PB-201 410

EMISSION REDUCTION USING GASEOUS FUELS FOR VEHICULAR PROPULSION

Institute of Gas Technology
Chicago, Illinois

June 1971

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PB 201 410

INSTITUTE OF GAS TECHNOLOGY

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INSTITUTE OF GAS TECHNOLOGY
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EMISSION REDUCTION USING GASEOUS FUELS FOR VEHICULAR PROPULSION

Final Report
on
Contract No. 70-69
for

AIR POLLUTION CONTROL OFFICE
ENVIRONMENTAL PROTECTION AGENCY
Cincinnati, Ohio 45227

June 1971

SUMMARY

This study was undertaken to accomplish four objectives:

1. To provide a comprehensive assessment of the state-of-the-art and the potential for reducing vehicular pollution emissions by using gaseous fuels in commercially available engine systems.

2. To examine the logistics of gaseous fuels to assess the availability, cost, storage, and handling methods and safety requirements of gaseous fuels.

3. To determine the feasibility of using natural gas as a supplementary fuel in a two stroke cycle, diesel powered intercity bus as a means of reducing exhaust pollution while operating in urban areas and bus terminals.

4. To recommend specific research and development programs necessary to confirm or establish the low emission characteristics and economic feasibility of selected gaseous fueled vehicular engine systems.

The findings of the study as they relate to each objective are summarized below.

1. Reduction of Vehicular Pollution Emissions

The greatest benefit from conversion to gaseous fuels may be realized in the immediate future while pollution control devices are being perfected for use on gasoline-powered vehicles.

Four fuels were examined that can be injected into an internal combustion engine in gaseous form. These were propane, natural gas, ammonia, and hydrogen. Both ammonia and hydrogen have serious deficiencies from the point of view of harmful emissions as well as price and availability and cannot be recommended for motor fuel use.

Propane and natural gas have similar characteristics as far as emission reductions are concerned, particularly if no distinction is made between the reactivity of various hydrocarbons in producing photochemical smog. The use of either of them in a conventional gasoline engine will require the addition of pollution control devices in the exhaust system as well as adjustments in the engine itself in order to meet 1980 Federal Emissions Standards.

When the required ancillary equipment is added and engine adjustments are made, the levels of emissions from propane and natural gas engines are not greatly different than from a gasoline engine using the same equipment. The emissions of NO_x are reduced somewhat more in the case of the gaseous fuels.

2. Logistics Considerations

The rapidly increasing demand for clean fuels for stationary applications which has been created by air pollution control regulations, is beginning to tax the ability of the natural gas industry to supply both propane and natural gas.

The amount of energy consumed as motor fuel in the United States is about 80% of the amount of energy distributed by the natural gas industry. Thus, there is no hope of converting all or most of the automotive vechicle population to natural gas fuel since this would require the production of natural gas to be almost doubled — at a time when the industry is straining to maintain its normal growth of 6% per year.

For similar reasons, we cannot consider the complete conversion of motor vehicles to propane, for the entire propane industry is one tenth the size of the gasoline industry, and its principal source of supply is tied to natural gas production.

Since both ammonia and hydrogen are currently made in large measure from natural gas, they do not offer acceptable alternatives and their current prices do not permit them to serve as supplementary fuels if they must compete on a price basis. They have other technical limitations as well.

However, some natural gas and propane can be made available for use in the immediate future. The study shows that the diversion of natural gas from boiler fuel uses, such as electric generation, to motor fuel use results in a net reduction of harmful pollutants — at least in New York City. Diverting one half of the natural gas presently used for generating electricity in New York would furnish enough fuel to operate all of the commercial fleet vehicles in the city on natural gas.

Of the two forms of natural gas — liquid and gas, compressed natural gas is more readily available and currently more popular. Imported LNG from overseas may become quite attractive, however, because of its projected prices and the longer vehicle range that it provides.

At the same time, the production of lead-free gasoline results in an increase in the yield of propane from refineries. This could provide an additional source of propane for vehicle use although the amount to be expected from this source is difficult to determine at present because the conversion to lead-free gasoline is just beginning.

Nevertheless, we believe that sufficient supplies of natural gas and propane can be made available to fuel all of the vehicles that are likely to be converted to gaseous fuels in critical pollution areas before 1975 — barring some legislative edict that would require their use.

The handling and safety problems of both propane and natural gas are well known since these fuels have been used in motor vehicles for many years either in this country or in Europe. They are necessarily highly volatile, flammable fuels comparable to gasoline. While some individual characteristics serve to favor one fuel or the other, both have established acceptable safety records and should not be disqualified on this basis.

3. Conversion of Two-Stroke Diesel Engine

The methods currently available for converting the 6V-71N and 8V-71N diesel engines to the part-time use of natural gas cannot be recommended in view of their ineffectiveness in improving exhaust emission control and their high costs of conversion and inconvenience of operation. Except for some reduction in odor, none of the conversions promise reduction in regulated pollutants below those now reported for the engines when properly equipped with available pollution control devices offered by the manufactuer.

4. Recommendations

The findings and conclusions of the study indicate that further development of the use of natural gas and LP gas as motor fuel is justified wherever logistical and economic considerations permit their use. A number of specific recommendations are made and these are summarized below in order of their importance.

Further information is needed on the reactivity of various types of hydrocarbon emissions from engines in order to clarify the extent to which various gas engine emissions are harmful.

It is recommended that an optimized design of an IC engine to use gaseous fuels be built and tested to demonstrate the performance attainable as well as the emissions produced by such an engine.

Additional research and development is needed to better determine the effectiveness of exhaust catalytic reactors and afterburners in handling the lower concentration of pollutants from natural gas and LPG engines.

Further research is needed on the automatic duel-fuel concept in order to determine how to obtain the maximum number of clean vehicle miles with a minimum amount of gaseous fuels.

A need exists for odorants that can be used in LNG in the same manner as in natural gas.

It is recommended that more experimental work be done in measuring the pollution level from gas vehicles as a function of engine characteristics and modifications.

It is recommended that a controlled test program be undertaken to document the history of a fleet of gas-fueled vehicles as far as emissions, fuel costs, maintenance expense, and other significant items over an extended period of operation.

It is recommended that a survey be made of European experience in gas-fueled vehicles, particularly in France and Italy.

It is recommended that additional urban areas besides New York City be examined to determine the potential of gaseous fuels to reduce overall pollution levels in other local urban areas.

There is a need to examine in more detail the possibility and potential price of liquefied petroleum gas imported into the United States from overseas.

It is recommended that further studies be made of the feasibility of increasing the yield of propane from oil refineries at the expense of gasoline production and the resultant effects upon cost of both fuels and upon their distribution expense.

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1. INTRODUCTION

The exhaust emissions from automotive vehicles comprise the greatest single source of air pollution in our urban atmosphere. The growing concern for the quality of our environment has caused a great deal of effort to be expended in finding ways to reduce the harmful emissions from automotive exhausts. In general, there are five methods to reduce these emissions from automobile exhausts. They are —

1 Remove the pollutants from the engine exhaust stream
2. Modify the engine so that pollutants are not formed
3. Use a new kind of engine that inherently has a cleaner exhaust
4. Change the fuel in some ways so that formation of pollutants will be minimized
5. Use a completely new fuel that produces less harmful emissions

Most of the effort to date has been expended in modifying the existing internal combustion engine system or in developing new engines such as the gas turbine, steam engine, or other external combustion engines.

This report is concerned with the fifth method listed. It is specifically limited to those fuels that are gaseous in form when introduced into the engine, although they may be handled and stored in liquid form prior to injection.

Of the five methods listed only the first four have been thoroughly examined to date. None of these first four methods has produced a completely acceptable solution to the problem although there is a possibility that a combination of 1, 2, and 4 may produce an acceptable solution to the overall problem by the year 1975 or 1976. In the meantime, the lack of an acceptable solution has led many people to investigate the use of certain gaseous fuels that have inherently cleaner burning characteristics than gasoline. These fuels include natural gas, liquefied petroleum gas (LPG), ammonia, and hydrogen. Natural gas and LPG are, of course, the most practical ones. Ammonia and hydrogen have been included in order to complete an objective analysis of all the possible contenders. These particular gaseous fuels were selected because their combustion chemistry is relatively simple and they are less likely to produce the heavy hydrocarbons and the partially completed reactions that cause so much of the problem with conventional gasoline. There were a number of reservations about including ammonia,but it was decided to include it in order to document the information that is available on this relatively unknown fuel.

LPG has been used as an automotive fuel for many years. The number of LPG vehicles estimated to be in operation total approximately 300, 000. While this represents a very small portion of the automotive population, it does mean that the technical and economic problems associated with its use in competition with gasoline fueled vehicles have in some measure been resolved. However, its use has been dictated by considerations other than air pollution control and it is necessary to examine the emissions from LPG-fueled engines and the logistics of LPG supply to assess its potential as a means of air pollution abatement.

Although natural gas has not been used extensively in the United States as an automotive fuel, it has an extensive history of operation in Italy and France dating back to World War I. Recently the Pacific Lighting Corporation, a gas utility serving the Los Angeles area, made a number of experimental installations of compressed natural gas fuel systems in conventional automobiles in order to demonstrate their practical value in reducing automotive pollution levels in the Los Angeles area. At about the same time the San Diego Gas & Electric Company made several experimental installations of fuel systems using natural gas in liquid form (LNG). These experimental installations created considerable interest in gas fueled vehicles both in California and elsewhere. There are currently more than 2000 natural-gas-fueled vehicles in experimental operations throughout the country. Most of these vehicles use compressed natural gas and many of them are operating in California. Thus far, they are almost entirely experimental operations.

One might dismiss gas-fueled vehicles from consideration as a means of relieving our air pollution problem simply because of the tremendous logistic problem that exists in converting our automotive population from gasoline to either or both natural gas and LPG. Such large-scale conversion is impractical not only from the point of view of its impact on the automotive industry, but also because of its effects upon the natural gas industry as well. However, much of our air pollution problem is centered around our large urban areas where fleets of commercial vehicles comprise a greater portion of the pollution problem than in the general case. We believed, therefore, that consideration can and should be given to the use of gaseous fuels for many fleet vehicle operations as a means of alleviating the pollution problem in our major cities.

At about the same time that this study was proposed to the Air Pollution Control Office (APCO), the Institute of Gas Technology had also presented a proposal to the Greyhound Bus Company to study the feasibility of using gaseous fuels in intercity buses during the period of time that they were operating in urban areas and enclosed bus terminals. As a result of conversations among all of the parties involved, we agreed to include that study as Task IV of the subject study. The work was, therefore, carried out in the course of the study and reported in Section 8 of this report.

2 VEHICULAR POLLUTION CHARACTERISTICS OF GASEOUS FUELS

Gaseous fuels by nature of their lower molecular weights and lesser amounts of carbon tend to produce fewer of the heavy hydrocarbons that contribute to the formation of photochemical smog. In addition, the combustion of these lighter hydrocarbon fuels within the engine cylinder can proceed more quickly because no evaporation of liquid droplets is required before the fuel is brought to the ignition temperature. Thus, the combustion process can proceed more nearly to completion during the brief power stroke of the cycle carrying less unburned fuel into the exhaust.

Some gaseous fuels such as ammonia and hydrogen contain no carbon at all and therefore cannot produce the ingredients necessary to form photochemical smog. Unfortunately, they have other drawbacks that detract from their use as automotive fuels.

2.1. Combustion Characteristics of Gaseous Fuels

The combustion chambers of an automotive engine can be visualized as a group of batch reactors connected in parallel, and the exhaust system as a flow reactor. The combustion of fuel in an engine represents a large number of simultaneous and sequential nonsteady-state chemical reactions at widely varying temperature and pressure condtions, with the exhaust emission as their final reaction products. This analogy has prompted attempts at development of mathematical models to accurately predict engine performance and exhaust emission compositions from inputs of engine design, operating parameters, and fuel composition. Although these modelling efforts have not been completely successful, they have contributed toward a better understanding of the engine emission phenomenon. Since a change of engine fuel represents a drastic change in the combustion reactions, its effect on exhaust emission of engines is partially a reflection of the combustion characteristics of the fuel involved.

2.1.1. Basic Properties

There are several basic physical and chemical properties of fuels relevant to the combustion reaction. Some of these properties of common gaseous fuels, together with those of a few liquid fuels that are representative of gasoline in molecular complexity and volatility, are presented in Table 2.1.1.-1.

2.1.2. Combustion Characteristics

In the internal combustion engine cycle, power and efficiency would be maximum if complete combustion were to occur instantaneously at TDC (top dead center) ignition timing. The power then is proportional to the total rise in pressure that occurs at constant volume, and both power and efficiency increase proportionally to the amount of expansion that occurs in combustion.

In actual practice, however, a fuel-air mixture does not react instantaneously but exhibits a finite mass rate of burning which varies with the nature of the fuel and with engine conditions. Thus, the kinetics of the combustion process must be coupled with the timing of the cycle by advancing or retarding the spark timing to optimize pressure rise, efficiency and power at varying rpm. It is apparent, therefore, that the fundamental burning velocity of the fuel is an important parameter affecting the coupling of fuel to engine design. Table 2.1.2.-1. shows that the burning velocity is more or less constant for ethane and higher alkanes.

The unsaturated hydrocarbons have higher values at low molecular weights, but decrease rapidly as the gasoline range is approached. Benzene and cyclohexane also have burning velocities about the same as those of the alkanes. Therefore, the burning velocity of gasoline, which is a mixture of alkanes, cycloalkanes, alkenes, and aromatics in the range of four to ten carbon atoms, should be only slightly higher than the end-alkane level of about 39-40 cm/s. Thus, the fundamental burning velocity of propane is close enough to that of gasoline so that a minimum of engine modification

Table 2.1.1.-1 BASIC PROPERTIES OF GASEOUS FUELS

Fuel	Chemical Formula	Molecular Weight	Hydrogen/ Carbon Ratio	Heat of Formation (Kcal/g-mole)	Heat of Combustion (Btu/lb)	Specific Gravity, 60°F	Boiling Point, °C	Freezing Point, °C
Methane	CH_4	16	4	−17.86	21,480	0.3[a] 0.554[b]	−161.5	−182.5
Ethane	C_2H_6	30	3	−20.24	20,416	0.377[a]	−88.6	−192.0
Propane	C_3H_8	44	2.67	−24.82	19,916	0.508[a] 1.522[b]	−44.5	−189.9
N-Butane	C_4H_{10}	58	2.5	−29.81	19,665	2.06[b]	−0.50	−138.4
Hydrogen	H_2	2	--	0	60,957	0.0696[b]	−252.5	−259.1
Carbon Monoxide	CO	28	0	−26.42	4,343	0.967[b]	−192	−207
Ammonia	NH_3	17	--	−11.04	8,000	0.617[a] 0.588[b]	−33.4	−77.7
Ethyl Alcohol	C_2H_5OH	46	3	−56.00	11,550	0.794[a]	78.5	−117.3
Reformed Hexane*	--	17.1	4.35	−31.30	9,200	0.043[b]	--	--
Iso-Octane	C_8H_{18}	114	2.25	−49.70	19,080	0.702[a]	125	−56.5
Benzene	C_6H_6	78	1	19.70	17,270	0.884[a]	80.1	5.5
Acetylene	C_2H_2	26	1	52.54	20,743	0.897[b]	−83.4[c]	−81.0

[a] Liquid.
[b] Gas (air = 1).
[c] Sublimation point.

* Composition:
CH_4 35.3% (mole)
H_2 30.3%
CO 3.3%
CO_2 16.4%
H_2O 15.0%

Table 2.1.2.-1. FUNDAMENTAL BURNING VELOCITIES FOR HYDROCARBONS[115]

Fuel	Maximum U_o,† cm/s	Maximum U_f,* cm/s	Volume % Fuel at Maximum U_f
Methane	84.5	33.8	9.96
Ethane	102.8	40.1	6.28
Propane	99.5	39.0	4.54
Butane	96.2	37.9	3.52
Pentane	98.0	38.5	2.92
Hexane	98.0	38.5	2.51
Heptane	98.3	38.6	2.26
2-Methylpropane	87.5	34.9	3.48
2,2-Dimethylpropane	83.0	33.3	2.85
2-Methylbutane	92.5	36.6	2.89
2,2-Dimethylbutane	90.0	35.7	2.43
2,3-Dimethylbutane	91.7	36.3	2.45
2,2,3-Trimethylbutane	90.5	35.9	2.15
2-Methylpentane	93.0	36.8	2.46
3-Methylpentane	92.7	36.7	2.48
2,3-Dimethylpentane	92.2	36.5	2.22
2,4-Dimethylpentane	89.9	35.7	2.17
Ethene	184.5	68.3	7.40
Propene	113.4	43.8	5.04
~~1-Butene~~	~~111.5~~	~~43.2~~	3.87
1-Pentene	110.0	42.6	3.07
1-Hexene	108.5	42.1	2.67
2-Methyl-1-propene	95.0	37.5	3.83
2-Methyl-1-butene	99.5	39.0	3.12
3-Methyl-1-butene	106.9	41.5	3.11
2-Ethyl-1-butene	100.3	39.3	2.65
2-Methyl-1-pentene	101.2	39.6	2.80
4-Methyl-1-pentene	104.0	40.5	2.62
Propyne	189.1	69.9	5.86
1-Butyne	155.0	58.1	4.36
1-Pentyne	140.0	52.9	3.51
1-Hexyne	127.0	48.5	2.97
4-Methyl-1-pentyne	116.9	45.0	2.87
2-Butyne	135.6	51.5	4.36
3-Hexyne	118.0	45.4	3.05
Cyclohexane	98.4	38.7	2.65
Benzene	104.5	40.7	3.34

* Calculated from using the average values $A = 5.07$ sq cm and $A_f = 11.25$ sq cm.

† U_o = observed linear flame velocity, U_f = fundamental flame velocity.

should be required Methane, although its burning velocity is distincly lower, should offer no major problem

The fundamental burning velocity of hydrogen is about seven times as fast as that of propane or gasoline and efficient engine-fuel coupling might require major engine modifications A more serious difficulty is associated with hydrogen's poor antiknock properties.

Ammonia presents even more difficult problems since its burning velocity is only 1/38 that of propane. Coupling such a slow combustion process to the internal combustion engine is quite difficult. The spark timing must be advanced from the 20-40 deg BTC (before top center) required for gasoline to 100-120 deg BTC. Even then, complete burning is approached only at low rpm At high speeds, complete burning can be accomplished only if the area of the flame front is increased by increasing turbulence or the combustion characteristics are improved by premixing with faster burning hydrogen

The ignition of a fuel-air mixture is dependent not only on fuel-air ratio, but on a number of other factors as well. These include temperature, pressure, concentration of inert diluents, initiating or inhibiting species, chamber diameter, surface to volume ratio, and characteristics of the wall surfaces. Changes in engine variables that affect any of these factors will also affect the ignition characteristics of the system. Failure to match engine parameters to the ignition characteristics of the fuel can produce misfiring and thus result in the loss of power and efficiency together with increased emission of unreacted or partially reacted hydrocarbons and carbon monoxide. A complete understanding of the ignition characteristics of a particular fuel-oxidant system, therefore, is essential to the effective coupling of that system to the engine cycle

Autoignition is defined as the self-ignition of a homogeneous mixture or a fuel oxidant. In an internal combustion engine the autoignition phenomenon associated with knock proceeds in three stages[96] —

1. Peroxide stage — alkyl peroxides are produced and reactions are not exothermic.
2. Cool flames stage — excited formaldehyde produces a blue radiation and exothermic reactions are present.
3. Hot flame stage — reactions are rapid and highly exothermic, producing intense radiation and an audible knock.

According to Walsh,[176] knock ratings are a sensitive function of molecular structure. He associates knock resistance with cool flame formation and says that cool flames only arise when the net chain branching factor is sufficiently great. Chain branching increases with the presence of CH_2 groups and since neither methane nor ethane contain CH_2 groups autoignition is not a problem with these fuels.

The current trend toward elimination of lead additives from gasoline makes it both difficult and expensive to meet octane number requirements of modern cars. The gaseous fuels exhibit a distinct advantage in regard to antiknock performance. The octane numbers of nonleaded gasoline, methane, propane, and ammonia are 93, 120, 97.4, and 111 respectively. One of the major problems associated with ignition and internal combustion engines is that of misfire limits. Misfire tends to occur either on the rich or lean side of stoichiometric ratio, but particularly on the lean, probably because the volumetric rate of heat release falls below that of the heat loss. Emission of both carbon monoxide and hydrocarbons is minimized by operation further on the lean side and this can be obtained without misfire by use of gaseous fuels.

One major difference between gaseous hydrocarbons and gasoline is that the latter involves droplet combustion whereas gases are combusted in a homogeneous state. Physical processes in droplet combustion strongly influence burning velocities so that the rate of heat release per unit volume can be much less than that of homogeneous combustion. Also in the gasoline-fueled engine poor mixing in the carburetor-manifold system leads to variations in cylinder to cylinder air fuel ratios which, in turn, leads to cylinder to cylinder variations in temperature and pressure.

2.1.3. Formation of Exhaust Pollution Products

2.1.3.1. Hydrocarbons (HC)

2.1.3.1.1. Sources of Exhaust Hydrocarbons

There are certain fuels, such as hydrogen and ammonia, that do not involve hydrocarbons at all in their combustion reaction. Therefore, a discussion on exhaust hydrocarbons would be completely irrelevant to these types of fuel. On the other hand, the exhaust hydrocarbons are closely related to the combustion of fossil fuels, notably hydrocarbon fuels.

In an ideal combustion process of hydrocarbon fuels such as gasoline, in which thermodynamic equilibria are attained, the combustion products should contain no hydrocarbons. The presence of hydrocarbons — either fuel type or nonfuel type — in the exhaust is a positive indication of incomplete combustion.

One obvious cause of incomplete combustion in an engine is the insufficient oxygen supply which occurs at extreme engine operating conditions such as rich fuel-air ratio, poor fuel mixing, and at light load.[47] However, in normal operation of a well-adjusted engine, such extreme conditions are rarely encountered, the fuel air ratio is generally maintained close to the stoichiometric value. Therefore, the hydrocarbons found in the exhaust of well-adjusted engines must be contributed by other factors.

One major source of exhaust hydrocarbons is the unburned gas in the quench zone of the combustion chamber.[38, 39, 48, 78, 146] It is well known that when flame approaches a cool surface, such as engine head, chamber walls, and piston face — the flame temperature is drastically reduced and the flame is thus extinguished, resulting in incomplete oxidation of fuel. This drastic temperature reduction due to wall quenching is illustrated in Figure 2.1.3.-1.

The temperature difference between chamber wall and flame center can be so large (usually on the order of 3000°-4000°F) that fuel-air charge near the wall may fail to ignite. Although some of the unburned gases may be

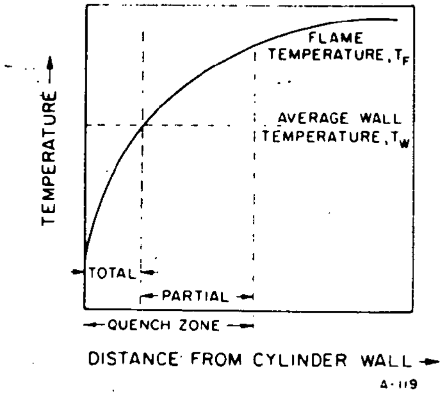


Figure 2. 1. 3.-1. TEMPERATURE PROFILE OF QUENCH ZONE

oxidized later during the expansion and exhaust processes, a sufficient amount remains unchanged. One investigation estimated that almost 50 % of exhaust hydrocarbons came from the quench zone and about 30 % of them entered the atmosphere.[48]

Another major source of exhaust hydrocarbons is the unburned fuel trapped in combustion crevices — such as the space around the piston, space between the engine head and block, and crevices around valve seats[80, 177] (Figure 2. 1. 3. -2). Due to the narrow passage of these crevices, the flame is prevented from propagating into the regions beyond the restriction. One such region is the crevice below the top piston ring. It has been estimated that, under some conditions, the piston-ring crevices alone contribute up to 50 % of the exhaust hydrocarbons.[177]

A complete combustion cycle of an SI-engine consists of many processes, thus the hydrocarbons from quench zones and chamber crevices are subjected to the influence of these processes before being expelled into the

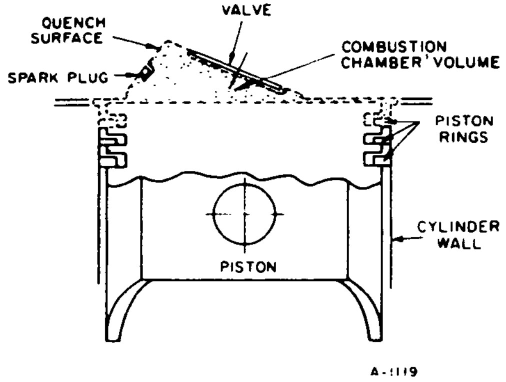


Figure 2. 1. 3. -2. QUENCH SURFACE AND PISTON-RING CREVICES OF AN SI-ENGINE COMBUSTION CHAMBER

atmosphere. The major factors are the extent of postcombustion oxidation of unburned gases in the combustion chamber and the extent of oxidation in the exhaust system.[99] Both factors are influenced by some of the engine variables to be discussed later.

Another potential source of unburned hydrocarbons from an engine is the blowby of unburned charge. In a conventional four-stroke cycle SI-engine, the blowby loss is usually to the crankcase and only a small portion of unburned mixture is lost through the exhaust valve and during the valve overlap period. However, the blowby loss could be significant in a two-stroke cycle compression ignition engine and in a rotary engine.

2.1.3.1.2. HC Concentration and Engine Operation Variables

A positive approach of eliminating exhaust hydrocarbons is to eliminate the sources of unburned gases. In an SI-engine, this approach would mean the elimination of quenching and a crevices' effect during combustion. However, due to practical limitations in engine design and modification, both the wall quenching and the crevices' effect can only be minimized not eliminated. A significant reduction in exhaust hydrocarbons has been achieved by minimizing the quench surface area and the size of piston-ring crevices.[50,78,146] Further reduction in exhaust hydrocarbons may be realized by increasing the amount of oxidation occurring in the combustion chamber and exhaust system.

Since the mass of unburned fuel resulted from wall quenching of the flame and the crevices' effect is directly determined by the volume and density of fuel-air charge in the quench zones and combustion chamber crevices, it is, therefore, under the influence of some engine variables, such as fuel-air ratio, ignition timing, air-flow rate (percent of throttle), engine speed, and compression ratio. However, their effect on fuel-air charge volume and on fuel-air charge density are not similar. The volume change predominates in two cases: fuel-air ratio and ignition timing. The density change predominates in the other three cases: air-flow rate, engine speed, and compression ratio. Furthermore, the effect of engine variables on the amount of unburned gases due to wall quenching does not always correlate with that due to the crevices' effect. The net effect on exhaust hydrocarbons depends on the relative magnitude of hydrocarbon contribution from these two sources.

In addition to their effect on the volume and density of fuel-air charge inside the combustion chamber, some of the engine variables can also affect the temperature and residence time of the combusted gases. Therefore, the engine variables permit further oxidation of the unburned gases to proceed inside the chamber and exhaust system prior to being ejected into the atmosphere. For example, retarding the ignition timing increases the total

volume of quench gas (increasing hydrocarbons) while reducing the density of the crevice gases (reducing hydrocarbons), the net effect of ignition retardation on the source of unburned hydrocarbons may be insignificant. However, retarding the ignition timing in an SI-engine increases the temperature of combustion products during the expansion and exhaust cycles, thus allowing additional oxidation and resulting in reduced exhaust hydrocarbons.[38,39] The magnitude of the effect of spark timing on exhaust hydrocarbon concentration depends on the setting of other engine variables, notably fuel-air ratio.

The fuel-air ratio affects the flame speed and the amount of excess oxygen available to post-flame reactions, thus affecting the exhaust hydrocarbon concentration. The availability of excess oxygen promotes the post-flame reactions. However, excess air tends to reduce flame velocity, resulting in lower peak temperature and pressure, and therefore retarding the post-flame reactions. The optimum air-fuel ratio for minimum exhaust hydrocarbon emission varies among fuels and depends on other variables such as combustion chamber volume and surface area and ignition timing. The approach of reducing exhaust hydrocarbons emission through improved post-flame reactions has been found to be more effective in engines having large cylinder displacement, low compression ratio, and small bore-stroke ratio.[80,99,152]

2.1.3.1.3. Composition of Exhaust Hydrocarbons

Gasoline consists of many hydrocarbons, varying among the grades sold. More than 40 individual hydrocarbons have been identified among different grades of gasoline.[132] Therefore, it is not at all surprising to detect various fuel hydrocarbons in the exhaust of gasoline-fueled engines knowing that unburned fuel is a source of exhaust hydrocarbons. One investigation, using a gas chromatography technique, identified more than 25 various hydrocarbons in the exhaust of gasoline-fueled automobiles, as shown in Table 2.1.3.-1.

Table 2.1.3-1. EXHAUST HYDROCARBON COMPOSITION OF GASOLINE-FUELED AUTOMOBILES (Average of 62 Vehicles)[132]

Hydrocarbons	Mole %	Hydrocarbons	Mole %
Methane*	16.7	n-Hexane	1.2
Ethylene*	14.5	2, 2, 4-Trimethylpentane	1.0
Acetylene*	14.1	o-Xylene	0.9
Propylene*	6.3	Isobutane	0.8
n-Butane	5.3	2, 3-Dimethylpentane	0.9
Isopentane	3.7	2, 4-Dimethylpentane	0.3
Toluene	3.1	Methylacetylene*	0.9
Benzene*	2.4	Ethylbenzene	0.7
n-Pentane	2.5	1-Methyl-4-ethylbenzene	0.7
m+p-Xylene	1.9	Trans-2-Butene*	0.6
1-Butene*	1.8	2, 3-Dimethylbentane	0.5
Ethane	1.8	1, 3, 5-Trimethylbenzene	0.4
2-Methylpentane	1.5	1, 2, 4-Trimethylbenzene	0.4
	Total	84.9 moles	

* Products of engine combustion.

The data presented in Table 2.1.3-1 indicate that roughly 60% of the total exhaust hydrocarbons are products of engine combustion, consisting of partially oxidized and/or cracked gasoline constituents. The remaining 40% of the identified exhaust hydrocarbons resemble the original fuel, even in the relative composition ratio. This 40% portion represents the unburned and unchanged fuel. These data indicate that the composition of exhaust hydrocarbons does vary with that of the fuel, provided the difference in fuel composition is significant enough.

Laboratory investigation using 99%-pure propane in a single-cylinder spark-ignition engine also showed the relationship between the composition of exhaust hydrocarbon and that of fuel (Table 2.1.3-2).

Table 2.1.3-2. EXHAUST HYDROCARBON COMPOSITION OF PROPANE-FUELED SI-ENGINE[2]

	Volume Percent of Total Hydrocarbons	
Hydrocarbon	Combustion Chamber	Exhaust
Ethane C_2H_6	0.6	1.6
Methane CH_4	2.6	11.7
Propylene C_3H_6	2.9	7.2
Acetylene C_2H_2	3.9	10.8
Ethylene C_2H_4	6.9	19.8
Propane C_3H_8	83.1	48.9

* At air-fuel ratio of 15.5 and ignition timing of 20 deg BTC.

Data presented in Table 2.1.3-2 indicate that approximately half of the exhaust hydrocarbons are of original fuel while the other half are combustion products. However, the composition of the exhaust hydrocarbons is by no means constant. The investigation with propane[38] found that the fuel portion varied from 16 to 86% (on carbon basis) of the total exhaust hydrocarbons, depending upon the experimental setting of engine variables. In general, fuel-air ratio and ignition timing exert the most significant influence on the composition of exhaust hydrocarbons.

The composition of exhaust hydrocarbons is important in the fact that some hydrocarbons could contribute to the manifestations of photochemical[4,5,22] smog more than others.[14,15,17] In general, olefinic hydrocarbons (particularly C_3, C_4, C_5 olefins) have much higher reactivity – smog contributing – than paraffinic and aromatic hydrocarbons.[46,90,151] Therefore, the absence of higher olefins and the relatively lower C_2 and C_3 olefins concentration contribute to the significantly lower reactivity of the propane-fueled engine exhaust (Table 2.1.3-2) as compared to that of gasoline-fueled engine exhaust (Table 2.1.3-1). Further discussion of hydrocarbon reactivity will be presented in the sections dealing with various gaseous fuels.

2. 1. 3. 2. Nitrogen Oxides (NO_x)

The exhaust of automotive engines — both spark-ignition engines and diesel-type engines — is known to be a significant source of nitrogen oxides. Among the many existing species of nitrogen oxides, only nitric oxide (NO) can be found in appreciable quantities at the combustion temperatures of fuels, as shown by both thermodynamic data of equilibrium constants of various nitrogen oxides[152, 178] and actual measurement of engine exhaust.[22] It has also been thought that, although nitric oxide can be readily oxidized to form nitrogen dioxide (NO_2), the short time that combustion gas remains inside an engine and its exhaust system does not allow the completion of oxidation. Therefore, the only nitrogen oxide concerned in engine exhaust emission is the nitric oxide.

2. 1. 3. 2. 1. Reaction Mechanism of NO Formation

The exact formation mechanism of nitric oxide in a combustion engine is not well understood. Traditionally, the formation of nitric oxide is represented by the bimolecular mechanism for nitrogen fixation.[88]

$$N_2 + O_2 = 2\ NO \qquad (1)$$

which is an expression of conservation of mass rather than of an elementary reaction.

Other investigators proposed the incorporation of some elementary reactions involving atomic species such as N and O to explain the unusually high nitric oxide concentration found in the combustion of ammonia[145] and hydrogen. Some of the suggested possibilities of an atomic reaction mechanism are[123] —

$$O_2 + N \rightarrow NO + O \qquad (2)$$

$$N_2 + O \rightarrow NO + N \qquad (3)$$

$$N + O + M \rightarrow NO + M \qquad (4)$$

However, in view of their small atomic dissociation in air (Figure 2. 1. 3-3), especially nitrogen, under engine temperatures and pressure, the contribution of atomic oxygen and nitrogen in overall nitric oxide formation in engine combustion may be quite small.[52] Others have suggested an atomic scheme involving N_2O,[179] where the final results are identical to those of the bimolecular mechanism expressed by equation (2).

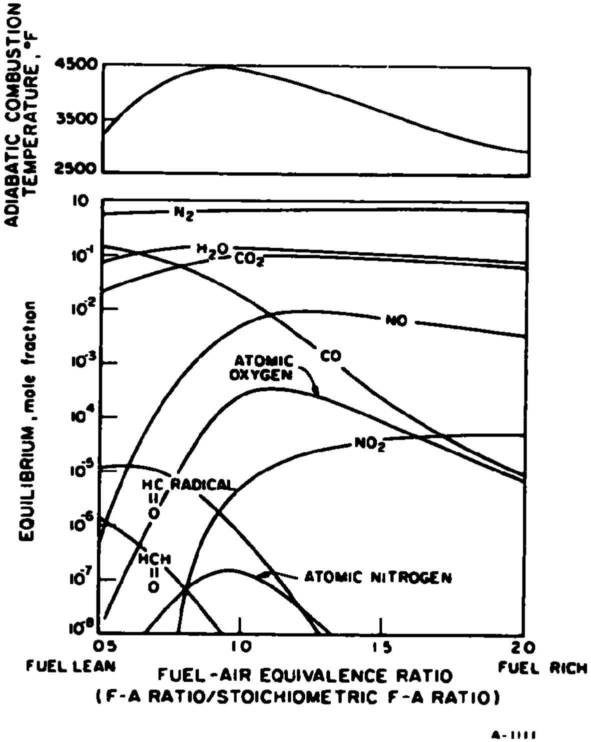


Figure 2. 1. 3-3. COMPUTED EQUILIBRIUM COMPOSITION FOR CONSTANT-VOLUME ADIABATIC COMBUSTION OF n-OCTANE[160]

2.1.3.2.2. Equilibrium Theory of NO Formation

Numerous attempts were made to correlate the amount of nitric oxide found in engine exhausts to that obtained through theoretical calculations. These attempts involved studies of not only the formation mechanism at the combustion of fuel but also the change of nitric oxide concentration under other conditions of an engine cycle, namely, expansion, compression, and exhaust.

Earlier studies with gasoline-fueled SI-engines[65,153] indicated that the nitric oxide concentration in the exhaust corresponds approximately to the chemical equilibrium concentration calculated for the peak combustion temperature. This observation led some investigators to conclude that chemical equilibrium is reached inside the combustion chamber. However, it was also observed that the approximate concentration correlation exists only with a fuel-rich mixture and not at all with a fuel-lean mixture. It was also observed that NO concentration found in exhausts is several orders of magnitude greater than the equilibrium concentration calculated on the basis of exhaust temperature.

The attainment of equilibrium was also suggested by another more recent investigation[125] in which the concentration of nitric oxide under normal operation of a CFR engine was found equal to that under a large excess of nitric oxide added to the carbureted air-fuel mixture. The equilibrium theory was further strengthened by the approximate correlation of the nitric oxide concentration between the observed values from the exhaust of an SI-engine and those predicted for constant-volume adiabatic combustion of various hydrocarbon fuels (Table 2.1.3-3). The information presented in Table 2.1.3-3 indicates that the equilibrium nitric oxide concentration is closely related to some combustion properties inherent to the fuel involved.

Table 2.1.3-3. ADIABATIC FLAME TEMPERATURES AND NITRIC OXIDE CONCENTRATIONS[160]

	Constant Pressure Combustion*		Constant Volume Combustion*	
Fuel	Adiabatic Flame Temp., °F	Nitric Oxide Concentration, ppm	Adiabatic Flame Temp., °F	Nitric Oxide Concentration, ppm
Methane	3619	1577	4346	4,314
Ethane	3691	.927	4398	5,051
Propane	3707	2030	4443	5,270
n-Octane	3727	2161	4465	5,551
Ethylene	3930	3312	4675	7,597
Acetylene	4305	6812	5082	13,320

* Air-fuel equivalent ratio = 1, T = 77°F, P = 10 atm

However, more recent investigations found that nitric oxide, once formed in combustion, does not decompose during the expansion process.[124,125,156] It was observed that the kinetics of decomposition reactions, as expressed by Equations (1), (2), and (3), are not rapid enough for the temperature-pressure path imposed on the combusted gases by the engine operation. In fact, the concentration of nitric oxide was found to reach a peak at "peak flame temperature" and remain constant throughout the expansion and exhaust processes. A term of "frozen equilibrium" was used to describe this observed phenomenon.

The attempts to predict the NO concentration in the exhaust by the equilibrium theory has not been completely successful. The difficulties may be related to the invalid assumption that a single flame temperature prevails throughout the combustion chamber, which is known to be nonexisting as illustrated by the temperature profile in the quench zone of a combustion chamber (Figure 2.1.3.-1). Also mixing and fuel distribution may be significant factors in this phenomenon. Furthermore, the engines, in reality, are operated under conditions that have neither constant volume nor constant pressure. The extreme temperature sensitivity of equilibrium concentration of nitric oxide — concentration increases exponentially with the increase in temperature as shown in the kinetic equations (Equations 5 and 6) of nitric oxide formation (Equations 3 and 4) and Figure 2.1.3-4. Experimental difficulties in temperature measurement and sampling technique further complicate the study.

$$r = k \sum_{j=1}^{n} c_j^{\gamma_j} \qquad (5)$$

$$k = Ae^{-\frac{E}{RT}} \qquad (6)$$

where r = reaction rate

k = specific rate constant

c_j = concentration of component j

γ_j = order of reaction with respect to component j

A = frequency factor for the reaction

E = activation energy

R = universal gas constant

T = absolute temperature

2.1.3.2.3. Kinetics of NO Formation

It has been suggested recently that the nitric oxide formation may never reach an equilibrium in engine operation and that the equilibrium theory may be irrelevant to the calculation of NO concentration in the exhaust. It has been shown that equilibrium in nitric oxide formation could not be reached in the engine due to the insufficient time.[52] Using the reaction mechanism represented by Equation (1), the minimum times required to reach equilibrium NO concentration under various temperatures, while keeping pressure, volume, and concentration constant, are shown in Figure 2.1.3-5.

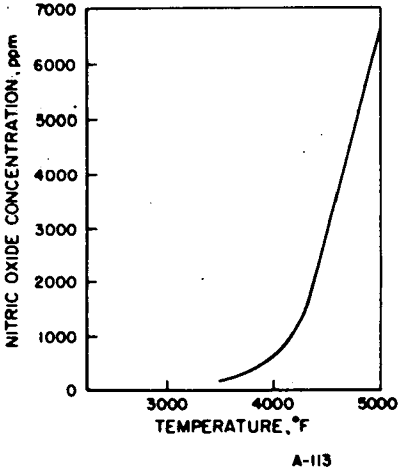


Figure 2.1.3-4. TEMPERATURE VERSUS EQUILIBRIUM NITRIC OXIDE CONCENTRATION [122]
(At 600 psi and fuel-air equivalence ratio of 1:1)

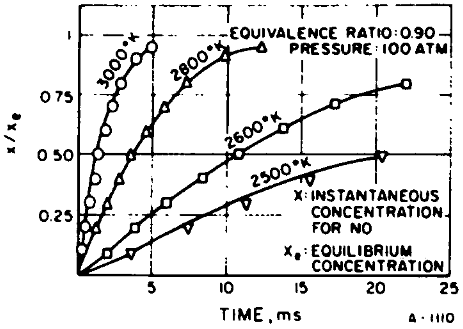


Figure 2.1.3.-5. KINETIC PROGRESSION OF NITRIC OXIDE FORMATION UNDER VARIOUS TEMPERATURES[23, 52]

The data presented in Figure 2. 1. 3-5 indicate that the attainment of 90 % of equilibrium nitric oxide concentration at 3000°K will require 4 milliseconds — which may well exceed the total period of combustion of an SI-engine operating at 3000 rpm. Furthermore, as combustion proceeds, temperature and concentration vary appreciably, and in all cases sufficient time is not likely to be available to attain the equilibrium concentration values. The time scale of events in an operational engine is illustrated in Figure 2. 1. 3-6, which shows that the completion of the power stroke — which includes the combustion of fuel and expansion of burned gas — requires a time duration of approximately 8 milliseconds at 3000 rpm.

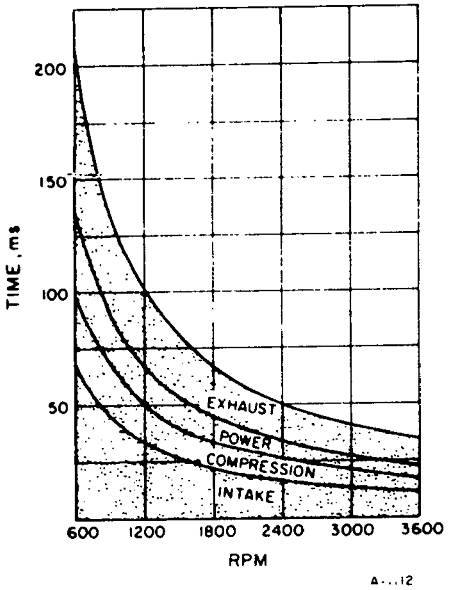


Figure 2. 1. 3-6. DURATION OF ENGINE EVENTS FOR A PRODUCTION 318 CID V-8 ENGINE [47]

The time-dependent nature of the nitric oxide concentration is further illustrated in the combustion of hydrogen and air (Figure 2. 1. 3-7).

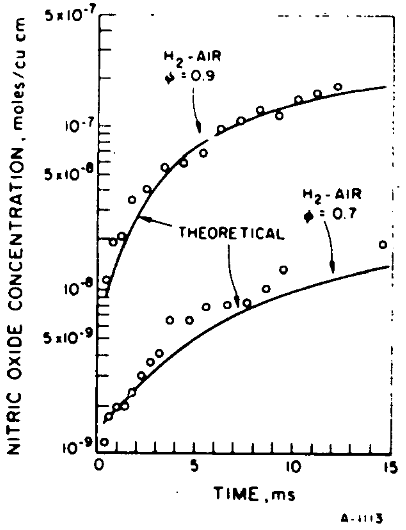


Figure 2. 1. 3-7. RATE OF NITRIC OXIDE FORMATION IN HIGH PRESSURE HYDROGEN-AIR FLAME [124]
Ø = fuel-air equivalence ratio

The kinetic analysis of the NO formation also explains the nitric oxide concentration freeze observed during the expansion process of the engine operation. During expansion, the mean bulk temperature of the burned gas decreases abruptly, and below approximately 1500°K, the rate constants of nitric oxide formation will be too small to register the slightest change.

The kinetic analysis of the nitric oxide formation further indicates that the NO concentration in the engine exhaust is governed by the temperature-pressure-time path of the combustion process, and also by the initial concentration of nitric oxide. Due to the nonexistence of uniform temperature inside the combustion chamber, the concentration of nitric oxide in the combustion gases does not seem to reach the equilibrium value calculated for the peak cycle temperature. However, the attainment of equilibrium nitric oxide concentration on a local basis cannot be ruled out.

2.1.3.2.4. NO Concentration and Engine-Operation Variables

Nitric oxide concentrations in engine exhaust are affected by some operating parameters in both spark-ignition and compression ignition engines.[79] For SI-engines, the major parameters are fuel-air equivalence ratio and spark timing. Manifold air pressure, compression ratio, and engine speed are also important. The fuel-air ratio and spark timing are particularly important to nitric oxide concentration.

The fuel-air ratio governs the amount of heat that can be released by the fuel and the rate at which the enthalpy of fuel is being released during combustion. Thus, the fuel-air ratio is closely related to the peak temperature and pressure that can be attained by a specific fuel in a given combustion chamber.

