratio of the mixture supplied to the cylinders is altered by the carburetor deposits, and this alteration may significantly affect fuel economy and emissions. Many gasolines now contain detergent additives to prevent the formation of these deposits in the induction system and to remove existing deposits. Alkyl amines and their derivatives are used in amounts ranging from 5 to 40 lb/1,000 bbl. The so called "deposit control" type of detergents (polybutene amines) are used in amounts of up to 100 lb/1,000 bbl.

"Deposit Modifier" additives. As compression ratios increase beyond about 10, engine performance tends to become limited by surface ignition. The higher compression ratios raise the peak temperature in the combustion chamber and cause combustion chamber deposits to glow leading to premature ignition. The presence of lead compounds in the carbonaceous deposits caused by incomplete scavenging of lead alkyl anti-knocks increases the tendency toward surface ignition. The "deposit modifiers" were introduced to reduce surface ignition. These additives -- generally phosphate esters -- act by modifying the deposits to decrease their glowing temperature and oxidation rate so that their heat release rate is smaller. Also, lead phosphates are less electrically conductive than other lead salts. Hence, by increasing the electric resistance of the deposits the use of additives containing phosphorus decreases spark plug fouling and, thereby, misfiring. The use of "deposit modifiers," however, has been declining and has now been essentially discontinued in light of the reduction of compression ratios in recent model year vehicles. Unleaded fuels, of course, do not contain these additives.

Gasoline composition, additives, and the ORI. As has been indicated in section II.D, the octane requirement increase (ORI) is one of the important determinants of the octane requirements of motor vehicles. The deposits which cause the ORI depend, among other things, on the physical and chemical natures of the gasoline and the lubricant of the engine, and on the additives in the gasoline and in the lubricant. However, the mechanisms which produce the ORI are not well understood. Also, the available information regarding the magnitude of the ORI is not conclusive. Therefore, more data is needed. This must include the effects on ORI of the composition of the gasolines, the lubricants, and the additives in both fuels and lubricants.

Anti-icing additives. "Surface-active" additives (such as ammonia salts) are added to prevent ice from adhering to the throttle of the carburetor. The surface-active additives work by forming a film on the metal which discourages adhesion of ice. "Freezing point depressants" (alcohols or other compounds with a large affinity for water) are used to lower the freezing point of any water present in the gasoline to such a degree that no ice formation can occur.

Color dyes. These are added to identify different grades of gasoline. They do not, however, affect gasoline quality.

## VII. Gasoline Injection versus Carburetion

The information and discussion that have been presented in this paper apply specifically to gasoline and automotive engines in the case where the engines are equipped with carburetors -- the most common, by far. However, the number of motor vehicles using gasoline-injection systems is increasing.

This section indicates the principal types of gasoline-injection systems. It also discusses, summarily, the most significant changes in engine performance resulting from the use of gasoline injection instead of carburetion, and the possible impact on the characteristics of gasoline.

### VII.A. Classification of Gasoline Injection Systems

The gasoline-injection systems for motor vehicles can be classified in three basic categories:[5,35,36]

a. Direct Cylinder Injection
b. Port Injection
c. Injection Carburetor.

As its name indicates, in the direct cylinder-injection systems the gasoline is injected directly into the cylinders during the inlet or compression strokes in a similar fashion as in the Diesel engine. Because of its higher complexity and cost this injection system is very uncommon in motor vehicles. The Mercedes-Benz, Model 300 SL, has been one of the few automobiles equipped with such a system. In stratified charge engines, however, direct injection is common; examples are the Ford PROCO[37] and Texaco TCCS[38].

In the port-injection system, the gasoline is injected by nozzles located at the inlet ports and aimed toward the inlet valves. The injection can be continuous (as in the Bosch continuous injection system[36]) or timed (as in the Bosch electronic system[40]).