Since the enthalpy value that can be released during combustion (heat of combustion) is an inherent property of a fuel, the effects of the fuel-air ratio on peak combustion temperature and pressure vary among different fuels (Table 2.1.1.-1). The effects can be illustrated by the theoretical peak Otto-cycle temperature and pressure of various types of fuel, assuming that flame speed (heat-release rate) is not affected (Figures 2.1.3.-8 and 2.1.3.-9).

Due to its temperature and pressure dependent nature, the nitric oxide formation in an engine is, therefore, closely related to the fuel-air ratio. Such relationships can be indicated by the effect of the fuel-air ratio on the calculated equilibrium peak cycle concentration of nitric oxide for various types of fuel, assuming, of course, that the equilibrium in nitric oxide formation is attained in the engine combustion (Figure 2.1.3-10).

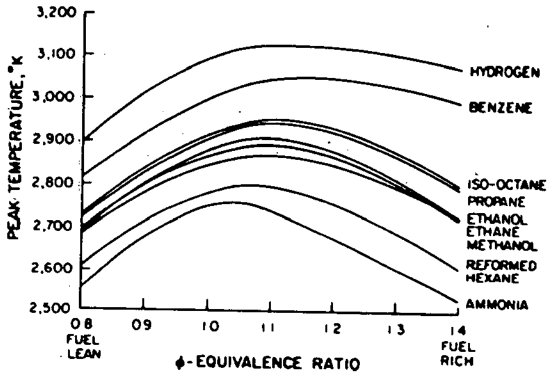


Figure 2.1.3-8. THEORETICAL PEAK OTTO CYCLE TEMPERATURE OF VARIOUS FUELS [159]

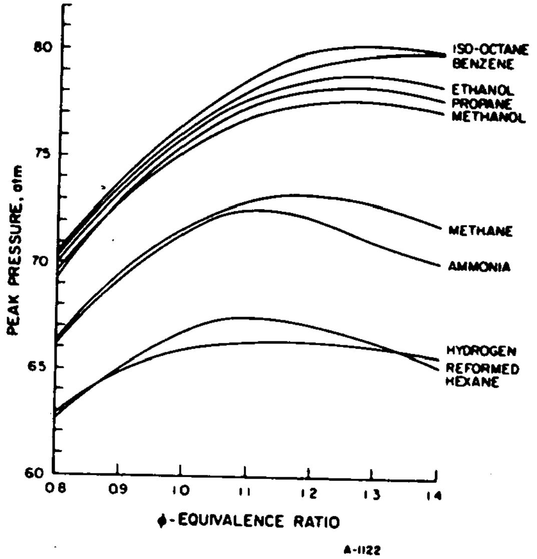


Figure 2.1.3-9. THEORETICAL PEAK OTTO CYCLE PRESSURE OF VARIOUS FUELS [159]

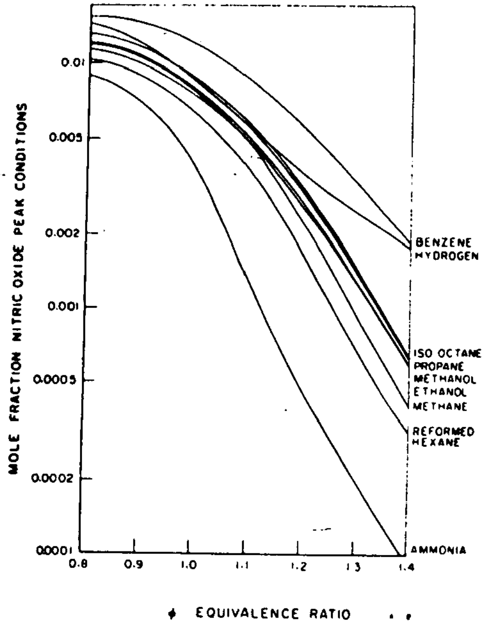


Figure 2. 1. 3-10. PREDICTED EQUILIBRIUM PEAK CONCENTRATION OF NITRIC OXIDE[159]

It should be remembered, however, the nitric oxide formation is also affected by other engine combustion variables, notably flame speed and residence time in the combustion chamber (determined by ignition timing and other engine variables), the actual nitric oxide concentration in the engine exhaust is not exactly represented by the calculated equilibrium concentrations. A typical plot of nitric oxide concentration in the engine exhaust against air-fuel ratio of a gasoline-fueled standard spark-ignition automobile engine is shown in Figure 2. 1. 3-11, in which the effect of spark timing is also indicated.

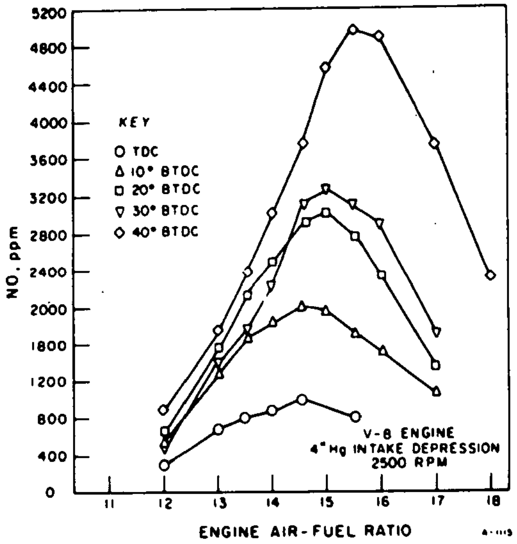


Figure 2. 1. 3-11. NITRIC OXIDE CONCENTRATION VS. AIR-FUEL RATIO IN A STANDARD GASOLINE-FUELED SI-ENGINE[32]

In a compression-ignition engine, the fuel-air ratio also has a predominant effect on the nitric oxide concentration but in a different way compared to that in an SI-engine.[83, 106, 182] Since the fuel-air ratio in a CI-engine generally increases with the increase in load, so does the nitric oxide concentration. The exact point of fuel-air ratio where peak NO concentration occurs depends on some engine characteristics.

In a prechamber type CI-engine, NO concentrations rarely exceed a value of 1000 ppm, and the peak concentration generally occurs near the middle of full torque value.[93, 98] On the other hand, high NO concentrations exceeding 2500 ppm have been recorded in the exhaust of direct fuel-injection type of engines, in which the fuel injection timing becomes a significant factor — comparable to the effect of spark timing in an SI-engine.[182] A general comparison of NO concentration in the exhaust of the two types of CI-engines is presented in Figure 2. 1. 3-12.

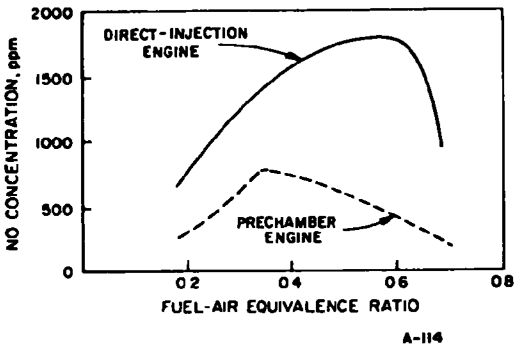


Figure 2.1.3-12. COMPARISON OF EXHAUST NO CONCENTRATIONS OF TWO TYPES OF CI-ENGINES[52]

The reduced exhaust nitric oxide concentration of CI-engines compared to that of SI-engines has been attributed to the high heterogeneity of fuel in the combustion chamber.[106,182] The nitric oxide emission was reduced by the locally fuel over-rich conditions in the combustion zones. The prechamber type engines have greater fuel-air heterogeneity than the direct fuel-injection type engines, thus lower NO.

The effect of fuel-air heterogeneity on NO emission can also be seen in the combustion of a stratified SI-engine. A stratified charge engine, such as the Baudry engine,[15] brings a fuel-rich mixture to the vicinity of the spark plug while the normal intake manifold is fed either with pure air or with a fuel-lean mixture. Thus, a high heterogeneity in fuel distribution is achieved. Furthermore, the stratified charge engine meets the load variations by adjusting the strength of the fuel-rich mixture instead of using throttle adjustment as in the case of normal SI-engines. Therefore, the fuel heterogeneity is maintained, resulting in lower nitric oxide emission over a wide range of load, even though having a higher localized peak NO emission (Figure 2.1.3-13).

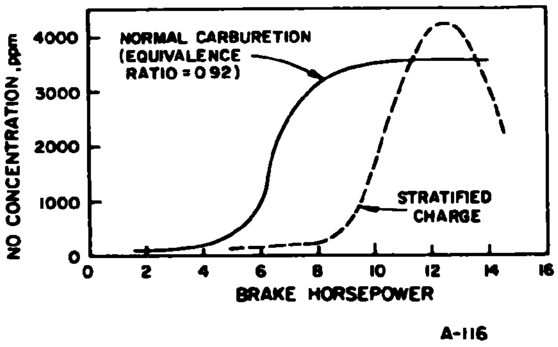


Figure 2.1.3-13. COMPARISON OF NO EMISSION OF STRATIFIED CHARGED AND NORMAL SI-ENGINES[15]

The engine operation variables affect the nitric oxide emission through their effects on the temperature-pressure-time diagram of the combustion process. These variables and their effect on exhaust emission in different types of engines using various types of fuels will be discussed in more detail in later parts of this report.

2.1.3.3. Carbon Monoxide (CO)

2.1.3.3.1. Sources of Exhaust Carbon Monoxide

It is generally accepted that carbon monoxide in an engine exhaust, similar to nitric oxide, originates in the high-temperature region associated with the flame in the combustion chamber. In a fuel-rich mixture, the formation of carbon monoxide is largely due to an insufficient supply of oxygen for the complete oxidation of fuel. This is believed to be true regardless of the homogeneity of the fuel-air mixture.[80] However, in a fuel-lean mixture, the controlling mechanism of the carbon monoxide formation is not as clear, and the homogeneity of the fuel-air mixture may become significant.

It has been observed[28] that carbon monoxide concentration in the exhaust of an SI-engine nearly corresponds to the equilibrium concentration predicted on the basis of peak cycle temperature, but does not decrease according to equilibria as exhaust gas temperature decreases during expansion. At the end of the expansion cycle, the exhaust concentration is much greater than that predicted on the basis of equilibrium kinetics (Figure 2.1.3-14).

The reaction mechanism believed to be responsible for carbon monoxide oxidation can be represented by the elementary reaction:

$$CO + OH \rightleftharpoons CO_2 + H \qquad (1)$$

This reaction has been shown to be fast enough to reach equilibrium in the post-flame gases.[123] Therefore, the kinetics of the reaction are dependent on the concentration of various constituents. It is also known that recombinations of hydrogen

$$H + H = H_2 \qquad (2)$$

$$H + OH = H_2O \qquad (3)$$

are termolecular reactions which do not proceed rapidly enough to reach equilibrium in post-flame gases. Thus, there is an excess of atomic hydrogen, and the hyperequilibrium concentrations of atomic hydrogen tend to shift the carbon monoxide oxidation toward the left, resulting in large concentrations of carbon monoxide in the exhaust.

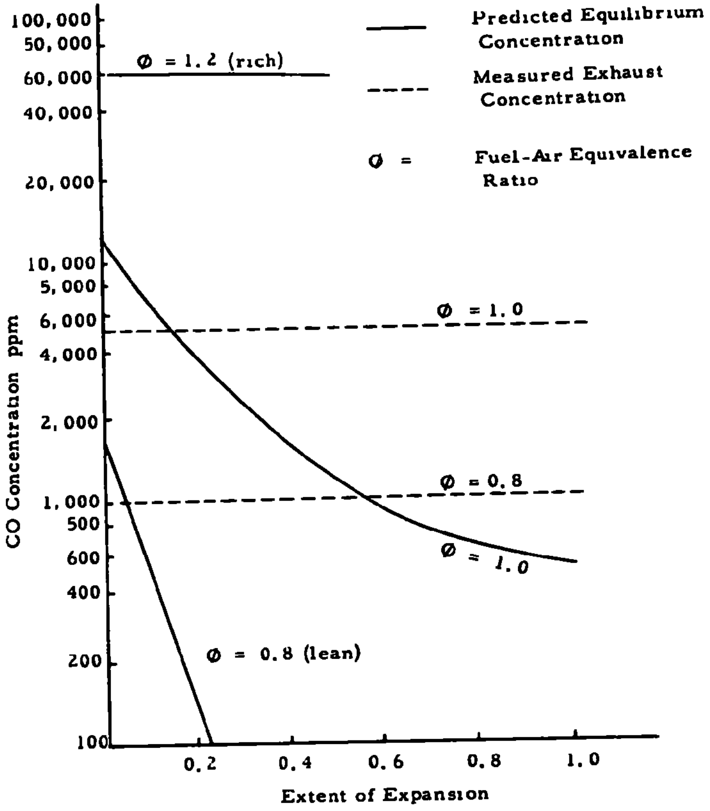


Figure 2.1.3-14. CARBON MONOXIDE CONCENTRATION DURING EXPANSION CYCLE – THEORETICAL VS. MEASURED EXHAUST LEVELS[156]

2.1.3.3.2. CO Concentration and Engine Variables

The only engine operating variable that has a significant effect on the exhaust concentration of carbon monoxide is the air-fuel ratio. Others, such as ignition timing, throttle position, engine speed, air-fuel charge, and coolant temperature, have little or no influence on the exhaust carbon monoxide emission.[50, 80] Some engine design variables, on the other hand, may affect the carbon monoxide emission through their effect of air-fuel ratios. In gasoline-fueled engines, the fuel-air mixture, vaporization and distribution are known to affect the carbon monoxide emission. Such problems, however, are minimized when gaseous fuels are used. With gaseous fuels, the fuel-air mixing will be much more efficient, and there will be no vaporization and distribution problems.

The high carbon monoxide emissions are primarily associated with fuel-rich operations. As the air-fuel ratios are varied from fuel-rich to stoichiometric, the carbon monoxide emission decreases rapidly. Once the air-fuel ratio reaches stoichiometric or leaner, very little carbon monoxide will be produced. A typical air-fuel ratio versus a carbon monoxide emission relationship is shown in Figure 2.1.3-15.

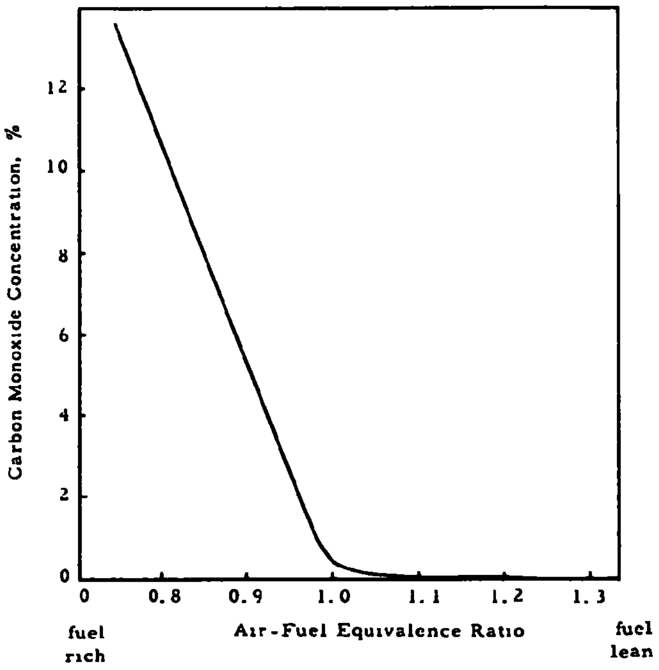


Figure 2.1.3-15. AIR-FUEL RATIO VS. CARBON MONOXIDE EMISSION[56]

2.2. Exhaust Emission Characteristics in SI-Engines

2.2.1. General Discussion

A realistic comparison of the exhaust emission control potential of various types of fuels can only be made on an overall basis using the type of engines and operating conditions that are designed for the specific fuel involved. Unfortunately, such a comparison is not possible because most of the available automotive engines are designed to operate on gasoline or diesel fuel, and are usually designed for maximum power output rather than optimum exhaust emission control. Therefore, emission studies on gaseous fuels using engines designed for gasoline may not reveal the true emission-control potential of the gaseous fuel involved.

However, if the interest is in the gaseous fuel's potential to reduce exhaust emissions of existing automotive engines, then emission studies have to be made on the simple basis of switching the fuel on the currently available engines. The attentions are then focused on finding the optimum operating conditions of the engine and necessary modifications required to achieve the full potential in the exhaust emission reduction of suitable gaseous fuels. Since most of the existing automotive engines are spark-ignition types, emphasis is thus placed on the engine factors relevant to this type of engine. However, other types of engines that are used in increasing numbers in vehicles are also discussed and presented under separate sections.

2.2.2. Determining Factors of Exhaust Emission

The level and composition of the exhaust emissions of an engine are known to be influenced by many engine variables. These variables can be divided, according to the magnitude of their effect on emission, into two groups:

Primary Variables

- Type of Engine
- Type of Fuel

- Operation Variables
  - Fuel-Air Ratio
  - Ignition-Timing Schedule
  - Engine Mode or Duty Schedule

Secondary Variables

- Fuel-Air Charge Distribution
- Fuel-Air Charge Temperature
- Compression Ratio
- Engine Deposit
- Ambient Conditions
- Ignition System Design
- Fuel Composition

In all emission studies, the type of engine and fuel are usually fixed. Thus the primary variables are engine operation variables — fuel-air ratio, ignition timing, and engine mode. In the case of laboratory data, using research engines, the engine mode is usually expressed in terms of engine speed and power output. Furthermore, the power output of the engine mode may be expressed in various ways depending upon the type of engine involved. With CFR or other research engines, the power output may be expressed in terms of throttle position which is usually defined as the ratio of actual airflow rate to the maximum attainable airflow rate at wide open throttle (WOT). In the case of a production engine, the power levels may be expressed in terms of brake horsepower or percent of maximum power.

The effect of these variables on the emission characteristics of various gaseous fuels will be discussed on the basis of available information from laboratory investigations in which emission studies are made by isolating the variables. Exhaust emission characteristics based on a road test or a dynamometer driving-cycle test to simulate traffic patterns will be discussed under separate sections.

2. 2. 3. Emission Characteristics of Propane

2. 2. 3. 1. Fuel-Air Ratio

In general, the exhaust hydrocarbon concentration of a propane-fueled engine decreases from both extremes of fuel-rich and fuel-lean operations and reaches a minimum at a fuel-air ratio slightly leaner than stoichiometric. The exact location of the minimum and the magnitude of hydrocarbon concentration are affected by other variables, notably ignition timing and throttle opening (Figures 2. 2. 3. -1 and 2. 2. 3. -2).

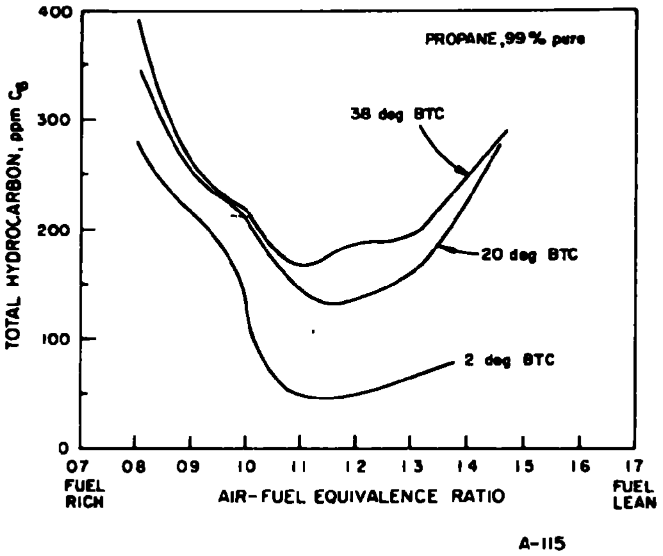


Figure 2.2.3.-1. EFFECT OF AIR-FUEL RATIO ON EXHAUST HYDROCARBON CONCENTRATION OF PROPANE-FUELED SI-ENGINE[38]
(Single-Cylinder Engine, Speed 1360 rpm, Compression Ratio 9:1, Air-Flow Rate 8. 2 SCFM, Inlet Charge Temperature 135°F, Hydrocarbon Analysis by Gas Chromatography)

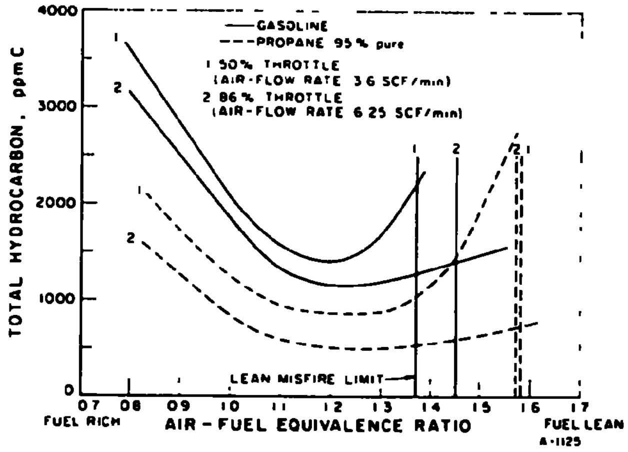


Figure 2.2.3.-2. EFFECT OF AIR-FUEL RATIO ON EXHAUST HYDROCARBON CONCENTRATION[56]
(CFR Engine, Engine Speed 1000 rpm, Compression Ratio 8:1, Ignition Timing 30 Deg. BTC, Inlet Charge Temperature 160°F, Hydrocarbon Analysis by FID)

We observe a substantial difference in the magnitude of the exhaust hydrocarbon concentrations between the two sets of research-engine data presented in Figures 2. 2. 3. -1 and 2. 2. 3. -2. The difference may be attributed to the different settings of other engine variables — such as airflow rate, engine speed, and compression ratio — and the difference in fuel composition as well as in the analytic method used in the investigation.

The composition of exhaust hydrocarbons of a propane-fueled SI-engine has not been found to vary with the air-fuel ratio.[38,39] The major components include propane, ethylene, methane, and acetylene (Table 2. 1. 3. -1). The concentration of propane in the exhaust tends to decrease from fuel-rich to stoichiometric and then increase as more air is added. The amount of methane and acetylene decreases rapidly from fuel-rich to stoichiometric and remains low. Ethylene and propylene content also decreases from fuel rich to stoichiometric but rises slightly in fuel-lean operations. Such trends were found to be true at various settings of ignition timing.

The air-fuel ratio also has a significant bearing on the exhaust concentration of carbon monoxide. As in the case of gasoline, the carbon monoxide concentration decreases rapidly from fuel rich to stoichiometric and remains low as more air is added (Figure 2.2.3.-3)

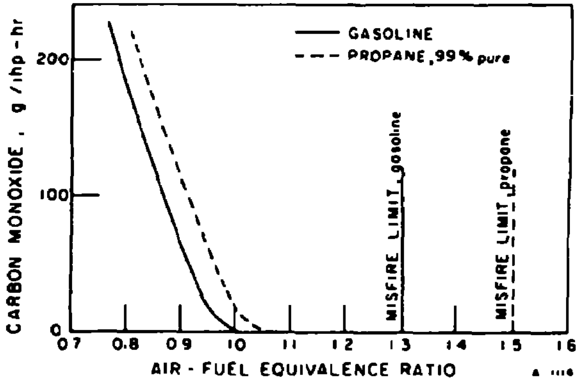


Figure 2.2.3.-3 EFFECT OF AIR-FUEL RATIO ON EXHAUST CARBON MONOXIDE CONCENTRATION [95]
(CFR Engine, Engine Speed 1000 rpm, Compression Ratio 8:1, Inlet Charge Temperature 125°F, Maximum Power Spark Timing, 80% Throttle Setting)

Once the air-fuel ratio is given, other engine variables — such as engine speed, ignition timing, and air-flow rate (or throttle setting) — have relatively little effect on the exhaust carbon monoxide concentration.[56,95] However, changing some engine variables changes the lean misfire limit of the engine

(Figure 2.2.3.-4) which can have significant bearing on the practicality of engine variable adjustment. The lean misfire limit will be further discussed later.

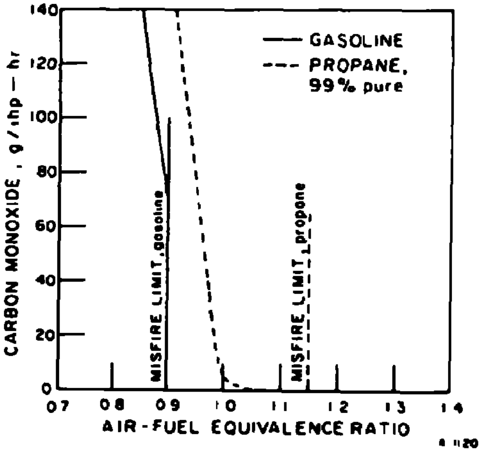


Figure 2.2.3-4 EFFECT OF AIR-FUEL RATIO ON EXHAUST CARBON MONOXIDE CONCENTRATION [95]
(CFR Engine, Engine Speed 1000 rpm, Compression Ratio 8:1, Inlet Temperature 125°F, Spark Timing 5 deg BTC, 30% Throttle Setting)

The fuel-air ratio is also the most significant single variable affecting the exhaust nitric oxide concentration in propane-fueled engines. In general, the nitric oxide concentration increases from both fuel-rich and fuel-lean settings and reaches a maximum at a fuel-air ratio slightly leaner than stoichiometric, which follows a similar pattern to that of gasoline (Figure 2.2.3.-5)

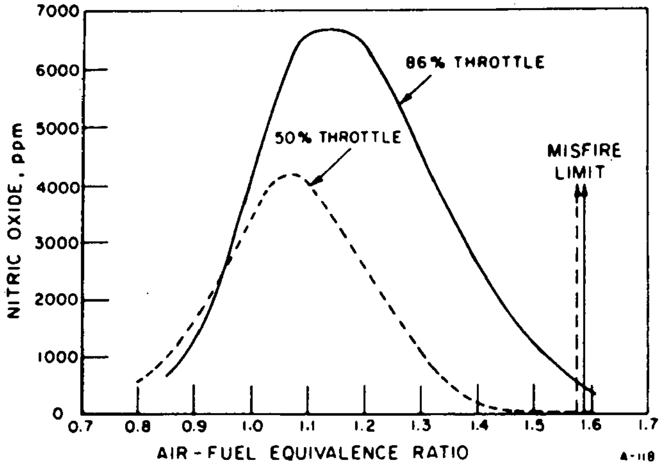


Figure 2.2.3.-5 EFFECT OF AIR-FUEL RATIO ON EXHAUST NITRIC OXIDE CONCENTRATION OF PROPANE 56
(CFR Engine, Engine Speed 1000 rpm, Compression Ratio 8:1 Ignition Timing 30 deg BTC, Inlet Charge Temperature 160°F, Nitrogen Oxides Analysis by NDIR)

Other engine variables such as ignition timing, throttle opening, and engine speed, also have a significant effect on nitric oxide concentration.

2.2.3.2. Ignition Timing and Engine Speed

As in gasoline-fueled engines, the concentration of exhaust hydrocarbons of propane-fueled SI-engines decreases at all air-fuel ratios, as the ignition timing is retarded (Figure 2.2.3.-6). The effect of ignition timing retardation on hydrocarbon emission is most pronounced at low engine speed. Increasing engine speed generally decreases hydrocarbon emission.

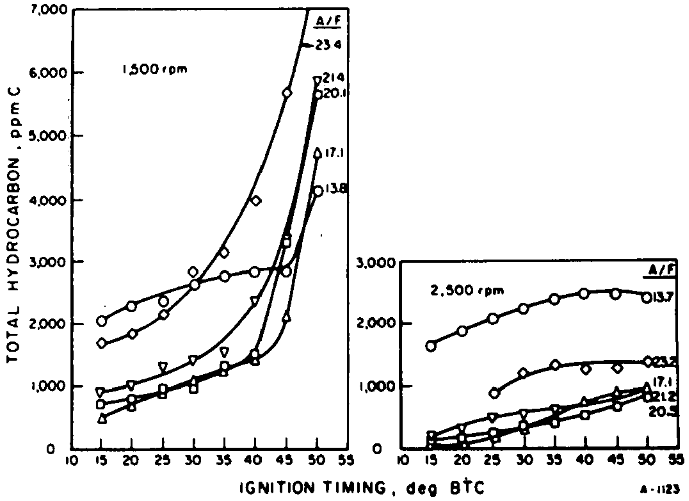


Figure 2.2.3.-6. EFFECT OF IGNITION TIMING ON HYDROCARBON EMISSION AT CONSTANT POWER 56
(Production V-8 Engine Maintained at Road Load and at Each A-F Ratio by Varying Throttle Position)

The effect of ignition timing on hydrocarbon emission at low engine speed is particularly important for indoor applications such as a lift truck where idling is a significant part of engine operation. It has been observed that additional retardation of spark timing at an air-fuel ratio slightly leaner than stoichiometric provides low hydrocarbon emission without increasing carbon monoxide emission or fuel consumption (Figure 2.2.3.-7)

The ignition timing has a very significant influence on nitric oxide emission with propane fuel. Generally, advancing the ignition time increases the concentration of nitric oxide. This effect is particularly evident at air-fuel ratios near the stoichiometric value (Figure 2.2.3.-8).

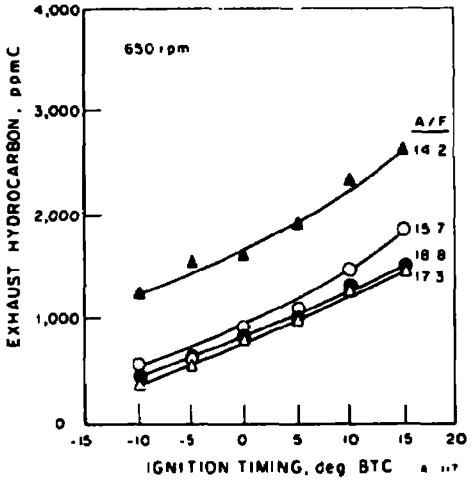


Figure 2.2.3.-7. EFFECT OF IGNITION TIMING ON HYDROCARBON EMISSION OF PROPANE-FUELED ENGINE AT IDLING SPEED [56]
(Production V-8 Engine Maintained at Road Load and at Each A-F Ratio by Varying Throttle Position)

At constant power output and ignition timing, increasing engine speed increases nitric oxide emission slightly. The increase is more pronounced with lean mixture ratios and is believed to be caused by the change in throttle setting.

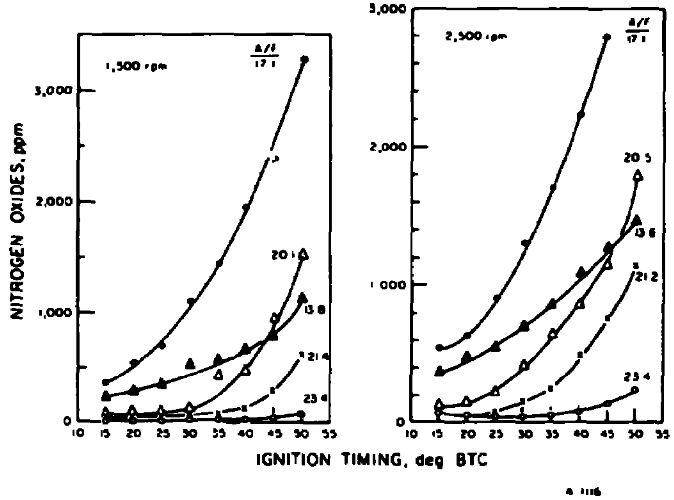


Figure 2.2.3.-8. EFFECT OF IGNITION TIMING ON NITRIC OXIDE EMISSION OF PROPANE-FUELED ENGINE AT CONSTANT POWER AND VARIOUS AIR-FUEL RATIOS [56]
(Production V-8 Engine Maintained at Road Load and at Each A-F Ratio by Varying Throttle Position)

2. 2. 3. 3. Throttle Position

In addition to the air-fuel ratio and ignition timing, another engine variable that is closely related to the exhaust emission level as well as engine power output of an SI-engine is the throttle position which determines the maximum power that can be extracted from the fuel.

However, the actual power obtainable is dependent on the fuel-air ratio of the mixture and ignition timing. Spark ignitions that are too early or too late yield less than the maximum power obtainable. And the maximum-power ignition, in turn, is a function of virtually every other engine parameter, both fixed and variable. Therefore, if some of the engine parameters — such as engine speed and fuel-air charge temperature — are fixed, the power output of an SI-engine may be determined by the combination of the three major engine variables — fuel-air ratio, ignition timing, and throttle position. The throttle position-fuel-air ratio-power output relationship of a propane-fueled CFR engine is illustrated in Figure 2.2.3.-9 in which the power output is expressed in terms of percent of maximum indicated mean effective pressure (IMEP) obtainable with gasoline under test conditions. (Maximum IMEP of gasoline is 133 calculated on the basis of combustion chamber pressure versus time relationship over the compression and expansion portions of the engine cycle.)

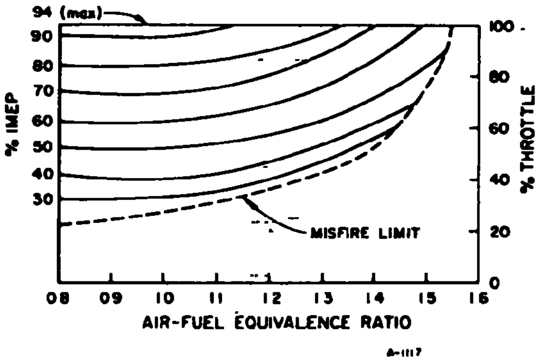


Figure 2.2.3.-9 POWER CONTOURS OF PROPANE-FUELED CFR ENGINE[95]
(At Maximum Power Ignition Timing, Engine Speed 1000 rpm, Compression Ratio 8:1)

It is indicated in Figure 2.2.3.-9 that various combinations of air-fuel ratios and throttle position will yield the same power level. For example, at the maximum-power ignition timing, the propane-fueled CFR engine will yield 40% IMEP at air-fuel equivalence ratio of 1.0 and 40% throttle.

The same power level can be produced at an air-fuel equivalence ratio of 1.25 and 55% throttle, or at 1.375 air-fuel equivalence ratio and 60% throttle. The range of air-fuel ratio - throttle position combinations is, as indicated by Figure 2.2.3.-9 widest at low and medium power levels, and becomes narrower as power level is increased. The power contours presented in Figure 2.2.3.-9 are established under certain given conditions. If these conditions, such as engine speed, compression ratio, and ignition timing, are changed, the shape of the power contours as well as the range of misfire limit will be changed also.

Since the exhaust emission level of an SI-engine is very much influenced by air-fuel ratio, it is obvious that various combinations of air-fuel ratios and throttle position will yield different emission concentrations. Furthermore, power contours for minimum hydrocarbon emission are different from those of minimum nitric oxide emission. An example of such a plot relating power levels to emission levels is presented in Figure 2.2.3.-10 in which emission-power level relationships for minimum HC and NO of both gasoline (premium grade, leaded) and propane are presented.

The data presented in Figure 2.2.3.-10 are based on maximum-power ignition timing for power levels greater than 25% IMEP (30% in the case of gasoline) and 5° BTC retarded ignition timing for power levels below 25% IMEP. The nitric oxide emission levels are obtained on the basis of the leanest possible air-fuel ratios for minimizing specific fuel consumption (not closer than five percentage points to the lean misfire limit). The hydrocarbon emission levels are obtained under the conditions selected for the nitric oxide emission, and are found to be quite close to that obtained on the basis of air-fuel ratios yielding the lowest hydrocarbon emission under the given test conditions. Therefore, neither the nitric oxide nor the hydrocarbon curves represent the lowest emission level obtainable at a given power level.

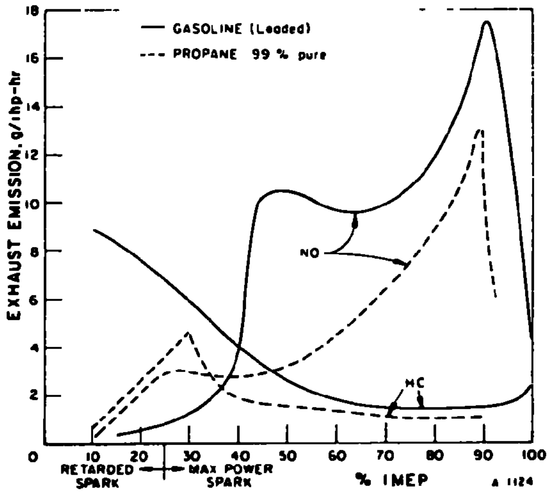


Figure 2.2.3.-10. EXHAUST EMISSION VERSUS POWER LEVEL FOR PROPANE-FUELED CFR ENGINE [95]
(CFR Engine, Engine Speed 1000 rpm, Compression Ratio 8:1, Inlet Charge Temperature 125° F)

As shown in Figure 2.2.3.-10 the highest nitric oxide emission of propane, 13 g/ihp-hr, occurs at 90% IMEP, and is obtained, according to information revealed by the reference, on the basis of leanest air-fuel equivalence ratio (1.11) capable of producing 90% IMEP at 100% throttle. However, the same power level can also be produced, according to Figure 2.2.3.-9 by other combinations of air-fuel ratio and throttle setting, such as 0.95 air-fuel equivalence ratio and 95% throttle which would yield a nitric oxide level of only 5.2 g/ihp-hr.

The reduction of nitric oxide as a result of fuel-rich operation has been clearly indicated in Figure 2.2.3.-5 which also shows that the effect of throttle position on nitric oxide emission is much less pronounced when the air-fuel ratios are less than stoichiometric. As the air-fuel ratio becomes leaner than stoichiometric, increasing the throttle opening is accompanied by a significant increase in nitric oxide emission.

The slightly fuel-rich operation at high power levels has another advantage in ignition retardation. It has been shown that retarding the ignition timing reduces nitric oxide emission. However, retarding the ignition timing from that of maximum power, reduces the engine power output. The amount of power reduction resulting from ignition retardation is much less at air-fuel ratios richer than stoichiometric.(See Section 2.4.1.) Therefore, further reduction in nitric oxide emission can be realized by retarding the ignition timing.

However, enriching the fuel-air charge at high-power operation increases the hydrocarbon and carbon monoxide emissions. The amount of increase in emission is proportional to the amount of fuel enrichment. The carbon monoxide emission, in particular, will be increased significantly if the fuel-air ratio is made richer than stoichiometric. Therefore, a compromise may be necessary if all three pollutants are to be kept within certain allowable limits. Furthermore, power output and fuel consumption also have to be considered and a compromise in engine performance may also be necessary.

Data presented in Figure 2.2.3.-10 also indicate that if the engine is operated in medium and low power levels, the pollution emission level can be kept low. Therefore, one way to reduce emissions is to use a powerful engine and operate it well below its maximum power output.

2.2.3.4. Compression Ratio

Increasing the compression ratio of an SI-engine increases the surface-to-volume ratio of the combustion chamber and the cylinder pressure. Theoretical calculations indicate that at compression ratios greater than 5, the exhaust hydrocarbon concentration of a propane-fueled engine increases with increasing combustion ratio, and the effect of compression ratio is more pronounced in engines with small cylinder volume.[183] Experimental results using a research engine also indicate that increasing the compression ratio from 7 to 11 increases the exhaust hydrocarbon concentration by 67%.[39]

2.2.4. Emission Characteristics of Methane

2.2.4.1. Air-Fuel Ratio

The effects of air-fuel ratio on exhaust hydrocarbons and carbon monoxide concentrations of methane-fueled engines follow a similar pattern to that of a propane-fueled engine. The hydrocarbon emissions decrease from both fuel-rich and fuel-lean settings and reach a minimum at air-fuel ratios slightly leaner than stoichiometric (air/methane = 16.9). The exact magnitude of hydrocarbon emission at each air-fuel ratio depends on the setting of other engine variables, notably ignition timing and throttle position.

As in the propane-fueled engines, the exhaust hydrocarbons of methane or natural gas powered engines have been found to consist primarily of unburned fuel.[95, 107] The olefinic hydrocarbon content in the exhaust is considerably lower than that of gasoline-fueled engines. The magnitude and composition of the exhaust hydrocarbons are influenced by the composition of the fuel — whether it is pure methane, liquefied natural gas (LNG), or pipeline natural gas of certain compositions.[107]

In a methane-fueled engine, the air-fuel ratio is also the single most important factor in determining the exhaust concentration of carbon monoxide. The carbon monoxide emission is associated primarily with fuel-rich engine operations and decreases very rapidly as the air-fuel ratio nears stoichiometric. Once the air-fuel ratios are leaner than stoichiometric, very little carbon monoxide emissions are observed. Once the air-fuel ratio is fixed, other engine variables have a relatively insignificant effect on carbon monoxide emission. The effect of air-fuel ratio on hydrocarbon and carbon monoxide emissions of a methane-fueled SI-engine is illustrated in Figure 2.2.4-1 in which natural gas rather than pure methane was used and airflow rate (throttle position) was varied.

The effect of air-fuel ratio on the exhaust nitrogen oxides concentration of a methane-fueled SI-engine also follow a similar pattern to that of a propane-fueled engine, increasing from both fuel-lean and fuel-rich settings

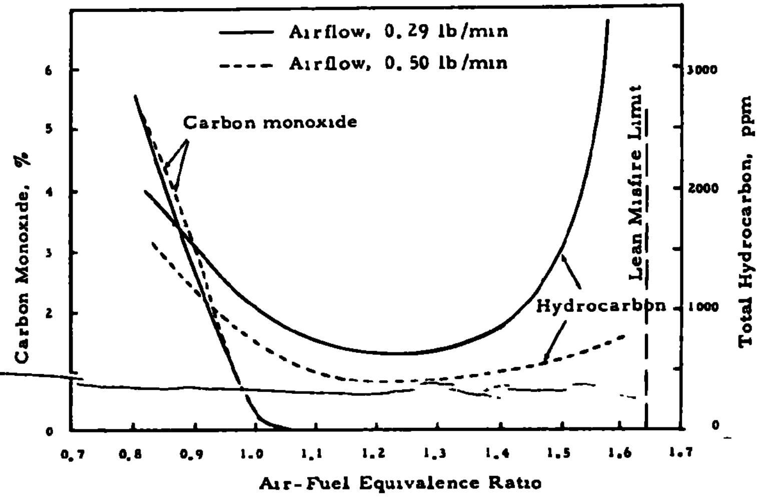


Figure 2.2.4.-1. EFFECT OF AIR-FUEL RATIO ON EXHAUST CARBON MONOXIDE AND HYDROCARBON CONCENTRATION OF NATURAL GAS-FUELED ENGINE[56]
(CFR Engine, Engine Speed 1000 rpm, Compression Ratio 8:1, Ignition Timing 30 deg BTC, Inlet Charge Temperature 160°F, Hydrocarbon Analysis by FID)

and reaching a maximum at an air-fuel ratio slightly leaner than stoichiometric. The exact magnitude of nitrogen oxide emissions at various air-fuel ratios is affected, similar to propane and gasoline cases by the settings of other engine variables, noticeably ignition timing and throttle opening. The effect of air-fuel ratios on nitrogen oxides emission of a methane-fueled engine is illustrated in Figure 2.2.4.-2. Again, natural gas instead of pure methane was used.

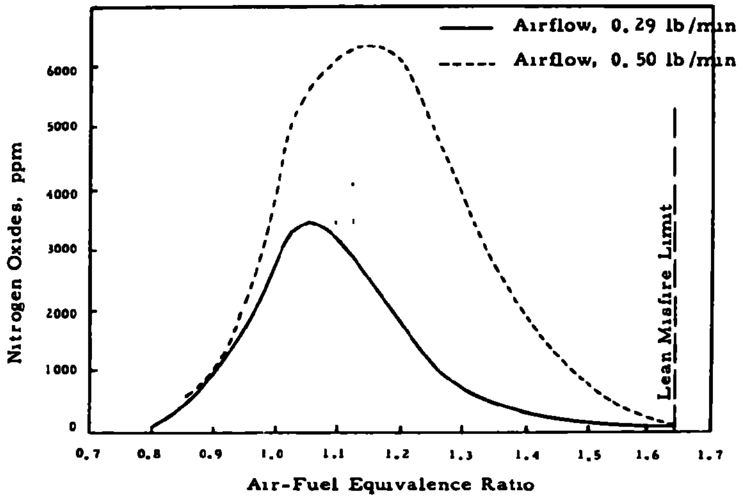


Figure 2.2.4.-2. EFFECT OF AIR-FUEL RATIO ON EXHAUST NITROGEN OXIDES CONCENTRAION OF NATURAL GAS-FUELED ENGINE[56]
(CFR Engine, Engine Speed 1000 rpm, Compression Ratio 8:1, Ignition Timing 30 deg BTC, Inlet Charge Temperature 160°F, Nitrogen Oxides Analysis by NDIR)

2.2.4.2. Throttle Position

The effect of throttle position on exhaust emissions of a methane-fueled SI-engine is also very similar to that of a propane-fueled one. In general, increasing the throttle opening of an engine increases the fuel consumption and power output, thus affecting the exhaust emissions. The throttle position has a very significant effect on the level of nitric oxide emissions, particularly at air-fuel ratios leaner than stoichiometric (Figure 2.2.4-2).

Increasing the throttle opening increases the filling of the engine cylinder with an air-fuel mixture and, therefore, the nitric oxide emission increases. At the same time, opening the throttle increases the total amount of air and improves the fuel combustion, thus reducing the hydrocarbon emissions. Since the amount of fuel inducted into the engine is also increased as a result of increasing the throttle opening at constant air-fuel ratios, the reduction of hydrocarbon emission is not as pronounced as the increase in nitric oxide emission.[95] The carbon monoxide emission, on the contrary, is not significantly affected by throttle position even at air-fuel ratios much richer than stoichiometric.[45,95]

It has been indicated that the low exhaust emission of an SI-engine is associated with engine operation at air-fuel ratios leaner than stoichiometric. Therefore, the potential of an engine fuel to reduce exhaust emission depends on its ability to burn in lean mixtures. Both methane and propane have shown that they are superior to gasoline in this important respect. In addition to the lower overall emission levels than that of gasoline, both methane and propane can be operated leaner than gasoline at any given throttle position without misfire (Figure 2.2.4.-3). Furthermore, both methane and propane, as indicated in Figure 2.2.4.-3 can be operated at leaner air-fuel ratios and at lower throttle settings than is possible with gasoline. These features enable an engine to be operated at lower load without producing significant carbon monoxide emission — a feature of significant importance in normal urban traffic and indoor vehicular engine applications.

2.2.4.3. Ignition Timing

Although detailed information is not available, it is believed that ignition timing has a significant effect on the exhaust emissions of a methane-fueled SI-engine. Furthermore, it is believed that the relationship between ignition timing and exhaust emissions of a methane-fueled engine is quite similar to that of a propane-fueled engine. Therefore, it can be surmised that

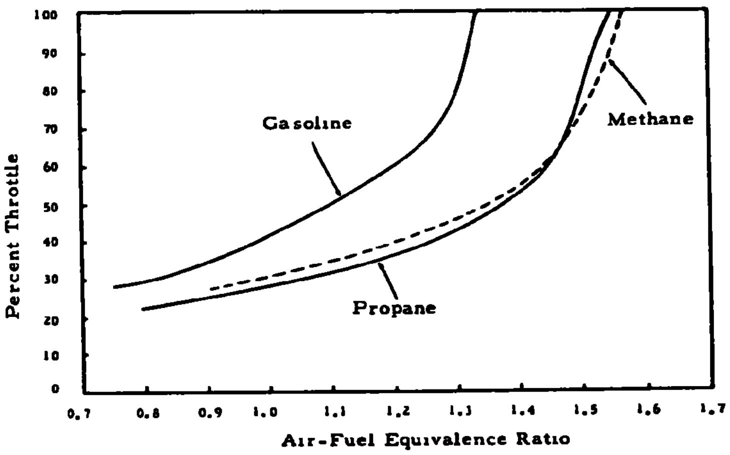


Figure 2.2.4-3. COMPARISON OF LEAN MISFIRE LIMITS[95] (CFR Engine, Engine Speed 1000 rpm, Compression Ratio 8:1, Maximum Power Ignition Timing, Inlet Charge Temperature, 125°F)

exhaust emissions of methane-fueled engines can be substantially reduced by retarding the ignition timing but at a sacrifice of engine performance.

Due to the lack of detailed information on the effect of engine variables on exhaust emissions it is not possible at this time to make an accurate comparison of the emission-reduction potentials of methane and propane. However, available information does indicate that these two gaseous fuels are quite similar in many respects, and methane is slightly better in terms of engine exhaust emissions — producing lower levels of carbon monoxide, hydrocarbons, and nitric oxide under identical conditions.[56,96]

2.2.5. Emission Characteristics of Ammonia

2.2.5.1. Combustion of Ammonia

The stoichiometric equation of ammonia combustion can be represented by:

$$4\ NH_3 + 3O_2 \rightarrow 6\ H_2O + 2\ N_2$$

With the absence of carbon in its structure, the combustion of ammonia yields no carbon monoxide and hydrocarbons. Oxides of nitrogen are the only combustion products considered to be harmful. However, in an engine fueled with ammonia, unburned ammonia is also exhausted. This could present a pollution problem.

In contrast to theoretical predictions based on the equilibrium concentration at peak cycle temperatures and pressures, ammonia has been found to produce more nitrogen oxides than gasoline,[32,107] as shown in Figures 2.2.5-1 and 2.2.5-2.

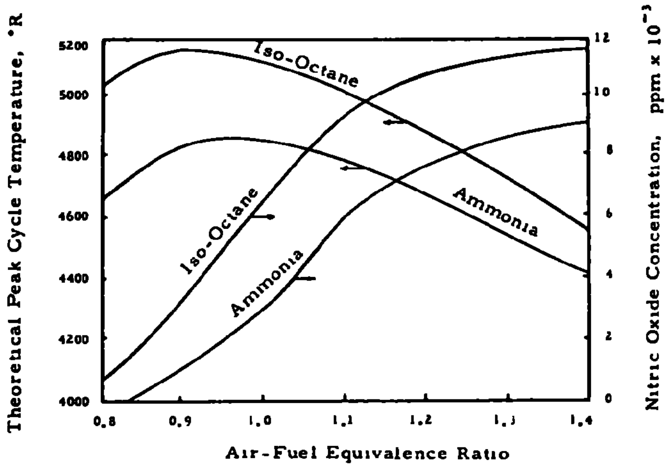


Figure 2.2.5-1. THEORETICAL PEAK CYCLE NITRIC OXIDE CONCENTRATION OF AMMONIA COMBUSTION[145]

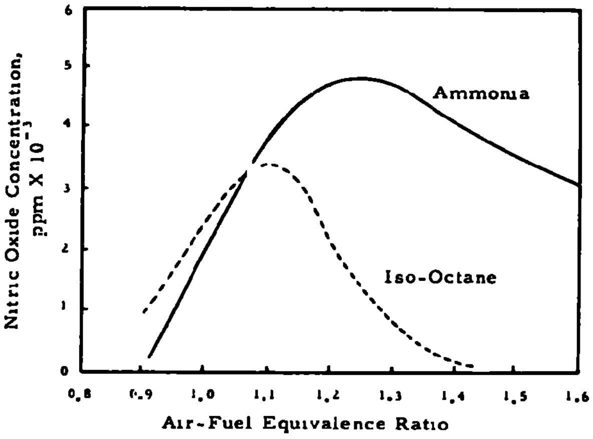


Figure 2.2.5.-2. NITROGEN OXIDES IN ENGINE EXHAUST[145]
(CFR Engine, Compression Ratio 10:1, Engine Speed 1800 rpm, Manifold Pressure 30 in. Hg)

2.2.5.2. Effect of Engine Variables

The exhaust nitric oxide concentrations of an ammonia-fueled SI-engine are found to increase when thermal efficiency of the engine increases. At 15% thermal efficiency the nitric oxide concentration was found to be 200 ppm, which increased to 1200 ppm at 30% thermal efficiency.[37] This relationship between nitric oxide concentration and thermal efficiency of the engine has been observed in gasoline-fueled engines.

The thermal efficiency of an SI-engine fueled with ammonia is dependent upon, similar to the gasoline-fueled engine, many engine variables, including air-fuel ratio, spark-ignition timing, and compression ratio.[37,72,158] In all cases, the adjustment of engine variables that increase the engine's thermal efficiency will also increase the exhaust nitric oxide concentrations. Hydrogen has also been used to improve the combustion of ammonia, which, in turn, increases the nitric oxide emission.

The slow-burning characteristics of ammonia causes a large quantity of unburned fuel to be expelled into the exhaust.[37,158] An ammonia concentration 81,000 ppm, calculated on dry basis, has been found in the engine exhaust.[37] The addition of 2% hydrogen reduces the nitric oxide concentration by 94%, down to 5300 ppm. The effect of hydrogen addition in ammonia is quite similar to that of increasing the air-fuel ratio on carbon monoxide emissions of gasoline-fueled engines. In addition to adding hydrogen, other potential methods of reducing exhaust ammonia include catalytic conversion of ammonia to hydrogen and nitrogen, chemical conversion, and ammonia adsorption. Supercharging the ammonia has also been found effective in reducing unburned ammonia.[28,135,138]

In fact, nitric oxide concentrations as high as 1.5 to 4.5% have been measured in the cylinders of an ammonia-fueled SI-engine. The nitric oxide concentrations in the exhaust are substantially reduced from that found in the cylinder, but are still significantly higher than that of gasoline-fueled engines.

The high nitric oxide concentrations produced by ammonia combustion led some investigators to believe that a part of the nitric oxide is formed through pyrolytic reactions in which nitric oxide may be evolved from HNO radicals which, in turn, are evolved from successive kinetic steps in the oxidation of ammonia.[125,145,159]

2.2.6. Emission Characteristics of Blended Gas

Lee and Wimmer[95] tested the emission characteristics of a fuel gas having the following composition:

Methane	35.3% (mole basis)
Hydrogen	30.0%
Carbon Monoxide	3.3%
Carbon Dioxide	16.4%
Water	15.0%

It was found that this fuel gas, produced by the steam reforming of hexane, provides satisfactory performance as an engine fuel and produces lower exhaust emissions than either propane or methane. The reduced emissions were attributed to the presence of hydrogen which extends the lean misfire limits of methane. However, in view of the composition of the fuel gas, the presence of inerts — carbon dioxide and water — can also be credited with the reduced emissions, particularly in nitric oxide emissions.

The ability of hydrogen to extend the lean misfire limit of hydrocarbon fuels is well known. However, due to hydrogen's high burning velocity, only a limited amount of hydrogen can be incorporated without experiencing knock or other engine performance problems. However, recent investigations into the combustion of pure hydrogen in an SI-engine indicate that hydrogen can be successfully used by utilizing special fuel-injection techniques.[140] Moreover, it was found, in contrast to predictions on the basis of peak cycle temperature, that a research SI-engine fueled with hydrogen produces surprisingly low emissions of nitric oxide.[140] Thus, there is no reason to doubt that hydrogen cannot be blended with methane to further reduce the level of exhaust emissions.

2.2.7 Emission Characteristics of Hydrogen

As in the case of ammonia, the combustion of hydrogen yields no carbon monoxide or hydrocarbons. The only stoichiometric product of hydrogen combustion is water. Hydrogen's wide limits of flammability when mixed with air (4.1 to 74% hydrogen in air) enable the combustion to take place at extremely fuel-lean and fuel-rich conditions, greatly reducing the possibility of incomplete combustion in an engine Therefore, as an engine fuel, the only pollution concern of hydrogen, particularly in view of its high heat of combustion, is its emission level of nitrogen oxides.

Recent studies sponsored by the Air Pollution Control Office, Environmental Protection Agency, and conducted at Oklahoma State University indicated that with the use of suitable fuel injection, a spark-ignition internal combustion engine can be fueled with hydrogen.[190] One of the test engines involved in the study was a modified four-stroke, air-cooled, single cylinder 3.5 horsepower Clinton Model 494-0301 engine equipped with a special gaseous hydrogen injection system. The operation of the test engine was found to be quite satisfactory and the emission level of nitrogen oxides surprisingly low. A comparison of nitrogen oxides emission of this engine to that of similar gasoline- and benzene-fueled research engines is presented in Figure 2.2.7.-1.

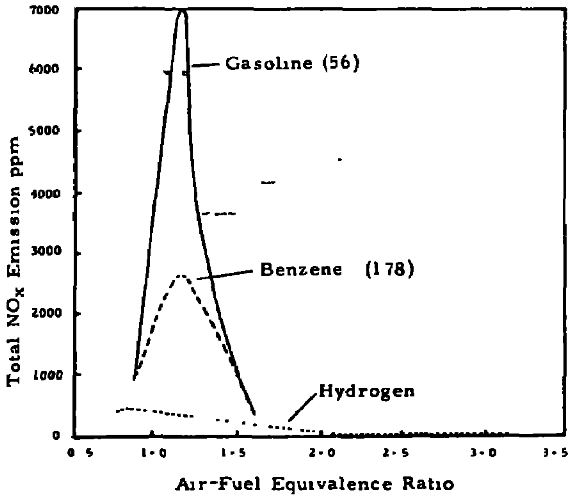


Figure 2.2.7.-1. EMISSION OF NITROGEN OXIDES OF A HYDROGEN-FUELED SI-ENGINE[190] (Spark timing 7°BTC, Compression Ratio 8 1. Engine speed 2000-4000 rpm, wide-open throttle)

The results indicate that the peak nitrogen oxides emission occurred at peak engine power output — which is synonymous with fuel-rich operation under the test conditions. The magnitude of nitrogen oxides emission of the hydrogen-fueled engine at peak power was found, however, to be much lower than that of other common gaseous fuels. Further reduction of this magnitude can be obtained by increasing the air-fuel ratio. As in the case of hydrocarbon-fueled engines, increasing the air-fuel ratio of the hydrogen-fueled engine decreases the power output, but the amount of reduction in engine power output, due to hydrogen's high flammability is considerably less than that of other fuels.

The data presented in Figure 2.2.7.-1 also indicate the extended lean misfire limit of hydrogen is greater than 3.0 (as compared to 1.4 for gasoline and 1.7 for propane and methane), which indicates that the nitrogen oxides emission can be significantly reduced if an automotive engine can be suitably converted to hydrogen.

It should be noted, however, that the NO_x emission shown in Figure 2.2.7.-1 are much lower than we have any reason to expect in view of the relatively high combustion temperature of hydrogen. This leads to speculation as to the possibility that some of the NO_x formed may not have been measured in the exhaust gas. It is at least possible that some nitric oxide may have combined with the water present and was separated out before the remaining exhaust gas was analyzed for NO_x.

These data demonstrate the attractions of hydrogen as a clean motor fuel from the combustion viewpoint However, the broad air/fuel range that makes it attractive also makes it more hazardous from a safety standpoint. It is possible by the use of hydrogen mixtures, such as hydrogen and methane for example, to reduce the explosive mixture range and still provide suitable misfire limits. Much more work needs to be done with such mixtures however before a suitable fuel mixture can be found that will meet the safety and logistics requirements of motor fuels in addition to the combustion requirements.

2.3. Vehicular Exhaust Emissions

2.3.1. Exhaust Emission Testing Procedure

The first regulation on automotive exhaust emissions was established by the California State Department of Public Health in 1959 in which standards for exhaust concentrations of hydrocarbons and carbon monoxide were adopted.[30] This early regulation was later expanded to cover crankcase, fuel tank, and carburetor emissions and to include detailed testing procedures for measuring automotive exhaust emissions, including the 7-mode driving schedule (Figure 2.3.1.-1).

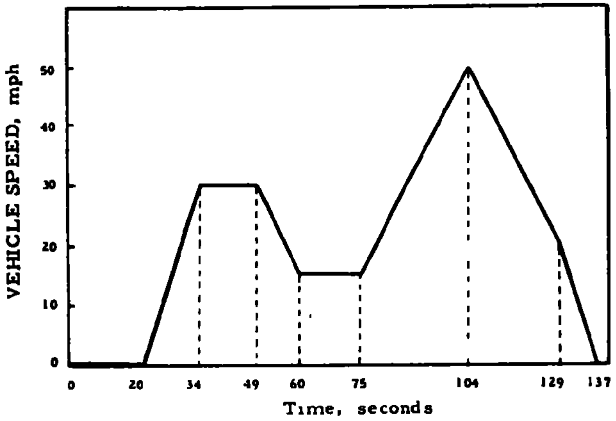


Figure 2.3.1.-1 DRIVING SCHEDULE OF CALIFORNIA 7-MODE CYCLE TESTING PROCEDURE[31]

The California testing procedure was later modified and adopted by the Federal Government and became the 1970 Federal automotive exhaust emission testing procedure.[169,170]

The early automotive exhaust emission regulations were expressed in terms of concentration of pollutants in the exhaust. Such regulations allow cars with higher exhaust flow rates to discharge a greater weight of emissions into the atmosphere. Thus, attempts were made to make the emission measurement more equitable, and resulted in regulations based on emission weight.

Various mass emission measurement techniques have been proposed, including the proportional sampler, fuel flow with exhaust concentrations, total bags, exhaust flow rate with concentrations, and the constant volume sampler recently proposed by the Air Pollution Control Office (APCO).[24] However, each of the proposed techniques had, at the time they were proposed, certain limitations although most of these techniques have been used by some investigators over the years. Therefore, the 1970 Federal standards were adopted on the basis of calculated mass emissions.[170]
This calculation requires measurement of the emission concentrations in the exhaust and then assumes an average exhaust volume flow rate for each weight class of vehicle. While this procedure on the average requires equal mass emission control for different size vehicles, it does not recognize the variation in the exhaust volume flow rate for different vehicles in the same weight class.

Since it was first proposed, changes and improvements have been made in the constant volume sampler technique that appears to have solved many of the problems found in the earlier mass emission techniques. The constant volume sampler (CVS) technique measures a constant volume of a mixture of exhaust gas and dilution air. A small sample of the exhaust flow is stored in a plastic bag and the concentration is then measured. Since the total air flow and sample flow are known, the actual mass of each constituent of the exhaust can easily be measured. This emission test procedure has been proposed by APCO to be used for 1972 and later new vehicle certifications.[114,171]

2.3.2. Effect of Testing Procedure on Exhaust Emission Data

During the development of a suitable testing procedure for measuring exhaust emission, many changes were made in practically all parts of the procedure, including vehicle preparation, driving schedule, test cycle, weighting factors, method of calculations, and instrumentation. Each change made in the test procedure invariably affects the final emission data. For example, the effect of driving schedule and weighting factors on emission measurement can be seen in Figure 2.3.2.-1, which illustrates the emission levels of a gasoline-fueled vehicle under various modes of driving.

The data presented in Figure 2.3.2.-1clearly indicate that the level of exhaust emissions vary markedly among the various driving modes. From the concentration point of view, the two deceleration modes have the highest levels of hydrocarbons and carbon monoxide while the two acceleration modes are highest in nitrogen oxides. However, after the introduction of assigned weighting factors, it becomes evident that the two acceleration events are the largest emission contributors. The significance of these two events can be further illustrated by the effect of changes made in the acceleration mode on emission measurement (Figure 2.3.2.-2).

In addition to the driving schedule, there are other factors related to the test cycle that are equally important in determining the final emission levels These include the starting condition of the engine — hot or cold, soak time of the engine, and whether the test cycle is open or closed. Therefore, unless the driving schedule, test cycle, and many other related factors are exactly alike, the emission measurements of a vehicle made under different test conditions can be significantly different.

The analytic instrumentation as well as sampling technique are also known to have intimate influence on emission measurement. For example, two of the most commonly used techniques for determining exhaust hydrocarbon emission are nondispersive infrared(NDIR) analysis and flame ionization detector (FID). The NDIR technique has fast response capable of following

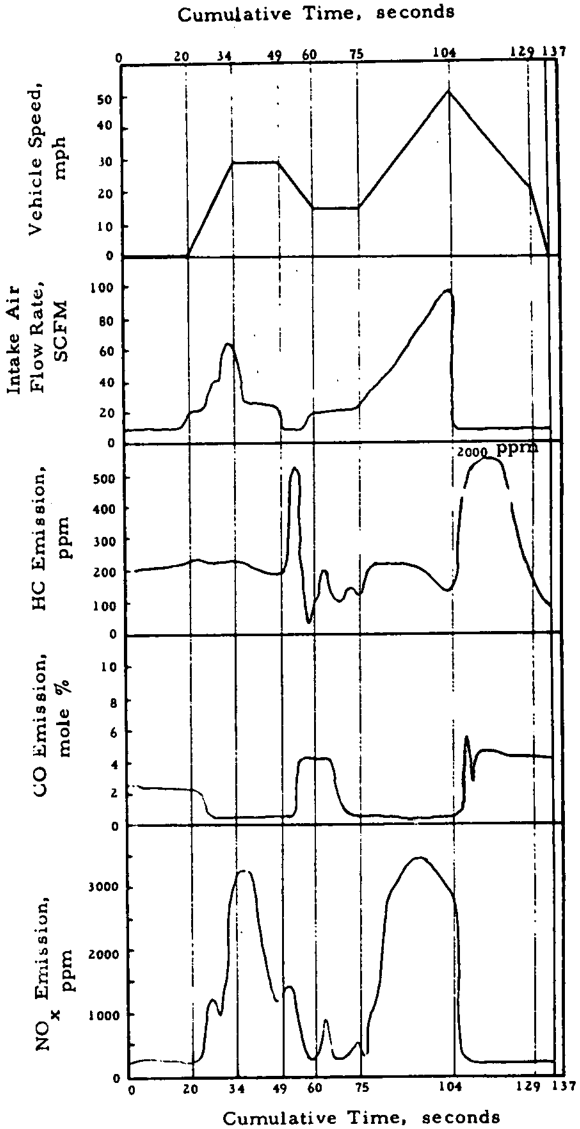
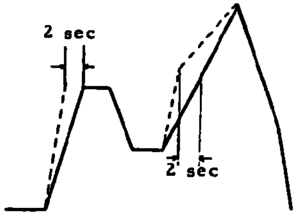


Figure 2.3.2.-1EXHAUST EMISSIONS OF A GASOLINE-FUELED VEHICLE UNDER VARIOUS MODES OF DRIVING[163]

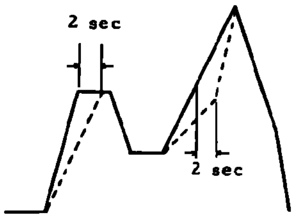


Faster Acceleration

Exhaust Volume, 46.28 CF/mile

Exhaust Emission

$CO = 1.24\%$ (19.2 gm/mile)
$HC = 318$ ppm (2.60 gm/mile)
$NO_x = 1560$ ppm (3.80 gm/mile)



Slower Acceleration

Exhaust Volume, 43.72 CF/mile

Exhaust Emission

$CO = 1.52\%$ (22.0 gm/mile)
$HC = 307$ ppm (2.37 gm/mile)
$NO_x = 965$ ppm (2.35 gm/mile)

Figure 2.3.2.-2 EFFECT OF ACCELERATION CHANGE ON EXHAUST EMISSION MEASUREMENT[105]
(4-Cylinder Gasoline-Fueled Vehicle, Federal 7-Mode Hot Cycle)

rapid exhaust concentration changes from the cyclic operation of a vehicle; but it is known to have unequal response to various hydrocarbons. If n-hexane is used as sensitizer in NDIR analysis, only paraffins will respond properly, while olefins, acetylenes, and aromatics, that are structurally different from n-hexane, will give lower response values. The FID, on the other hand, eventually gives the same response, on a total carbon basis, to all hydrocarbons but requires proper flame conditions, i.e., a proper ratio of hydrogen-oxygen-nitrogen for accurate measurement. The FID is found to be slower than NDIR in response time and vulnerable to oxygen interference.[71,164] The significant differences between these two techniques prevent the direct comparison of hydrocarbon emission measurements. In general, the FID technique gives a substantially higher level of hydrocarbons than the NDIR analysis. An accurate conversion or comparison of the emission data using these two techniques requires accurate correlation data.

A similar situation is also found in a nitrogen oxide determination in which various techniques — such as phenoldisulfonic acid (PDA) methods, Saltzman and modified Saltzman methods,[73] mass spectrometric technique,[32,125] nitrous fume analyzer, nitrogen dioxide colorimeter, and nondispersive infrared analysis — have been proposed and used in many investigations. Although a comparison of measurement data can be made more accurately than in the case of hydrocarbons, it may also require suitable correlation information particularly at low concentration levels.

2.3.3. Exhaust Emission of Gasoline-Fueled Vehicles

Since the gasoline-fueled spark-ignition internal combustion engine was first invented, efforts in the automotive industries have been aimed primarily at improving its performance. During the last decade, however, increasing attention has been placed upon the control of pollution emissions. In 1966, the first legislative regulation was established to curtail the automotive emissions. As a result, changes were made in the design of gasoline-fueled engines to meet the immediate needs. Additional efforts in research and development are also being made toward the realization of a "pollution-free" vehicle. The challenge that the automotive industry faces can be illustrated by the forthcoming Federal regulations of automotive emission control (Table 2.3.3.-1).

To meet the emission standards established in 1966 and 1970, some changes and innovations in engine design have been made primarily to reduce the hydrocarbon and carbon monoxide emissions. These changes include the following:

- Closed positive crankcase ventilation (PCV) system to prevent crankcase exhaust emission.[62,63,75]

Table 2.3.3.-1. PROGRESSION OF AUTOMOTIVE EMISSION STANDARDS

Emission	Preemission Control Vehicle Pre-1966	1966 California Standard	1970 Federal Standard	1972 Federal Standard	Proposed Federal Standard 1975	Proposed Federal Standard 1980
Exhaust						
Hydrocarbons, gm/mile	13-16	3.5	2.2*	3.4	0.5	0.25
Carbon Monoxide, gm/mile	83-130	36	23*	39	11	4.7
Nitrogen Oxide, gm/mile	3.5-7	--	--	--	0.9	0.4
Particulates, gm/mile	0.3	--	--	--	0.1	0.03
Evaporative, gm/test	50	--	--	2	6%	6%
Crankcase, gm/day	100	--	--	Nil		

* Converted from concentration values (180 ppm HC and 1% CO) on the basis of average 4000-lb cars.

- Fuel evaporation control system for stopping evaporative emission. System includes thermal-expansion fuel tank, venting system for fuel vapor, carbon vapor-adsorption canistor and air-purging system, and carburetor vapor control.[41,144,147]
- Exhaust air injection system — injecting air into exhaust port or manifold for oxidizing exhaust hydrocarbons and carbon monoxide. System includes engine-driven air pump, antibackfire and check valves.[26,144,147]
- Modified ignition system — retarded ignition timing at idle and low engine speed, transmission controlled vacuum advance at low engine speed for maintaining retarded timing, and temperature override for advancing spark timing at high engine temperatures.[144,147,181]
- Modified carburetion — heated intake manifold for improving uniformity of air-fuel charge and its distribution among cylinders, increased idle speed at leaner air-fuel ratio, deceleration throttle control for reducing "decel" hydrocarbon emissions, leaner air-fuel ratio at power mixture for reduced hydrocarbon emission during acceleration, and heated intake air to maintain near-constant air temperature.[10,91,144,147]
- Modified combustion chamber design — reduced surface-volume ratio, sealed piston-ring orifices, and contoured cylinder head gasket.[51,99,131,133]

With these engine modifications, the automotive industry has been able to produce vehicles meeting the 1970 Federal standards for exhaust hydrocarbon and carbon monoxide. However, since further reduction in both hydrocarbon and carbon monoxide emissions and control of nitrogen oxide emission were proposed for 1975 and 1980, it has been apparent that the engine modifications listed above alone would not meet the requirement. One example is the exhaust manifold air injection system whose effectiveness is dependent upon engine operation because of the variations in the exhaust temperature, exhaust port static pressure, flow rate, and hydrocarbon concentration during the exhaust cycle. Thus, with the air injection system alone, there exists a limitation in the maximum possible reduction in hydrocarbon and carbon monoxide emissions. The continuing research and development efforts to further reduce the exhaust emission of a gasoline-fueled SI-engine include the following:

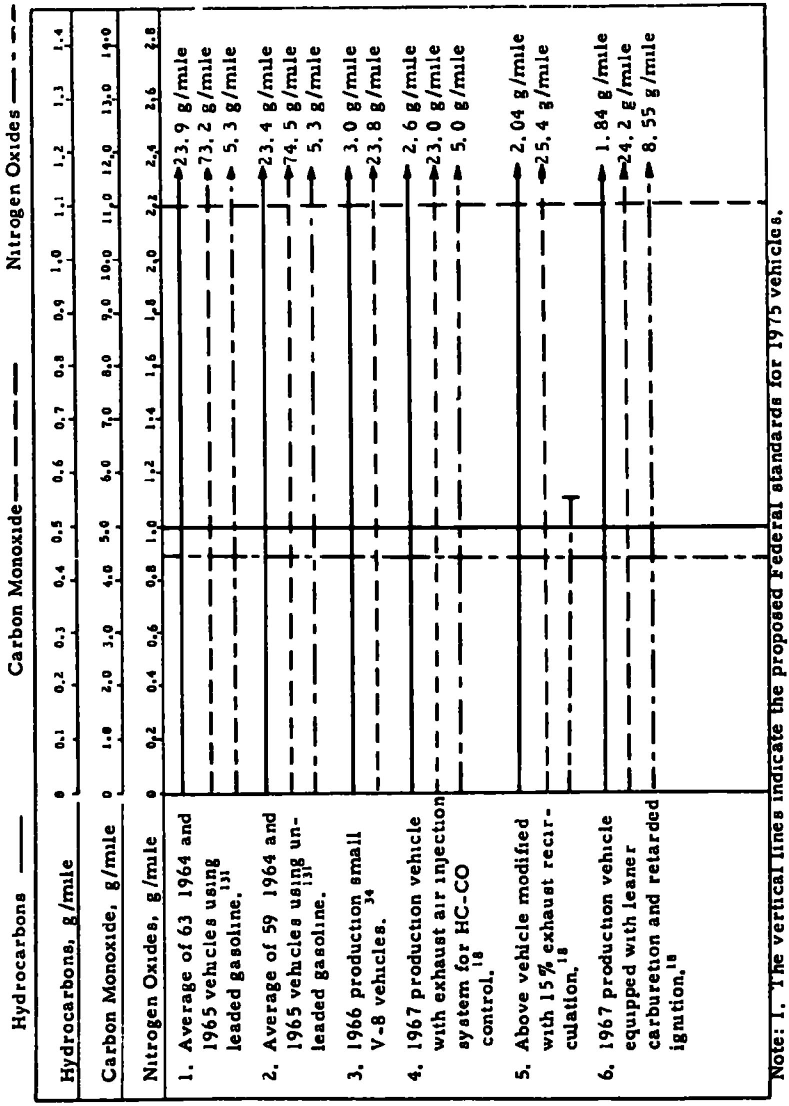
- Exhaust recirculation for reducing nitrogen oxide emission. Recycling up to 15% of exhaust gas has been proposed.[18,67,122,128,141,181]

- Modified carburetion for enriched fuel-air mixture at high power operation.[2,41,181]
- Exhaust thermal reactor to improve the effectiveness of air injection system and to allow enriched operation for lowering nitrogen oxide emission without sacrificing the hydrocarbon and carbon monoxide control.[33,45,66,148]
- Development and optimization of catalytic coverter systems for reducing hydrocarbon and carbon monoxide emissions.[149]
- Development of catalytic converter systems for reducing nitrogen oxide emissions.[8,9,75,150]

The results of research and development and improvements made in exhaust emission control of gasoline-fueled vehicles are summarized and tabulated in graphic form in Figure 2.3.3.-2, in which all data are on the basis of either California 7-Mode or 1970 Federal 7-Mode testing procedures, and were converted to weight basis using a vehicle weight of 4000 lb. Some of the data are hot-cycle values while others are composite-cycle values. The hydrocarbon emissions are based on NDIR analysis.

Recent results of research and development efforts have indicated the approach that automotive and oil industries are taking to meet the immediate needs in exhaust emission control of gasoline-fueled vehicles. It has been indicated that, prior to the development of emission-free engines, the vehicles to be produced in the next few years most likely will have catalytic converters for reducing exhaust emissions to the levels of proposed 1975 and 1980 standards. The vehicles may also have exhaust recirculation, enriched carburetion during power-mode operations, and retarded ignition timing for reducing the nitrogen oxide output. There will be an air injection and exhaust thermal reactor system for post-exhaust oxidation of hydrocarbons and carbon monoxide emissions that are increased as a result of engine adjustment for controlling nitrogen oxide. The pollutants coming out of the exhaust thermal reactors will be reduced by the catalytic converters. In order to maintain the effectiveness of catalytic converters, the use of unleaded gasoline may become mandatory.

Figure 2.3.3.-1. IMPROVEMENTS MADE IN EXHAUST EMISSION REDUCTION OF GASOLINE-FUELED VEHICLES



Note: 1. The vertical lines indicate the proposed Federal standards for 1975 vehicles.
2. Some of the emission values are estimated weight-based figures converted from concentrations by assuming 4000 lb vehicle weight and automatic transmission, and using 1970 procedure.

Figure 2.3.3.-1. Continued. IMPROVEMENTS MADE IN EXHAUST EMISSION REDUCTION OF GASOLINE-FUELED VEHICLES

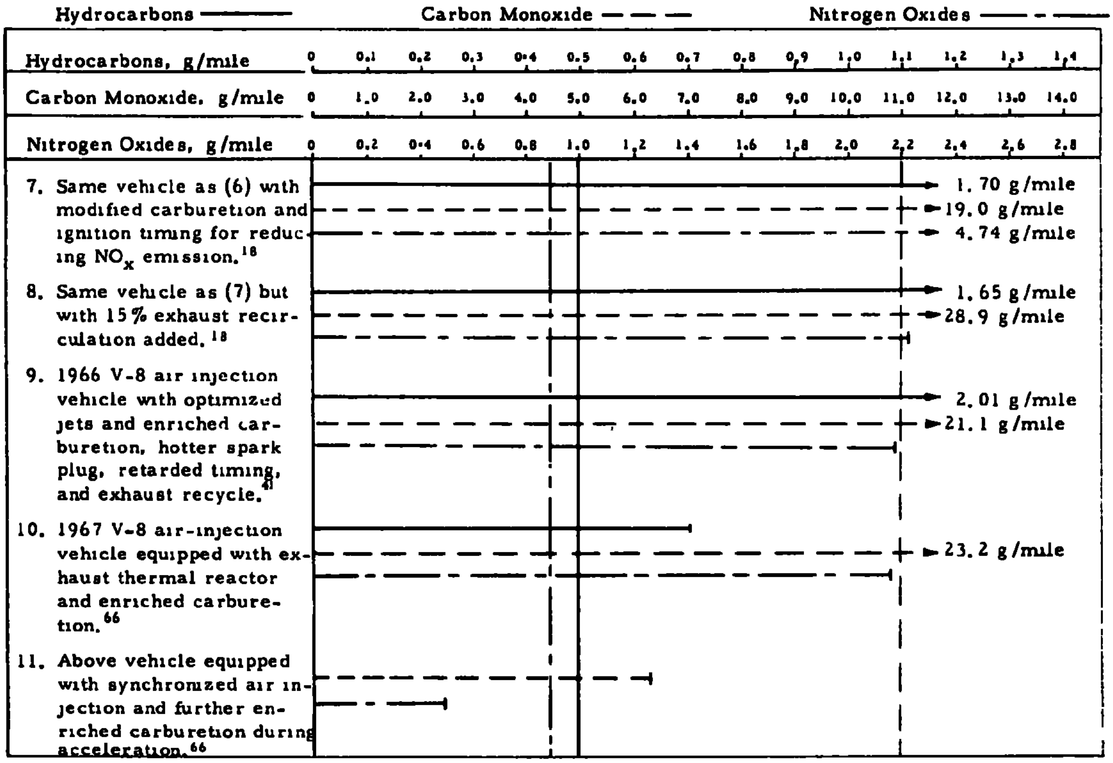
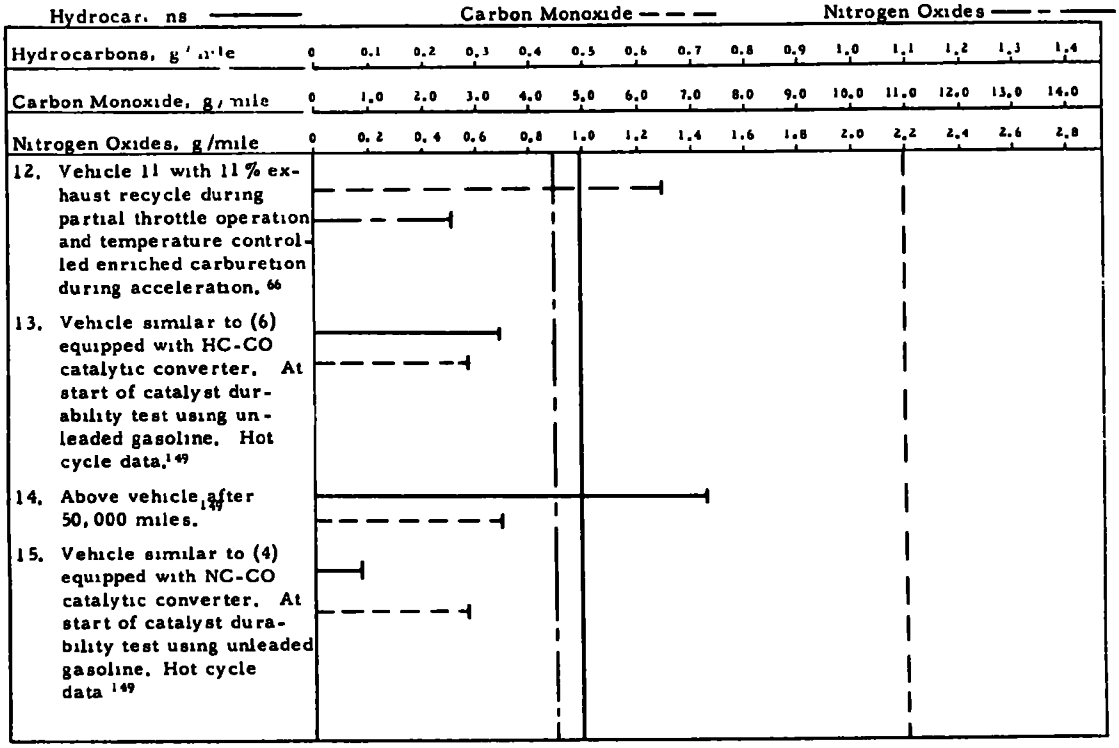


Figure 2.3.3.-1 Continued. IMPROVEMENTS MADE IN EXHAUST EMISSION REDUCTION OF GASOLINE-FUELED VEHICLES



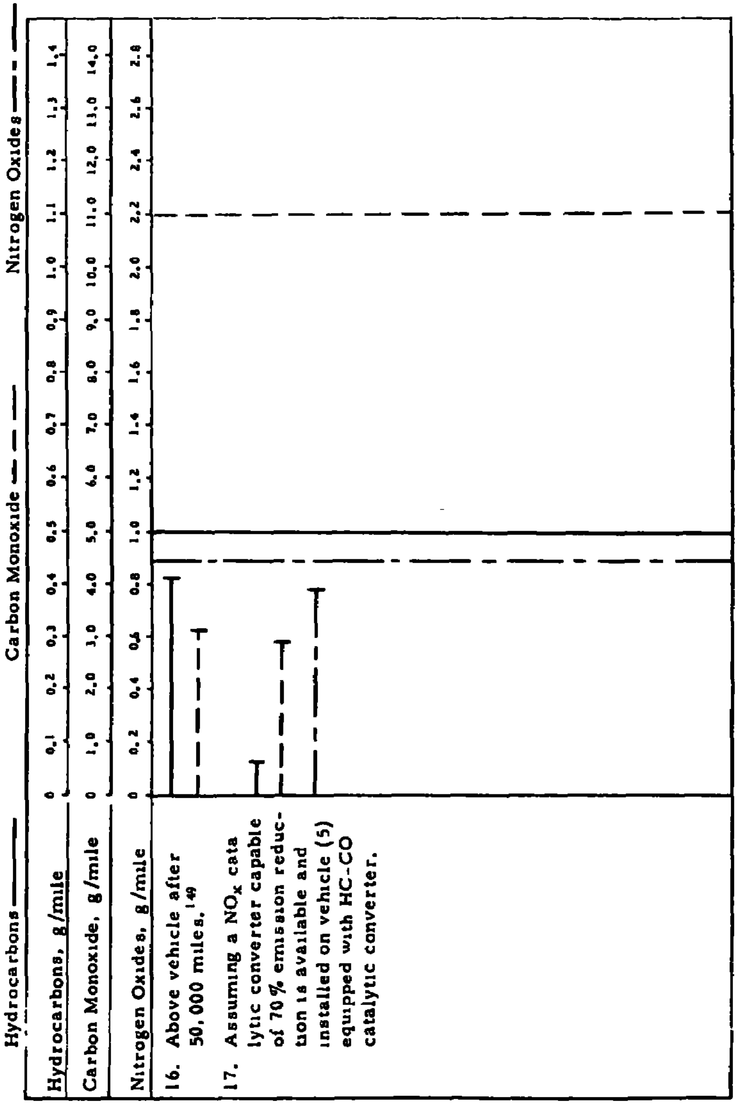


Figure 2.3.3-1. Continued. IMPROVEMENTS MADE IN EXHAUST EMISSION REDUCTION OF GASOLINE-FUELED VEHICLES

The vehicles described above are rapidly becoming a reality and the reduction in exhaust emission can be envisioned. However, there are some questions concerning the durability of the emission-control subsystems. Looking at the standards proposed for 1975 and 1980, one can easily realize the narrow allowable margin for maladjustment or malfunctioning of the future engine and its emission control subsystems. This situation can be illustrated by the results of vehicular emission tests conducted on 1970 vehicles by the New Jersey State Department of Health (Table 2.3.3.-2).

Table 2.3.3.-2. AVERAGE EMISSIONS OF 1970 VEHICLES TESTED ACCORDING TO THE NEW JERSEY ACID CYCLE PROCEDURE[49]

	Exhaust Emission	
	Hydrocarbons	Carbon Monoxide
	gm/mile	
New Jersey ACID Cycle	4.5	50
1970 Federal Standard	2.2	23

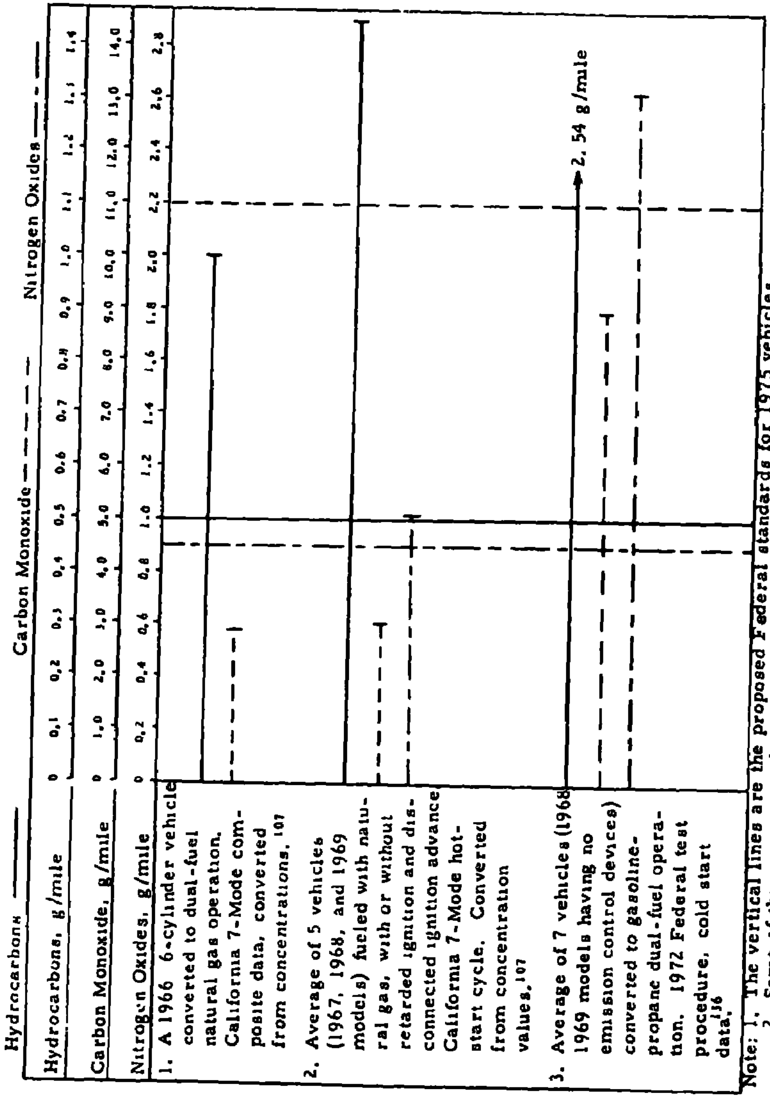
Since all 1970 vehicles are assumed to have passed the emission standards established for 1970, and the cited reference has indicated that the New Jersey ACID cycles results correlate with the Federal procedure results, the difference in exhaust emission indicated in Table 2.3.-2 can only be attributed to the deterioration of emission-control engine adjustment and systems. Under the stringent standards proposed for 1975 and 1980, the problem of maintaining emission control systems will be much more difficult.

2.3.4. Exhaust Emission of Gaseous Fuels Powered Vehicles

Although some of the gaseous fuels, particularly propane or LPG, have been used as motor fuel for some time, the exhaust emission of these vehicles has been taken for granted and has not been investigated in depth until recently. Therefore, information on the exhaust emission of vehicles powered by gaseous fuels as a function of engine design and operation are very limited. Even propane or LPG – the best known gaseous fuel, has only been investigated on the basis of simple fuel conversion on existing gasoline-fueled vehicles for the purpose of either single-fuel or dual-fuel operation. The conversion usually involves the installation of a gaseous fuel storage tank and fuel line system, a pressure regulator, a fuel-air mixer, and a vaporizer if LPG or liquefied natural gas (LNG) is used. Some engine adjustments, such as ignition retardation, blocked manifold heat riser, and/or disconnection of vacuum ignition advance, may also be involved. The emission data of some of the converted vehicles are presented in Figure 2.3.4.-1.