The basic difference between the injection carburetor (also called pressure carburetor) and the conventional carburetor is that the pressure difference across the venturi, while providing the metering function, is not used directly to cause fuel flow. Instead, the fuel is supplied under pressure by means of a power-driven pump to one or several nozzles located somewhere downstream from the throttle. Injection carburetors were developed for aircraft engines and for engines which must operate in all positions, but the basic principle can be applied to motor vehicle engines, with the possibility of injecting the fuel at each intake port.

## VII.B. Pros and Cons of Gasoline Injection

In general, a well developed fuel-injection engine would have the following advantages when compared with the engine equipped with the conventional carburetor system:

1. Easier starting due to improved fuel distribution, and because atomization of the gasoline for fuel injection is practically independent of cranking speed.

2. Decreased volatility requirements for the gasoline, since fuel distribution is independent of vaporization. Also, engine warm-up may be faster and allow leaner fuel-air mixtures.

3. Some decrease in octane number requirements since heat is not necessary to assist fuel distribution. Also, some decrease in octane number requirements because of the equal distribution of gasoline components -- and related combustion chamber deposits -- among all the cylinders. (Relaxation in octane number requirements can also be obtained when the charge is stratified).

4. Decreased fuel-air ratio variations arising from changes in position or motion, since fuel-air ratio is not dependent on float level.

5. Better vehicle driveability. In particular, faster throttle response since the gasoline is injected into, or close to, the cylinders and need not flow through the inlet manifold.

6. Increased torque and power because of increase in volumetric efficiency arising from

   a. Large inlet manifolds with small pressure losses.

   b. Elimination of carburetor pressure loss (except that a venturi pressure loss remains if a venturi if used for metering purposes).

   c. Elimination of manifold heating.

7. In general, less emissions because of reduced fuel-air ratio variations among the cylinders. Also, there is a potential for less HC emissions on deceleration, by cutting off fuel injection, and less HC and CO on acceleration by eliminating the acceleration pump (since manifold wetting is eliminated or minimized, and fuel response is faster).

8. Lower height of engine -- and hood -- since position of the injection unit is not critical.

On the other hand, gasoline injection systems have the following disadvantages:

1. Increased complexity and cost.

2. Difficulty of metering equally in all the individual cylinders the small amount of fuel required for idle and road load, due to injector tolerances and repeatability. Furthermore, deposit build-up on the fuel nozzles as mileage increases may seriously upset the fuel delivery balance between cylinders, leading to lower fuel economy, poor driveability, and higher emissions. This, and the increased complexity of the systems, results in increased maintenance requirements.

3. Engine deposits, spark-plug fouling, and crankcase dilution may be increased if the injected fuel is not atomized properly.

4. Injection systems may be more sensitive to vapor lock problems. Therefore, they must be carefully designed for vapor handling capability.

Engines with good carburetors and manifold systems can provide better performance than with* fuel injection systems improperly designed or matched with the engines. Therefore, the need for developmental work, and the higher complexity, cost, and maintenance have limited the use of gasoline injection. However, the number of motor vehicles equipped with gasoline injection systems is increasing, and more general use of these systems is expected in the future.

From the viewpoint of conservation of fuel, it appears that the general use of properly designed gasoline injection engines would be beneficial.[42] This follows from the greater tolerance of gasoline injection engines for gasoline volatility -- which would permit a higher yield of gasoline from crude oil -- and from the potential of these engines for better utilization of fuel octane numbers (especially with sensitive gasolines). In practice, however, the realization of this improvement in the conservation of fuel would be extremely difficult. This is due to the very complex and extensive developmental work that would be required to equip all motor vehicles with satisfactory gasoline-injection engines for gasoline of wider volatility limits; and also because the fuel requirements of the existing carbureted engines still would have to be satisfied. Nevertheless, the potential for improved fuel conservation associated with gasoline injection exists, and should not be overlooked.

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* Also, additional refinements and unconventional carburetion principles -- such as the use of variable throat and supersonic flow effects introduced in the Dresser carburetor -- could improve carburetors further.[41]