Comparing the data presented in Figures 2.3.3.-1 and 2.3.4.-1, it is apparent that a simple conversion of existing vehicles from gasoline to propane or methane results in a significant direct reduction in exhaust emissions, particularly in hydrocarbons and carbon monoxide, although not enough to meet the 1975 Federal standards. The available information also indicates that a simple switch of fuel from gasoline to gaseous fuels alone, or together with some simple adjustment of engine variables, will not meet the requirement. However, when propane or methane is used, the degree of engine adjustment required for exhaust emission reduction is less than that of gasoline. According to information derived from studies made for gasoline-fueled vehicles, it is apparent that many innovations made for emission reduction are also applicable to propane and methane due to their similar combustion characteristics. For example, there is no reason to doubt that in a propane or methane-fueled vehicle, the nitric oxide emission would be reduced by exhaust recirculation, or the hydrocarbon and carbon monoxide emissions would be reduced by the installation of exhaust thermal reactors. It has also been known that catalytic converters designed for gasoline would work well with propane and methane. In fact, the absence of lead and the relatively simple composition and clean combustion of

Figure 2.3.4-1. EXHAUST EMISSIONS OF VEHICLES CONVERTED TO GASEOUS FUELS



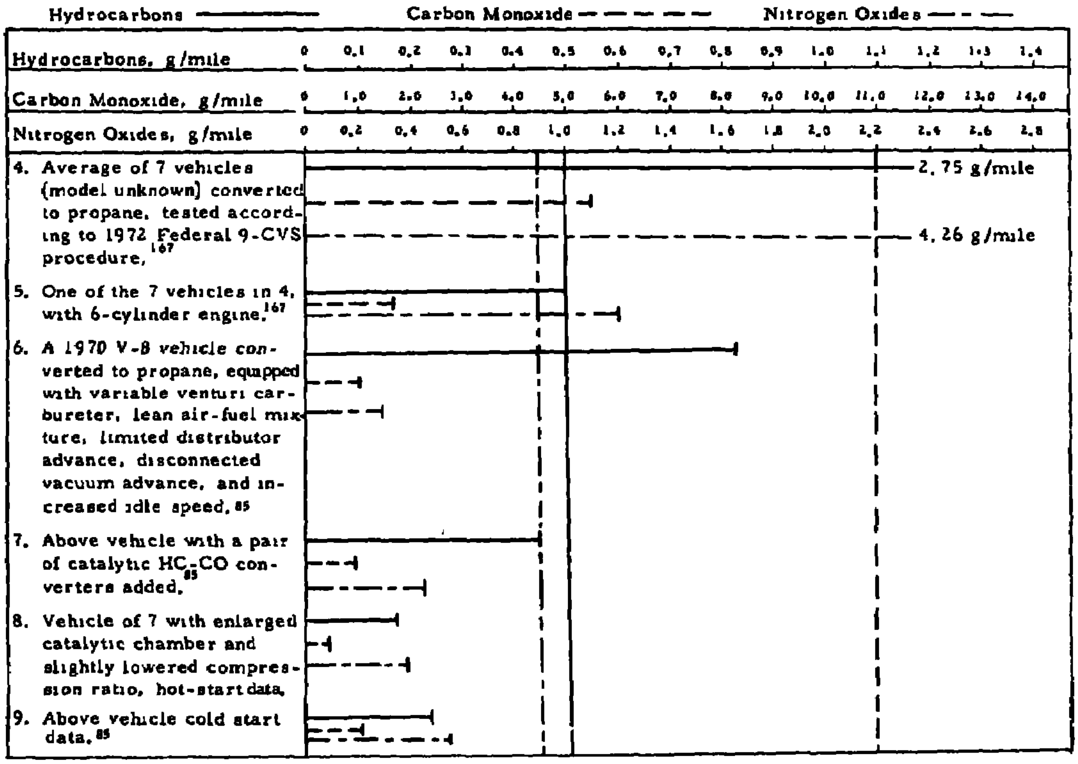
1. A 1966 6-cylinder vehicle converted to dual-fuel natural gas operation. California 7-Mode composite data, converted from concentrations.[107]

2. Average of 5 vehicles (1967, 1968, and 1969 models) fueled with natural gas, with or without retarded ignition and disconnected ignition advance. California 7-Mode hot-start cycle. Converted from concentration values.[107]

3. Average of 7 vehicles (1968 1969 models having no emission control devices) converted to gasoline-propane dual-fuel operation. 1972 Federal test procedure, cold start data.[136]

Note: 1. The vertical lines are the proposed Federal standards for 1975 vehicles.
2. Some of the emission values are estimated weight-based figures converted from concentrations by assuming 4000 lb vehicle weight and automatic transmission, using 1970 procedure.

Figure 2.3.4.4. Continued. EXHAUST EMISSIONS OF VEHICLES CONVERTED TO GASEOUS FUELS



fuel-grade propane and methane would enhance the durability of catalytic converters.

2.4. Operating Characteristics of Gaseous Fuels in SI-Engine

2.4.1. Propane

2.4.1.1. Power Capability

With a simple fuel-system conversion, the maximum power output of a propane-fueled engine has been found to be 82 to 95% of the same engine fueled with gasoline.[1, 16, 19, 55, 77, 92, 95, 104, 106] The observed reduction in power output is believed to be the result of reduced volumetric efficiency of gaseous fuels. The exact amount of power reduction depends on the changes made on the engine during the conversion.

The power output of a propane-fueled engine is affected by several major engine variables. One of these variables is the air fuel ratio. Using a CFR engine fueled with propane, the maximum torque was found to occur at an air-fuel ratio slightly richer than stoichiometric.[95] Changing the air-fuel ratio from this setting results in a power loss. The power loss is more significant when the air-fuel charge is made leaner. In addition to greater power loss, leaning the air-fuel ratio also increases the cycle-to-cycle variations in peak pressure, burning time, and rate of pressure rise that result in inferior operation of the vehicle.[21] The effect of air-fuel ratio on power output of a propane-fueled engine has been illustrated by Figure 2.2.3.-9 in which the power outputs at various air-fuel ratios and throttle positions are indicated.

Ignition timing is another engine variable affecting the power output of a propane-fueled engine. Switching from gasoline to propane changes the value of the least advance for best torque (MBT) of an engine. The exact change in MBT varies among various sources. The MBT value of a propane fueled engine also varies with the air-fuel ratios, advancing with the leaning of air-fuel charge (Figure 2.4.1.-1). Varying the ignition timing from the MBT value results in loss of engine power; the loss is particularly significant at lean air-fuel ratios (Figure 2.4.1.-1.) The magnitude of power loss varies with engine speed, but the engine speed has no significant effect on the shape of power contours at various air-fuel ratios.[1,56]

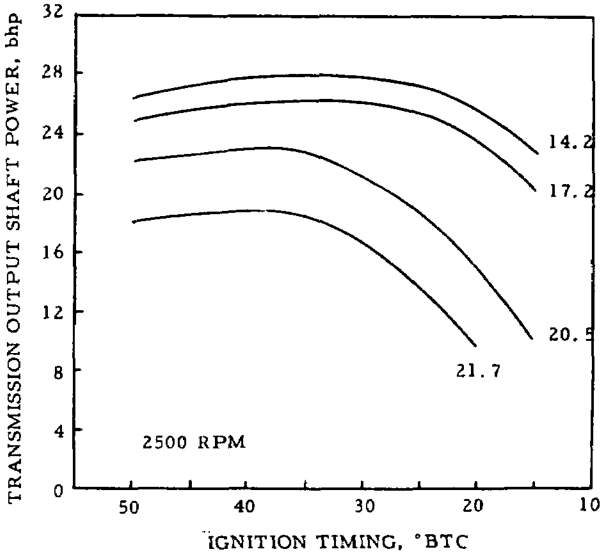


Figure 2.4.1.-1. EFFECT OF IGNITION TIMING ON POWER OUTPUT OF PROPANE-FUELED ENGINE AT VARIOUS AIR-FUEL RATIOS [56]
(Production V-8 engine maintained at road load and constant intake airflow rate)

Due to propane's superior antiknock characteristics,[20] the power output of a propane-fueled engine can be increased by increasing the engine's compression ratio.[1,92] Increasing the propylene content in the fuel gas reduces the antiknock quality of LP-gas.[1]

The performance of a propane-fueled engine has been found to depend on the design of the carburetion system.[19,110] Testing with three types of commercially available LP-gas carburetion systems, one investigator found that none of them provide optimum performance.[110]

The power output of a propane-fueled engine can be significantly improved by utilizing the latent heat of vaporization of LP-gas to cool the intake air charge.[1,19, 77, 109,110] Field operation of a vehicle equipped with such a carburetion system showed performance comparable to that of a gasoline-fueled vehicle, and experienced no wintertime freeze-up by using underhood air during winter operations.[110]

2.4.1.2. Fuel Consumption

On the basis of brake specific fuel consumption (BSFC, lb/bhp-hr), an engine has shown lower fuel consumption with propane than that with gasoline, varing from 9 to 12% among various sources.[1, 16, 19, 55, 77, 92, 95] The reduced fuel consumption of a propane-fueled engine, as compared to gasoline, is greater in part-throttle, low-speed operations than in wide-open-throttle, high speed operations — a feature of some importance in urban vehicular uses. However, due to the lower specific weight of propane, and the richer setting of the air-fuel ratio for maximum power, a propane-fueled engine will require more fuel, on volume basis, than a comparable gasoline-fueled engine.

The fuel consumption of a propane-fueled engine is dependent on the setting of many engine variables, ·articularly air-fuel ratio and ignition timing, as shown in Figure 2.4.1.-2.

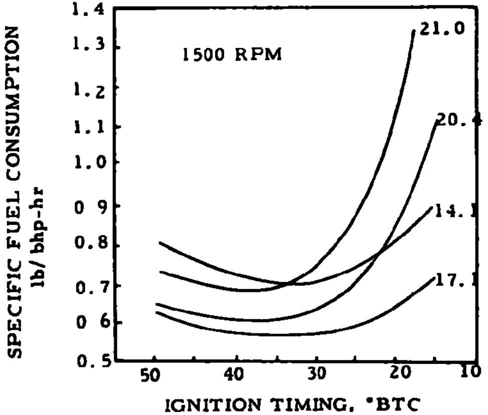


Figure 2.4.1.-2. EFFECT OF IGNITION TIMING ON FUEL CONSUMPTION OF PROPANE-FUELED ENGINE AT VARIOUS AIR-FUEL RATIOS[56]
(Production V-8 engine maintained at road load and constant intake air-flow rate)

At a given ignition timing schedule, increasing the throttle position of a propane-fueled engine allows a leaner air-fuel charge, thus lowering the specific fuel consumption.[95] However, the specific fuel consumption is increased if the air-fuel mixture is leaned near the misfire limit, particularly at high throttle positions

Data presented in Figures 2.2.3-9, 2.4.1.-1, and 2.4.1.-2 indicate that from the point of view of performance a propane-fueled engine has an optimum ignition timing (about 30 to 35°BTC) and air-fuel ratio (approximately 17 1) that provide lowest fuel consumption and power loss resulting from retarding the ignition timing. As the air-fuel ratio is made leaner, the fuel consumption will not be reduced if power output is kept constant, and a greater amount of power will be lost if ignition timing is retarded from the optimum setting for reducing exhaust emissions.

2.4.1.3. Engine Maintenance

The propane-fueled engines have shown certain advantages over gasoline-fueled engines in the area of engine maintenance. The cited advantages include the following·

- Much less scale and gum buildup inside the combustion chamber and engine cylinders, thus requiring less frequent engine overhaul.[95, 154, 161]
- Less contamination of lubricating oil, thus allowing longer service between oil changes and less frequent replacement of oil filters.[136, 154, 161, 167, 185]
- Improved spark plug life.[154, 185]
- Improved service life of exhaust system.

2.4.2. Methane

2.4.2.1. Power Capability

The potential maximum power output of a methane-fueled engine is quite similar to that of a propane-fueled engine. Due to the reduced volumetric efficiency of gaseous fuel, an approximate reduction of 10% in peak power output occurs in an SI-engine when the fuel is changed from gasoline to methane.[95,107] If liquefied natural gas is used, the utilization of latent heat of vaporization to cool the intake air charge will improve the volumetric efficiency of the fuel, thus increasing the power output. Increasing the compression ratio further increases the power output.[184] Methane or natural gas has also been satisfactorily used in a compression ignition type engine using spark ignition.[186]

Using a CFR engine and operating at maximum-power spark timing, the power output—air-fuel ratio—throttle position relationship of a methane-fueled engine has been found to be similar to that of propane (Figure 2.4.2.-1). The effect of spark timing on power output of a methane-fueled engine has not been thoroughly investigated, but is believed to be similar to that of propane. Vehicles fueled with natural gas have been satisfactorily operated with retarded timing and disconnected vacuum advance.[107] Similar vehicular uses have been reported in trade journals.

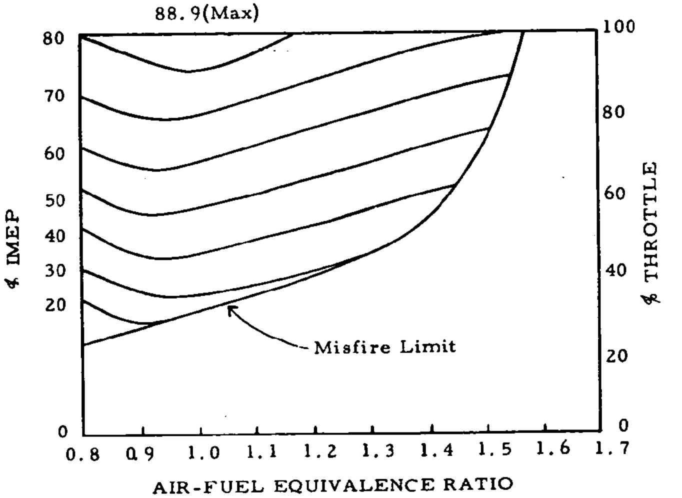


Figure 2.4.2-1. POWER CONTOURS OF METHANE-FUELED CFR ENGINE[95]
(At Maximum Power Ignition Timing, Engine Speed 1000 rpm, Compression Ratio 8:1)

2.4.2.2. Fuel Consumption

On the basis of brake specific fuel consumption (BSFC, lb/bhp-hr), a 13% reduction in fuel consumption has been observed on CRF engines as the fuel is switched from gasoline to methane.[95] Testing with vehicles converted to dual-fuel operation under urban driving conditions, an average of 10% reduction — on the basis of Btu/mile — in fuel consumption has been recorded with methane.[107]

Like propane, methane allows leaner air-fuel ratios than gasoline at all throttle positions, thus permitting further potential reduction in fuel consumption, particularly at greater throttle openings (Figure 2.4.2-1). However, like propane, the specific fuel consumption of a methane-fueled engine will be increased if the air-fuel ratio is made too lean — near the misfire limit.

In addition to air-fuel ratio, ignition timing also affects the fuel consumption of a methane-fueled engine. Although detailed information is not available, it is believed that the effects of ignition timing may be similar to those of a propane-fueled engine (Figure 2.4.1.-2). Retarding the ignition timing lowers the power output, thus increasing the specific fuel consumption.

2.4.3. Ammonia

2.4.3.1. Power Capability

On the basis of the ideal Otto cycle with partial decomposition of ammonia into hydrogen and nitrogen during the compression stroke, the theoretical maximum power output of an ammonia-fueled SI-engine was found to be about 77% of that of a gasoline-fueled engine.[158] Experimental measurements of power output of ammonia-fueled engines vary widely, ranging from 17.5 to 70% of the peak power of gasoline-fueled engines, depending upon the engine modifications made.[37, 72, 145, 158] Adding hydrogen or utilizing catalytic decomposition of ammonia increases the power output.[37, 158] Increasing the compression ratio and supercharging at higher engine speeds further increase the power output of an ammonia-fueled engine and can raise it up to that of a gasoline-fueled engine.[37]

The power output of an ammonia-fueled engine is critically affected by the air-fuel ratio. The leanest air-fuel ratios for best torque (LBT) were found to be slightly leaner than stoichiometric (6.06:1), but are comparatively much richer than that of a gasoline engine.[37,108] Changing the air-fuel ratio from the LBT value reduces the engine power output rapidly, and the effect varies with the change in engine speed.[158]

The minimum spark advance for best torque (MBT) of ammonia-fueled engines was found to be much greater than that for gasoline, indicating the relatively slow burning rate of ammonia. MBT values of around 100°BTC have been recorded with ammonia (20° to 40°BTC in gasoline engine) and were found to be essentially constant despite the change in engine speed.[37]

2.4.3.2. Fuel Consumption

Theoretical calculations indicated that the specific fuel consumption of an ammonia-fueled engine is 2.5 to 3.5 times that for gasoline.[158] Experimental results have shown that an engine will consume twice as much or more ammonia than iso-octane regardless of whether the engine is operated at peak-power or peak-economy conditions.[158]

2.4.3.3. Engine Maintenance

Due to its alkalinity and the large quantity of water and nitric oxide it produces in combustion, ammonia has been thought to be corrosive to engine materials. Experimental results indicate that certain materials such as rubber, neoprene, and cast copper-lead bearings have shown definite deterioration as a result of handling ammonia.[72] Common engine metals such as cast iron and aluminum have shown slight weight gain and surface discoloration after exposure to ammonia combustion. The effect of ammonia combustion is particularly significant on aluminum and other copper-containing alloys, rendering them less compatible.[72] The combustion of ammonia has been found to present no particular problem to lubricating oil.[72]

3. EFFECT OF GASEOUS FUELED VEHICLES ON POLLUTION LEVELS IN NEW YORK CITY

This section assesses the possible impact on the pollution level using the gaseous fueled vehicles in a major urban area. New York City was chosen because of its severe automotive pollution problem and because its traffic patterns differ from Los Angeles, which has already been given close attention by automotive pollution analysts.

Since it may be impractical to convert the entire motor vehicle population including private automobiles to gaseous fuels because of logistics problems alone, this question was subordinated to the more practical one of converting commercial fleet vehicles only. The analysis attempts to answer the following questions:

1. If all of the commercial fleet vehicles in New York City were converted to gaseous fuel, how much would the automotive pollution level be reduced?
2. Does it matter whether the fuel is natural gas or propane?
3. How much fuel would be required in each case and how could it be obtained?
4. From the point of view of pollution control, is it more desirable to burn gaseous fuels in automobiles or in electric generating stations?

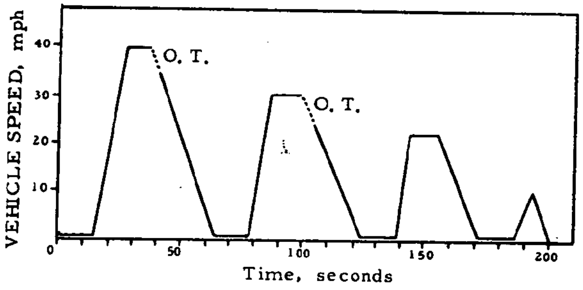
3.1. New York City Traffic Patterns

In order to determine the extent of motor vehicle pollution in New York City, the State of New York, Department of Health, conducted a survey in 1968 in which the NYC vehicle population and traffic patterns were characterized. Vehicle emission test procedures were then developed based on regional traffic patterns.[127] The areas included in the survey were most of Manhattan, and the adjacent areas of Brooklyn, Queens, and the Bronx. The traffic patterns were classified according to three general classifications of NYC streets: 1) expressways, 2) arteries, and 3) capillaries. The vehicular mileage (a two-way street was counted as twice the equal length of a one-way street) of the selected areas were--

Expressways, 96.1 miles
Arteries, 383.1 miles
Capillaries, 986.5 miles

Traffic counts were also made at selected points to determine the number of vehicles using each of the three categories of streets at any given time of day. In addition to this, the average speed of the vehicles using each type of street was determined. It was found that NYC vehicles spend approximately 34% of their time idling and travel at a weighted average speed of 13 miles per hour.

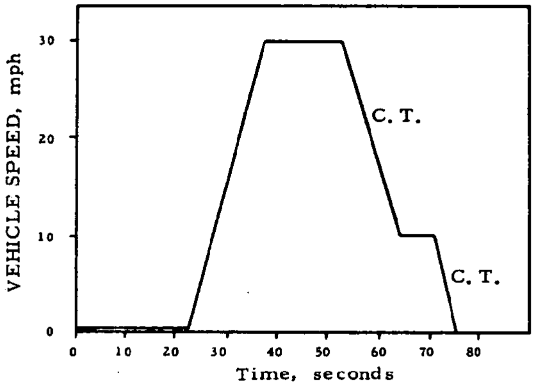
Subsequent to the establishment of NYC traffic patterns and operating modes, a comprehensive dynamometer driving cycle was developed for measuring emissions from NYC automobiles (Figure 3.1.-1).



O. T. = open throttle.

Figure 3.1.-1. COMPREHENSIVE DRIVING CYCLE OF THE CITY OF NEW YORK[127]

Based on the comprehensive driving cycle, the test procedure was reduced to a quick cycle by mathematical techniques to provide a more efficient method of emission measurement. The quick cycle developed is shown in Figure 3.1.-2.



C. T. = closed throttle

Figure 3.1.-2. QUICK DRIVING CYCLE OF THE CITY OF NEW YORK

The NYC vehicle population was broken down into the following categories: passenger vehicles, medallion taxicabs, rental cars and private taxicabs, and commercial vehicles.[126] The commercial category includes all trucks without a further breakdown according to gross vehicle weight or engine displacement. The 1969 NYC registrations were as follows:

Passenger Vehicles	1,558,754
Medallion Taxicabs	11,760
Rental cars and private cabs	45,618
Trucks	115,018

The principal variable used in the determination of emission levels is the number of vehicle miles driven. Average national figures were used to obtain the number of vehicle miles driven within each category of registrations. The basis for this method and its explanation is found in Reference 174 The total number of vehicle miles is then determined by the number of vehicles registered in each category. The total number of vehicle miles is then divided by 300 to arrive at an average daily value of emissions. Three hundred was chosen as a means of allowing for the time during which a vehicle may not be in use as much as on business days. The number of vehicle miles and the factors used in their calculation are presented in Table 3.1.-1.

Table 3.1.-1. CHARACTERISTICS OF VEHICLE POPULATION USED FOR CALCULATION OF EMISSION LEVELS

Category	Number	National Average Miles Driven	Total Miles Diven	% Urban Travel	Total Urban Miles
Passenger Cars	1,558,754	9,488[118]	14,789,457,952	55[118]	8,134,201,874
Medallion Taxi Cabs	11,760	45,000	529,200,000	100	529,200,000
Rental Cars and Private Cabs	45,618	30,000	1,368,240,000	95	1,299,828,000
Trucks	115,018	11,571[118]	1,330,665,000	90	1,197,598,500

The privately owned passenger vehicle is not regarded as one that could be converted to a gaseous fuel. This is primarily due to the handling characteristics of the fuel itself, the conversion expense, and the variance of the vehicle operation. The same may apply to rental cars, with some exceptions.

Rental cars are subject to intercity use, but because of servicing procedures, such as refueling at central garages, they may be easily operated as a dual-fueled vehicle. With the dual fuel system the rental car could be driven using gasoline in rural areas and gaseous fuels in urban driving. Therefore, for discussion in this report they are considered as a gaseous fueled vehicle.

3.2. Emissions From Present Vehicle Traffic

Both the comprehensive and quick driving cycles were used by New York City for measuring exhaust emissions of passenger automobiles on a chassis dynamometer. A 198-car fleet, representative of NYC car population in 1968, was tested with the developed cycles as well as with the 1968 Federal procedure.[169] Good correlations in hydrocarbon, carbon monoxide, and carbon dioxide emissions were found between the two cycles. A comparison of the emission measurements using the NYC quick cycle and the 1968 Federal procedure is shown in Table 3.2.-1.

Table 3.2.-1. COMPARISON OF EMISSION DATA OBTAINED WITH NYC CYCLES AND 1968 FEDERAL PROCEDURE[127]

	Hydrocarbons (ppm vol as C_6)			Carbon Monoxide (volume %)		
% Vehicle Cumulative	NYC Cycles Comp	NYC Cycles Quick	Federal Hot Cycle	NYC Cycles Comp	NYC Cycles Quick	Federal Hot Cycle
10	460	460	270	1.50	1.12	0.97
25	630	660	370	1.97	1.67	1.43
50	850	840	500	2.52	2.21	2.10
75	1110	1090	650	3.15	3.00	3.00
90	1540	1500	890	3.98	4.05	3.90
Mean	1152	1108	602	2.78	2.65	2.34

The hydrocarbon emissions as determined by NYC cycles are distinctly higher than would be indicated by the 1968 Federal cycle. This difference is most likely caused by the prominence of the idle mode in the NYC cycles. The carbon monoxide levels as determined by NYC cycles are also higher than indicated by the Federal hot cycles, but the difference is not as pronounced as in the case of hydrocarbon emissions. The difference in emission levels produced by the NYC and 1968 Federal cycles reflects the basic difference in traffic pattern between the City of New York and the West Coast.

In the New York survey, the emission measurements were made by using the variable-dilution bag sampling technique and NDIR hydrocarbon analysis. The Federal test procedures for motor vehicle emissions have been changed and new procedures based on the constant-volume sampling technique and FID hydrocarbon analysis have been put in effect. For estimating the potential benefit in emission reduction with gaseous fuels, it is necessary to have emission information in terms of a mass unit, such as grams per mile. The NYC emission data provided by the cited reference[127] (Table 3.2.-1) are in concentration units. Although a mass conversion formula was included, we found that the emission data converted to mass units according to the given formula are unreasonably low. For example, the mean hydrocarbon emission produced by NYC quick cycle shown in Table 3.2.-1 is 1108 ppm, which corresponds to 0.109 lb/hr, or 3.74 g/mile, according to the given mass conversion formula, since the NYC quick cycle has a time duration of 0.021 hour and a distance of 0.18 mile. Comparing this value with other available emission data based on Federal procedures, it was noticed that the value of 3.74 g/mile is exceptionally low in view of the fact that NYC quick cycle produces twice as much hydrocarbon emission as the 1968 Federal hot cycles. Examining the procedures used in the NYC survey, we found that detailed information on sampling technique, such as volume of sample gas collected and the ratio of total volume of gas through a variable-dilution sampler to bag sample, is not available, thus mass conversion formula could not be verified.

However, we noted that subsequent to the development of NYC test cycles, the State of New Jersey embarked a similar survey for the purpose of developing an emission testing procedure for its urban motor vehicles.

The result is a 4-mode short driving cycle (ACID cycle) that closely resembles the NYC quick cycle. A comparison of the two driving cycles is presented in Figure 3.2.-1.

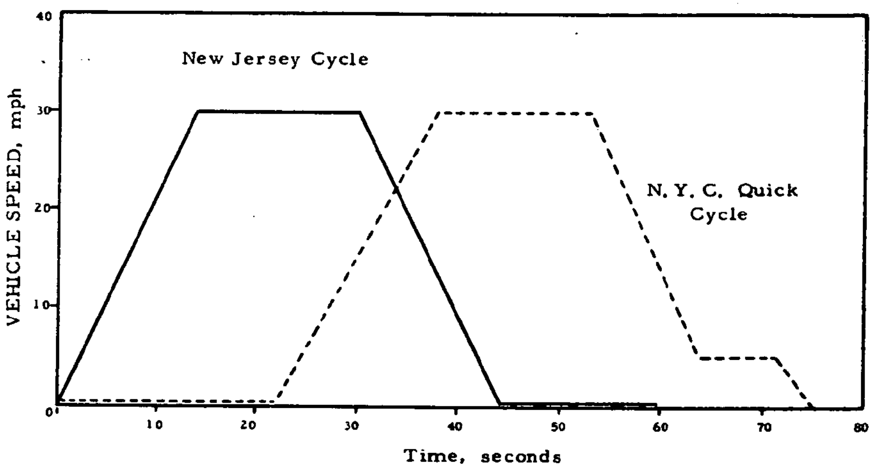


Figure 3.2.-1. COMPARISON OF NEW JERSEY ACID DRIVING CYCLE AND NYC QUICK DRIVING CYCLE[49]

The New Jersey ACID driving cycle was developed through the use of techniques and procedures similar to those used in the NYC survey, aimed at simulating the urban traffic pattern of the state. The developed technique utilizes a chassis dynomometer with fixed inertia and proportional road load, and the emissions are measured by using a constant-volume sampling technique, thus directly yielding the total mass of pollutants emitted during the cycle. The hydrocarbon emissions are determined by the flame ionization detector (FID) technique, which has been specified in the new Federal specifications.

The ACID driving cycle has been used by the New Jersey Department of Health in measuring the exhaust emissions (hydrocarbons and carbon monoxide only) of over 1000 New Jersey vehicles, and has been found to correlate well with the 1970 Federal procedure. In view of the fact that suitable NYC emission data are not available, the New Jersey data were chosen for estimating the effect of selected gaseous fuel on exhaust emission of the NYC motor vehicles.

The emission factors for gasoline-fueled vehicles were compiled by IGT to be as follows:

Hydrocarbons	6.8	g/vehicle mile*
Carbon Monoxide	78.0	g/vehicle mile*
Nitrogen Oxide	4.0	g/vehicle mile†

The above factors and the data summarized in Table 3.2.-1 were used to determine the emissions from the listed classifications of vehicle registrations. In Table 3.2.-2, it can be seen that the passenger vehicle contributes approximately 73% of the total vehicle emissions. Due to the unlikelihood of converting vehicles in this classification to a gaseous fuel, the emissions from this category are not shown to be reduced in Table 3.2.-2 and are carried over into Columns 2 and 3 of the table.

Emission factors for gaseous fueled vehicles are presented in Table 3.2.-3 from work done in Section 2. The same factors would apply to both propane and natural gas. It was found that propane and natural gas can reduce vehicle emissions by comparable amounts. Two values for gaseous fuel emissions are given, a high and low value. The low value is dependent upon various degrees of sophistication employed in the actual engine conversion.

From Table 3.2.-2, it can be seen that through conversion of fleet vehicles, taxi cabs, trucks, rental cars, and private cabs, the level of emissions can be reduced from 3682 tons/day to 2756 tons/day (using an average value of the high and low emission figures). This is equivalent to an approximate reduction of 24% in the number of tons emitted into the atmosphere daily.

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* The average of 1968, 1969, and 1970-model sample vehicles of the State of New Jersey. Emission data were obtained by using New Jersey ACID test procedure, which closely resembles the NYC quick-cycle procedure.

† Estimated from available vehicular emission data.

Table 3.2.-2. EMISSIONS PRODUCED BY NYC VEHICLES

1969 Vehicle Population	Gasoline Column 1	Gaseous Fuel (high figure)[c] Column 2 Tons/Year	% of Col 1	Gaseous Fuel (low figure)[d] Column 3	% of Col 1
Passsenger Cars					
1,558,754 registered					
HC[a]	60,969	60,969		60,969	
CO[a]	699,354	699,354		699,354	
NO_x[b]	44,830	44,830		44,830	
Total	805,153	805,153		805,153	
Daily Avg for 300 days	2684	2684	100	2684	100
Taxi Cabs					
11,760 registered					
HC	3,965	1,749		117	
CO	45,483	2,916		583	
NO_x	2,915	1,749		466	
Total	52,363	6,414		1166	
Daily Avg	174	21	12.1	3.9	2.2
Rental Cars & Private Cabs					
45,618 registered					
HC	9,744	4,299		287	
CO	111,773	7,165		1433	
NO_x	7,165	4,299		1146	
Total	128,682	15,763		2866	
Daily Avg	429	53	12.6	9.6	2.2
Trucks					
115,018 registered					
HC	8,972	3,958		264	
CO	102,917	6,597		1319	
NO_x	6,597	3,958		1056	
Total	118,486	14,513		2639	
Daily Avg	395	48	12.2	8.8	2.2
Total Emissions	1,104,684	841,843		811,824	
Daily Avg	3682	2806	76.2	2706.3	75.5

[a] The average of 1968, 1969, and 1970 model sample vehicles of the State of New Jersey. Emission data were obtained by using New Jersey ACID test procedure, which closely resembles the NYC quick-cycle procedure.

[b] Estimated from available vehicular emission data.

[c] Estimated on the basis of simple conversion involving the installation of gaseous fuel system, pressure regulator, air-gas mixer, blocked manifold heat, and some minor adjustments of engine variables — such as lean air/fuel ratio, slightly retarded timing, increased idle speed, and disconnected vacuum advance.

[d] Estimated by assuming the use of —

- More sophisticated venturi carburetor, which allows lean air to fuel mixture at low fuel levels and enriched mixture at high-power operations.
- More refined adjustment of engine variables and an engine equipped with exhaust recirculation, exhaust air-injection thermal reactor system, and catalytic HC-CO converter (simulating automobiles that will be produced in the next few years).

Table 3.2.-3. EMISSION FACTORS FOR GASEOUS FUELED VEHICLES

		g/mile
1. High Figures.*		
	Hydrocarbons	3.0
	Carbon Monoxide	5.0
	Nitrogen Oxides	3.0
2. Low Figures:†		
	Hydrocarbons	0.2
	Carbon Monoxide	1.0
	Nitrogen Oxides	0.8

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* Estimated on the basis of simple conversion involving the installation of gaseous fuel system, pressure regulator, air-gas mixer, blocked manifold heat, and some minor adjustments of engine variables — such as lean air/fuel ratio, slightly retarded timing, increased idle speed, and disconnected vacuum advance.

† Estimated by assuming the use of —

- More sophisticated venturi carburetor, which allows lean air to fuel mixture at low power levels and enriched mixture at high-power operations
- More refined adjustment of engine variables and an engine equipped with exhaust recirculation, exhaust air-injection thermal reactor system, and catalytic HC-CO converter (simulating automobiles that will be produced in the next few years).

3.3 Comparison With Gaseous Fuel Use in Central Electric Generating Stations

For comparative purposes the emissions were calculated for central electric generating stations. Data are based on the amount of electricity generated by Consolidated Edison of New York for 1969.[130] With the use of emission factors reported by Esso Research[11] and Stanford Research Institute,[142] the total emission level for 1969 was calculated. The electrical generating data and the emission factors for each type of fuel are summarized in Table 3.3.-1.

Six cases were developed with the intent of determing how CO, HC, and NO_2 emissions would change by fuel substitution on an equivalent Btu basis. These cases are summarized in Table 3.3.-2.

Case I shows actual fuel consumption in 1969 and the emissions resulting. Case II shows how the emissions would change if the coal consumed was replaced by an equivalent amount of natural gas. The greatest decrease is found in the amount of CO emitted, while the next major change is found in the amount of NO_2 emitted. Hydrocarbons show the least change.

Case III was developed to determine how the emission pattern would change if the amount of natural gas necessary to fuel fleet vehicles was used in electrical generation, decreasing the amount of coal by an equivalent amount. The amount of natural gas consumed would increase from 89.1 to 119.1 trillion Btu. The end result, although less dramatic than in Case II, is a reduction of all the emission components.

Case IV is intended to show the same as Case III with the substitution of natural gas for fuel oil. It can be seen that there is little change in the total value of emissions. However, the amount of CO and HC emitted is reversed. That is, in Case III CO is 429 tons less than in Case IV, while the HC in Case IV is 325 tons less than the HC in Case II. The overall effect is a net reduction of 104 tons when Case III is compared to Case IV. Both represent a decrease of approximately 29 tons or 8.0¢ in the overall daily emissions based on Case I.

Table 3.3.-1. EMISSION CONVERSION FACTORS FOR ELECTRICAL POWER GENERATION

Fuel	CO[173]	NO_2[11]	HC[142]	SO_2[142]	Part.[175]
	lb/10^6 Btu				
Coal (2¢ sulfur)	0.0192	0.769	0.00769	2.52	0.61
Fuel Oil (2¢ sulfur)	0.00027	0.695	0.0239	2.1	0.067
Natural Gas	-N-	0.390	-N-	-N-	-N-

N = negligible

Btu conversion factors —

Coal: 13,000 Btu/pound, 26 million Btu/ton
Fuel Oil: 150,000 Btu/gal
Natural Gas: 1000 Btu/CF

1969 Fuel Consumption for Electric Generation Consolidated Edison of New York[118]

Coal:	3,758,047 tons	97.7 trillion Btu
Fuel Oil:	1,148,330,710 gallons	172.7 trillion Btu
Natural Gas:	79,076,044,000 CF	79.1 trillion Btu

kWhr Generated 1969: 30,987,890,278
Peak Load: 7,266,000 kW
System Load Factor: 51.8¢

Cases V and VI were developed in light of the current natural gas supply situation. With natural gas supplies being extremely limited, would diversion of the amount of natural gas required to fuel fleet vehicles in the New York area from electrical generation increase or decrease pollution levels? The amount of gas required (approximately 40 billion CF) could be replaced by coal (Case V) or fuel oil (Case VI). There is little change in the overall emisssion level when Case V is compared to Case VI. However, noticeable change is found when the HC and CO levels are compared. When comparing Cases V and VI with Case I there is an overall increase in emissions of approximately 15.2¢ or 10¢, respectively.

At this point a comparison can be made between vehicle emissions and those resulting from electrical generation. With the natural gas required for vehicle fuel supplied by diverting from electrical generation, an increase

Table 3.3.-2. ELECTRICAL GENERATING EMISSION SUMMARY*

	Col 1 Case I	Col 2 Case II	Col 3 Case III	Col 4 Case IV	Col 5 Case V	Col 6 Case VI
Fuel Consum, 10^9 Btu	Fuel Used in Electrical Generation	Replacing All Coal With Natural Gas	Vehicle Natural Gas to Reduce Coal⁺	Vehicle Natural Gas to Reduce Oil⁺	Supplementing Natural Gas in Power Plants With Coal	Supplementing Natural Gas in Power Plants With Fuel Oil
Coal	97.7	-0-	57.7	97.7	137.8	97.7
Oil	172.2	172.2	172.2	132.2	172.2	212.3
Nat Gas	79.1	176.8	119.1	119.1	39.0	39.0
Total Fuel	349.0	349.0	349.0	349.0	349.0	349.0
Emissions, tons/yr						
SO_2	304,000	180,000	239,000	262,000	355,000	346,000
Particulate	30,672	572	18,272	30,540	43,072	30,807
CO	961	23	527	956	1,346	967
NO_2	114,760	94,246	103,778	105,328	120,360	118,945
HC	2,433	2,058	2,280	1,955	2,588	1,915
Total	452,826	276,899	363,857	400,779	522,366	498,624
Avg tons/day	1,240.6	758.6	996.9	1,098.0	1,431.1	1,366.1
¢ Change From Col 1		−28	−17.3	−10.0	+15.5	+10.3

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* Based on generation of 31 × 10^9 kWhr of electricity.

⁺ 40 x 10^9 CF.

occurs in emissions of 191 tons/day in Case V or 126 tons/day in Case VI. However, if fleet vehicles were converted from gasoline to a gaseous fuel, the amount of emissions from vehicles is reduced by 876 tons/day, using the high value from Column 2, Table 3.2.-2. This results in a net reduction of approximately 750 tons/day if the gas is replaced by oil (Case VI).

Since this comparison is based on coal and oil containing 2¢ sulfur, this net reduction can be expected to increase when compared to lower sulfur fuels.

The analysis reveals that all of the commercial vehicles in New York City consume about 318 million gallons of gasoline annually. If they were all converted to natural gas, it would reduce the total pollution from all motor vehicles by about 25¢ and would require about 40 billion CF of natural gas. This is 16¢ of the 250 billion CF of natural gas consumed annually in the New York area and amounts to half of the natural gas consumed for electric power generation by the Consolidated Edison Company. It is also equivalent to about 20 LNG tanker loads per year.

Thus, all of the commercial vehicles in New York City could be operated on natural gas if half of the gas being burned in the area for electric generation were diverted to this use or if one tanker load of LNG were imported about every 2 weeks.

It is also estimated that the same reduction of 25¢ in motor vehicle pollution could be obtained by converting all of the commercial vehicles in New York City to propane. This would require about 390 million gallons of propane annually. While data on LPG consumption in New York City are lacking, this requirement can be compared to the total LPG shipments in all of New York State, which amounted to only 155 million gallons in 1968. In order to provide 390 million gallons of propane annually, it would be necessary to either convert oil refinery production to propane or to import the required amounts from foreign countries such as Venezuela and Algeria.

While it is possible to provide additional fuel supplies for gas-fueled vehicles in the New York city area, it will take some time to make the conversion. New supplies of either LNG or LPG imported from overseas would require several years to negotiate and set up importation programs. The present LNG importation programs are expected to begin operation in the 1975 time period. The importation of propane could begin somewhat earlier because more propane shipping capacity is available and the government has recently removed import controls on propane brought into the United States from the Western Hemisphere. However, the determining factor may be the rate at which commercial vehicles can be converted to the use of either propane or natural gas.

The commercial vehicle population in New York City in 1969 was about 172,000 vehicles and can be expected to grow to perhaps 200,000 vehicles by the time they could be completely converted. At the same time the total nationwide production of LPG carburetors in the United States was 133,000 units.[189] Only about 12,000 of these were sold on the east coast. The number of LP gas cylinders of appropriate size (23.5 gallon capacity) that were produced in the United States amounted to 140,000.[189] The production of suitable LNG tanks is considerably less. Thus, even if annual production of these components were doubled, it would require 18 months production to convert the vehicles in New York city alone. If additional cities were being converted at the same time the conversion period would be drawn out accordingly.

Obviously these manufacturers must make large capital commitments for additional production facilities in order to carry out such a conversion program. They are not likely to make these investments to support a temporary business that will serve only until the automotive industry can provide a clean gasoline fueled vehicle. Thus, as long as the conversion to gaseous fuels is regarded as a temporary expedient, the rate of conversion could be limited by component manufacturing capacity to such an extent that the time required for conversion could drag out for several years, perhaps exceeding the time required to provide clean gasoline-powered vehicles.

Under these conditions, the rate of conversion will in all probability be limited to those that can be justified on an economic basis without regard for competition from future clean gasoline-powered vehicles. This rate of conversion can be accelerated by forcing legislation such as preferential fuel tax treatment, conditioning of federal support for urban transportation projects and similar measures. However, the resulting impact upon overall vehicle pollution levels will be minor because of the relatively small segment of the vehicle population affected.

In conclusion we can say that the conversion of commercial vehicles in New York City to gaseous fuel appears to be feasible both technically and logistically. The quantities of fuel required can be obtained, although that will require some effort. The price of either LNG or LPG, if imported, should be competitive with gasoline. Prices of domestic CNG or LNG may be somewhat higher. However, this may tend to conserve domestic supplies for other uses, leaving the imported gaseous fuels to serve the automotive market.

4. LOGISTICS OF GASEOUS FUELS

4.1. Natural Gas

4.1.1. Natural Gas Industry

The natural gas industry plays a major role in the energy economy of the United States, supplying more than 32% of the energy annually consumed in the United States. In 1969 this amounted to approximately 22 trillion CF of natural gas. Of this, about 15 trillion CF was distributed and sold by the natural gas transmission and distribution industry. The remainder was used internally by the industry or sold directly by producers.

The gas transmission and pipeline industry operates a vast network of over 900,000 miles of underground pipelines that reach into every state in the Union and serve virtually every city of any size. It is a nationwide distribution system designed to take natural gas from the wellhead at a value of approximately 16-20¢/million Btu and to transport it throughout the country selling it to various users at prices dependent upon the distance of transmission and the quantities and terms of sale to each individual type of customer. The cost of the gas itself is only a small portion of the total price paid by the user. The retail price must cover the cost of transmission, distribution, metering, service and other expenses associated with the operation of this pipeline network. Thus the user pays from 2 to 10 times the cost of the gas at the wellhead depending upon the expense involved in providing him with gas service.

There are four general headings under which the sales of natural gas is classified. By definition these headings are —

4.1.1.1. Residential Sales

Generally consisting of customers using natural gas in household quantities for space heating, water heating, cooking and other uses. Because of the small quantities and high service costs, this category of use has the highest rate structure of all.

4.1.1.2. Commercial Sales

Generally consisting of customers primarily engaged in the wholesale or retail trades, apartment dwellings of five or more families, and any application not related directly to a manufacturing process. The nature of the customers' primary business or economic activity at the location served usually determines this classification although classification practices vary throughout the industry. Retail rates are lower than residential sales, but higher than large industrial users.

4.1.1.3. Industrial Sales

Customers engaged primarily in industrial activities calling for large quantities of fuel for heating or processing are classed as industrial users. Many utilities further classify these customers by SIC numbers. Energy sold under interruptible or off-peak rates is generally placed under this category. It has the lowest retail rate structure because of the large quantities purchased.

4.1.1.4. Other Sales

This classification includes municipalities or divisions of Federal or local governments under special contracts or agreements applicable only to public authorities using the energy for general or institutional purposes. Table 4.1.1.-1. summarizes the quantity of gas sold and revenues derived from each sales classification during 1968.

4.1.1.5. Capital Structure

The gas industry requires very large amounts of capital to provide the service that it renders. In 1968 approximately $890 was invested for each customer served. The extensive pipeline network in the United States is now worth approximately $35 billion. If the industry continues its present growth rate of 6% per year, by 1980 an additional $30 billion worth of facilities will be required. In order to obtain these facilities, the industry must spend approximately $3 billion annually for additional equipment and facilities. One of the major problems facing the industry is how to raise this amount of capital in the face of rising construction costs and high interest rates.

Table 4.1.1.-1. QUANTITY OF GAS SOLD AND REVENUES BY SALES CLASSIFICATION

Class of Service	Trillions of Cubic Feet	Revenues, $million
Residential	4.5	4,482.0
Commercial	1.7	1,295.0
Industrial	7.5	2,648.0
Other	0.6	221.0
Total	14.3	8,646.0

4.1.2. Natural Gas Supply

The projected use of natural gas as a motor fuel must be tempered by consideration of the available supplies. This subject is discussed in some detail because of current concern for future gas supplies.

Clearly, the price of natural gas at the wellhead has been regulated at a level too low to generate sufficient new supplies to meet the heavy demands created by the low regulated price. This is evident from the fact that during the last two years, less gas was added to the inventory of "proved reserves" than was removed by deliveries to consumers.

Historically, additions have been made to reserves that were greater than the amount removed from the ground and consumed; the long-term trend had been to gradually increase the quantities of natural gas reserves. Much of the reserve additions have come as a byproduct of oil exploration. However, during the past decade the attention of the oil industry has shifted to fields outside of the United States and the rate of drilling within the country has declined to its lowest level in 27 years. This has resulted in smaller additions to reserves; since 1968, the additions were considerably less than the amount of gas produced. This is the principal cause of concern and has stimulated the discussion regarding the potential supply shortage.

The FPC is currently reviewing its pricing regulations in order to alleviate the present supply situation. It has shown signs of willingness to improve the economic incentive that would, in turn, improve the supply situation. Nevertheless, the amount that the wellhead price must be raised is difficult to determine as well as the impact on the reserve situation.

The amount of proved reserves supporting U.S. natural gas production represents less than 20% of the total amount of potential gas reserves that are estimated to lie under the United States and its offshore areas. Table 4.1.2.-1 presents estimates of the potential U.S. gas supply situation.

Table 4.1.2-1. ECONOMICAL RECOVERABLE U.S. GAS SUPPLY[97]

	Potential Gas Committee, December 31, 1968	IGT, December 31, 1969
	trillion CF	
Proved Reserves (including storage)	287	275
Future Discoveries	1227*	660-883
Remaining Recoverable	1514*	935-1108
Produced to Date (excluding stored gas)	344	370†
Ultimately Recoverable	1858*	1305-1478†

* Includes over 400 trillion CF of Alaskan gas.

† Includes 47-58 trillion CF of pre-1946 field waste.

The primary problem is one of providing additional incentives to prove out those gas reserves which are now classified as future discoveries. We should note that if sufficient drilling and exploration efforts were made to transfer half of the 660 trillion CF shown as Future Discoveries, to the category of Proved Reserves, it would more than double the Proved Reserves that currently limit annual production. Thus our ultimate reserves appear ample but we must pinpoint their locations so that they may be connected to the pipeline network.

4.1.3. Demand

The use of natural gas in the United States will continue to grow, but at a slower rate than it has in the past. Table 4.1.3-1 summarizes the forecast U.S. natural gas requirements and the market share of natural gas as a percent of total U.S. primary energy consumption.

Table 4.1.3.-1. TOTAL PRIMARY CONSUMPTION IN U.S. AND SHARE PROVIDED BY NATURAL GAS[97]

Year	U.S. Natural Gas Requirements, trillion CF	Share of Primary Energy Consumption Supplied by Natural Gas
1969	21.5	32.1%
1970	22.4	33.0%
1971	23.3	--
1975	26.5	33.0%

The natural gas industry has experienced a growth rate of approximately 5.5% per year from 1961-1968. This growth rate is expected to decline to approximately 4% per year during the first half of the next decade. Further declines may occur depending upon the duration and severity of the present supply pinch.

However, the demand for gas as a measure of the desire to buy gas is considerably higher than the quantities presented in the table above, due to the increases in prices of competitive fuels that has been brought about by air pollution control regulations and the general short supply of low sulfur fuels.

Residual oil having a sulfur content of 1% presently commands a price premium of $0.50/bbl or about 8¢/million Btu. Oil having less than 0.37% sulfur may cost as much as an additional $1.00/bbl or about 16¢/million Btu. This increase in the price of oil creates a sharp increase in the demand for natural gas. The same situation applies to low sulfur coal although this price increase is more difficult to estimate because of the variation in mining, transportation, and stack cleanup costs.

These are major factors to consider in the industrial sector. In many situations the use of natural gas has proved to be the best economic alternative in the search for nonpolluting fuels.

Industrial gas sales patterns have shown a substantial increase in recent years when compared to past patterns increasing 5.4% in 1967, 8.3% in 1968, and 9.5% in 1969. In addition, consumption of natural gas for central power generation has shown even sharper increases. The Federal Power Commission reported increases of 5.3% in 1967, 14.6% in 1968, and 10.8% in 1969.

Additional factors accounting for increased natural gas consumption for power generation other than pollution abatement are long, unexpected delays in nuclear power plant construction; local resistance to power plant construction forcing power utilities to seek cleaner fuels other than nuclear; increased cost of capital resulting in construction postponement; regional shortages of coal supplies resulting from labor shortages; and safety legislation.

Some of these factors can be looked upon as short term and will level off after industry has had enough time to adjust its energy logistics and build pollution control equipment that will allow it to return to less costly fuels.

However, the gas industry is a regulated industry and is unable to increase prices to curb this increased demand for industrial gas. Instead it is currently forced to curtail expansion of new industrial customers in some areas and to restrict sales to interruptible customers in order to ensure continued service to its firm residential and commercial users.

This situation will continue until additional gas supplies can be brought to market in sufficient quantities to fill the demand or until price adjustments are made to bring supply and demand more nearly into balance.

4.1.4. Sources of Supplemental Natural Gas Supply

Supplemental sources of natural gas include pipeline imports from Canada and Mexico, imported LNG, pipeline or LNG shipments from Alaska, development of new offshore gas fields, and gasification of coal and lignite. All of the aforementioned are listed in the order that they are expected to occur from near- to long-term feasibility.

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4.1.4.1. Imported Canadian Gas

Recently a study was made by the Canadian Energy Board[120] of the quantity of natural gas that could be exported to the United States on the assumption that all of the Canadian gas reserves were limited to the Western sedimentary basin. These quantities are presented on line 1 in Table 4.1.4.-1. They represent the quantities of gas we might expect to import at near current prices, or somewhat higher,as more gas is drawn from the northern areas of this sedimentary basin.

Table 4.1.4.-1. CANADIAN GAS AVAILABLE FOR EXPORT
Trillion CF[120]

	1966	1975	1980	1985	1990
Western Sedimentary Basin	0.432	1.165	1.359	1.449	1.626
Percent of U.S. Requirements	2.5	4.0	4.0	3.75	3.6
Northern Frontier Areas	--	0.110	0.941	2.251	3.774
Total	.432	1.275	2.300	3.700	5.400
Percent of U.S. Requirements	2.5	4.35	6.85	9.5	12.

These data indicate that the quantity available for import from the Western sedimentary basin amounts to only about 4% of our anticipated gas requirements as projected by the Future Requirements Committee.

If we are to increase importation of Canadian gas from its present 3-1/2% to about 12% of the U.S. demand by the year 1990, it will require the development of additional Canadian gas reserves in the Northwest Territories or elsewhere.

It is reasonable to expect that future growth of gas reserves will be found in the northern frontier areas as present exploration activities continue. Early in 1969, the Canadian Petroleum Association published its estimate that Canada's ultimate recoverable natural reserves would be 725 trillion CF of which the Western Canada's sedimentary basin is expected to yield 270 trillion CF. Thus, the Northern frontier areas might be expected to yield 455 trillion CF. On this basis, another estimate was made by the Canadian Energy Board[120] of the quantities of additional gas that could be exported to the United States if the reserves expected in the Northern frontier areas materialize. These additional quantities are shown on line 3 of Table 4.1.4.-1.

4.1.4.2. Imported Mexican Gas

Imports from Mexico are expected to remain at the level of 0.04 trillion CF reported in 1968. Mexico has estimated reserves of approximately 12 trillion CF. Its annual production is about 575 billion CF including gas exported to the U.S. The domestic consumption in Mexico is about 440 billion CF. Thus, the reserve-to-production ratio including export gas is about 21, and even excluding exported gas, the reserves-to-production ratio is about 27. Thus, Mexico has a supply of gas that is barely more than adequate for its own domestic needs; unless substantial new reserves are uncovered, we can expect little relief for our domestic gas shortage from below the Rio Grande River.

4.1.4.3. Gas From Alaska

The recent discoveries of oil at Prudhoe Bay in Alaska have revealed substantial quantities of natural gas as well. While estimates of the total quantities vary, we can probably count on 200 trillion CF of natural gas reserves in Northern Alaska. Since about 25 trillion CF of natural gas reserves are needed to back up one 48-in. pipeline, there appear to be ample reserves to serve several pipelines from Alaska to the United States. However, it will require about 4 or 5 years to build even the first pipeline from Prudhoe Bay to the United States. Thus we cannot expect to obtain gas from Alaska until about 1975. The first such pipeline might have a capacity of about 3 billion CF/day.

4.1.4.4. Imported LNG

Thus far four projects for the importation of LNG into the United States have been announced — all of them to the East Coast. Several additional projects are known to be in the planning stage. It is possible that by the late seventies, LNG importation could exceed 3 billion SCF per day if a sufficient number of LNG tankers are built.

Of the 33 LNG tankers that have been built or are known to be on order, only 11 will be available for East Coast shipments. These ships will be able to import LNG at a rate of about one billion SCF/day by 1975. To increase the importation rate to three billion SCF/day will require about 20 additional large LNG tankers. These must be ordered during the next year or two if all of the projected importation plans are to be in full operation by the late 1970's. There are about 12 shipyards with LNG tanker experience, (all of them European) so the problem is one of fitting new LNG tanker orders into busy shipyard schedules.

4.1.4.4.1. El Paso Project

The largest LNG import project announced thus far is that of the El Paso Natural Gas Co. In July of 1969, El Paso announced a 25-year agreement with SONATRACH, a national Algerian gas and oil producing company, to import 1 billion SCF/day of Algerian natural gas into the East Coast of the United States beginning in 1973. The size of the project has recently been increased to 1.5 billion SCF/day. The price of this gas delivered to the U.S. will be about 58.5¢/million Btu. This represents a sizable increase over the price of about 50¢/million Btu reported earlier.

The project will require from 12 to 14 large LNG tankers. Contracts for two of them have been announced. These will be 750,000 bbl capacity ships and are scheduled for delivery in late 1974 and late 1975. The estimated cost of the original project was $900,000,000, but has probably increased somewhat due to increased tanker costs.

4.1.4.4.2. Philadelphia Gas Works Project

Philadelphia Gas Works and Corporacion Venezolana del Petroleo (CVP) have signed a 20-year contract to allow PGW to import 500 million CF/day of Venezuelan LNG. Total investment for the project, which should begin in the fall of 1974, is expected to be $400 million: $200 million for Venezuelan liquefaction plant and port facilities, $102-$160 million for three or four 680,000-bbl capacity tankers, and about $40 million for the Philadelphia port and vaporization facilities. The investment is thus 80¢/ million CF of daily capacity.

4.1.4.4.3. Distrigas Project

Distrigas Corp. plans to bring Algerian LNG into the New England area, primarily for peakshaving purposes. Recently the company asked the Federal Power Commission for permission to import up to approximately 6 billion CF/yr of natural gas in liquefied form over a 20-year period starting November 1, 1971. The LNG will be bought from Alocean, Ltd., a joint organization of SONATRACH and GazOcean International, and will come from the liquefaction plant at Skikda, Algeria.

To transport the LNG, Distrigas chartered the Descartes which has a capacity of 1 billion CF of natural gas (300,000 bbl) and should be in service in the spring of 1971. Contracts call for the delivery of two shiploads between August 1, 1971 and March 31, 1972; four shiploads in the 12-month period starting April 1, 1972; and six shiploads each year thereafter. Shipyard space has also been reserved for a 440,000-bbl (1.47 billion CF of natural gas) tanker for 1973 and a 600,000-bbl (2 billion CF of natural gas) tanker for 1974.

4.1.4.4.4. Columbia – Standard Oil Project

Recently, Columbia Gas System, Inc. contracted with subsidiaries of the Standard Oil Company to import LNG at a rate equivalent to 425 million CF of gas per day from Venezuela. The gas will be liquefied in a plant to be built by Creole Petroleum Corporation in a joint venture with the Venezuelan Government. The plant is estimated to cost $154 million.

The LNG will be delivered to Columbia Gas at its planned facility at Cove Point, Maryland on the Chesapeake Bay for a price of about 53.5¢/million Btu which is subject to future escalation. Columbia will buy the supply from Esso LNG under a 20-year contract for 40.5¢/million Btu and Esso Oceanic will deliver to Cove Point for an additional 13¢/million Btu. It is estimated that this gas can then be delivered in the Washington D.C. area at prices around 60¢/million Btu.

4.1.4.4.5. Importation on the West Coast

Very serious consideration is currently being given to the movement of LNG to the West Coast of the U.S., particularly the Los Angeles area from the South Coast of Alaska. This does not necessarily involve gas from the Prudhoe Bay area. There are estimated reserves of about 6 trillion CF available in Southern Alaska that are presently used to supply the Phillips Marathon LNG project transporting LNG to Japan. Additional gas could be supplied to the Los Angeles area by pipelining gas from Northern British Columbia to the Pacific Coast and liquefying it for transport by sea to Los Angeles. Both of these alternate sources have been examined. The Canadian alternative, of course, has the advantage of avoiding the complications of the Jones Act. Studies made by Arthur D. Little of comparative costs of shipping LNG from Alaska to Los Angeles indicate that the Jones Act results in an increase of about 8¢/1000 CF.

A comparison of the cost of importing LNG to Los Angeles on three different bases is presented in Table 4.1.4.-2. We can see that LNG transported from the Cook inlet in Alaska to Los Angeles could be vaporized at a Los Angeles terminal for about 71¢/1000 CF, and LNG transported from British Columbia to the sea coast at Stewart, B.C. and liquefied there for transportation to Los Angeles would also cost about the same price. If the Jones Act could be set aside, LNG could be brought into Los Angeles for about 63¢/1000 CF and would gain a competitive advantage over importation from British Columbia.

Table 4.1.4.-2. LNG COSTS AT LOS ANGELES @ 500 MILLION SCF/DAY

	LNG From Cook Inlet (Under Jones Act)	LNG From Cook Inlet (No Jones Act)	LNG From British Columbia
		¢/1000 CF	
Gas Cost	15.0	15.0	18.0
Pipeline Transport to Coast	--	--	6.9
Liquefaction Cost	28.	28.	28.
Sea Transport	22.9	14.8	12.6
Terminal Costs	5.0	5.0	5.0
Total Cost of LNG (Vaporized)	70.9	62.8	70.5

4.1.4.5. North Atlantic Continental Shelf

In recent years there has been increasing interest in exploration for oil and gas off the East Coast of the United States and Canada in areas ranging from Labrador to as far south as Norfolk, Virginia. The rapid evolution of deepwater drilling and underwater pipeline technology makes it possible to give serious consideration to the development of any oil and gas reserves that may exist in this area. The Continental Shelf is defined as the submerged part of the continent out to a water depth of 600 ft. The North Atlantic Shelf is approximately 100 miles wide and extends approximately 750 miles from Norfolk, Virginia to the outer tip of the Georges Bank east of Boston. This area is larger than the Continental Shelf off Louisiana and Texas.

The geophysical exploration that has been carried out has been primarily limited to aeromagnetic surveys and no data are currently available as to the possible yield of gas from the region. Drilling activity in this offshore area has been delayed because of increasing concern over control of drilling and well completion techniques. The Canadians have moved more rapidly and a number of exploratory wells have been drilled offshore Nova Scotia in the vicinity of Sable Island. These initial efforts have been sufficiently promising to encourage further exploration. This potential source of additional gas supplies is a particularly important one for it is the one area from which gas could be supplied to the large energy markets of the Eastern Seaboard at prices that would be competitive with present-day gas prices.

4.1.4.6. Synthetic Pipeline Gas

The technology required to make a synthetic gas that is completely interchangeable with natural gas is quite different from the technology used to make the low Btu manufactured gas that has been used by the gas industry for many years before the advent of natural gas. To produce a high Btu gas comparable to methane, the waste material must be removed and enough hydrogen added to increase the hydrogen of the product gas about 25%. This hydrogen is added chemically and does not appear as free hydrogen.

At the present time there are three pilot plants under construction to demonstrate the technology and the economics of producing synthetic pipeline gas from coal and lignite. The projected development schedules will permit the manufacture and sale of commercial quantities of synthetic gas by about 1978. However, it will be 1980 before large quantities of gas from this source could begin to make a significant contribution to the nation's gas supply. It is presently projected that synthetic gas can be produced and delivered to major market areas for prices ranging from 60-70¢/million Btu depending upon transportation distances and local coal costs.

4.1.5. Supply Deficiency

If the gas available from the various supplemental gas supply sources are added to the projected natural gas supply, the total projected supply of gas still falls short of the estimated future requirements that have been projected by the Future Requirements Committee. This is shown in Figure 4.1.5.-1.

This figure does not include any projection of additional natural gas production which could result from an increase in wellhead prices. However, since it will be several years before such increases in prices will result in additional production due to the time required for exploration and completion of production wells, the supply deficiency of natural gas is expected to gradually increase until 1975. If additional supplies of natural gas can be brought to market in addition to the projected alternate supplies, the deficiency can be reduced beyond that date. It is unfortunate that this period of gas supply deficiency coincides with the period during which it would be most desirable to have an alternative fuel available for use in automobiles to serve until such time as pollution control devices and clean engines can be developed to operate on conventional motor fuels.

4.1.6. Compressed Gas

Natural gas used to fuel those motor vehicles designed for operation on compressed natural gas must first be compressed to the very high supply pressures required for this service.

Normally natural gas is transmitted by pipeline at pressures ranging from perhaps 300 psi up to 1000 psi or more. The distribution utility will reduce these gas pressures in the course of distributing gas through its pipeline network so that gas supplied to the ultimate consumer may range in pressure from a few inches (water column) up to a few psi although some commercial and industrial users may be supplied with gas at pressures as high as 50 or 60 psi.

In order to store a useful quantity of gas in a motor vehicle, it is necessary to store it at pressures on the order of 2000 to 3000 psi. Therefore it is

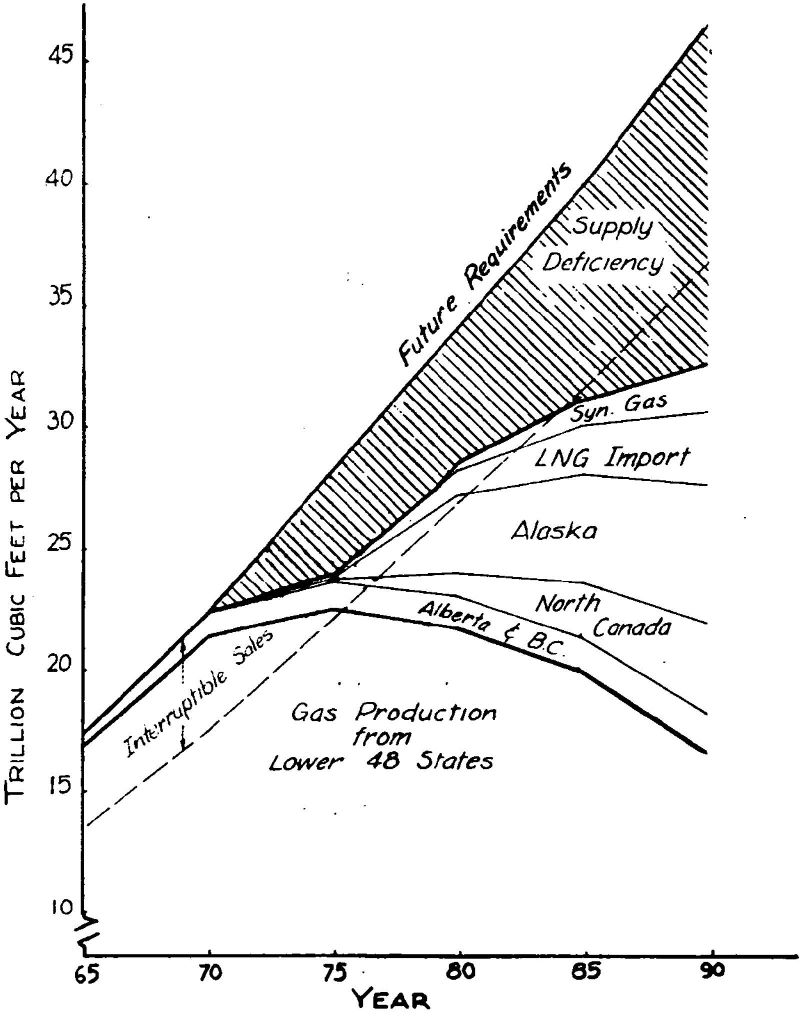

Figure 4.1.5.-1. UNITED STATES GAS SUPPLY

necessary to compress the gas available at a refueling point from whatever the local distribution pressure may be to a level of about 3000 psi. This compressed gas is either stored in a manifold of high pressure tubing containers or is delivered directly to the high pressure fuel tank installed in the vehicle.

In supplying compressed natural gas for motor vehicle use it is desirable to have the compression as close to the point of use as possible in order to avoid the cost and complications of distributing high pressure gas. For this reason, relatively small compressors are used at the refueling station rather than at some central point away from the vehicle; the compressors used are relatively small in size and compression costs are relatively high. On the other hand, it is a simple matter to add this compression equipment to the facilities of a normal automotive fuel service station in order to permit the servicing of a vehicle with either gasoline, natural gas, or both fuels.

4.1.7. LNG

The problem of supplying LNG for motor vehicle use is quite different however. It cannot be liquefied economically in small quantities close to refueling stations. The liquefaction process is sensitive to the economics of scale and it must be done in large scale plants in order to achieve the cost levels necessary to compete with automotive fuels. It must then be distributed by truck or rail transportation in much the same manner as gasoline motor fuel.

Favorable economics can be achieved in coastal areas using imported LNG which is produced in very large scale plants and delivered in bulk liquid form at points close to many large automotive fuel markets. Most of these large projects will not get underway until about 1975. Nevertheless, the Distrigas Corporation has already requested permission from the FPC to import some LNG for this use by 1971.

However, in the interior of the country, we must rely upon LNG from domestic liquefaction plants. At the present time there are 13 such plants in operation as listed in Table 4.1.7-1 along with others under construction or planned. These are gas utility peakshaving plants that are designed to liquefy and store natural gas during the summer months for revaporization and use during periods of peak demand in the wintertime.

This is a relatively new activity, for until 1965 there were no such plants at all. Now there are over forty companies that have built or are planning to build LNG facilities, and twelve are expanding or duplicating their existing plants. The average peakshaving plant has a liquefaction capacity on the order of 5,000,000 CF/day which is rather small to achieve the cost levels needed to provide LNG at prices competitive with other motor fuels. Those utilities having LNG available offer it for sale at prices ranging from 8¢ to 15¢/gal. As the use of LNG increases, larger liquefaction plants will be built and the cost of liquefaction can be reduced. Nevertheless, the peakshaving application of LNG is not growing rapidly enough to provide adequate sources of LNG for motor fuel use in the near future. Such growth would have to be stimulated by a demand for LNG as a motor fuel.

4.1.8. Price of Natural Gas for Motor Fuel Use

4.1.8.1. Compressed Natural Gas

Since compressed natural gas for automotive use is obtained by compression of locally available supplies in small compressor service stations, it is difficult to provide general price data on gas in this form.

Generally a large commercial or small industrial rate will apply to the gas used and these may range from 35¢ to 70¢/million Btu in various areas. The compression costs will also vary depending upon the volume handled, the pressure ratio of compression, and the duty cycle used. Compression costs on the order of 70¢ to 90¢/million Btu have been reported in some installations.[42] Compressor costs cannot be considered alone. For example,

Table 4.1.7.-1, Part 1. LNG FACILITIES IN THE U.S. AND CANADA

Company & Plant Site	Status	Liq Capacity, 10^6 CF/day	Storage, 10^6 CF	Vaporization, 10^6 CF/day
1. Alabama Gas Corp. Birmingham, Ala.	On-Stream	4.65	625	127
(Second tank)	On-Stream	--	625	--
2. Atlanta Gas Light Co. Riverdale, Ga.	Under Construction	10.0	1000	--
3. Baltimore Gas & Electric Co. Spring Gardens, Md.	Under Construction	2.75	500	150 (plus 2 plug-in units)
4. Boston Gas Co. Boston, Mass.	On-Stream	6.0	1000	187.5
(Second tank)	Under Construction	--	1000	--
5. British Columbia Hydro & Power Authority, Vancouver, B. C.	Under Construction	2.50	625	150
6. Brooklyn Union Gas Co. Green Point, N. Y.	On-Stream	5.68	625	100
(Second tank)	Under Construction	--	1000	--
7. Citizens Gas & Coke Utility Indianapolis, Ind.	Under Construction	5.0	1000	180
8. Commonwealth Natural Gas Corp. Tidewater, Va.	Under Construction	5.0	1200	100
9. Consolidated Edison of New York New York City, N. Y.	Planned	5.0	1000	NA
10. Fall River Gas Co. Fall River, Mass.	Under Construction	0.5	150	10
11. Gaz Metropolitain Riviere des Prairies, Que.	On-Stream	10.0	1000	120
(Second tank)	Under Construction	--	1000	--
12. Linde Div. of Union Carbide Corp. a) Sacramento, Calif. b) Ontario, Calif.	On-Stream	NA	NA	--

Table 4.1.7.-1, Part 2. LNG FACILITIES IN THE U.S. AND CANADA

Company & Plant Site	Status	Liq Capacity, 10^6 CF/day	Storage, 10^6 CF	Vaporization, 10^6 CF/day
13. Long Island Lighting Co., Holbrook, L. I., New York	Under Construction	3.0	600	150
14. Lowell Gas Co. Tewksbury, Mass.	On-Stream	4.5	1000	60
15. Memphis Light, Gas & Water Division Memphis, Tenn.	On-Stream	5.0	1000	200
16. NEGEA-Air Products Hopkinton, Mass. (Subject to FPC approval of purchase from Tenn. Gas Pipeline Co.)	Planned	18.5	NA	248
17. New England Electric System, Lynn, Mass.	Planned	7.85	1000	57.6
18. Northern & Central Gas Co., Hager, Ont.	On-Stream	2.5	625	85
19. Northern States Power Co., Eau Clair, Wisc.	On-Stream	2.0	270	24
20. Northwest Natural Gas Co., Portland, Ore.	On-Stream	2.5	625	120
21. Philadelphia Electric Co., West Conshohocken, Pa.	Under Construction	6.0	1200	300
22. Philadelphia Gas Works Philadelphia, Pa. (Completed except for storage tank)	Under Construction	16.0	4000	500
23. San Diego Gas & Electric Co. Chula Vista, Calif.	On-Stream	2.0	625	120
(Addition)	Under Construction	7.0	1200	120

Table 4.1.7.-1, Part 3. LNG FACILITIES IN THE U.S. AND CANADA

Company & Plant Site	Status	Liq Capacity, 10^6 CF/day	Storage, 10^6 CF	Vaporization, 10^6 CF/day
24. Southern Conn. Gas Co., Bridgeport, Conn.	Under Construction	6.6	1200	NA
25. Texas Eastern Trans. Company, Staten Island, N.Y.	On-Stream	10.08	2040	240
26. Transcontinental Gas Pipe Line Corp. Carstadt, N.J.	On-Stream	7.0	1000	200
(Second tank)	Planned	--	1000	200
27. Union Light, Heat & Power Company (Cincinnati Gas & Electric Co. Subsidiary) Erlanger, Ky.	Under Construction	1.0	13.7	--
28. Wisconsin Natural Gas Co. Oak Creek, Wisc.	On-Stream	1.0	252	50

a small compressor operated continuously can pump a large reservoir to the required pressure over a 24-hr period and serve to refuel a vehicle daily. Alternatively a larger compressor can pump up the vehicle tank pressure directly without using a reservoir. The choice of either system or some combination of the two is a function of the characteristics of the individual application; the number of vehicles, refueling schedules, tank capacities, etc.

Regular gasoline costs about 12 to 14¢/gal at the refinery level and perhaps 14¢ to 16¢/gal to fleet vehicle operators before taxes. Each gallon contains about 120,000 Btu of energy which is equivalent to about 115 CF of natural gas. Actual experience has shown that differences in engine fuel economy permit the use of 100 CF of gas (or 1 therm) as a rough comparison to 1 gallon of gasoline. This means that compressed gas must sell for 12¢/therm or $1.20/million Btu in order to be competitive with regular gasoline in many areas.

4.1.8.2. LNG

Since LNG is vaporized before injection into an engine, its performance is comparable to that of compressed natural gas. The San Diego Gas & Electric Company has reported automobile fuel consumption on LNG of 13 miles/gallon compared to 15 miles/gallon using gasoline in the same vehicle.[81] On this basis the cost of LNG equivalent to gasoline at 12¢/gal is also about $1.20/million Btu.

It has already been mentioned that imported LNG is projected to cost less than $1.00/million Btu and in large quantities it may be available for as low as 65¢/million Btu. This leaves sufficient margin to permit LNG to be sold in a rather broad area before the distribution expense adds sufficient costs to exceed comparable prices for gasoline.

The cost of liquefying domestic LNG is another matter, however. Very large liquefaction plants such as those built in Alaska and Algeria would permit domestic natural gas to be liquefied at costs of perhaps 35¢/million Btu.

Using gas that itself cost 35¢/million Btu would produce LNG for about 70¢/million Btu — well below the $1.20/million Btu equivalent to gasoline at 12¢/gal.

However, LNG peakshaving plants produce LNG at much higher costs because of their relatively small size and adverse utilization factors. These plants only operate about 200 days per year and have relatively high storage costs because they must hold the total annual production to meet the winter demand.

A large demand for LNG in the motor fuel market would permit an expansion of these plants both in size and in utilization factors that would permit them to approach the large base load importation plants in performance. However to liquefy gas domestically on the same scale as importation plants would require quantities of domestic gas comparable to those being imported. This would tend to defeat the purpose of LNG importation.

While this procedure might be feasible economically, it could only be justified where the use of LNG in motor vehicles is shown to be a more desirable way of using our natural gas resources than current use patterns.

4.2. Propane

The supply of domestically produced propane results from two sources. In 1967, 70% of propane was produced by natural gas processing plants (NGL). The balance, 30% was produced by petroleum refineries (LRG). In 1969, these figures changed to show that 72% of propane was produced in NGL plants and 28% was produced by refineries. Thus, natural gas processing increased its portion of total production while LRG production declined.

Quick response to supply and price pressures is one of the factors causing wide swings in propane prices. The combined production capacity of propane has averaged an 11% annual growth rate during the period from 1965 to 1969.

LP-gas, or propane, is a by-product in natural gas processing and petroleum refining. Because of this by-product nature the economics of production are subject to the following characteristics:

- Availability is controlled by demand for the primary product
- Markets are generally sporadic or cyclic in nature
- Small surpluses or shortages tend to cause erratic variations in price

4.2.1. Field Production of Propane

Production of propane at natural gas processing plants is dependent on the following factors: demand for natural gas, content of extractable liquids in the stream, and the heating value required for the residual gas stream. As the demand for natural gas increases, the volume of gas processed also increases. Industry estimates for 1975 indicate production will increase from the 20.9 trillion CF of 1969, to approximately 25 trillion CF, assuming a 3% annual growth rate. Since only 77% of total gas withdrawals are being processed, 16.09 trillion CF of natural gas is the base supply.

Projections anticipate an 87% processing level by 1975, which would mean 21.75 trillion CF would be processed.[166] This would provide an increase of

48% in available input supply for propane manufacturing. However, as volumes of natural gas are increased, a greater percentage will come from the southern Louisiana fields.

This gas is leaner than the west Texas casing head gas that it will replace. In the period 1955-1960, the propane and heavier material content of natural gas was 1.5 gal/1000 CF. In 1966 the content dropped to 0.66 gal/1000 CF and is expected to be 0.534 gal/1000 CF by 1975. This represents a 20% decrease in liquids available per 1000 CF.

Since ethane and propane are not completely extracted in present processing, it is reasonable to expect deeper extraction to offset the declining liquid content. It should be noted that this is not true for butane, whose current recovery is quite high. The ethane content of natural gas is twice that of propane. At 30% ethane recovery, nearly all propane is recovered. The generally accepted economical limit of ethane recovery is 60%. Since ethane is considered to be the more desirable feedstock for ethylene, further extraction is foreseen, with a resultant slight increase in propane yield.

The extent of extraction is limited, however, by the Btu values imposed by contract price schedules. It is expected that industry averages will fall far short of 50% ethane extraction, and some indications are that a 25% level is a realistic figure. For example, the recommended heat value for southern Louisiana is 1025-1075 Btu/CF. After 90% propane extraction, the gas has a value of 1006 Btu/CF; after 30% ethane recovery, the value is only 999 Btu/CF. The penalties on the price of natural gas and the market value of propane and ethane will determine the economically feasible level of extraction. The effect on propane pricing can be illustrated as follows:

If natural gas sells for 15¢/mm BTU at the wellhead and has a heating value in excess of the required minimum, the propane it contains is worth approximately 1.4¢/gal as a component of the natural gas. If the propane in excess of that required to maintain minimum heating value is removed and sold separately it has a value of approximately 3.0¢/gal or twice its value as a natural gas component. Thus the producer has an incentive to remove excess quantities of propane where its cost of extraction is less than the difference between these two values.

Since the normal price range of propane sold is 3-5¢/gal, a sharp increase in cost of input natural gas could seriously disrupt the economics of merchandising propane, for the use of propane as a feedstock by the petrochemical industry is highly dependent on the price and availability of product.

However, the validity of this argument is dependent on the present existence of excess quantities of propane in the residual natural gas streams that are not being charged to the user. The argument loses strength if the gas sold has a Btu basis for pricing, or if the residual propane is not economically extractable. The establishment of pricing guidelines along Btu lines is more common today because of the availability of equipment developed to measure thermal content with a volume-measuring orifice meter.

4.2.2 Refinery Production

In refinery operations, production propane and other light hydrocarbons may be sold as products or used internally as fuel. Thus, production depends greatly on price because propane must economically justify its alternative uses. To the extent that natural gas is often the substitute fuel when propane is sold to the market, the price of natural gas will determine the minimum or heating value of propane and set the floor level price of propane. The final limiting factor on refinery production is the physical capacity for producing propane.

Production of propane from refineries, unlike production from natural gas, is less dependent on input source volume. Thus, while the volume of crude is a determinant, the type of processing step plays a more significant role in determining production quantities.

In 1969, LRG production was 20,000 bbl/day and the amount of propane produced is on the order of 1.5% of the crude feedstock.

4.2.3. LPG Importation

In 1968 the United States imported a total of 236 million gallons of propane, virtually all of it from Canada. This was an increase of 34% over 1967. During the same year 107 million gallons of propane was exported. Thus, net imports of LPG are quite small — less than 130 million gallons annually.

One reason for this is that oil import quotas apply to LPG as well as heavier oils and serve to restrict importation of LPG. Recent concern for fuel supplies in the United States, however, have caused some revisions in these oil import quotas and the climate is now more favorable to large scale importation of LPG.

The most probable sources of propane aside from Canada are those countries such as Venezuela, Algeria, and Libya that are potential suppliers of LNG, since LPG is a by-product of natural gas production. Thus, its availability depends upon the rate of development of the markets for foreign natural gas — such as importation of LNG into the United States.

The LNG importation programs planned for the U. S. alone could yield as much as 400 to 500 million gallons of propane annually if maximum amounts are recovered.

Large quantities of LPG can be imported into the United States if American buyers can contract for excess LPG from foreign gas fields. There is currently little history of negotiations for such gas both because domestic supplies have so far been adequate and because import quotas have discouraged them. Nevertheless the growing shortage of LPG has stimulated interest in this question and it is anticipated that such importations will be made in another year or so provided suitable pricing can be arranged.

The price of propane in New York Harbor ranged from 7.25¢/gal to 8.75¢/gal during 1968 or about 0.50¢ to 1.00¢/gal less than in 1967. Current prices are 9¢ to 9.5¢/gal.

4.2.4. Domestic Supply Outlook

In previous supply studies it had been estimated that demand would outstrip supply by the early 1970's, most likely during the 1972-73 heating season.[84] Because of the growing fuel shortage, this situation will develop earlier than anticipated. Industry forecasts indicate that we are now on the brink of a supply shortage. Once established, this imbalance will result in increased propane prices. This will tend to curtail the consumption of propane in the petrochemical industry as other users outbid them for available supplies. This trend is being accelerated by the growing shortage of natural gas and other fuels that will increase the demand for propane as an alternative to natural gas or low sulfur oil.

There is general agreement in industry sources that demand will exceed supply. The area of disagreement lies in the anticipated magnitude of the situation.

Supplies of LP-gas have increased 25.5% over 1966 levels in 1969. Some industry forecasters feel that supply will increase 10-15% in 1970, up from the 5-7.5% increase for 1969. After the 1970 increase, supply rate of growth is expected to stabilize at 2.5% per year until 1980, the combined rate of growth from both refineries and gas plants. (See Figure 4.2.4.-1)

The largest increase in propane production will come from refinery produced propane (LRG).[100] As mentioned earlier, LRG production is not dependent upon the volume of natural gas produced as is propane produced in NGL plants. The production rate 20,000 bbl of propane per day in 1969 is expected to grow at 5%/year until 1975 and 4.5% thereafter to 1980. The amount of propane recovered in refinery operations has increased faster than crude runs.[53] In 1960 the propane recovered amounted to 14.9 bbl/1000 bbl crude and could reach 23.5 bbl/1000 bbl crude by 1980, if the chemical makeup of gasoline is not significantly changed. If the nature of gasoline is changed this ratio will be higher.

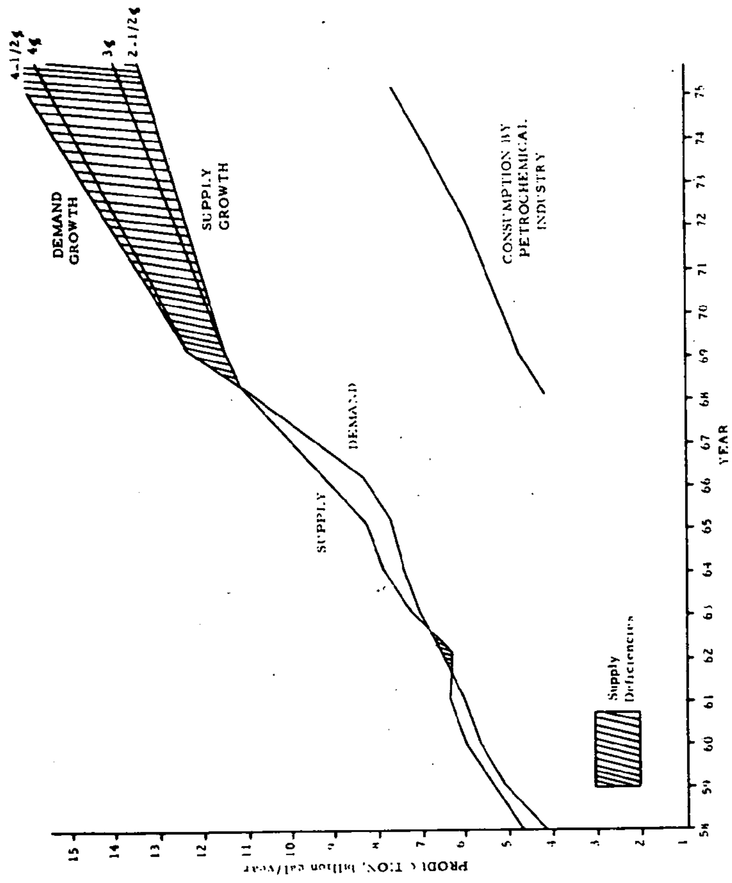

Figure 4.2.4.-1. PROPANE SUPPLY AND DEMAND

The removal of lead from gasoline would greatly improve propane supply from refinery sources.[63] Lead removal results in a lower octane fuel which can only be burned in engines of lower compression ratios than those of today. The amount of increased propane supply is related to the degree of lead removal.

A Federally indorsed program (proposed by HEW) provides for the gradual reduction of lead in gasoline. Following these recommendations California has passed a bill in the Senate (now before the House) calling for the following provisions:

1. As of July 1, 1971 each gasoline marketer in California must make available one grade of low-lead regular gasoline, probably 91 octane rating, maximum 0.5 g lead/gal.
2. July 1, 1974 each marketer must supply one lead-free regular grade of gasoline, probably 91 octane rating.
3. July 1, 1977 no lead can be contained in any gasoline, premium or regular.

Before discussing the potential impact of each of the above provisions certain assumptions must be drawn. These are —

- The product nature of propane will not change — that is, it will remain a by-product in other refinery processes
- No allowance is made for imports and exports, all production is domestic
- Major uses of propane, by market, will remain relatively unchanged
- This discussion is principally concerned with the engine fuel market

California has been the most active in terms of antipollution legislation. In its role of precedent setting legislation, it is feasible that the program outlined above will be adopted on a national basis.

Provision (1) presented above is the mildest in terms of change from present conditions and is the least effective in terms of changing the supply picture. Low-lead gasoline requires the least deviation from current production methods and can be made at an additional cost of a fraction of a cent per gallon. Cost at the pump would increase about 1¢ or 2¢ per gallon reflecting additional distribution costs and added pumps.

The use of 91 octane fuel in a car requires a reduction of compression ratio from about 9.0 to 8.2:1. This results in a reported loss of approximately 8% in gasoline economy or between 1 and 2 miles per gallon. However, lead is still present and the car would require a thermal reactor to meet air pollution requirements. A catalytic reactor could not be used since it would be poisoned by any trace of lead. Due to the pressure drop from the required air recirculation an additional 15% penalty would be imposed on fuel economy, resulting in a total decrease in efficiency of 23%. To move a vehicle the same distance as with standard regular grade gasoline approximately 23% more fuel would be required.

Provision (2) requires a gasoline completely free of lead. A recent Government panel established the cost of producing a completely lead-free gasoline at 0.5¢ to 1.5¢/gal. The retail price has been found to average 3¢ above the price of regular grades of gasoline, again reflecting additional marketing and distribution costs. The same loss of fuel economy (8%) would apply as in provision (1) with an additional proposed loss of 7% resulting from the use of a catalytic exhaust reactor. A total loss of 15% in fuel economy could be expected. A catalytic reactor would be required to completely remove the intensified pollution effect of aromatics, present to a higher degree in unleaded gasoline.

Provision (3) calls for the removal of lead from all gasolines and maintaining present octane levels of 94 for regular gasoline and 100 for premium grades. This provision would require extreme alteration of refinery processes and increased capital investment.

Processing steps required to produce unleaded premium would be:

1. Reforming. This process produces more aromatics and increases propane production. As the octane rating increases, the amount of reforming increases resulting in a higher propane yield at the same time decreasing the amount of gasoline. To make the same amount of gasoline 6-7% more crude oil would have to be processed with a higher amount of propane being produced.

2. Alkylation and Polymerization use propylene to make gasoline and propane production is not affected.
3. Isomerization does not affect propane availability
4. Hydrocracking and catalytic cracking. The former has preference in the production of jet fuel while the latter maximizes gasoline production. Both processes produce greater amounts of propane

Table 4.2.4.-1 summarizes the effect of the three provisions providing for the lead removal from gasoline under each stage of enactment.

Table 4.2.4.-1. REFINERY PROPANE PRODUCTION

Year	Lead Not Removed	Provision 1	Provision 2	Provision 3	Propane Produced From Natural Gas
	1000 bbl/day				
1970	225	225	225	225	575
1975	275	290	315	--	600
1980	250	420	510	640	625

Compliance with provision (3) would require a capital outlay of $5-$10 billion over the next 10 years to meet demand requirements.[63] This would increase current refinery investment by approximately 40%.

During the course of this study a question was raised concerning the by-product nature of propane. What would be the effect of changing propane from a by-product to a primary product? Several discussions were held with producers and various associations.

According to one major producer, if propane were to be converted to a primary product, additional capital expenditures would be required of the magnitude of $5-$10 billion as already mentioned, with adoption of reforming and hydrocracking as the primary method of production. These methods are generally more expensive than alternative methods. Secondly, the price of propane would be greatly affected.

For propane to become a primary product it would have to carry a greater share of refinery operating and investment costs. The best way to break this down would be on a ¢/Btu basis in comparison with gasoline. The following assumptions would have to be made:

- A regular grade of gasoline* contains 113,200 Btu/gal and sells for 13.0¢/gal excluding transportation and taxes.
- A gallon of propane* contains 91,800 Btu and costs 6.25¢/gal excluding transportation and taxes
- All other factors remain the same

At 13.0¢/gal the price of gasoline is equal to $1.15/million Btu, the price of propane is equal to $0.68/million Btu. Assuming the cost burden to be carried by propane is equal to that of gasoline, the net effect would be to increase propane prices to about 10¢ to 11¢/gal excluding transportation and taxes. However, a propane price of 8.5¢/gal would be equivalent to a refinery price of 12¢/gal considering differences in density and heating value. Thus, this projected price would represent a significant increase in the price of propane.

Other important factors also enter into the picture. At this increased price much of the propane consumed by the petrochemical industry would be freed for other applications. Ethane would become a more favorable feedstock. An increase in propane cost may raise the price of other hydrocarbons, but it is felt the increase would not be proportional to that of propane.

In 1969 the amount of propane produced by NGL processing plants averaged 535,000 bbl/day. Propane is the largest single by-product of natural gas processing. Industry forecasts indicate that the amount of propane produced will increase approximately 2¢/year until 1980. This is a sharp decline when compared with an average increase of 6.5¢ for the period 1960-1970.

The decline in rate of growth is primarily attributable to the drier gases found on the Gulf Coast. It is estimated that the overall liquid content will decline 1.4¢/year until 1980. A second factor contributing to the decline of natural gas processes is the current supply situation. What effect a price increase will have on natural gas availability is unknown, and cannot realistically be predicted. As of January 1, 1970, the capacity of natural gas processing plants in the U.S. was 68 billion CF/day. Throughput of natural gas during 1969 amounted to 56.2 billion CF/day or 82.7% of rated capacity. The high production reflects deeper extraction levels and short cycle extraction from small-volume streams which are not processed when demand is depressed.

The combined growth rate of natural gas processing and refinery propane has been estimated to be 2.5-2.9¢/yr from 1970-1975 and decline to 1.9¢ per year from 1975-1980. The decline during the second half of the decade can be attributed to leaner gas available for processing.

4.2.5. Demand Outlook

Demand in all segments of the propane industry increased approximately 34% during the period 1966-1969.[6,139,165] A 5% increase was posted for 1969 over 1968.[6] Utilizing industry forecasts, it is anticipated that demand will continue to grow at the rate of 4¢/year from 1970-1980. This rate is based on the assumption that petrochemical demand will not exceed an 8% rate of growth.[7]

The petrochemical industry is highly sensitive to propane price in the establishment of the amount consumed. Chemical feedstock of propane is priced in the area of 3¢-4¢/gal. This corresponds closely with the industry rule of thumb of paying approximately 1¢/lb for propane. In the long term analysis it is anticipated that the price of propane will approach and stabilize at 6.5¢/gal. During 1969 combined average daily production of propane from natural gas processing and refineries was 790,000 bbl/day, of which

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* Price plus or minus 0.25¢ f.o.b. refinery or terminal (Texas West Coast).

approximately 213,000 bbl/day was consumed by the petrochemical industry. If the price of propane is increased it is expected that petrochemicals would seek other feedstocks, thus freeing approximately 27% of domestically produced propane for consumption in other market segments.

4.2.5.1. Residential and Commercial Markets

The largest sales category is the residential and commercial market which in 1968 accounted for 41.5% of the total sales. This represents an increase of approximately 7% over sales in 1967. Industry consensus is that sales in the residential and commercial area will tend to decline in the next 10 years.

The pressures causing this trend include natural gas encroachment, electrical competition for cooking and space heating, and pricing practices that limit development of this market. The growth pattern of this market has tended to follow the supply situation, as is evidenced by 7.2% growth in 1963, 2.5% in 1964, 3.2% in 1965, and 6.2% in 1966.

4.2.5.2. Petrochemical Market

Chemical feedstocks represent the second largest sales category of LP-gas sales, and 1968 estimates of sales placed it at 38.7% of total sales. This market segment is extremely sensitive to the price structures of alternative feedstocks. Ethane forms the principal feedstock source, but butane, naphtha, and other hydrocarbons can be used. The flexibility of the input varies from plant to plant, depending on the type of process used.

The popularity of ethane as a feedstock is readily apparent in terms of the ethylene output. When ethylene is the only product desired, the 75% conversion of the ethane feedstock is far superior to any alternative source. The remaining 25% of by-products include hydrogen, methane, propylene, propane, and mixed C_4's and C_5's. These products have value in their own right and can contribute to revenue; however, their volume is small enough so that lack of by-product sales would affect overall returns only minimally.

With propane, the ethylene yield is about 40%, but 18% propylene is produced along with appreciable quantities of C_4's and heavier liquid products. Thus, the profitability of propane is more dependent on the realization of revenues from coproducts.

4.2.5.3. Engine Fuel Market

Engine fuel use is the third largest market for LP-gas and amounted to 7.6% of the total sales.[129] Sales in this area have been affected recently by the propane shortage. Low supply has led to reduced conversions and loss of sales because fuel customers' needs were subordinated to the heating customers' requirements in the 1965-66 shortage season.

Propane dealers generally prefer to sell to the engine fuel market because of its steady year round sales. However, during shortages of winter fuel, heating customers will outbid motor fuel users for available supplies not under long term contract. This creates uncertain supply situations that can be expected to be more common during the next few years as the general fuel supply situation becomes tighter.

The high price of propane during recent years has contributed to a decline in this market, for it is difficult to pass along price increases when the competitive fuel sources are on a steadier base. The greatest loss in sales volume occurred in Oklahoma and Texas — that is, in areas close to production facilities where initial sales were made on the basis of low price.

This market also reflects the amount of sales and service effort made, which in recent years has not been aggressive. Furthermore, the utilization of propane as a fuel necessitates the modification and alteration of a gasoline or diesel engine. This lack of an engine designed specifically for propane results in a nonmaximum utilization of propane as a fuel. At this time, there seems to be little hope of altering this condition, as most engine manufacturers show little interest in developing propane engines, although factory converted gasoline engines are available.

Hope for improvement in this market lies in engine development, steadier prices, available supplies, and sales based on advantages and performances rather than price. The demand for air pollution control also enhances the position of propane. Industry forecasters expect this market segment to show the largest increase during this decade. While little or no change is anticipated in other segments, the mobile fuel market is expected to increase 200% by 1980 or a total of 3.5 billion gallons. The largest sales increases are expected to come from urban fleets, fork lift trucks, stationary engines, farm tractors, and highway fleets. In general, equipment sales are expected to increase 60% and fork lift sales in the 30-40% range. See Figure 4.2.5.-1.

In recent years this market has shown the best increase in terms of sales and has made a turnaround from the sales decline experienced in the mid-1960's. This decline in sales has been attributed to several major factors: variable product quality, unsuitable equipment, and unstable prices.

The problem of product quality is related to composition of propane. HD-5 is the accepted industry specification for propane to be used in internal combustion engines. This specification covers a wide variation of product composition. The variable products are methane and propylene. The propylene content can vary 5 percentage points from 0 to 5%. This, in turn, has an effect on the volatility of the product. To a large degree quality control is the responsibility of the distributor who sells the product to the consumer. It is his responsibility to establish standards regarding water content, and sediment which collect in transport.

Equipment has also been a factor in the adoption of propane as a fuel. There are no engines currently available that were designed specifically for propane use. A high percentage of the engines using propane had to be converted from other fuel uses. Many of the conversions were poorly designed and operators soon lost their confidence in the ability of propane to meet their demand. They then went back to fuels previously used. For example, the Chicago Transit Authority operates the largest propane fueled bus fleet in the world and it has not purchased any additional propane units since 1963.

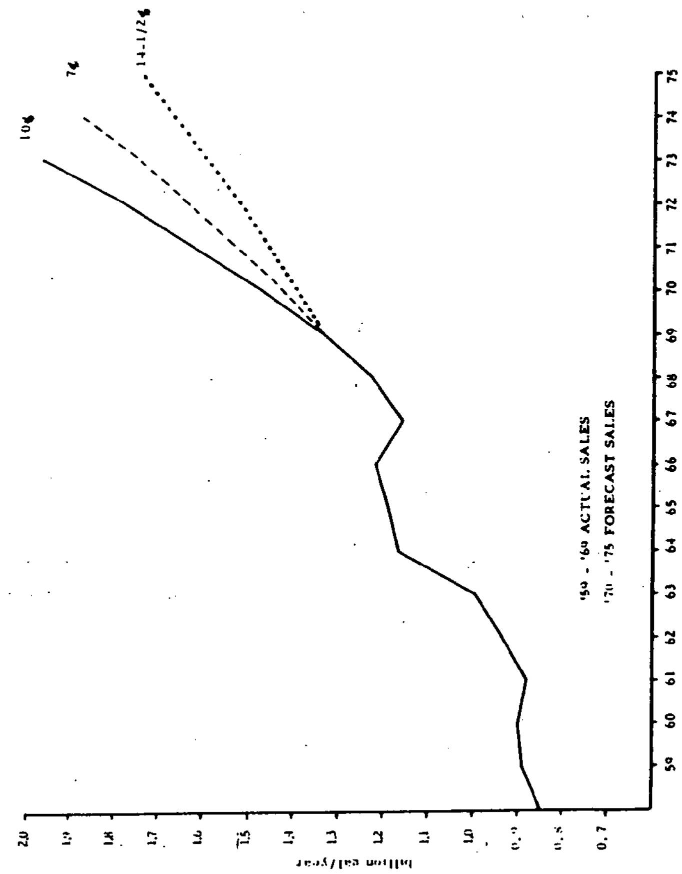

Figure 4.2.5.-1. SALES OF PROPANE FOR VEHICLE APPLICATIONS

This is primarily due to the nonavailability of equipment specifically designed to run on propane and the CTA does not wish to install engine conversion kits.

Propane price has also been an important factor in its adoption for vehicle fuel use. The price of propane is very unstable and historically has been subject to wide variations. As previously mentioned, at low price levels large amounts are consumed by the petrochemical industry. Thus, less product is available for consumption in other segments. When price begins to increase larger amounts are made available to other markets, but then the major cost advantage of propane is lost when compared to other fuel prices. The historical pattern of propane price is shown in Figure 4.2.5.-2.

Table 4.2.5.-1 lists the breakdown by state of propane sales used for vehicular fuel as reported by the National LP-Gas Association. The states consuming the largest amounts of propane are either major producers of LP-gas or located near pipeline transport depots, indicating the significance of transport and storage costs in its price structure. Figure 4.2.5.-3 shows major pipeline and terminal locations.

On a national basis, propane's use as a fuel for internal combustion engines can be broken down as follows: industrial fork lift trucks 46.8¢, farm tractors 25.0¢, buses and trucks 15.6¢, stationary engines 8.4¢, automotive 2.9¢, and truck refrigeration units 1.3¢. This information is from a survey of members of the National LP-Gas Association.

4.2.5.4. Other Markets

In the order of declining markets, the balance of demand is distributed between industrial 4.9¢, synthetic rubber 4.7¢, utility gas 1.1¢, and all other uses 1.3¢.

Included under "other uses" is refinery fuel. Refinery use to a great extent mirrors the price movements of propane. When prices are high the propane is worth more as a salable by-product and consequently it becomes uneconomical for use as an internal fuel. As prices decline, the use of propane becomes an economic alternative and refinery usage

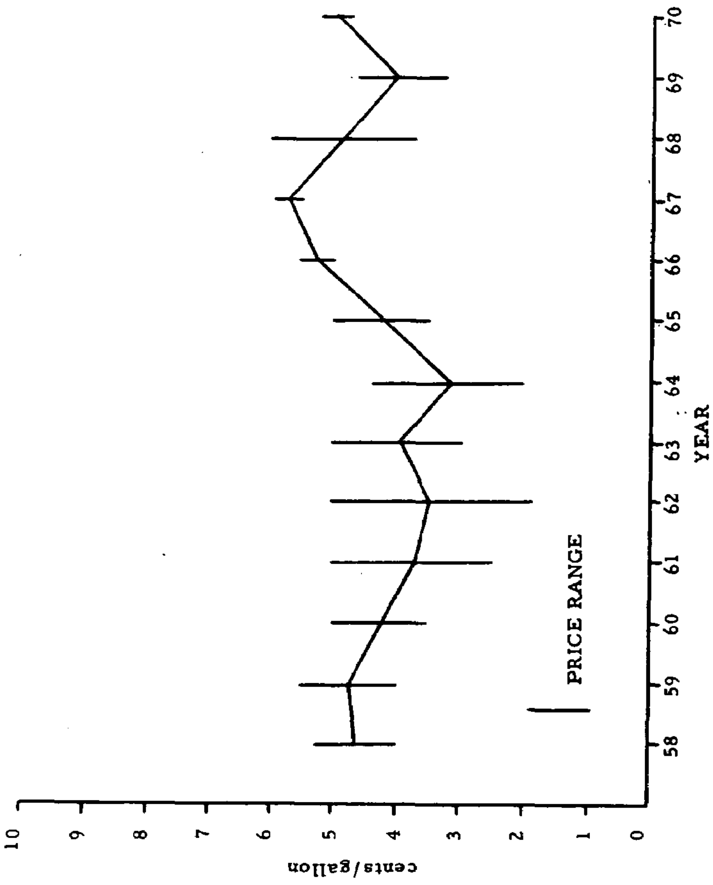

Figure 4.2.5.-2. HISTORICAL PROPANE PRICE PATTERNS

Table 4.2.5.-1. PROPANE SOLD FOR VEHICLE FUEL BY STATE

State	1965	1968
	1000 gal	
Alabama	6,241	10,527
Alaska	21	--
Arizona	5,750	6,043
Arkansas	62,904	59,098
California	30,192	25,896
Colorado	11,727	17,333
Connecticut	727	1,256
Delaware	423	423
Florida	19,362	20,293
Georgia	10,030	8,164
Hawaii	508	1,067
Idaho	617	826
Illinois	46,105	64,480
Indiana	7,580	12,252
Iowa	7,916	9,696
Kansas	42,738	52,598
Kentucky	5,148	9,804
Louisiana	23,027	31,379
Maine	232	245
Maryland & D.C.	1,416	1,768
Massachusetts	3,196	2,195
Michigan	4,883	8,524
Minnesota	5,397	15,469
Mississippi	33,694	42,441
Missouri	6,822	12,038
Montana	1,926	7,907
Nebraska	14,284	28,567
Nevada	1,273	739

Table 4.2.5.-1, Cont. PROPANE SOLD FOR VEHICLE FUEL BY STATE

State	1965	1968
	1000 gal	
New Hampshire	204	386
New Jersey	5,789	7,651
New Mexico	29,472	25,534
New York	5,525	6,769
North Carolina	2,488	3,563
North Dakota	3,234	7,659
Ohio	13,574	17,908
Oklahoma	70,860	64,147
Oregon	511	1,090
Pennsylvania	8,654	8,287
Rhode Island	558	688
South Carolina	1,805	2,530
South Dakota	3,543	6,972
Tennessee	7,881	13,364
Texas	664,403	558,440
Utah	1,804	1,274
Vermont	136	54
Virginia	3,408	3,329
Washington	2,994	2,821
West Virginia	522	100
Wisconsin	5,249	9,325
Wyoming	7,065	7,579
TOTAL	1,193,818	1,228,498

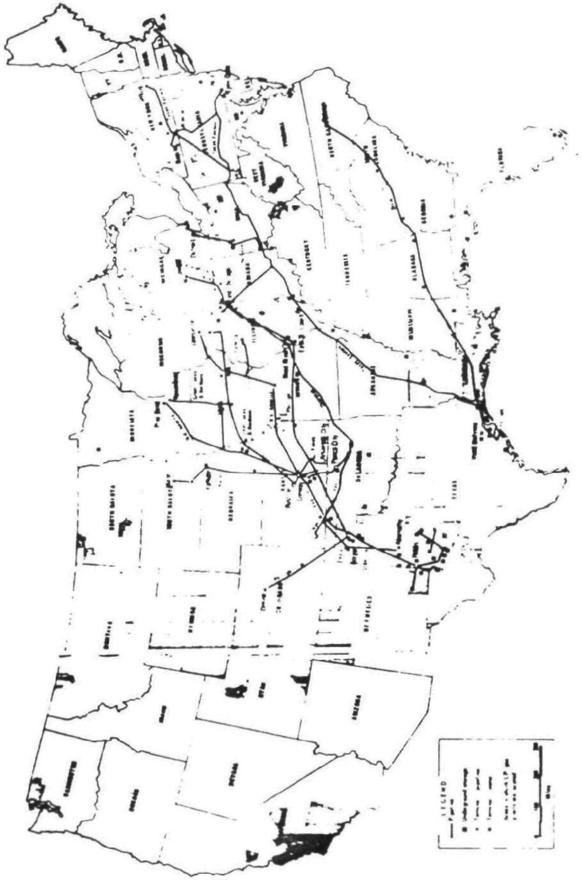

Figure 4.2.5.-3. LOCATION OF MAJOR LP-GAS PIPELINES AND TERMINALS

Source: Oil and Gas Journal, May 11, 1964

increases. Propane use in the production of synthetic rubber represents a relatively stable application and can be expected to maintain a gradual growth rate.

4.3. Ammonia

Although ammonia is not usually regarded as a fuel, it does in fact have all of the necessary qualities and has been used as a rocket fuel for many years.

4.3.1. Product Characteristics

Anhydrous ammonia consists of one part nitrogen and three parts hydrogen by volume. It is a liquid at −28°F and atmospheric pressure. At higher temperatures it is a colorless gas with a pungent odor and is lighter than air.

Ammonia has a flammability limit of 16-27% by volume in air at atmosheric pressure. It is completely soluble in water. In a closed system ammonia is a liquid at pressures at or above its vapor pressure.

Ammonia will vigorously attack copper, silver, zinc, and many alloys, particularly those containing copper. Iron and steel are generally not affected in anhydrous ammonia service.

Anhydrous ammonia has various effects on personnel that are dependent upon its concentration and physical state. Concentrations of 5000 ppm and above of the gas in air can cause immediate death; 700 to 5000 ppm can cause burns, blisters, eye damage, and damage to respiratory system membranes.

However, ammonia is easily detectable at concentrations of 40 to 50 ppm due to its pungent odor. Since its odor can be readily detected at concentrations well below its toxicity level, individuals tend to vacate areas of vapor concentrations before harmful levels are reached.

The physical characteristics of ammonia are summarized in Table 4.3.1-1.

4.3.2. Ammonia Supply

The production of ammonia in the past has utilized a variety of raw materials as a feedstock. Any substance capable of being converted into free hydrogen without introducing unfavorable side reactions or impurities can be used as a feedstock for the production of ammonia.[74] In the past, coke from coal was reacted with steam to produce a hydrogen-rich gas mixture. Some ammonia plants have been built to utilize refinery off-gases which were rich in hydrogen, and others utilize heavier hydrocarbon feedstocks.

Table 4.3.1-1. PHYSICAL CHARACTERISTICS OF ANHYDROUS AMMONI

Molecular weight	17.032
Boiling point	−28.0°F
Vapor pressure	212
Freezing point	−107.9°F
Specific gravity	0.6173 (air = 1)
Pounds per gallon	5.14
Specific gravity of liquid	0.5880 (water =1)
CF of gas per pound	22.28
CF of gas per gallon liquid	114.7
Btu/CF HHV	434
Btu/CF LHV	359
Flammability limits, % Volume in air	15.5-27.0%

The use of natural gas as a raw material for making the ammonia synthesi gas mixture has gained wide acceptance throughout the country since its introduction in the early 1940's. It has become the principal feedstock for ammonia production in the United States and is used exclusively in recently constructed plants. Approximately 93% of the ammonia produced today is synthesized from natural gas, while the remaining 7% is produced from coke oven gas, natural organics, or imported materials. The large scale use of ammonia as a motor fuel would require other raw material sources than natural gas since it is already in short supply.

The production of anhydrous ammonia in the United States has continued to increase following a general expansion trend established during the mid-

1950's. A reduction in the rate of growth was experienced during 1957 and 1958. The annual rate of growth was between 7-9%/year. A dramatic increase took place from 1965 to 1968 when production capacity went from a little over 10 million tons/year to more than 18 million tons/year in 1968. An expansion rate exceeding 25%/year was experienced. Figure 4.3.2.-1 depicts the growth pattern of the U.S. anhydrous ammonia industry. The rate of growth experienced during the mid-60's will not continue, but will probably decrease to a more modest 5-6%/year.

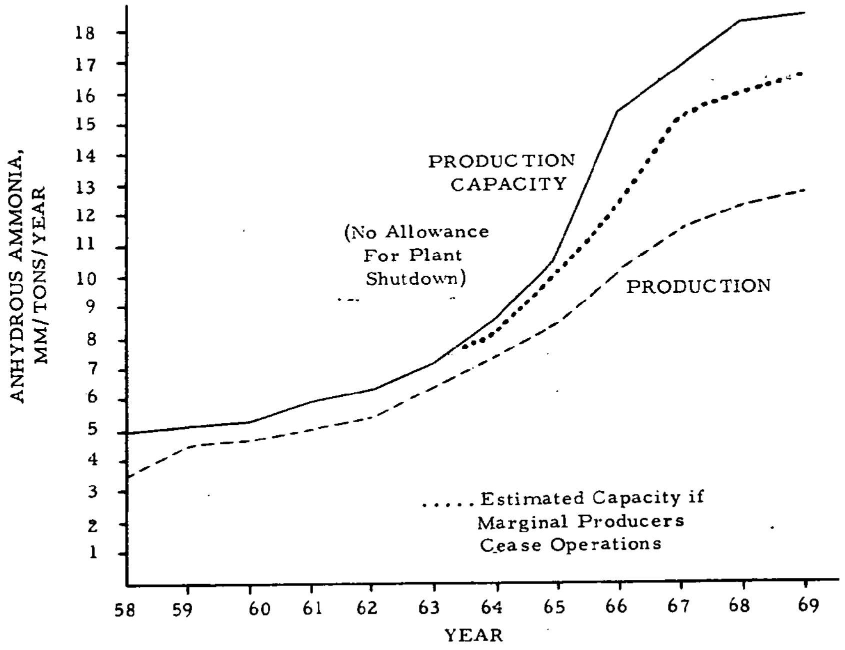

Figure 4.3.2.-1. PRODUCTION AND CONSUMPTION OF ANHYDROUS AMMONIA IN U.S.

There are several reasons for this growth pattern. Among them are oil industry diversification and production by the chemical industry. Petroleum companies were seeking ways to diversify and to upgrade refinery products. The easiest way to achieve this was to switch to low-cost ammonia production utilizing refinery by-product hydrogen. This, coupled with the government's new rapid amortization programs allowing faster tax write-offs enhanced ammonia production to the industry.

The chemical industry is characterized by strong competition for particular products, one of them being ammonia. Large capacity plants reduce the capital investment cost per unit of production. The lower production cost results in higher profit margins as well as the ability to meet strong competition.

The high rate of growth will not continue. Newer, more efficient plants are forcing less efficient producers of smaller capacity out of production. Approximately 3 million tons of yearly production will be lost in this manner. However, the net increase does not lose its significance when overall capacity is concerned.

4.3.3. Demand

The amount of ammonia produced is dependent upon agricultural demand. Approximately 80% of the ammonia produced in the United States is used for agricultural purposes. In 1969 approximately 12.7 million short tons of ammonia was produced; 10.2 million tons were consumed by agriculture.[17] Of this 10.2 million tons approximately 50% is applied to the soil as anhydrous or aqua ammonia with the remainder applied in combined form with other fertilizers. The rate of increased demand for agricultural application is expected to stabilize at approximately 7-8%/year. Figure 4.3.2.-1 shows total anhydrous ammonia production through 1969.

The remaining 20% of ammonia produced is consumed by industries other than agriculture. Approximately 2500 industrial outlets for ammonia exist consuming 2.5 million tons of product. The bulk of this output is directed toward captive end uses and the remainder is sold for further processing or direct-use as ammonia.

Direct uses account for approximately 1% of all ammonia produced. Largest direct uses consist of applications in steel treating, sulfite pulping, petroleum refining, and fermentation. These outlets are well established and are expected to grow at the same rate as the general economy.

Ammonia is a raw material used for the manufacture of four major industrial intermediates: nitric acid, amines, hydrogen cyanide, and urea.[94] Growth in this segment is expected to be the same rate as for direct uses above.

Production patterns for anhydrous ammonia reflect the seasonal nature of its principal market, agriculture. Agricultural demands are dependent upon the field crop and its growing season. The seasonal fluctuation is not as severe when observed on a national basis due to the balancing effect of the variety of crops and seasons. Certain regions, in particular the northern section of the country, are more affected by the seasonal nature of the market. Figure 4.3.3.-1 describes the national seasonal fluctuation of anhydrous ammonia production.

It is expected that the agricultural market will continue its dominance in the demand for anhydrous ammonia, assuming there will be no radical change in the Government's soil bank policy. The Government's liberal attitude toward high-yield crops on limited acreage provides an incentive to the farmer to increase the yield per acre, resulting in stimulation of the fertilizer market. In addition, research tests have shown that nitrogenous fertilization of forest and grazing lands increases the yield per acre. It is expected that the growth rate for consumption of fertilizer in this application will increase and eventually exceed consumption for field crops. This will broaden the ammonia market and aid in the utilization of current surplus production capacity.

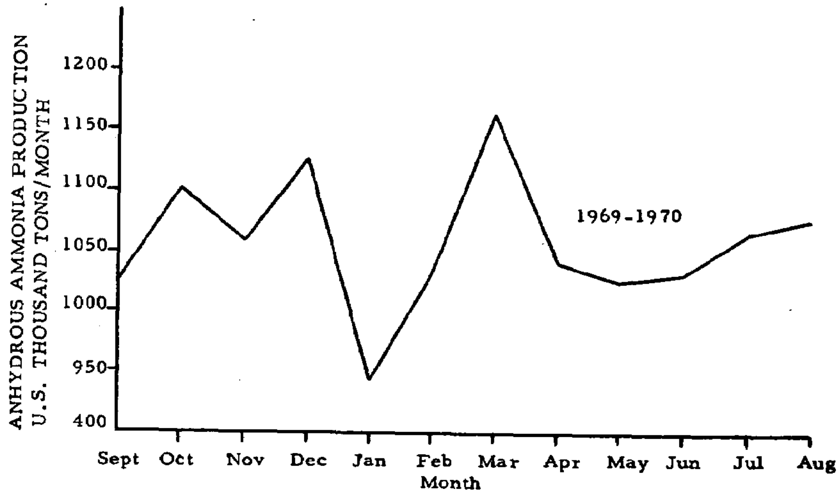

Figure 4.3.3.-1. SEASONAL FLUCTUATIONS IN ANHYDROUS AMMONIA PRODUCTION[160]

Industrial consumption, although relatively small when compared to the agricultural market, is looked upon as a stabilizing factor by the ammonia industry. The market is characterized by a stable rate of growth and it is not subject to wide variations in demand. It can act to stabilize the seasonal variation and it is hoped that it will help to utilize surplus production.

Anhydrous ammonia production facilities are located in every geographical region of the United States. However, the percentage of capacity located within each region varies to a great extent from approximately 0.5% in New England to 30.0% in the West South Central region. The concentration of ammonia capacity is directly related to the availability of natural gas as a feedstock and ammonia consumption within the region. The natural gas in this area is relatively inexpensive when compared with other areas and there is the second advantage of shipment via water routes. Table 4.3.3.-1, shows ammonia production capacity by state and Table 4.3.3.-2, shows ammonia consumption by major consuming states. When considered together it can be readily observed how feedstock source and transportation relate to one another.

Table 4.3.3.-1. MAJOR AMMONIA PRODUCING STATES (CAPACITY)
1968

State	1968 Thousand Short Tons/Yr	% of U.S. Production
Texas	3,150	18
Louisiana	3,150	18
California	1,300	8
Mississippi	1,250	7
Arkansas	850	5
Iowa	800	5
Pennsylvania	625	4
Nebraska	600	4
Illinois	525	3
Ohio	450	2
Other	--	--
	17,250	--

Table 4.3.3.-2. MAJOR AMMONIA CONSUMING STATES
1967[162]

State	Agricultural Ammonia Consumption Direct Application, %
Iowa	16.60
Illinois	14.73
Nebraska	10.25
Texas	9.66
Indiana	5.94
Kansas	5.83
California	5.64
Minnesota	4.23
Missouri	3.32
Washington	2.51

4.3.4. Price

The actual price paid for ammonia is largely determined by consideration of the following factors:

- Nature of the ammonia purchaser's business (e.g. distributor, processor, wholesaler).
- Quantity of product purchased annually
- Season or time of year when purchase is to be delivered
- Prevailing product supply-demand situation at time of purchase.

The ammonia industry is largely oriented toward agriculture. Thus, at the present time there is no way of determining what effect a nonagricultural market would have on the industry. An almost universal method of price adjustment in this industry is the "coproducers discount." This is the discount customarily offered by one producer to another. Interpretation of the term coproducer is very liberal and includes virtually all bulk ammonia customers. The universal use of discounting procedures minimizes its competitive effectiveness. However, it frequently is connected to one or more of the other pricing factors.

The discount may range from $3 to $9/ton reduction in the price of ammonia. The actual value of the discount is difficult to estimate since it is related to the other price factors. The seasonal discount is most significant during the late fall-early winter period. Ammonia is normally produced on a year-round basis. During the off-season, the product is stored in producer-owned facilities. In order to increase the overall storage capacity available to a producer, a seasonal discount is offered as an incentive to the distributor or processor to purchase ammonia during the off-season.

This practice is universal throughout the industry. The normal seasonal discount ranges from $5 to $11/ton, and in some cases this may be higher.

The prevailing product supply-situation is the most important pricing factor.

The quantity of product purchased plays an important role in the price determination. Almost all bulk purchases involve tank car volumes of product. Therefore, differentials in delivery costs are very slight. The quantity discount is a very important consideration in dealing with cooperative associations or purchasing groups representing smaller volume users.

The peak demand period for product is from early March to late June. During this time prices are at their highest level and seasonal discounts are not employed. If there is not enough product to meet demand, the discounts discussed take on less meaning; if supply exceeds demand, they would play a more important part in price determination.

The price of anhydrous ammonia moves over a wide range dependent on the aforementioned factors. Reported prices range from $50 to $95/ton and in some instances higher up to $102/ton. This is equivalent to approximately 13¢ - 29¢/gal. However, this price can be misleading. As discussed in Section 2.4, if ammonia were used as a fuel, 2 to 2-1/2 times the volume of ammonia would be required (on a per gallon basis) to travel the same distance as with gasoline. This would more than double the cost of fuel per mile of travel in comparison to gasoline. A second factor is that the above price is based on the use of natural gas as a feedstock. Increased production from other feedstocks would result in higher prices.

4.4. Hydrogen

Hydrogen is a gaseous fuel like methane or natural gas. It becomes a cryogenic liquid at −423°F, about 160°F lower than the temperature of LNG. It is the lightest fuel we have, weighing only 4.37 lb/CF in liquid form, about one sixth the density of LNG.

Hydrogen has been used for military purposes both as a rocket engine fuel and experimentally as a jet engine fuel. For such applications its great heat energy of 60,957 Btu/lb is an asset. For motor vehicle use, however, its low density, high cost, and hazardous nature present various objections to its use.

The physical properties of hydrogen are presented in Table 4.4-1.

Table 4.4-1. PHYSICAL PROPERTIES OF HYDROGEN

Molecular Weight	2.016
Boiling Point	− 423°F
Freezing Point	− 434°F
Critical Temperature	− 398.8°F
Critical Pressure	12.8 atm
Gas Density @ 68°F & 1 atm	0.005234 lb/CF
Liquid Density @ −423°F	4.37 lb/CF
Liquid/Gas Expansion Ratio	865
Gas Constant	66.8 ft/°R
Specific Heat (cp @ STP)	3.42 Btu/lb/°F
High Heat Value @ 60°F & 30" Hg	319 Btu/SCF
Limits of Flammability in air	4 to 75%
Max Flame Temperature (air)	3990°F
Auto Ignition Temperature	1060°F

4.4.1. Hydrogen Supply

The hydrogen industry in the United States can be divided into two categories: 1) proprietary production and 2) production for resale. The amount of hydrogen produced on a proprietary basis cannot be readily ascertained due to integration with other processes. Large quantities of hydrogen are produced and used internally by several industries for annealing, production of chemicals, treating fats and oils, and hydrocracking. It is assumed that hydrogen produced internally is not available for resale and would not enter the gaseous fuel market.

Hydrogen produced for resale is termed "merchant hydrogen." Sales in this category are to small users, whose requirements are not large enough to support a plant internally, and sales to the Federal Government. There are four major suppliers of merchant hydrogen in the United States. They are National Cylinder Gas Corp.; Air Products; Airco; and Linde, Division of Union Carbide.

Production of merchant hydrogen in the past 3 years has been on the decline. This is attributable to the cutback in the aerospace program resulting in smaller government requirements for rocket fuel. Thirty-one billion CF of high purity hydrogen was produced in 1969, while production reached a high of 34.7 billion CF in 1968; anticipated 1970 production is 27.6 billion CF. Figure 4.4.1.-1 shows annual projected production up to 1975.

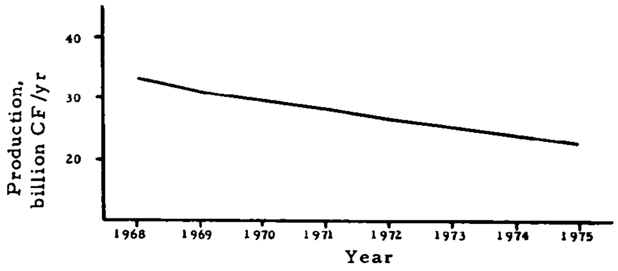

Figure 4.4.1.-1. ANNUAL MERCHANT HYDROGEN PRODUCTION, high purity

The largest hydrogen producing facilities are in Florida and California indicating the influence of the aerospace industry on production patterns.

Much of the hydrogen produced is made from natural gas since this offers the lowest raw material and process costs of the several methods available. It takes about 500 SCF of methane to produce 1000 SCF of hydrogen. Stated somewhat differently it requires 500,000 Btu of methane energy to produce 319,000 Btu of hydrogen energy. Since we have inadequate supplies of methane already, it does not appear wise to use them to produce hydrogen for engine fuel. Other sources would have to be used. The cost of hydrogen from these sources along with methane is presented in Table 4.4.1.-1.[119]

Table 4.4.1.-1. COMPARISON OF THE MANUFACTURING COSTS OF HYDROGEN FROM SEVERAL PROCESSES[a]

	Cost, ¢/10³ SCF H_2			
	Steam methane reforming[b]	Steam naphtha reforming[c]	Partial oxidation of fuel oils[d]	Coal gasification using steam and oxygen[e]
Raw materials	12.4	20.6	13.8	16.0
Utilities[f]	4.0	4.2	5.1	3.8
Labor at $4/hr	1.2	1.2	1.4	2.8
Overhead, 60% of labor	0.7	0.7	0.8	1.7
Maintenance and operating supplies, 4% of capital investment	1.7	2.0	2.1	4.6
Fixed charges at 9%	3.8	4.5	4.6	10.3
Total, ¢/10³ SCF	23.8	33.2	27.8	39.2
	Capital investment, $ millions			
	5.8	6.6	6.9	15.3

[a] Based on hydrogen production, 40 million standard cubic feet; hydrogen delivery pressure, 1700 psig; fixed charges, 9%

[b] Natural gas at $0.25/10⁶ Btu.

[c] Naphtha at $20/ton

[d] Fuel oil at $2/bbl; 150,000 Btu/gal.

[e] Bituminous coal at $5/ton; 12,700 Btu/lb.

[f] Includes electricity, cooling water, and boiler feedwater.

The most probable source is the partial oxidation of fuel oil. It should be noted that the cost of 27.8¢/1000 SCF is based on a price of $2.00/bbl for fuel oil. Current prices are $3.00 and may well go to $3.50/bbl. At 3.50/bbl the above cost of hydrogen would increase to about 38.2¢/1000 SCF. On this basis hydrogen from natural gas would still be competitive at a gas cost of 54¢/million Btu based on the above data. Thus, unless gas prices to this market are increased to above 54¢/million Btu, hydrogen can continue to be made from methane as the lowest cost method. As long as gas is used as the raw material for making hydrogen, the increased use of hydrogen for motor fuel will drain larger quantities of natural gas from the supplies available than would the use of natural gas directly.

4.4.2. Prices of Hydrogen

The above problem need not be of great concern since the price of hydrogen in any case is much too high to be competitive with other alternative clean fuels.

The above production cost of 38.2¢/1000 SCF is equivalent to $1.20/million Btu for gaseous hydrogen at the production plant. It must still be liquefied or further compressed and distributed to the user. Because of the low density of hydrogen, the distribution cost is relatively high and results in high prices to the user when compared with other fuels on a cost/million Btu basis.

The price paid for merchant hydrogen varies inversely with the amount used over a specified period of time, usually one month. All prices are f.o.b. storage terminal or plant. The price of liquid hydrogen ranges from 36¢/100 CF when purchased in tank wagon lots of 7800 gallons, to $1.70/liter (29.65 CF) in small volume containers. Gaseous hydrogen ranges from $2.50/100 CF, in high-pressure cylinders to 37.5¢/100 CF in 80,000 CF tube trailers. The price of 36¢/100 CF is equivalent to about $11.25/million Btu for liquid hydrogen while the 37.5¢/100 CF for gaseous hydrogen is slightly higher.

Other volume price schedules are presented in Table 4.4.2.-1.

Obviously the cost of distributing hydrogen to small users becomes prohibitive when compared to other alternative gaseous fuels.

Table 4.4.2.-1. MERCHANT HYDROGEN COST

99.9 percent purity
113.4 CF/gal

Liquid hydrogen[*] (delivered in 7800 gal tank trucks to customer storage	36¢/100 CF (40.8¢/gal)
Gaseous hydrogen delivered in tube type trailers (80,000 CF, average capacity)	
0-20,000 CF/month	$2.00/100 CF
next 20,000-80,000 CF/month	0.75/100 CF
next 80,000-3000 CF/month	0.45/100 CF
next 300,000-600,000 CF/month	0.38/100 CF

Note: Customer is allowed to unload gas as used, no charge for trailer storage.

Gaseous hydrogen delivered in high pressure steel cylinders (56" high, 9"dia. 191 CF/cylinder 2000 psi)	
0-2000 CF/month	$2.50/100 CF[†]
next 2000-5000 CF/month	1.50/100 CF[†]
next 5000-10,000 CF/month	1.20/100 CF[†]
next 10,000-20,000 CF/month	1.05/100 CF[†]

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[*] Price does not include cost of customer storage.

[†] Plus monthly cylinder rental fee.

5. STORAGE AND HANDLING OF GASEOUS FUELS

5.1. Natural Gas

5.1.1. Bulk Storage

Most of the bulk-storage facilities of the natural gas industry are underground. The large gas holders that can still be found in many large cities were usually built as accessories of a local manufactured gas plant. Since the gas industry has now converted almost completely to natural gas supply, these manufactured gas plants are no longer in operation. The gas holders themselves are no longer needed, but many of them are kept in service as a means of maintaining steady gas pressures under the fluctuating loads that may be experienced during the daily load cycle. Few, if any, of these gas holders have been built in recent years, and reliance is placed upon line pack and underground storage. In 1968, the gas industry stored approximately 1.4 trillion CF of natural gas underground, usually near the downstream end of gas transmission pipelines, in order to be able to serve the winter heating loads without overtaxing the capacity of transmission lines themselves. This quantity is about 10% of the total amount of gas distributed by transmission and distribution utilities. These underground storage facilities usually consist of either depleted gas wells or other underground formations that are capable of holding gas under pressure for indefinite periods of time. A relatively small but increasing amount of gas is stored in liquid form as LNG, usually in aboveground metal tanks.

5.1.2. Compressed Gas

The gas industry stores small amounts of gas under pressure either by packing transmission lines or by filling high-pressure pipe and tubing manifolds where the gas can be held as a cushion against load fluctuations. Line pack is a technique of building up gas transmission line pressures by pumping gas into the line faster than it is used by customers at the burner tip. As the load fluctuates during a daily cycle, the line pressure may fall as the gas consumption exceeds the pumping capacity of the gas compressors and recover when consumption drops below pumping capacity. Where the transmission line or the distribution pipeline network itself does not provide sufficient storage capacity to take care of such fluctuations, additional volume can be added by building piping or tubing manifolds that are connected to the piping system and pumped to high pressure during periods of low demand for use when the demand exceeds the capacity of the pipeline distribution system.

5.1.3. LNG Storage

During the last 6 years, the gas utility industry has begun to build liquefied natural gas storage facilities. The first of these was placed in operation in 1965 by the Wisconsin Natural Gas Company at Oak Creek, Wisconsin. Since then, approximately 13 LNG peakshaving facilities have been placed in operation; over 40 gas utilities at the present time either have in operation or have planned some form of LNG storage facilities. A tabulation of these facilities is presented in Table 4.1.7.-1.

This is an aspect of the gas utility industry that is growing quite rapidly. Of the 13 utilities having facilities in operation, 12 of them have announced plans for additional facilities or for additions to existing ones. The purpose of these plants is to hold natural gas from summer to winter. During the summer months when the demand for gas is low and pipelines have excess capacity, natural gas is liquefied at a relatively slow rate in a liquefaction plant that might be operated for a period of perhaps 200 days during the year. This LNG is accumulated in a storage tank for use during the very cold days of the winter when the demand for natural gas increases sharply. Generally speaking, there are from 10 to 20 days per year when unseasonally cold temperatures create exceptionally high demands for natural gas. By using these peakshaving LNG plants, the gas demands can be met without requiring the additional pipeline capacity necessary to serve this relatively infrequent load.

Geographically,these peakshaving facilities may be located anywhere there is a sufficient fluctuation in demand from summer to winter to justify their use. Table 4.1.7.-1 shows such plants in operation in Birmingham, Alabama,and Memphis, Tennessee,as well as in Wisconsin, New York, and Massachusetts. Since they contain LNG in some amount at all times, they provide a nucleus of a distribution system for LNG for other purposes such as motor fuel use.

At importation points for base-load LNG along the coastline, it is necessary to install large receiving tanks to hold the LNG delivered by tankers. The tanks must have 1-1/2 to 2 times the capacity of the LNG tanker serving the facilility. This amounts to 1 million barrels of liquid or more. At the present time one such facility is in operation, two are under construction, and it is anticipated that six or eight more unloading facilities will be built on the East Coast during the next several years. Possibly two more will be built on the West Coast as well.

These unloading facilities will have a much greater capacity to supply LNG in the coastal areas of the country than peakshaving plants. However, their construction and financing is justified by long-term contracts to supply LNG to utilities for normal utility purposes. Any large supplies of LNG from these facilities for motor fuel use will require either expansion of the presently projected facilities or diversion of LNG from planned utility uses.

5.1.4. Vehicular Storage

5.1.4.1. Compressed Natural Gas

Compressed natural gas is stored in high-pressure steel cylinders identical to those used for the storage of other compressed gases such as oxygen, nitrogen, argon, etc. These cylinders are designed to hold gas at about 2200-psi pressure and to withstand the rigors of handling in normal industrial use.

The ICC Type3AA cylinder is used in many current vehicle installations. At 2000-psi pressure, a Type-3AAA2265 tank will hold only 250 CF of oxygen but, because of the compressibility characteristics of natural gas, it will hold about 312 CF of natural gas. This is roughly equivalent to 3 gallons of gasoline and will provide a range of about 45 miles; thus, more than one such cylinder is usually installed. Each one weighs about 130 lb when filled and occupies over 2 cubic feet of space.

It is necessary to use most of the trunk space in a passenger-type automobile to install sufficient capacity for a 100-mile range. However, this is not a serious problem in short-range vehicles, which ordinarily do not utilize the trunk space. In commercial vehicles more space is usually available and cylinders can be buried in inaccessible locations since no access is required once they are installed. It is general practice to leave the cylinders installed in a vehicle and to refuel by connecting high-pressure lines from a service station supply reservoir or gas compressor.

These cylinders may cost in the neighborhood of $60.00 each and comprise a major portion of the cost of converting a vehicle to natural gas. Since the tanks are already made in significant quantities, it is not likely that mass production of natural-gas-fueled automobiles would result in substantial reductions in this cost unless radically new types of pressure vessels are developed for this service.

5.1.4.2. LNG

5.1.4.2.1. Transportation Vehicles

LNG is transported in vacuum-jacketed steel tanks mounted on trucks and semitrailers. They are similar in most respects to the liquid oxygen and liquid nitrogen trucks and trailers that have been in use for many years. Two sizes have been popular: 6000-gal and 11,000-gal capacities The larger size represents the maximum-size semitrailer that can be used in most states. In some instances, this size trailer is weight limited as well as size limited.

These trailers are designed to hold an internal pressure of about 70 psi before a relief valve will open to prevent further pressure increases. Normal transfer operating pressures are about 30 psi, and liquid is usually transferred by vaporizing the product liquid to increase tank pressure to

30 psi to force liquid from the vehicle. The vacuum jacket is designed to provide a sufficiently low boil-off rate to permit the trailer to stand for 48 hours without venting gas through the relief valves.

LNG has been transported between Philadelphia and Boston for many months on regular daily schedules, and less frequently throughout many other states of the country. At least four companies are presently engaged in the business of transporting LNG. To date, there have been no reported highway accidents resulting in LNG spillage, although LNG trailers have been involved in a half-dozen highway accidents, which is not unreaonable for the mileage they have accumulated.

Railroad tank cars and river barges can be designed to carry LNG in the same manner as highway trailers; nevertheless, the economics and distribution patterns of the industry have not yet required them. However, tank cars have been designed and at least one barge has been ordered for operation on the East Coast.

5.1.4.2.2. Vehicle Fuel Tanks

Vacuum-jacketed fuel tanks are also built in small sizes for use as motor-vehicle fuel tanks. A tank of 15 - 20 gal capacity can be installed in the trunk of a passenger car to provide a range comparable with conventional gasoline fuel tanks. Like the larger trailer tanks they have low boil-off rates and can be left unattended for up to 72 hours without venting; however, they must be vacuum-jacketed to achieve these low boil-off rates. Plastic foam or perlite insulation alone does not provide sufficient thermal protection to prevent pressure buildup during a 72-hour storage period. The 72 hour period is sufficient to allow a vehicle to be parked over a weekend or during a servicing period without the necessity of draining the fuel tank.

At least two manufacturers produce vacuum-jacketed cryogenic tanks, suitable for use as motor-vehicle fuel tanks. These tanks presently cost about $400 or more in small quantities. Manufacturers have estimated that this price could be reduced substantially if production rates were increased sufficiently to justify hard-tooling and continuous production.

5.1.5. Handling Procedures and Practices

5.1.5.1. Compressed Natural Gas

One of the primary attractions in using compressed natural gas is its ready availability. Virtually every industrial plant, commercial garage, and potential refueling station has natural gas service nearby. It is only necessary to install a compressor and storage reservoir to provide fueling service. The price of the compressor depends on its rated capacity. A compressor with a capacity of 8 CF/min is available for approximately $2900, and the cost of one that would compress 100 CF/min is approximately $12,000.

The equipment required is quite simple and consists of a high-pressure compressor, a bank of high-pressure storage cylinders, and a valve, fitting regulators, and hoses to make up the system. Operations may be conducted in one of two ways:

a. When a few vehicles are operated on a regular schedule and can be refueled overnight, the high-pressure storage cylinders are not necessary since the natural gas is available directly from distribution lines and the compressor can be connected to a manifold which feeds the vehicle fuel tanks directly. The pressure in the vehicle tank is built up overnight, much like charging a battery. This system is less convenient, but is more economical for small fleets. The slow-charge system can refuel more than one vehicle at a time if a manifold system is used. The number of vehicles that can be charged at one time is determined by the size of the compressor. The cost of such a system capable of refueling 25 vehicles at one time can vary between $2000 and $3000, excluding the compressor.

b. When larger fleets are operated or when vehicle refueling schedules are unpredictable, the compressor is used to maintain a supply of high-pressure gas in a bank of gas cylinders. The vehicles are refueled from the high-pressure bank as required.

Some combination of the two systems may also be used.

The compressor presents an unusual requirement because of the extremely high pressure ratio required. Gas must be accepted at less than 1 psi, and be compressed to 2500 or 3000 psi. A few compressors are available commercially that can operate over this pressure range, but the selection is limited and costs are high. This is the major cost item in providing compressed natural gas for motor fuel purposes.

Comparative costs for compressing gas by the slow-charge system are presented in Table 5.1.5.-1. Because of the nature of the system, no high-pressure storage facilities are required. The calculations are made using the following assumptions:

- 20 vehicles in fleet
- Each vehicle driven 50 mile/day
- Gas consumption is 9 mile/100 CF
- 600 CF/day required for each vehicle
- Each vehicle is operated 260 day/yr
- Each vehicle requires 156,000 CF/yr
- Entire fleet requires 12,000 CF/day
- Entire fleet requires 31.2 million CF/yr
- Cost of natural gas is $0.72/1000 CF
- Fuel taxes not included
- Compressor is driven by natural gas engine

The cost as calculated in Table 5.1.5.-1 will vary according to the type of application. It is intended to show only the approximate cost based on the assumptions stated above. The cost of the compression equipment is based on information obtained from 2 suppliers of CNG equipment. Other costs are subject to change according to the type of accounting system used by individual operating company. Some firms may elect to adopt a longer depreciation life which would result in a reduction of annual cost. The maintenance expense is based on the purchase of an annual maintenance contract from the seller of the equipment. The price of such a contract was found to vary from $1.00 to $0.25 per running hour. The cost of the contract is based upon the size of the installed system. The fleet operator may elect to perform his own maintenance work and the cost of the system would change accordingly.

Table 5.1.5.-1. CNG COMPRESSION COSTS USING ENGINE-DRIVEN COMPRESSOR

Capital Cost	100 CFM	25 CFM
Compressor Cost	$12000	$ 5500
Manifold Piping & Installation	3000	2500
	$15000	$ 8000
Operating Cost		
Depreciation, 10 yr straight line, no salvage value	$ 1500	$ 800
Return on investment before tax (15¢ of investment with 10 yr average year-end amount)	2025	1080
Compressor Fuel Cost (6CF/100CF compressed gas required - cost $0.00432)	135	135
* Maintenance expense, on contract basis per running hour @ $1.00/hr	520	1300 @$0.50/hr
Total Cost of Compression	$ 4180	$ 3315
Cost/100CF Compressed Gas	13.4¢	10.6¢
Cost of Gas/100CF	7.2	7.2
Total Cost of Gas	20.6¢	17.8¢

* Varies according to type of contract purchased.

The refueling operation does not require full time personnel. It is based on the assumption that drivers will connect and disconnect the vehicles to the refueling system. The cost of the natural gas itself will vary in different geographical locations throughout the country. Other factors which would affect compression cost include on-site storage of pressurized gas and electrically driven compressor. A storage tank capable of holding 2800SCF of gas at a pressure in excess of 2250 psi is available for $3200 excluding installation, labor and material.

The high pressure used, from 2000 to 3000 psi, requires some indoctrination and training on the part of operating personnel. Gas utilities have discouraged broad and indisriminate use of high-pressure equipment by the general public and have generally confined their interest to commercial and industrial fleet vehicle operations where personnel can be properly trained and supervised.

5.1.5.2. LNG

Unlike compressed natural gas, LNG must be delivered to the vehicle refueling point from some distant location by LNG tank trucks. The distribution pattern is more comparable to the current distribution of gasoline or LPG.

This practice of distributing LNG is already established in the gas utility industry. A number of utilities operate satellite peakshaving facilities located remotely from their main liquefaction plants. LNG is regularly transported by trailer to these satellite tanks for storage until needed locally for peakshaving. Although the practice is not yet wide spread throughout the country, it has been demonstrated to be a safe, practical means of distributing and storing natural gas.

The refueling of vehicles is similar to the refueling of compressed gas vehicles except that no high pressures are involved. Some liquid is flashed to vapor upon filling warm tanks and hoses, but this need not be hazardous for vented gases are either returned to the system or piped to points from which they can be safely discharged.

At the present time there are no suitable odorants for use in LNG. The odorants normally used in natural gas are removed before liquefaction and replaced only during revaporization of the liquid into a utility system. These odorants do not function properly over the extreme temperature range of LNG use. Liquid leaking from an LNG vessel would contain a disproportionate amount of odorant compared to vapor being vented from the same tank. Thus the amount of odor may have little relationship to the amount of leakage. However, some research is being carried on to develop both new odorants and methods of using present odorants to maintain odorant concentration in both liquid and vapor phases over the range of temperatures involved. Until such odorants are available it may not be desirable to park LNG-fueled vehicles indoors for any length of time that might permit unodorized leakage or vented gas to accumulate.

The quality of LNG is generally superior to the quality of conventional natural gas and much higher than LPG. The higher hydrocarbons such as ethane, propane, pentane, etc., which are present in natural gas are largely removed during the liquefaction process. Thus LNG is closer to pure methane and has a higher octane rating and more consistent physical properties than most supplies of natural gas. However, during storage, LNG is continually boiling and selectively distills the methane vapor out of the liquid, increasing the proportion of any hydrocarbons which may be present. This process is called aging, and if carried to extremes could result in lowering of the octane rating of the fuel.

This is not a serious problem in normal operations because the continued use and turnover of supplies tend to keep the supply fresh. Also, the octane rating of LNG is about 115 to 117. This is well above the 90-95 range presently being advocated for automotive fuels. Thus the LNG would have to age very severely before encountering trouble of this kind. No reports of any difficulty due to LNG quality have been found in automotive use. Data supplied by the San Diego Gas & Electric Company (Table 5.1.5.-2) shows there is no appreciable change in the composition of LNG over a period of

Table 5.1.5.-2. COMPOSITION OF LNG SAMPLES WITHDRAWN FROM STORAGE (625 X 10^9 CF)

DATE	mol % NITROGEN	mol % METHANE	mol % ETHANE	mol % PROPANE
4/24/69	0.30	92.60	6.79	0.31
6/24/69	0.32	91.86	7.41	0.31
8/25/69	0.27	93.07	6.30	0.36
10/17/69	0.21	92.45	6.96	0.38
11/26/69	0.31	93.20	6.15	0.34
1/05/70	0.39	93.72	5.66	0.23
2/03/70	0.39	94.81	4.50	0.30
3/04/70	0.80	92.35	6.50	0.35
4/10/70	0.85	92.78	5.80	0.58
5/04/70	2.68	93.83	3.12	0.37
6/03/70	0.92	93.79	4.88	0.41
7/08/70	0.58	92.08	6.96	0.38

time greater than 1 year. The data are based on monthly analyses of the composition of LNG stored at their liquefaction plant in Chula Vista.

In aircraft use of LNG some concern has been expressed for the amount of inert material that may be present. Some species of LNG contain significant quantities of nitrogen (up to 10% or so) which are not always removed. It is normally of no consequence since gas is sold on a heat energy basis. However, it does increase the weight of fuel carried in an aircraft. For this reason NASA and those aircraft companies experimenting with LNG for aircraft have taken care to limit the amounts of such inert materials as nitrogen that may be present.

5.1.6. Safety

5.1.6.1. Compressed Natural Gas

The use of compressed natural gas in a motor vehicle may be safer than the use of gasoline. The high-pressure cylinder is not likely to be ruptured in any collison that would not completely destroy the vehicle anyway. Experience with high-pressure gas cylinders in the industrial gas supply industry has demonstrated a high level of safety. The major area of concern is neither the gas cylinder nor the flammability of its contents but the possibility of breaking or accidentally disconnecting a high-pressure line or fitting. This can be minimized by sound engineering and careful installation. There is ample experience in the compressed gas industry to provide this knowledge. However, it is not a problem that should be turned over to the average automobile mechanic.

5.1.6.2. LNG

Even LNG may be a safer motor fuel than gasoline. The LNG tank is a double-walled vessel of much heavier construction than a gasoline tank and will usually be installed in a better protected location on the vehicle.

Large-quantity spillage should be less hazardous for several reasons: LNG is more difficult to ignite than gasoline. It is lighter than air and will

evaporate and rise into the atmosphere rather than settle into pits and sewers. When it burns the flame is less luminous and radiates less heat to surrounding metal structures. Once extinquished it is less likely to reignite because of lower metal temperatures and its own high ignition temperature.

LNG and CNG fuel systems have been found to be as safe as conventional gasoline fuel systems by insurance underwriters. No incidents of increased insurance premiums have been reported to IGT.

5.2. LPG

5.2.1. Bulk Storage

The seasonality of the demand for propane presents a storage problem to suppliers in their effort to provide supply in peak-usage months. The ratio of winter to summer demand may range from 1-1/2:1 to 5:1. Because of this wide variation, production in excess of demand must be stored during the slack season. In 1966 stored propane ranged from 368 million to 1.265 billion gal.

Underground storage capacity increased by 13.6¢ in the year following the 1965-66 supply shortage. During this time storage capacity was 141 million bbl (5.922 billion gal). In addition, aboveground storage is increasing, but this figure — amounting to 200 million gal in 1968, and increasing to 295 million gal in 1970 —can be considered unavailable as it represents pipeline fill, terminal and bulk plant storage, and industrial working stocks. The increase of 95 million gal in the 3-year period is due largely to additional pipelines, increased underground storage, and additional capacity of other types of storage. The bulk of storage will remain underground where cost/gallon is 5-15¢ as opposed to 40-50¢ for aboveground storage.

However, the storage areas are concentrated at the production end of the distribution line. For example, the top three states in underground storage in the beginning of 1969 were Texas, 51.6¢ (3,044,870 gal); Kansas, 13.6¢ (800,650 gal); and Louisiana, 12.8¢ (754,110 gal). Efforts are being made to correct the imbalance between production-storage areas by attempting to increase storage in Pennsylvania, New York, and other major consuming areas.

5.2.2. Bulk Transportation

Assuming production and storage are adequate to meet peak demands, the question remains as to the availability of transports to provide supply at the locations where and when it is needed.

The major portion of LPG is transported by pipeline. In 1968 pipeline transportation accounted for 61¢ of the industry total, increasing from 3.6¢ in 1953. In 1968 rail transport fell to 9¢ from a high of 54¢ in 1953. Truck transport fell to 25¢ in 1968 from a high of 43¢ in 1962. Tank car and barge shipments remained relatively unchanged in 1968 at 1¢. The railroads had hoped to become more competitive with pipelines with the introduction of jumbo 30,000-gal tank cars, but their use has not affected its position in relation to other types of transport.

The 10,000-gal tank cars appear to be readily available during the winter season, but several considerations deter their use. The rail rates on the smaller cars are less attractive than rates on the high-volume cars and act to increase the fuel delivery cost. In addition, the available idle cars have usually been used for transporting ammonia in the spring and must be purged, at additional expense, before hauling propane. These added expenses greatly affect the cost of propane. However, in some cases, it is feasible to use the small tankers for increased storage capacity by filling and holding them on plant spurs.

5.2.3. Vehicular Storage

There are currently estimated to be about 250,000 LPG-fueled vehicles in operation, each one equipped with a steel cylindrical fuel tank capable of holding propane in liquid form under pressure. The pressure required is only a few hundred psi rather than the 2000 psi required with compressed natural gas.

These vehicles have established a safety record that justifies extended use of LPG as a motor fuel if other considerations demand it. Although indoor use of LPG for lift trucks is restricted in some industrial plants, this may be occasioned, in part at least, by the suitability of electric lift trucks for this type of service.

5.2.4. Handling Practices

Propane fuel is transported in truck trailers and delivered to pressure storage tanks at points of use in much the same manner as gasoline, LNG, ammonia, and other volatile liquids. The practice is widespread and long established. Since propane is capped and sealed during storage and transport, there are no vapor losses or emissions from propane fuel systems.

Vehicle fuel systems for propane use are manufactured by a number of suppliers; natural gas vehicles have drawn heavily from the equipment made for LPG vehicles. Virtually all of the natural gas vehicles use LPG carburetors, for example.

Of all the gaseous fuels, propane is probably the most convenient fuel to handle because it can be compressed to liquid at reasonable pressures and therefore does not require venting provisions or exceptionally high pressure equipment.

5.2.5. Safety

While LPG has been used for many years and has established an adequate safety record, it may suffer somewhat from comparison with both gasoline and natural gas.

Since it is a compressed liquid it will, upon the release of its pressure, immediately vaporize more quickly than either gasoline or LNG. An LPG container will release more combustible vapor than the same size compressed gas container and is more often used in larger sizes. The consequences of this have been observed in a number of propane railroad car accidents in recent years which prompted a review of transportation practices relating to propane shipment.

The problem is not as serious in vehicle fuel tanks, however, because the smaller tanks are less apt to rupture in an accident both because of their heavy construction relative to gasoline tanks and their more protected position in a vehicle.

5.3. Ammonia

Ammonia is moved by truck, barge, train, and pipeline. Large quantities are transported by barge and train shipment from the major producing area to storage and distribution terminals in major consumption areas. The basis for selection of a transport method is proximity to water terminals, availability of equipment, and distance. The least expensive form of transport is by barge. Barges can be brought from Brownsville, Texas, as far north as Minneapolis and St. Paul. A typical refrigerated barge has a capacity of 2500 tons (972,500 gal). Some considerations regarding barge shipment include size of receiving terminal and accessibility to receiving terminals. Some inland waterways cannot accommodate fully loaded barges.

Rail shipment of ammonia is the second most economical form of shipment. Many variables affect the cost of rail shipment. Among them are size of tank car, storage tank size, and degree of equipment utilization. The seasonality of ammonia use requires high utilization of equipment for a short period of time. Many leasing arrangements are for long-time periods and the possibility of idle equipment for a long period may not make rail shipment attractive to the producer. The expanding LPG markets limits the availability of rail car equipment. Both commodities can be shipped in the same equipment after the car is purged.

Truck shipment of ammonia is limited to small quantities for a relatively short distance, usually 100 miles or less. It is the most expensive form of transport and is usually restricted to transfers from distributor to end user.

Recent work has been completed on an ammonia pipeline generally paralleling the Mississippi River to Iowa. It is believed that the cost of pipeline transport will be one-half of the barge cost. A second advantage of pipeline transport would be greater dependability and ability to meet seasonal peak demands. Table 5.3.-1 summarizes the costs of the different types of transport.

Table 5.3.-1. COMPARATIVE COST OF AMMONIA TRANSPORT

Transport Type	Cost, mills/ton-mile
Barge	4
Rail Car — Standard	35-60
Jumbo	20-30
Truck	60
Pipeline (estimated)	2

Storage of ammonia is found to be concentrated in the areas of utilization. Table 5.3.-2 shows the percentage of storage found in the major consuming states.

Table 5.3.-2. LOCATION OF MAJOR AMMONIA STORAGE LOCATIONS

State	Percent
Illinois	18.06
Iowa	13.80
Texas	10.07
Nebraska	8.31
Louisiana	7.98
California	4.73
Mississippi	4.30
Missouri	2.98
Arkansas	2.79
Ohio	2.63

Louisiana is not a major consuming state. Storage here is used to compensate for fluctuations in inventory between barge shipments.

Anhydrous storage is made up of the following types: truck trailers, rail cars, barges, and stationary tankage. Stationary tankage accounts for approximately 85¢ of the volume stored. Approximately 75¢ of the agricultural ammonia produced is sold during the spring fertilizer season of about 1-month duration. Therefore, approximately 50¢ of all ammonia produced must be stored somewhere in the distribution network for 11 months. The size of stationary storage tanks ranges from 30,000 to 100,000 gallons. Size selection is determined by sales and demand requirements within the geographical area.

Ammonia is readily available in the United States, based upon the present production capacity and demand situation. Any increased demand would not produce a need for increased production capacity. New applications and uses are continually being sought, particularly in nonagricultural areas, to absorb excess capacity and reduce cyclical fluctuations in production.

The extent of its adoption as a motor fuel cannot be readily determined. Limited research has been carried out to determine the feasibility of fueling an internal combustion engine with ammonia. Conclusions from this research indicate that the use of ammonia as a fuel will not become popular.

Equipment required to use ammonia in an internal combustion engine does not vary a great deal from the equipment required for propane. However, as discussed in Section 2.4 of this report, the efficiency of the engine is reduced appreciably and the amount of fuel required (approximately 3 times the amount of gasoline) makes it impractical for vehicular fuel. No investigation has been made regarding the practical application of ammonia as a fuel.

5.4. Hydrogen

5.4.1. Storage and Handling

Merchant hydrogen accounts for the greatest share of transport. Proprietary hydrogen is produced onsite and does not require transport over any appreciable distance. Large quantities of liquid hydrogen are transported over the road in trailer-tractor combinations. Pipelines have been proposed, but the volume requiring transport and its reliability do not justify such a scheme over very long distances. Other methods of transport, which can be justified only by larger volumes, are not required. The cost/unit volume of transporting hydrogen is very high due to its low density and the extremely low temperature requirements.

Large quantities of hydrogen are distributed by the manufacturer from his plant or bulk storage facility. For example, in the Chicago area, liquid hydrogen, produced and shipped from California, is stored in bulk storage facilities. Gaseous hydrogen is generally produced in the marketing area.

Liquid hydrogen is distributed directly from the bulk storage plant. The cost of the gas includes delivery charges within 100 miles. Large quantities are delivered in cryogenic 7800-gal (884,520 CF gross cap.) tank trucks with smaller quantities shipped in special vessels with specially designed flatbed trucks. Large deliveries of liquid are then placed into the customer's storage facility. In the case of small quantities, the customer may rent the shipping vessel at an additional monthly charge.

Gaseous hydrogen is transported in one of two ways. Large quantities are shipped in high-pressure tube trailers with an average capacity of 80,000 CF. The trailer is delivered to the customer and left until it is empty. Generally, there is no transfer of the gas into storage and no rental fee for placement of the trailer. Small quantities of gaseous hydrogen are shipped in high-pressure cylinders. A 56-in.-high, 9-in.-diameter cylinder has a capacity of 191 CF at 2000-psi pressure. Cylinder gas is purchased

through a distributor, with prices and shipping arrangements established by each individual distributor.

Except for certain experimental military applications of hydrogen for engine fuel, there are no reported uses that provide much insight in handling and use of hydrogen as an engine fuel. However, the precautions that must be taken in such industrial applications as cooling of electric generators with hydrogen suggest that it will be a difficult and expensive fuel to handle where there is close contact with or involvement of persons not trained to handle hydrogen.

5.4.2. Safety

The wide limits of combustibility and the high flame velocity of hydrogen present more severe handling problems than either LPG or natural gas. While air can be premixed with natural gas, for example, the premixing of hydrogen and air is more apt to produce explosive mixtures. The flame velocity of hydrogen is much higher than methane and therefore the hazards of flashback and flame propagation upstream in flowing gas systems are much greater. These potential hazards require that hydrogen fuel systems be carefully purged with nitrogen before filling and precautions must be taken to prevent air from entering the system under any circumstances, including emergency repairs or replacement of parts.

Since hydrogen is colorless and odorless, it will require the addition of odorants as in the case of natural gas. The development of odorants for liquid hydrogen is probably even more difficult than for LNG.

The above discussion applies to the use of hydrogen alone. When it is blended with other fuels, it may become much easier to handle. The manufactured gas that was distributed by gas utilities for many years contained as much as 50¢ hydrogen and yet was distributed and used safely by the general public.

Until more definitive information is made available on possible blends of hydrogen and other fuels for automotive use, it is impossible to discuss their handling and safety problems in any detail.

6. ECONOMIC IMPACT OF THE USE OF GASEOUS FUELS

The impact of using gaseous fuel upon the petroleum industry, the automotive industry, and the transportation industries will vary depending upon the scope and manner in which these fuels are used. For this reason, this subject is discussed in two different phases. First, the impact is discussed on the basis of large-scale conversions that would be necessary to provide substantial relief to the overall air pollution problem. In this case, it is necessary to include consideration of the private automobile. Second, the impact is discussed on the basis of local commercial fleet vehicle operations,which would cause less disruption of the fuel supply patterns in the country, but might provide substantial relief to the air pollution control problem in congested urban areas.

6.1. Industrial Impact Based on Large-Scale Conversions

6.1.1. Effect Upon the Natural Gas Industry

In 1968 the United States consumed about 83 billion gallons of motor fuel. Of this, 58 billion gallons were consumed by passenger cars alone. This total amount of motor fuel is equivalent to approximately 97 billion therms of natural gas, or about 80% of the total amount of natural gas distributed by the gas utility industry. Therefore, if we wished to convert the motor fuel industry to natural gas, it would be necessary to almost double the production of the natural gas industry. This is obviously impractical in view of the problems which the natural gas industry faces in finding sufficient gas to serve its present markets.

6.1.2. Effect Upon the LPG Industry

It was explained in an earlier section that the LPG industry is growing more rapidly than the available supplies of LPG. It is projected that sometime during the next few years, the demand for LPG will exceed the available supplies and the increasing use of LPG for pollution control may hasten the day when this occurs. However, it was also noted that a few cents increase in the price of LPG would make it economically feasible to produce additional quantities of LPG from oil refineries by reducing the yield of gasoline and increasing the yield of propane.

Since a tightening of supply will cause an increase in propane prices as users outbid each other for available supplies, it is quite possible that the oil refinery industry will find it profitable to increase the yield of propane at the expense of gasoline in order to supply this demand with liquefied refinery gas (LRG). If other states follow the lead of California in reducing the tax on LPG used as motor fuel, sufficient incentive may easily be provided to increase the production of LRG at the expense of gasoline.

In any case, LRG is the only gaseous fuel having a sufficiently large potential source of supply to permit conversion of a large portion of the motor vehicle population to gaseous fuel.

6.1.3. Effect Upon the Oil Industry

The effect upon the oil industry of conversion to natural gas would, of course, be disastrous, but the question is academic since this alternative cannot be considered.

However, the conversion to LPG, or more precisely LRG, may not be as disruptive of the industry as might first be supposed. Natural sources of LPG would be quickly exhausted by any mass conversion to LPG, but the conversion of refinery processes to increase the yield of LRG at the expense of gasoline could permit an orderly transition to LRG motor fuel without disrupting other energy industries. The rate and extent to which it is carried would have to be carefully planned and might depend upon the ability of the industry to provide retail service stations with LRG-dispensing equipment.

A major problem of large-scale conversion to LPG would be that of distribution. Although product pipelining would be affected to some degree, the major impact would fall upon distribution to retail service stations.

Here all of the equipment for hauling, underground storage, pumping, and metering of fuels would have to be replaced. This would be a far greater expense than converting to lead-free gasoline because existing equipment could not be used. No attempt has been made in this study to estimate this cost and its effect upon the retail price of propane.

6.1.4. Effect Upon Equipment Suppliers

6.1.4.1. Engines

The effect of large-scale conversions to either natural gas or LPG in internal combustion engines would be relatively minor except for the conversion of diesel engines, particularly two-cycle diesel engines. The conventional automobile engine would require new accessory equipment such as carburetors, but would require no more modification than is often made in changing from one model year to the next. Thus, converting to LPG at the rate at which new automobiles replace existing ones would not be very expensive as far as engines are concerned. Conversion of existing vehicles is discussed later in this report.

The conversion of diesel engines to gaseous fuels would be more difficult and expensive. The simplest means would be to convert four-stroke diesel engines to spark-ignition engines accepting the greater maintenance and lower reliability of such engines compared to diesel engines. It would be relatively difficult to convert two-stroke diesel engines to natural gas fuel for it would require considerable research and development to enable such engines to operate on gaseous fuels. This subject is discussed in more detail in Section 8.

6.1.4.2. Tanks

The large-scale conversion of automotive vehicles to gaseous fuels would require completely new fuel tanks on all vehicles. These tanks would be more expensive and would require more space as well as more stringent manufacturing control, inspection, and approval by regulatory agencies. Propane tanks, high-pressure gas containers, and LNG tanks are presently being made and used in industry in sizable quantities. There appear to be no serious engineering problems involved, but there will be many production problems if the scale of this industry is expanded to produce the quantities required for large-scale conversion of the automotive industry to any gaseous fuel.

6.1.4.3. Other Components

The other components such as carburetors, heat exchangers, valves, regulators, etc., are available commercially in small production quantities. The production of these components by the various industries that manufacture them could be expanded to the quantity of production required for conversion to any of the gaseous fuels.

6.1.5. Effect Upon Vehicle Users

The large-scale conversion of automobiles to LPG would nessarily involve the private automobiles. It would cause little change to the vehicle user except for the increased cost of ownership and operation. He might experience some difficulty obtaining LPG supplies during the period of transition, but the range of the vehicle and the refueling and service practices would be similar. Maintenance costs for the engine and catalytic exhaust reactors would be reduced.

The cost of LPG fuel will necessarily be several cents higher per gallon; however, the quality, availability, and price will be more consistent than presently experienced in the LPG industry and should be comparable to present gasoline fuel practices.

The major factor will be the increase in the first cost of the vehicle. If such vehicles are produced at the factory, the net increase in cost will be considerably less than the costs of conversion that are discussed in Section 7 of this report. No new components of any consequence are added, and the major factor will be the net increase in cost of the fuel tank. Large-volume production will permit some reduction in cost of present LPG fuel tanks, and

credit can be taken for the cost of present tanks and fuel pumps that are deleted. The increased cost is difficult to predict without detailed estimates of component costs in volume production, but it might be on the order of $100 to $150.

This represents an increased cost to the user without any personal benefit other than the resultant reduction in air pollution. Thus he may resist buying such a vehicle unless legislation requires its use as in the case of other antipollution devices. This raises the question of how such a conversion program might be implemented. Although that is considered to be beyond the scope of this study, some observations may be worthwhile.

It does not appear that any large segment of the automobile population could be converted to any gaseous fuel at an earlier date than the present automotive industry program to provide a "clean" car by 1975 or 1976 using lead-free gasoline and exhaust reactor devices.

If that program is successful or promises to be successful in meeting air quality goals, then there will be little justification for gaseous fueled vehicles except where they offer economic advantages apart from their low pollution qualities. If, however, the automotive industry is only partially successful in meeting the air pollution goals, it may be desirable to consider the use of propane fuel as an additional step necessary to clear the air.

The information gathered in this study suggests that conversion of the private automobile to propane will be more expensive than the measures presently being planned by the automotive and oil industries. The modification of the oil refinery industry to produce sufficient propane and the cost of revising the distribution system to deliver propane in place of gasoline are much more drastic than making and distributing lead-free gasoline. Thus, the conversion to propane will be difficult to justify unless the present efforts of the automotive industry are demonstrated to be inadequate.

However, the conversion to lead-free gasoline is a step in the direction of increasing the yield of propane from refineries. Also, the use of exhaust system devices may still be necessary with propane-fueled vehicles in order to achieve projected pollution levels. Thus the present efforts of the automotive industry would not be wasted if it became necessary to convert to propane.

6.2. Industrial Impact Based on Commercial Fleet Vehicle Operation

The preceding section discussed the possible conversion of the total motor vehicle population to gaseous fuels,pointing out the limitations imposed by the logistics of supply. This section discusses the conversion of commercial fleet vehicles only. This is a much simpler problem for it avoids the private automobile and its special problems of consumer cost, servicing, etc., as well as reducing the magnitude of the logistics problem.

Since about 70% of the motor fuel consumed is burned in passenger cars, the logistics problem is reduced by 70%. Of course, the benefits from reduced pollution using gaseous fuels will apply to only 30% of the total vehicle population. Thus, this alternative represents only a partial solution to the problem. Nevertheless, there is considerable interest and activity on the part of gas and LPG suppliers as well as fleet vehicle operators and government air pollution control agencies in applying gaseous fuels to fleet vehicle operations.

At the present time, about 85,000 barrels/day of propane is consumed in the vehicle engine market. Approximately 48% of this is consumed by utility vehicles such as forklift trucks and the remainder is consumed by approximately 250,000 over-the-road vehicles.

The number of natural-gas-fueled vehicles is not nearly so large at the present time. A tabulation of vehicle conversions compiled by the Institute of Gas Technology indicates that over 2000 vehicles have been converted to compressed natural gas and almost 200 have been converted to LNG.

6.2.1. Vehicle Conversion Costs

The equipment necessary for the conversion of a gasoline-fueled engine for operation with gaseous fuels — CNG, LNG, and propane — is the same in some respects and different in others. All three fuels require the removal of the standard gasoline carburetor and replacement with a gas-air mixer. The standard gasoline tank must be disconnected and replaced with a tank suited to the fuel used. All of the systems also require installation of one or more pressure-regulating devices to control the flow of gas between the tank and the engine.

Some components required for conversion are not the same in all cases and can be a major cost item in the total conversion cost. An example of this is the fuel tank required for each of the three forms of fuel. The components required for conversion are examined in the following paragraphs.

Another factor influencing the conversion cost is the degree of sophistication employed. Some vehicle owners feel that merely installing the conversion kit without the use of instrumentation is adequate. Others prefer to modify the engine and adjust it to obtain maximum performance. This is an additional expense contributing to the conversion cost.

6.2.1.1. Compressed Natural Gas Conversion Cost

Conversion kits are available for compressed natural gas for approximately $300. These kits include the fuel line, two pressure regulators, a gas-air mixer which replaces the air cleaner, and solenoid valves to control the flow of gas in the vehicle. Fuel tanks are not included in the conversion kit. The number of tanks vary in each application according to the distance each vehicle is required to travel. The cost of a tank of 312 CF capacity at 2265 lb pressure is approximately $60. One tank will allow the operator to travel 30 to 40 miles between refills. Approximately 4 hours is required to install the conversion kit, excluding testing.

The cost of CNG conversion, including one vehicle tank, but excluding compression costs and storage, is approximately $360 per vehicle, although it may run as high as $500 if additional tanks are used and the vehicle is modified to improve performance.

6.2.1.2. LNG Conversion Cost

The equipment necessary for converting an engine for LNG use is the same as that required for CNG with the addition of a vaporizer, since the gas must be transformed from liquid to gaseous form. The cost of a kit, including the vaporizer, is approximately $350. As in the case of CNG, the labor and fuel tank are not included. The time required for installation is the same as for CNG.

The major cost factor in the LNG conversion is the fuel tank itself. Prices of the tank can vary depending on its construction and capacity. The cost, as stated in Section 5.1.4.2.2., for a vacuum-jacketed tank is approximately $400 for a 14-gal tank and higher for larger tank sizes.

The use of LNG as a fuel may require the installation of onsite storage facilities. This is dependent on the number of vehicles to be fueled and the proximity of the location to LNG supplies. The cost of onsite storage can vary a great deal due to tank construction and capacity. San Diego Gas & Electric Company has installed onsite refueling stations for the California State Highway Department and the San Diego Zoo for use in its LNG vehicle operations. The tanks used are rebuilt liquid nitrogen tanks of 1700-gal capacity. The initial cost of these tanks was $2500, excluding installation costs.

The cost of converting one vehicle to LNG is approximately $750, excluding onsite storage requirements and labor.

6.2.1.3. LPG Conversion Costs

The equipment required for LPG conversion is much the same as that for LNG. Estimates of conversion range from $350 to $500 depending on the sophistication of the equipment used. Some companies report the use of a dynamometer in timing the engine after conversion. The added instrumentation and time required account for the price variance.

The cost of the fuel tank is included in the conversion price. However, the price of the tank can vary from $104 to $200 depending on capacity and arrangement. A tank mounted in the vehicle trunk with a 19-gal capacity costs $104, while a saddle-type truck tank is approximately $200,excluding installation.

In summary, the cost of converting a vehicle to LPG fuel is $350 minimum,but can be more depending on the installation method and type of tank used. The conversion of an existing vehicle to compressed gas or propane involves an expenditure of $350 to $500,while conversion to LNG may cost from $800 to $1000.

6.2.2. Economic Incentives

To be economically attractive the user must obtain a reduction in other vehicle operating expenses sufficient to offset these costs during the life of the vehicle. Commercial fleet vehicle operators have indicated several factors that help to make gaseous fuel operations attractive economically.

- Lower fuel costs have been reported on compressed natural gas and LPG, and LNG costs promise to be attractive when imported supplies become available.
- Reductions in fuel taxes in vehicles meeting state pollution control requirements increase fuel cost savings and help to offset conversion costs.
- Federal Government purchasing regulations encourage purchase of pollution-free vehicle systems even at a premium price relative to conventional vehicles.
- In the case of compressed natural gas, elimination of fuel inventory costs provide additional economic advantages to large fleet operators.
- Reductions in maintenance expense of 7% have been reported.
- Transfer of conversion equipment items to successive vehicles reduces conversion cost per vehicle.

A recent development found in the propane industry is the leasing of the equipment used in vehicle conversions. Adoption of a lease arrangement is, of course, evaluated on an individual basis. In some cases, leasing of the equipment for a monthly fee over a specified time period can offer the lessee a tax advantage he could not obtain by purchasing the equipment outright. The same applies to acquisition of onsite storage facilities.

If the lease arrangement is selected, the only out-of-pocket cost to the lessee is the cost of labor involved in the conversion. The monthly cost is then as low as $8 per vehicle for equipment used in the conversion, depending on the vehicle.

These factors serve to stimulate interest in gaseous fuel vehicle operation apart from the resulting low pollution emissions. However, it is difficult to predict how rapidly the conversion of fleet vehicles to gaseous fuels will grow. Three factors will govern this rate; all of them are difficult to predict.

- Shifts in the relative prices of gasoline, compressed natural gas, LNG, and propane.
- Additional tax incentives and other legislated inducements offered by government bodies.
- Progress of the automotive industry in providing a "clean" car using gasoline fuel.

In the absence of some significant changes in these factors, the rate of conversion of commercial fleet vehicles is not likely to tax the ability of fuel suppliers or equipment manufacturers to serve the market.

Even the complete conversion of commercial vehicles in an urban area to gaseous fuels can reduce the overall pollution level by less than 30% because of the limited number of vehicles involved. It can be estimated that there would be a 15% to 25% reduction in HC, CO, and NOx emissions during the decade from 1973 to 1983. These reductions are shown by the shaded areas in Figures 6.2.2.-1, -2, and -3, for HC, CO, and NO_x respectively. These shaded areas have been added to figures presented in Reference 188 for Los Angeles County.

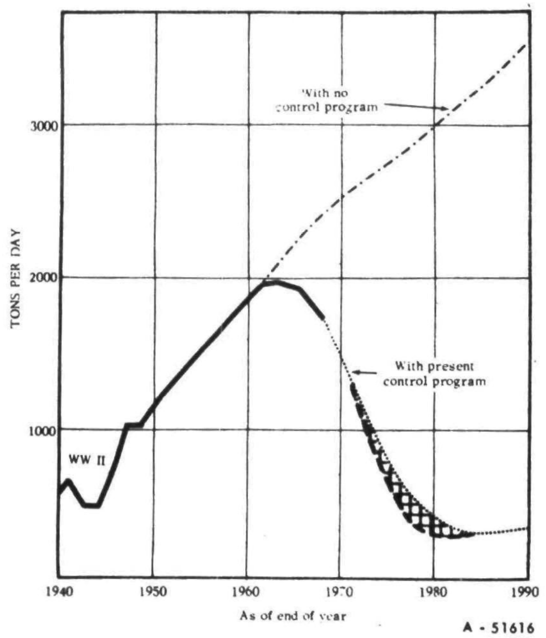

Figure 6.2.2.-1. EMISSIONS OF HYDROCARBONS AND OTHER ORGANIC GASES IN TONS PER DAY FROM MOTOR VEHICLES IN LOS ANGELES COUNTY

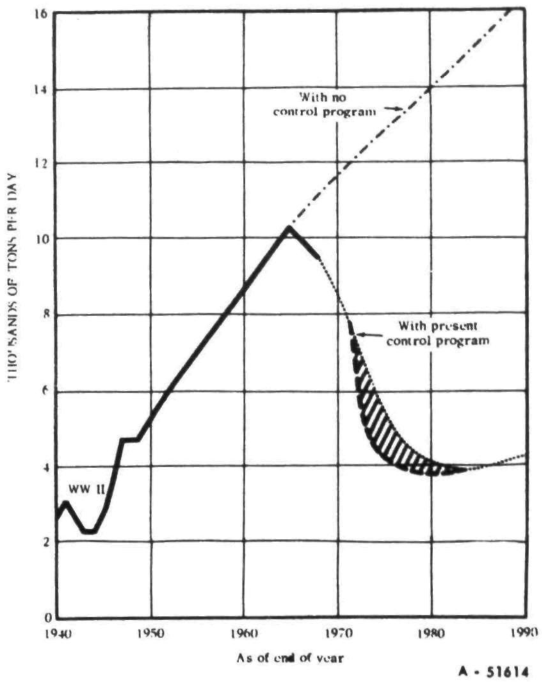

Figure 6.2.2.-2. EMISSIONS OF CARBON MONOXIDE IN TONS PER DAY FROM MOTOR VEHICLES IN LOS ANGELES COUNTY

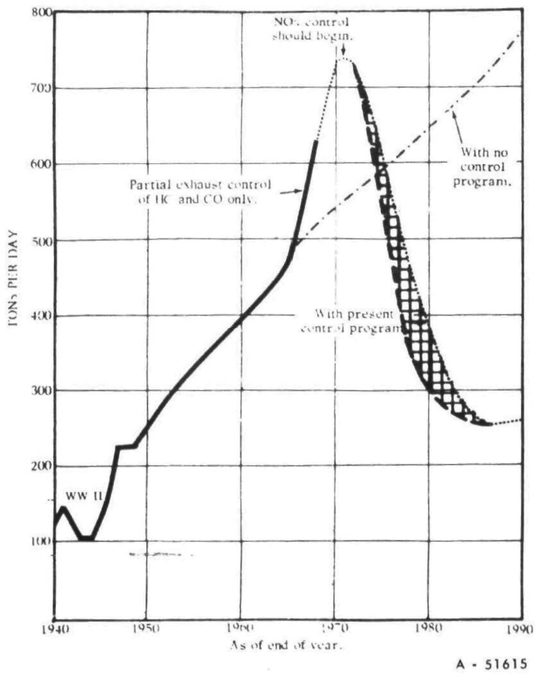

Figure 6.2.2.-3. EMISSIONS OF OXIDES OF NITROGEN IN TONS PER DAY FROM MOTOR VEHICLES IN LOS ANGELES COUNTY

It can be seen that the total emissions in tons per day of hydrocarbons and carbon monoxide from motor vehicles have already peaked and are now declining as the proportion of controlled vehicles in the total automobile population increase. Although the emission of nitrogen oxides has increased as a result of the steps taken to reduce hydrocarbon emissions, it is expected to peak in 1971 and will then begin to decrease as nitrogen oxide emission controls are incorporated into the existing automobile population. Since the last of these peaks occurs in 1971, it will be impossible for gaseous fueled vehicles to have any impact upon the maximum amount of emissions produced and they can only serve to increase the rate of decline in pollution emissions levels.

The upper dotted curves represent the projected decline in emissions from conventional vehicles under the present program of emission controls. The lower (dash line) curves defining the shaded area represent the reduction in emissions obtained by converting the commercial vehicles to natural gas or propane.

While the data are presented for Los Angeles County, the form of the curves is representative of what can be expected in other urban areas since the uniqueness of Los Angeles is its ability to accumulate emissions in its atmosphere, not in the rate at which they are generated. Since Los Angeles controls were imposed about two years ahead of Federal Control Regulations the time scale must be shifted to be representative of other urban areas.

The ultimate level of emissions that is finally achieved will be determined by the emission control standards that are established and enforced rather than by the means of achieving those standards. Since additional ancillary equipment is needed on gaseous fuel vehicles in order to meet the projected standards, there is an economic incentive to provide only enough equipment to reach the required level and not to exceed it. Thus, the two curves level off at the same emissions level which is determined by the governing control regulations.

These curves assume that all of the commercial vehicles are converted to gaseous fuel over a period of several years during which the shaded area widens. If only a portion of the commercial vehicle population is converted, the band will be correspondingly narrower. It would be difficult to estimate whether sufficient fuel is available to serve all of the vehicles represented by the shaded area in each of our urban areas. However, sufficient fuel could be made available by reallocation to serve certain urban centers. Each one must be examined individually because of the variations in energy logistics in various regions of the country.

One method of reducing the amount of gaseous fuel required is the dual-fuel vehicle.

6.2.3. Dual-Fuel Operation

Most of the experimental cars converted [illegible] compressed natural gas have incorporated a dual-fuel capability that permits the operator to switch to normal gasoline fuel even while the vehicle is in motion. This was originally conceived as an emergency procedure to avoid being stranded away from a source of gaseous fuel.

However, the switching has been demonstrated to be simple enough to consider a dual-fuel vehicle in which natural gas is automatically used under high emission driving conditions such as idle and acceleration while switching to lead-free gasoline under low emission conditions such as normal cruising speeds. To date no vehicles have been built to explore this technique for improving the effectiveness of utilizing the limited supplies of natural gas that will be available for motor vehicle operation. The amount of time such a vehicle would operate on each fuel may vary widely due to individual driving habits as well as traffic conditions and highway patterns.

However, by assuming that the vehicle is operated according to a known pattern of operation, for example, the New Jersey Cycle, it is possible to estimate the amount of time the vehicle will utilize gaseous fuel and gasoline.

It is known that transient modes of operation contribute the major portion of vehicle emissions. Therefore, operating with gaseous fuel only in those modes would contribute to a significant reduction in emissions at a savings in gaseous fuel consumption. Based on the transient time indicated in the above cycle, approximately 47% of the vehicle operations will be with gaseous fuels.

Since the modes of the cycle using gaseous fuel will involve higher than average fuel consumption, the quantity of gaseous fuel burned will be greater than 50% of the total.

A precise estimate requires a knowledge of the fuel consumption for each type of fuel during each mode of the cycle, a knowledge of the emissions from each fuel during each mode, a knowledge of the optimum combination of exhaust emission accessory equipment that [illegible] installed, and knowledge of the explicit means of [illegible]. Thus a rather involved study is required [illegible] data not found in the survey of the literature.

Additional experimental data is needed together with further study of the most favorable vehicle configuration in the light of the data accumulated in this report. This was considered to be beyond the scope of the study.

7. COMPARISON OF GASEOUS FUEL SYSTEMS

7.1. Emission and Performance

7.1.1. General Discussion

The information contained in Section 2 shows that the slow burning rate characteristic of ammonia and the knock rating of hydrogen make both of these fuels much less desirable for automotive use than natural gas and propane. In the case of ammonia, slow combustion results in emission of unreacted ammonia which is an offensive pollutant. With a hydrogen-fueled engine, nitrogen oxide emission levels will be high and cannot be reduced with proposed catalytic exhaust reactor systems. Therefore only natural gas and propane are discussed in detail.

The study also reveals that the differences in emissions and performance between natural gas and propane are slight. Therefore no distinction is made between them in comparing gasoline engine emissions and performance with those of these two fuels. If future standards recognize differences in reactivity of hydrocarbon emissions in causing photochemical smog, then natural gas will have an advantage over propane.

Simply converting to either propane or natural gas does not reduce exhaust emissions to the levels established by the 1980 Federal Standards. To achieve those levels, additional engine adjustments must be made and exhaust control devices must be added.

The reductions in emissions to be expected from the various steps that can be taken are summarized below. For comparison purposes, gasoline emission data from a 1967 Chevrolet equipped with PCV fuel vapor control and air injection were used as a reference[18] and all emissions are presented as percentages of that level.

7.1.2. Summary of Gaseous Fuel Emission Levels

Case 1. The simple conversion of gasoline-powered vehicles to gaseous fuels including propane, LNG, or CNG will reduce emissions of the reference vehicle defined above to the following relative levels:

50% of HC emissions
50% of CO emissions
95% of NO_x emissions

Table 7.1.2.-1. RELATIVE EFFECT OF MANUFACTURER'S MODIFICATIONS AND USE OF GASEOUS FUELS ON VEHICLE EXHAUST EMISSIONS

Case No.	Manufacturer's Modifications for Emission Control	Additional Modifications For Gaseous Fuel Conversion	Relative Emissions Compared to Reference Vehicle	Effect On Performance
1	Reference vehicle (1)	No changes made affecting emissions	50% HC 50% CO Negligible reduction in NO_x	Small loss of power ~ 10%
2	Same as Case 1	Retarding timing, limited spark advance, leaner air fuel ratio	15% HC 10% CO 20% NO_x	Major loss of power ~25% or more
3	Same as Case 1	Retarded timing, limited spark advance, leaner air-fuel ratio, rich carburetion in high power made	30% HC 30% CO 20% NO_x	Less loss of power ~15%
4	Same as Case 1 but with exhaust gas recirculation added	Same as Case 3 but with air-fuel ratio richer	30% HC 30% CO 10% NO_x	Larger loss of power ~20%
5	Same as Case 3 but with thermal reactor added	Same as Case 3	15% HC 10% CO 20% NO_x	Power loss about same as Case 3
6	Same as Case 4 but with thermal reactor added	Same as Case 4	15% HC 10% CO 10% NO_x	Same power loss as Case 4
7	Same as Case 6 but with catalytic reactors added for further reduction of HC, CO, NO_x	Same as Case 6	10% HC 8% CO 5% NO_x	Same power loss as Cases 4 and 6

(1) Reference vehicle[18], 1967 Chevrolet equipped with PCV, fuel vapor control, and air injecting using gasoline fuel.

In using LPG, a slight increase in NO_x emissions may be experienced while a slight decrease is more generally experienced with LNG and compressed natural gas.

Case 2. These emissions can be further reduced by optimizing the engine settings, to operate at leaner air-fuel ratios, retarded spark timing, and limited spark advance during acceleration and high-speed operation. These adjustments will further reduce emissions to the following relative levels:

15% of HC emissions

10% of CO emissions

20% of NO_x emissions

However, this results in a reduction in power output and deterioration of the operating characteristics compared to the reference vehicle.

Case 3. This deterioration in performance can be reduced by operating at richer mixtures during acceleration and high-speed operation but HC and CO emissions are increased to the following relative levels:

30% of HC emissions

30% of CO emissions

20% of NO_x emissions

Note that the nitrogen oxide emissions will remain approximately the same as the preceding case.

Case 4. It is possible by the addition of an exhaust recirculation system to further reduce the nitrogen oxides emissions by 50% to about 10% of the reference vehicle, with no increase in HC and CO. Thus this measure would result in relative emissions as follows:

30% of HC emissions

30% of CO emissions

10% of NO_x emissions

However, the addition of an exhaust gas recirculation system causes some deterioration in engine performance compared to that of the referenced vehicles.

Case 5. The use of an exhaust thermal reactor will give better performance than Case 4 with lower HC and CO emissions at some expense in NO_x emissions. This gives

15% of HC emissions
10% of CO emissions
20% of NO_x emissions

Case 6. The addition of both an exhaust reactor and an exhaust gas recirculation system combines to permit better performance than Case 5, lower hydrocarbon and CO emissions, and minimum nitrogen oxides emissions as well. In this case, the emission levels will be:

15% of HC emissions
10% of CO emissions
10% of NO_x emissions

Case 7. The further addition of a catalytic exhaust reactor system permits some further reduction in emission levels as follows:

10% of HC emissions
8% of CO emissions
5% of NO_x emissions

A vehicle equipped with all of these devices would still suffer a power loss comparable to the other two engine conversions involving an exhaust recirculation system.

These emissions are converted to grams per mile and compared with the 1980 Federal Standards presented in Table 2.3.3-1 and also shows the corresponding emissions from a gasoline-fueled vehicle using the same equipment installations.

Table 7.1.2.-2. ESTIMATED EMISSIONS IN GM/MILE FOR GASOLINE AND GASEOUS FUELS COMPARED WITH PROPOSED 1980 FEDERAL STANDARDS

	Reference Vehicle per Table 7.1.2-1. Case 7		
Emission	Gasoline Fuel	Gaseous Fuel	Federal Standard
Hydrocarbons	0.26	0.26	0.25
Carbon Monoxide	3.0	1.84	4.7
Nitrogen Oxide	0.5	0.25	0.4

It can be seen that although the nitrogen oxide emissions are reduced to within the 1980 Federal Standards, the differences in emissions between gas-fueled and gasoline-fueled vehicles using all of this accessory equipment is not great. We can therefore conclude that in the time period around 1975 when the automotive industry has met or is close to meeting the pertinent Federal Standards that the incentive for use of natural gas or propane will not be very large. The gains to be obtained in using natural gas fuels are much greater in the immediate future when the emissions from gasoline fueled vehicles are relatively higher. However, the logistics of supplying natural gas fuels will prevent the use of significant quantities of natural gas or propane for several years, approximately paralleling the time period of development of gasoline powered clean automobiles.

7.2. Logistics Considerations

Of all the gaseous fuels studied only LPG and natural gas are sufficiently attractive to warrant serious consideration for motor fuel use. Both ammonia and hydrogen can be eliminated because of their relatively high cost and limited availability as well as their technical limitations in engine use. Since both of them currently use natural gas as a raw material to achieve their present market prices they can be expected to increase in cost if produced from other raw materials in order to avoid depleting natural gas reserves.

Since LPG and natural gas are produced from the same gas fields,they are subject to the same limitations as far as future increases in supply are concerned. Both the natural gas industry and the LPG industry are being hard pressed to supply our current needs for these gases in existing markets. Any large additional quantities of gaseous fuels for motor vehicle use must come from some other source. Fortunately we have other sources to consider.

Both LPG and LNG can be imported from countries overseas such as Algeria, Venezuela, Libya, Nigeria,and the Middle Eastern countries which have large reserves of natural gas and natural gas liquids. However, the transportation facilities to move large quantities of these gases into the United States are currently nonexistent. The natural gas importation projects presently being planned will provide little excess LNG for motor fuel usage. In order to obtain financing,each of these projects has obtained commitments for delivery of its total supply before initiating the project. These commitments have been made to transmission and distribution utilities to supply existing gas markets. The importation of additional LPG from foreign countries is currently limited by a shortage of tankers. However, given a firm market demand for gaseous fuels in the United States, commercial projects could be organized to deliver significant quantities of both LPG and LNG into the coastal areas of the United States in a period of four or five years.

There are other domestic sources for both of these fuels, however, at the present time about 5 trillion CF or approximately 20% of our annual natural gas production is sold with the understanding that it will be delivered only when it is available and that the supply may be interrupted during winter months in order to supply firm heating customers. Much of the gas sold for industrial boiler fuel uses is sold on this basis. However, not all of the 5 trillion CF of gas is actually interruptible. Many utilities have sold interruptible gas to customers who have not provided alternate fuel burning equipment and they have never been interrupted. Nevertheless, many industrial plants and electric utilities are equipped to burn coal, oil, or gas and can switch fuels depending upon their relative cost and availability. It was shown in Section 3 that half of the natural gas presently burned by the Consolidated Edison Company in New York City would be sufficient to fuel all of the commercial fleet vehicles in New York City with natural gas. It was also shown that the conversion of such fuel use from boiler fuel consumption to motor fuel consumption would result in a decrease in the overall pollution level. Thus the diversion of interruptible gas supplies represents a potential source of natural gas for motor fuel use that should be adequate to supply the foreseeable growth in this area during the next several years.

The possibility of increasing the yield of propane from oil refinery production was discussed in Section 4. This appears to be the only source of gaseous fuels that has the potential capability of supplying a major share of the motor fuel requirements of the United States. It would, of course, take many years to convert from the production of gasoline to the production of propane. However, increasing the production of lead-free gasoline necessitates an increase in the yield of propane because of the shift in refinery processes necessary to produce higher octane species in lieu of

the addition of tetraethyl lead. Thus some increase in production of propane can be expected immediately and additional propane could be produced if the demand for this fuel continues to grow.

It does not appear likely that the operation of gas fuel vehicles will grow at a pace that will outstrip available supplies of natural gas and LP gas during the next few years unless some stimulus is provided by legislative action at the state or federal level. Such legislative action seems unlikely unless, or until, it becomes apparent that the present program of converting to lead-free gasoline will not achieve its objectives. Thus there is a period of perhaps 3 years in which to further develop our experience and knowledge of the use of gaseous fuels in various types of motor vehicles before it becomes necessary to make a decision on whether such fuels must be used more widely in order to solve the pollution problem.

7.3. Operating Costs

A comparison of gasoline, diesel oil, and gaseous fuel costs is presented in Table 7.3-1. The market prices presented are representative of the fuel prices available to very large fleet operators before taxes. These prices are shown in cents per gallon and also in cents per million Btu. In addition the price of each fuel that would be equivalent to gasoline at $1.04 per million Btu (12¢ /gal) is also shown. These prices are generally lower on a cents per gallon basis than gasoline because of differences in heat content and density.

Using the gasoline data, and assuming a vehicle travels 15 miles per gallon of gasoline using regular gasoline at 12¢/gal, it can be calculated that it will burn 7700 Btu per mile and will require 80¢ worth of fuel to travel 100 miles. The comparative cost of traveling 100 miles is also shown for each of the gaseous fuels; first, on the assumption that the same number of Btu is required and secondly on the basis of reported experience in fuel consumption with each of the gaseous fuels. On the basis of 7700 Btu per mile it can be seen from the table that operation on LPG would cost 66¢ to 99¢ for the range of fuel prices used instead of 80¢. LNG would cost from 54¢ to $1.05 per 100 miles for a range of LNG costs from 6¢ to 12¢ per gallon (70¢ to $1.37 per million Btu.) Compressed natural gas would cost approximately the same amount since its cost in cents per million Btu is closely comparable to that of LNG. However, reported experience with gas-fueled vehicles indicates that actual fuel consumption is lower than a comparison on an equivalent energy basis shows. A new fuel cost per 100 miles was therefore calculated for the comparable fuel consumptions presented in the table. At 13 miles per gallon of LNG it would cost approximately 46¢ to 90¢ per 100 miles based on LNG costs ranging from 6¢ to 12¢ per gallon. Also, compressed natural gas consumption at 15 miles per 100 SCF would result in a cost of 62¢ to 90¢ per 100 miles for the price range shown. A vehicle operating on LPG and obtaining 14 miles per gallon would incur a fuel cost of 57 to 86 cents per 100 miles. In the case of each gaseous fuel the cost per 100 miles of travel ranges from near the cost of diesel fuel (54¢) to somewhere above the cost of gasoline (80¢).

However, these possible savings in fuel cost must be sufficient to offset the additional cost of conversion of the automobile to gaseous fuel in order to be economically attractive. Where the cost of gaseous fuel is near the low end of the price range as shown in the table, this can be done. However, it is much more difficult to justify conversions of diesel engines to gaseous fuel because of the relatively low price of diesel fuels.

Because of variations in patterns of operation, installation costs and othe other factors it is difficult to generalize on the over-all costs of operation of gaseous fuel vehicles in comparison to gasoline powered cars. However, there are literally thousands of LPG vehicles in operation that have been justified on the basis of economic advantages alone. Similarly there are over 2000 natural gas-fueled vehicles, most of them using compressed natural gas, that are presently being evaluated to assess their operating cost in comparison to gasoline powered cars. Many of these vehicles have shown economic advantages as well as cleaner exhaust emissions. The cost of operation of gaseous fuel vehicles is sufficiently close to the cost of operating gasoline-powered cars that a small change in relative costs can easily swing the balance from one fuel to the other.

Table 7.3-1. COMPARISON OF GASOLINE AND GASEOUS FUEL COSTS

Item	Gasoline	Diesel Oil	LPG	LNG	CNG
Physical Properties					
Sp gr, liquid/water	0.72	0.82	.508	.424	—
Density, lb/gal	6.0	6.8	4.24	3.53	—
Btu/gal	115,000	135,000	91,800	86,000	1000 Btu/SCF
Prices					
¢/gal-market price*	12	10	8–12	6–12.0	—
¢/10^6 Btu	104	74	87–131	70–137	90 –130
¢/gal-equiv. to gasoline (@ 104¢/10^6 Btu)	12	14	9.5	9.0	—
Relative Consumption					
Miles/gal	15	18.5	14	13	15/100 SCF
Btu/mi based on rep. mi	7700	7300	6500	6600	6900
¢/100 mi of travel based on 7700 Btu/mi	80	57	66–99	54–105	70–100
¢/100 mi based on rep. mi	80	54	57–86	46–90	62–90

7.4. Potential for Early Commercialization

LPG vehicles have been in commerical operation for many years and represent a viable business even though the total population of 250,000 LPG vehicles represents an almost negligible proporation of the 105 million motor vehicles in operation in the United States. Natural gas-fueled vehicles have only been given serious consideration in the United States in the past three years, but at the present time, over 2000 vehicles are in operation. These are largely experimental vehicles being operated by utility companies, government agencies,and interested equipment manufacturers. However, because of the economic incentive to use gas-fueled vehicles in order to comply with pollution regulations, it is anticipated that the market will grow very slowly until there is some change either in the economic incentive or in regulatory requirements.

8. ANALYSIS OF THE USE OF NATURAL GAS IN AN INTERCITY BUS

8.1. Objective

The objective of this section is to determine the feasibility of using natural gas as a supplementary fuel in two-stroke cycle, diesel-powered intercity buses as a means of reducing exhaust pollution while operating in urban areas and bus terminals. This involves primarily two engines, a six cylinder 6V-71 engine and an 8 cylinder 8V-71 engine both made by the Detroit Diesel Division of General Motors Corporation.

8.2. Introduction

Because of fuel supply logistics problems, the most logical user of gas-fuel-supplemented diesel vehicles would be a large fleet owner with established maintenance facilities at central locations through the region of operation. It has been recognized that present supplies of natural gas, LNG, and even LPG may at times become limited which makes it desirable to consider intermittent operation of such a supplementary system to reduce emission of smoke and odor only in those areas where pollution is most severe — in central city operation.

With this in mind, it was agreed to examine the feasibility utilizing gaseous emission reduction systems on a bus fleet of 6,000 vehicles powered by 2-cycle Detroit Diesel Model 6V-71N or 8V-71N engines. These supplementary fuel systems would only be operated within urban areas, to reduce smoke and odor under city street traffic conditions (low speed, stop-and-go operation with a high percentage of idle)and in enclosed bus terminals.

Two systems have been developed that utilize gaseous fuels in the diesel engine and that are known to reduce smoke — the dual fuel and power boost systems. It is also expected that these systems will reduce odor because of their more homogeneous combustion, but such data are not available — indeed direct measurement of odor is not feasible at present. These systems, as applicable to the 71 series engine,are discussed subsequent to the following discussion on current emission requirements and experience relating to the 71 series diesel engine.

8.3. Emission Control Regulations

8.3.1. Current Status

There are currently no government standards in effect regulating gaseous emissions from diesel engines. Adoption of regulations specifically for heavy duty vehicles has lagged behind those for automobiles. There are several reasons for the lag. Heavy duty trucks comprise less than 4¢ of the total vehicle population. This small percentage has resulted in a lack of attention to the heavy duty vehicle and corresponding lack of emissions data.

Control devices were first developed for automobiles and later extended to heavy duty vehicles where feasible. Control devices established for passenger cars are not necessarily transferable to heavy duty vehicles. For example, the higher load cycle may make NO_X control more difficult.[101] The nature of emissions from heavy duty vehicles varies so widely that no generally applicable control techniques exist and controls for each unique powerplant design must be approached separately. More effort is required to develop control techniques although considerable progress has been made in a few areas.

Current and future heavy duty vehicle standards make a clear distinction between gasoline and diesel power plants (about 20¢ of the heavy duty vehicles in California in 1969 were diesels) because of the wide differences in the basic combustion processes and in the resulting emissions: Hydrocarbon emissions vary considerably in character. Smoke and odor are much more of a problem with diesels, while crankcase and evaporative emissions do not require control as with the gasoline engine.[101] Carbon monoxide is normally only found in minute traces in the diesel.

8.3.2. Future Regulations

However, by California law, emissions standards for carbon monoxide, oxides of nitrogen, and hydrocarbon in that state are to be established and

in effect by Jan. 1, 1973. A tentative 13 mode, 3 speed, weighted, steady-state dynamometer test cycle (Table 8.3.2.-1 and Figure 8.3.2.-1) has been developed using 10-minute stabilization periods for each mode for engine dynamometer testing (for state approval of the engine type) and 3-minute mode periods for chassis dynomometer testing (for field surveillance).

Table 8.3.2.-1. MODE DIESEL EMISSIONS CYCLE

Mode	Engine Speed	¢ Load†
1	Idle	--
2	Intermediate*	0
3	Intermediate*	25
4	Intermediate*	50
5	Intermediate*	75
6	Intermediate*	100
7	Idle	--
8	Rated	100
9	Rated	75
10	Rated	50
11	Rated	25
12	Rated	0
13	Idle	--

* Peak torque speed or 60¢ of rated speed, whichever is higher.

† Percent of maximum torque available at that speed.

Although the 13-mode cycle is basically steady state, it does include transient deceleration between modes 6-7 and acceleration between modes 7-8.[12] This legislation was adopted at a hearing on November 19, 1970. Limits established are 16 g/hp-hr of NO_2 + hydrocarbons, and 40 g/hp-hr of CO. Further reduced emissions limits, to become effective January 1, 1975 are for 5 g/hp-hr, NO_2 + HC, and 25 g/hp-hr CO.[112]

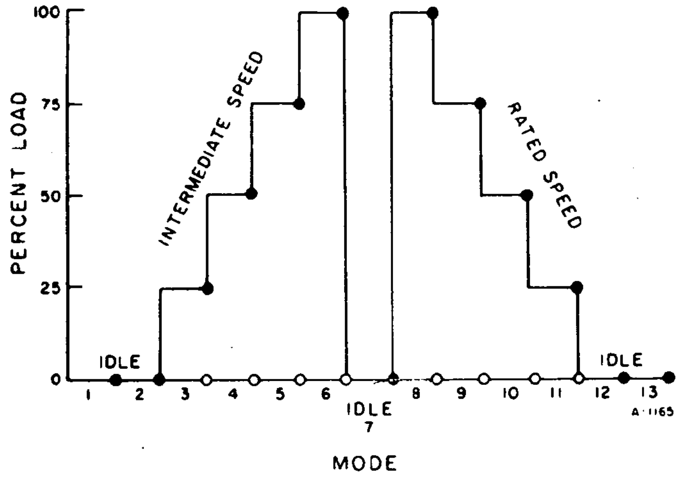

Figure 8.3.2.-1. 13-MODE DIESEL EMISSIONS TEST CYCLE

Under this law, a given engine family must pass the dynanometer mode-test for state approval. An engine family is established by models having 1) the same combustion system, 2) the same scavenge cycle (2 or 4), and 3) the same method of air aspiration. Models in a family may have different numbers of cylinders, different configurations (in-line or Vee), and different bore and stroke if they use the same block. The model tested for state approval as representative of an engine family must be that unit with the highest sales volume because the total gaseous emission quantity is the significant pollution factor.

There are currently several existing or proposed state and Federal laws regulating smoke from diesel vehicles. The Federal law establishing Federal Smoke Certification for engines was enacted in 1968 and sets smoke limits at 20¢ opacity, with 40¢ opacity allowed for 5 seconds. The testing is made after a 5 minute idle, during full lug down and during an acceleration. Measurement is made with a full flow light extinction smokemeter that measures light obscured by the total plan. The model selected from an engine family for certification must be the worst-case model, i.e., have the highest fuel rate in their family.[12, 111] Similar regulations exist or are in some stage of development in various states. Some such regulations call for "no visible smoke," which may be defined as 20¢ opacity although the actual threshold of visibiiity is about 5-6¢.[112]

There are currently no regulations for diesel exhaust odor that are being enforced, although California did develop legislation regulating odor and irritation, principally for buses, in 1966.[36] This legislation is difficult to enforce since there is presently no practical way of measuring odor or generally controlling it.

8.4. Current Equipment and Emissions Produced

8.4.1. Emission Related Features

The 6V-71 and 8V-71 series diesel engines are used so extensively in the intercity bus field that any reduction in pollution in this field must be achieved through the modification or replacement of these engines. The Detroit Diesel Division was helpful in providing information not only on this particular engine, but on diesel engine emissions in general.

In 1962 the "N" series engine was introduced as a replacement for the earlier "E" series. The significant differences in the improved "N" series are the injector type, which is a standard reduced-sac-volume needle valve type injector instead of the earlier crown valve type, and an improved design combustion chamber shape and volume, with increased compressed ratio. A 60¢ reduction in unburned hydrocarbons was achieved along with reductions in smoke, aldehydes, and odor. However, oxides of nitrogen increased because of the improved combustion system. The uncontrolled injector volume (that below the valve) was found to be the determining factor in hydrocarbon emissions of the 2-stroke Detroit Diesel engines. The "E" series crown-valve injector had an uncontrolled volume of 175 cu mm compared to the "N" series needle valve injector with a controlled "sac" volume of 3.5 mm. The significance of the fuel trapped in the small uncontrolled volume is illustrated by calculations showing that, for a Model 6V-71N engine operating at 2100 rpm, one cu mm of unburned fuel per cylinder entering the exhaust would result in an hydrocarbon emission level of 1100 ppm.[137]

Experimental evidence indicated that a portion of the uncontrolled volume of trapped fuel was expelled from the injector by heating and expansion late in the combustion cycle and the early portion of the scavenge cycle, such that it passed into the exhaust only partially burned. This type of emission was greatly reduced through use of needle valve injectors with a minimized uncontrolled "sac" volume.

8.4.2. Emissions Produced

As a result, the current 71N series engines are not smoke limited on power output. While current Federal smoke standards are set at 20% opacity, the 71N series smoke density is 2-4% opacity or below the visible threshold of 5-6% for properly maintained shift point rpms.[69,112] Further there is no concern about gaseous emission levels. It has already been noted that the diesel is inherently somewhat superior in this respect. The current low emission levels presented in Table 8.4.2.-1 — which have resulted from utilization of "low sac" injectors, and to some extent the catalytic muffler for hydrocarbon emission control, the catalytic muffler for CO control, and retarded ignition timing for NO_x control — are well below existing standards.

Further, there is confidence on the part of General Motors that anticipated future requirements can be met.[59,112]

These low level emissions were achieved through introduction in early 1970 of an emission reduction package for retrofit and new vehicle production assembled by GMC Truck and Coach Division. This package contains the

catalytic mufflers, further reduced "low-sac" volume injectors, vertical exhaust stacks, with aspirator for odor dilution and also contains engine sound proofing components. These modification allowed retarding the injector timing to reduce NO_x formation without adversely affecting other emissions.

Table 8.4.2.-1.[69] EXHAUST EMISSIONS FROM A 6V-71 (2V.)
DETROIT DIESEL DIV. ENGINE
(including Exhaust Reactor)

Pollutant	Full Load	1/3 Load
CO g/bhp-hr	5-50*	6-9
HC g/bhp-hr	0.1-0.3	1.8-2.7
NO_x g/bhp-hr	5-8	9-11
Smoke % Opacity	18%	1%
	@ 700 rpm	@ 2100 rpm

* Range of values over engine speed range tested

Note: Data presented is for 1.490 injector timing; some variations in relative emissions of each pollutant can be obtained by varying injection timing.

8.4.3. Anticipated Effects of Converstion to Gaseous Fuels

No data could be found that would permit a direct comparison of the emissions from a gas-fueled diesel engine using compression ignition with that for the 6V-71N engine presented in Table 8.4.2.-1. However, a general comparison of exhaust emissions from diesel and gas dual-fuel or quasi-otto cycle operation has shown the diesel to have certain advantages. It has somewhat lower exhaust hydrocarbons, comparable oxides of nitrogen, and considerably lower carbon monoxide emissions.[87] It would not be surprising then for a similar situation to exist for the specfic case of the 6V-71 engine with gaseous fuels inducted into the intake air. That the uncontrolled injector volume is the principal source of hydrocarbon emissions indicates that hydrocarbon emission due to this source would be just as great for pilot injection as for full load diesel operation. Thus dual or supplementary fuel operation would result from the 30% excess intake air which is short circuited to the exhaust during the scavenge cycle. This air would also carry 30% of the gaseous fuel into the exhaust unburned. A possible solution — the direct injection of gaseous fuel into the cylinder after completion of the scavenge cycle — was experimentally tested by Detroit Diesel a number of years ago.[112] However, no gaseous emissions data was taken on this or any other Detroit Diesel dual-fuel engine tests. In fact, experimental work at Detroit Diesel with dual-fuel conversions ceased about 10 years ago because of the very limited market prospects for such engines in the mobile vehicle field. Further, direct injection conversion of the current 71 Series engines is not economically feasible, as a new cylinder head design would be required.[103]

The greatest potential for emission reduction from gaseous fuels is for increasing smoke limited power output and reducing exhaust odor as a result of increased preflame reactions and more homogenous combustion.[3,23,108] However, the 71N Series engine is not reduced with the "N" series modifications and with the vertical exhaust stack-aspirator. Further, no current regulations for odor are under enforcement, and are not likely for some time because of the difficulty of odor measurement.

These factors have thus far deterred the General Motors Corporation, and other major diesel engine manufacturers as well, from developing gas-fueled versions of their automotive diesels. This does not however preclude the conversion of such engines by others.

8.5. Engine Modifications Required

There are several ways in which a diesel engine can be modified to burn a gaseous fuel such as natural gas or propane. All of them require very extensive modification of the engine however. Most of them actually convert the engine to the otto cycle or some quasi-otto cycle. They are discussed in turn below.

8.5.1. Conversion to Spark Ignition Engines

Virtually all high speed natural gas- or propane-fueled industrial engines used in stationary engine applications are 4-stroke, spark-ignition engines. Many of them are conversions of 4-stroke diesel engine designs in order to take advantage of the tooling and production facilities available. Although most of the high speed automotive type diesels offered in this country are 4-stroke engines, the GMC 71 series engine is a 2-stroke cycle engine. While it can be converted to a spark-ignition engine, it would be a 2-stroke spark-ignition engine. Such an engine can be expected to have higher emission levels than the present engine. A 4-stroke spark ignition engine that has been modified for use of natural gas or propane could be installed to operate as a dual fuel engine using gaseous fuel in terminals and urban areas, but a diesel engine cannot readily be switched back and forth from a compression-ignition engine to a spark-ignition engine. However, it can be approximated by modification to a dual-fuel cycle and this arrangement can be applied to the 2-stroke cycle diesel engine.

8.5.2 Dual-Fuel Conversion

A dual-fuel conversion of the 71 series diesel engine is available on the market, from Stuart & Stevenson, a firm specializing in such conversion work. It is applied to engines installed in stationary service for electric generation, water pumping, compressor drive, etc.

In the dual-fuel engine, the principal fuel is natural gas or LPG which is added to the intake air. As in diesel operation, power output is controlled by varying the amount of primary fuel while the intake air remains unthrottled. Ignition is provided by the pilot injection fuel, the amount of which is normally a constant quantity fixed at 5-10% of total full-load fuel. The dual-fuel engine can operate at compression ratios and maximum power output levels approaching the diesel, while operating an order of magnitude leaner than the spark-ignited engine.[29, 54, 87]

Advantages of the dual-fuel engine in addition to possible savings in fuel costs, are[29,54,87] —

1) less smoke than the diesel
2) less carbon monoxide
3) possible reduced engine wear because of cleaner engine conditions
4) generally lower rates of pressure rise under nonknocking condition
5) less dilution of lube oil

Present drawbacks that may occur with dual-fuel operation are —

1) a knock-limited power output and, corresponding, a generally reduced compression ratio and verified efficiency
2) a poor light load (lean) fuel utilization with corresponding poor light load efficiency
3) extensive modification for diesel conversion to dual fuel may cost an additional 30-40% of the original diesel engine price
4) additional fuel supply system must be installed to supply amount of gaseous fuel required

8.5.2.1. Dual-Fuel Engine Performance

Poor fuel utilization at light load results from appreciable quantities of gaseous fuel surviving the combustion process when the fuel/air ratio falls below a certain lean fuel limit that appears to generally correspond to the flammability limits of gas-air mixtures as extrapolated to engine conditions at ignition. Experimental evidence suggests that, for these lean mixtures, flame fronts propagating from various ignition centers of injected fuel fail to reach all regions of the cylinder, leaving some homogeneously dispersed in the fringes of the combustion zone. At loads above which gaseous mixtures exceed this limiting lean concentration, the flame sweeps throughout the mixture with corresponding faster heat release and pressure rise.[86] As the load increases, richer mixtures eventually lead to an upper limit condition of knock and excessive pressure rise.[54, 86]

As a result of poor combustion, or even ignition failure at very light loads, the specific fuel consumption of the dual-fuel engine is much inferior to the diesel; however, dual-fuel efficiency may surpass the diesel at full loads. Associated with this poor fuel utilization, carbon monoxide production may increase to an order of magnitude above that of the diesel, but remains considerably below that of spark ignition engines. Improved light load efficiency with corresponding reduced emission of unburned hydrocarbons (predominantly methane)and carbon monoxide, may be achieved by reducing the lower mixture limits, or by enriching the fuel/air ratio by decreasing intake air.[103] Downward extension of the lower lean limit may be achieved by —

1) injecting a larger proportion of diesel fuel at light loads, that assists combustion of the gaseous fuel by increasing the overall mixture temperature and providing more ignition centers. At higher loads, diesel fuel injection is decreased to a minimum for maximum efficiency.
2) injection pressures,as low as will provide satisfactory diesel operation, used to prevent too rapid dispersion of the pilot vapor before autoignition is achieved.
3) advanced injection timing increases fuel residence time in the[23, 86, 87] cylinder and enhances the activity of preflame oxidation reaction.

Knock, produced at the upper (rich) mixture limit, is predominately affected by the octane rating of the gaseous fuel, the degree of charge preheat, and, to a lesser extent, by liquid fuel quality.[29, 103] Knock limited power output for natural gas fuel may be as high as diesel power rating,[29,54]and high load efficiency may surpass that of the diesel.[54, 87] Due to its lower octane rating, knock limited power output for propane is about 70% of that for natural gas. Reduction of engine compression ratio to accommodate the gaseous fuel sacrifices some efficiency.[29] Studies have shown that the addition of reasonable quantities of lead alkyl antiknock compounds to propane can increase its knock limited power output to 30% above diesel rating.[29,54] Retarding injection timing at full load will also increase knock limited output and improve emission characteristics.[87] Nevertheless, the addition of lead antiknock compounds is not recommended if exhaust reactors are installed to reduce NO_x emissions.

8.5.2.2 Emissions From Dual-Fuel Engines

Very little emission data are available on dual-fuel engines, but smoke is generally reported to be below the diesel.[3,89] As mentioned, unburned hydrocarbon emissions from dual-fuel engines are largely methane.[87] A particular test has shown that maximum carbon monoxide production occurs about mid-load and is of the order of 0.3¢. NO_x formation is not believed higher than in the diesel in view of the more homogeneous mixtures and lower cycle temperatures.[87]

8.5.2.3. Engine Modifications Required for Dual-Fuel Operation

Rather extensive engine modifications may be required and the complete installation may cost up to 30-40¢ of the original diesel engine cost. Modification that may be required are –

1) an added inlet valve per cylinder and consequently a new camshaft or an added intake port in each cylinder wall
2) generally a reduced compression ratio requiring either new pistons or a spacer plate for the cylinder heads
3) addition of a gas manifold and possible fuel/air mixing device
4) modification of the injector to provide constant pilot fuel quantity during urban operation and full diesel fuel flow for highway travel when gaseous fuel is shut off
5) additional tankage and feed system that must be installed in the vehicle

8.5.3. Power Boost Systems

Another method of using gaseous fuel in a diesel engine is with a power boost system. Literature on the power boost system claims boost of horsepower up to 30¢,[61] up to 18.5¢ increase in smoke limited power output, and increased high load efficiency of up to 10¢.[3] Further investigation indicates that these are rather special cases and, in general, improvement will be considerably less. One such system, the Torque-Topper, manufactured by Century Gas Equipment, Marvel Schebler Division, Borg Warner Corporation, is illustrated in Figure 8.5.3.-1. This unit adds LPG to the intake air of the diesel at heavy load, as controlled by the exhaust temperature-sensing switch. At the preset exhaust temperature, the switch closes, activating a solenoid valve which in turn allows the demand type regulator to supply the required flow of LPG.[61]

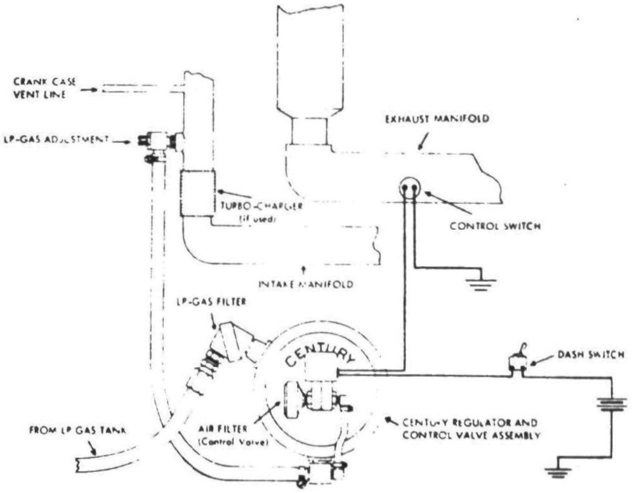

Figure 8.5.3.-1. THE CENTURY "TORQUE TOPPER" SYSTEM

It has been experimentally shown that the supplementary fuel added in such power-boost systems can assist in three ways: 1) Better air utilization – the ability of the engine to burn more pounds fuel per pound air;[3] 2) Increased heat release from the preflame oxidation reaction;and 3) The chemical ability of the constituents of preflame oxidation to permit flame propogation more readily than in air alone.[3,23] In normal diesel operation, the heat vaporization requirement of fuel injected initially exceeds heat liberation from preflame oxidation. The presence of relatively low concentrations of secondary gaseous fuel increases the heat liberated from preflame reaction, overcoming quenching by the injected fuel, and producing a noticeable cool flame pressure buldge. The heat so produced is evenly released, resulting in more power with less smoke.[3, 23]

Critical concentrations of preoxidation products have been shown capable of reducing smoke over the whole load range compared to the diesel.[23] As common boost schemes have no real control over the resulting preflame product concentrations, success is somewhat of a hit or miss process. As expected from thermodynamic considerations, brake specific fuel consumption was slightly higher than the conventional diesel over the low and intermediate load range, but improved under heavy load, sometimes surpassing the diesel.[3,23] Poor fuel utilization at light load is analogous to that observed for dual-fuel operation.[23] Benefits gained from fumigation vary widely with speed, generally medium speed range, and the best performance is achieved at or near full load.[3] In summary, the extent of benefits achievable with power-boost schemes are highly dependent on the individual situation.

No gaseous emissions data are currently available for power-boost systems.[60] Power-booster systems are generally frowned on by engine manufacturers because of the potential to exceed the maximum design power rating which voids the warranty.[108, 112]

8.5.4. Stratified Charge Gas Fueled Diesel Engine

Stratified charge engines have been known for many years and have been used in some special applications where steady loads permit them to be used.

For several years, the Southwest Research Institute has been conducting research under the sponsorship of the American Gas Association aimed at the development of a natural-gas-fueled engine operating on a diesel cycle. At the present time technical details of the project are considered proprietary pending completion of future development plans.

However, the method used has been demonstrated on both two- and four-stroke diesel engines and should be applicable to automotive type engines as well as stationary engines. No performance data and emissions data are available nor can the suitability of a 71 series Detroit Diesel engine for conversion to gas operation by this method be evaluated at the present time.

8.6. Alternatives Available

Of the various conversion possibilities discussed, the dual-fuel conversion is the most appropriate alternative aside from complete replacement of the 71 series engines. Even this conversion does not promise great improvement over the present engines and involves considerable expense and inconvenience.

A dual-fuel conversion of the 8V-71N series diesel is available on the market. Individual engine conversion cost (less fuel tank and supply lines on the basis of fleet of 6000 buses is estimated to be approximately 26% of the cost of the unmodified 8V-71N. The dual-fuel version decreases the compression ratio from 18.6:1 down to 17 :1. Estimated overall efficiency is 10% below that of the original engine, and has been operated with satisfactory fuel consumption on the 71 series diesel. Conversion details are considerably simpler than for a full dual-fuel conversion. Emission data for these systems are not available from the manufacturer. However, smoke benefits from these systems are known to be rather unpredictable, being highly dependent on speed and load. A specific test of 71 series diesels in buses with fumigation of diesel fuel (induction of atomized diesel fuel) resulted in significantly decreased smoke only at speeds below the operating range. The load and speed factors of city traffic are not generally considered to be conditions favorable to power booster operation.

8.7. Conclusions and Recommendations

In summary, the methods currently available for converting the 6V-71N and 8V-71N diesel engines to the part-time use of natural gas cannot be recommended in view of their ineffectiveness in improving exhaust emission control and their high costs of conversion and inconvenience of operation. Except for some reduction in odor, none of the conversions promise reductions in regulated pollutants below those now reported for the engines when properly equipped with available pollution control devices offered by the manufacturer.

While several schemes might be developed to accomplish the desired objective, they will require extensive research and development and may require replacement of the 71 engine. Such alternatives must be weighed against the possible use of gas turbines or other new engines as existing buses are replaced by new ones. The consideration of such longer range alternatives is beyond the scope of this study.

9. RECOMMENDATIONS

The findings and conclusions of this study support a recommendation to further the development and use of natural gas and LPG as motor fuels wherever logistical considerations permit their use. In line with that general recommendation, a number of specific recommendations are made in regard to problem areas that were uncovered during the course of the study. These recommendations are presented below in relative order of importance.

9.1. Further information is needed on the reactivity of various types of hydrocarbon emissions from engines in order to clarify the extent to which various gas engine emissions are harmful.

During the study it was discovered that opinions vary considerably on the contribution to air pollution that has been made by various species of hydrocarbons emitted from vehicle exhausts. Until sufficient information is available to determine the relative contributions from various types of hydrocarbons, it is difficult to compare various fuels on the basis of their pollution potential. In this study no distinction was made between various hydrocarbon species since present testing procedures and emission standards do not provide for them. Consequently, natural gas and LPG vehicles have comparable emission characteristics. If, as has been reported by many investigators, methane hydrocarbon emissions do not produce as much smog as heavier hydrocarbons, this should be accounted for in determining emission levels. This would make a significant difference in the choice between LPG and natural gas and might result in the elimination of exhaust reactor equipment on natural gas vehicles as well as widening the usable operating ranges of fuel/air ratio and ignition timing. This would make engine tuning less critical.

9.2. It is recommended that an optimized design of an IC engine for use of gaseous fuels be built and tested to demonstrate the performance attainable as well as the emissions produced by such an engine.

This design should take advantage of all the possible ways of improving engine performance as well as reducing emissions that can be used with gaseous fuels. The resulting engine should then be tested both on a dynamometer and in actual road tests on a comparative basis with a gasoline-fueled engine and with a simple gas engine conversion, where only the fuel supply has been changed.

The study revealed that additional ancillary equipment must be installed on gas-fueled engines in order to meet ultimate emission requirements. The study also suggests that some of this equipment might be eliminated if the engine were not required to operate on gasoline and could be optimized for gas fuel use alone.

9.3. Additional research and development is needed to better determine the effectiveness of exhaust catalytic reactors and afterburners in handling the lower concentration of pollutants from natural gas and LPG engines.

During the study it was noted that exhaust catalytic reactors operate more effectively when the content of the pollutants in the exhaust stream is high and that they become less efficient when operating on exhaust streams that are relatively clean. This raises the question of whether such devices manufactured for gasoline-fueled vehicles will be well suited to use on gaseous fueled vehicles, or whether special designs are needed.

9.4. Further research is needed on the automatic dual-fuel concept in order to determine how to obtain the maximum number of clean vehicle miles with a minimum amount of gaseous fuel.

It was impossible to make any precise estimate of the reduction in gas fuel consumption obtainable with automatic dual-fuel use because of a lack of detail fuel consumption and emission data for each mode of a representative driving cycle — particularly for gaseous fuels. These data should be obtained and a detailed analysis made to estimate the practicality of such dual fuel operation.

This is potentially a very valuable technique for achieving the extremely low levels of emissions being projected for the future while at the same time conserving the use of the cleaner fuels as much as possible.

9.5. A need exists for odorants that can be used in LNG in the same manner as in natural gas.

The gas industry currently does not have a strong incentive to develop odorants for LNG since in utility operations LNG is always in the custody of a utility company and the revaporized gas is odorized before distribution. However, in automotive use LNG would be widely distributed and leakage from vehicles and service stations would not be readily detectable unless a means is developed to add some identifying odor to LNG. It is not a simple problem because of the wide range of temperatures involved. A number of schemes have been proposed but none has been carried far enough to demonstrate feasibility.

9.6. It is recommended that more experimental work be done in measuring the pollution level from gas vehicles as a function of engine characteristics and modifications.

During the study much of the data reported on gas vehicles emissions proved to be of little value because they could not be correlated with specific engine characteristics. Test conditions varied widely and some significant parameters were not reported. The inability to compare the data taken on earlier test methods with the results of more recent measurements has made it difficult to compile comparable data that would indicate the effect of specific engine characteristics and modifications of gas engines on pollution levels. Thus, there is a need for standardization of reporting practices as well as the development of some method of correlating earlier test results with data taken using the new method of measurement. It is recommended that additional data be solicited on the operating characteristics of gas and LPG engines.

The data reported in the literature on operating characteristics of gas-fueled engines are less than anticipated. While there are several reasons for this situation, the fact remains that information of this kind is necessary in order to determine the engine operating conditions which will minimize harmful exhaust emissions without penalizing the operating performance of the engine.

This work would be a necessary prerequisite to the project recommended in 9.2.

9.7. It is recommended that additional test data be taken on commercial and industrial fleet vehicles to provide comparable emission data on various types of power plants and vehicle operations.

Virtually no data are available on emissions from trucks, buses, and other fleet vehicle operations that would provide a basis for comparison of one type of power plant with another. Such information, if made generally available, would provide a basis for selection of fleet vehicle power plants on the basis of pollution control as well as vehicle performance.

9.8. It is recommended that a survey be made of European experience in gas-fueled vehicles, particularly in France and Italy.

Natural gas has been used in automotive vehicles in France and Italy for many years. The relatively high cost of automotive fuels in Europe causes greater concern for fuel efficiency and economy in the operation of motor vehicles. Thus, there is not only background of experience in this area, but this experience should be oriented toward the economical operation of gaseous-fueled vehicles. Therefore, a survey of vehicle users and equipment manufacturers in Europe might be a rewarding investigation.

In addition to the technical and economic problems uncovered during the study, a number of problems relating to logistics require further investigation. The more important questions are discussed below:

9.9. It is recommended that additional urban areas besides New York City be examined to determine the potential of gaseous fuels to reduce overall pollution levels in other local urban areas.

It was noted in the study of the New York City area that of the three gaseous fuels considered — propane, compressed natural gas, and LNG — that LNG offers the easiest solution to the problem of logistic supply in the New York City area. It is anticipated that similar studies of other urban areas might show that LPG and, in some areas compressed natural gas, may offer the best solutions depending upon the relative availability of these fuels in individual geographic areas.

9.10. It is recommended that further studies be made of the feasibility of increasing the yield of propane from oil refineries at the expense of gasoline production and the resultant effects upon cost of both fuels and upon their distribution expense.

The possibility of converting gasoline production to propane production at some increase in the cost of propane is the most promising possibility for replacing gasoline as a motor fuel if that were to become necessary to eliminate automotive pollution. Because of this, we believe that it is very desirable to undertake further investigations of this potentially important question. The comments that have been made in this report are based upon the review of a relatively limited amount of information on this subject plus the results of interviews with knowledeable people in the industry. There does not appear to be any publicly available detailed examination of this question.

9.11. There is a need to examine in more detail the availability and potential price of liquefied petroleum gas imported into the United States from overseas.

This subject is discussed briefly in the report, but relatively little information exists on this subject primarily because until the recent energy shortage developed, the United States has been an exporter of propane overseas and there has been little need to import supplies except from Canada.

10. REFERENCES CITED

1. Adams, W. E. and Boldt, K., "What Engines Say About Propane Fuel Mixtures," *S. A. E. Trans.* *73*, 718-42 (1965).

2. Agnew, W. G., "Future Emission-Controlled Spark-Ignition Engines and Their Fuels," *Proc. Amer. Petrol. Inst.* *49* Section 3, 242-80 (1969).

3. Alperstein, M., Swim, W. B. and Schweitzer, P. H., "Fumigation Kills Smoke — Improves Diesel," *S. A. E. Trans.* *66*, 574-95 (1958).

4. Altshuller, A. P. et al., "Photochemical Reactivity of n- Butane and Other Paraffinic Hydrocarbons," *J. Air Pollut. Contr. Ass.* *19*, 787-90 (1969) October.

5. Altshuller, A. P. et al., "Products and Biological Effects From Irradiation of Nitrogen Oxides With Hydrocarbons or Aldehydes Under Dynamic Conditions," *Air Water Pollut. Int. J.* *10*, 81-94 (1966).

6. "And Now — What of the Decade Ahead," *Butane-Propane News* 21-29 (1970) January.

7. Bachman, W. A., "Forecast for the Seventies," *Oil Gas J.* *67*, 160-175 (1969) November 10.

8. Baker Sr., R. A. and Doerr, R. C., "Catalytic Reduction of Nitrogen Oxides in Automobile Exhaust," *J. Air Pollut. Contr. Ass.* *14*, 409-14 (1964) October.

9. Balgord, W. D., "Novel Catalysts and Catalyst Supports for Control of NO_x in Automobile Exhaust." Paper presented at the 2nd Int. Clean Air Congress, Washington, D. C., December 1970.

10. Bartholomew, E., "Potentialities of Emission Reduction by Design of Induction Systems," *S. A. E. Paper No. 660109* (1966).

11. Bartok, W. et al., "Systems Study of Nitrogen Oxide Control Methods for Stationary Sources," *Final Report GR-2-NOS-69* Vol. *2*, 3-63. Contract No. *PH-22-68-55* for the Division of Process Control Engineering, National Air Pollution Control Administration. Esso Research and Engineering Company, Government Research Laboratory, November 1969.

12. Bascom, R. C. and Hass, G. C., "A Status Report on the Development of the 1973 California Diesel Emissions Standards," *S. A. E. Paper No. 700671* (1970).

13. Bascunana, J. L. and Conta, L. D., "Further Research on Charge Stratification," S. A. E. Paper No. 660095 (1966).

14. Battigelli, M. C., "Air Pollution From Diesel Exhaust," J. Occup. Med. 5, 54-57 (1963) January.

15. Baudry, J., "Some Recent Results Concerning the Reduction of Pollution by the Stratified Charge I. F. P. Process." S. A. E. Trans. 74, 662-72 (1966).

16. Baxter, M. C., "LP-Gas — A Superior Motor Fuel," S. A. E. Paper No. 670054 (1966).

17. Baxter, M. C., Leck III, G. W. and Mizelle, P. E., "Total Emission Control Possible With LP-Gas Vehicle," S. A. E. Paper No. 680529 (1968).

18. Benson, J. D., "Reduction of Nitrogen Oxides in Automobile Exhaust," S. A. E. Paper No. 690019 (1969).

19. Blalock, W. S. and Little, R. N., "Carburetion and Other Factors Which Affect Propane-Fueled Engines," S. A. E. Paper No. 670058 (1966).

20. Boldt, K., "Motor (LP) Knock Test Method Development," Paper No. 670055 in S. A. E. Trans. 75, (1968)

21. Bolt, J. A. and Harrington, D. L., "The Effect of Mixture Motion Upon the Lean Limit and Combustion of Spark-Ignited Mixtures," S. A. E. Paper No. 670467 (1967).

22. Bonamassa, F. and Wong, H. W., "Composition and Reactivity of Exhaust Hydrocarbons From 1966 California Cars." Paper presented at the 152nd National ACS Meeting, New York, September 1966.

23. Boyce, T. R., Karim, G. A. and Moore, N. P. "An Experimental Investigation Into the Effect of the Addition of Partially Oxidized Reaction Products to the Intake Charge of a Compression Ignition Engine," J. Inst. Petrol. 52, 300-11 (1966) October.

24. Broering, L. C., Rose Jr., A. H. and Werner, W. J., "Automotive Mass Emission Analysis by A Variable Dilution Technique." Paper presented at the APCA Annual Meeting, Cleveland, June 1967.

25. Brown, W. J. et al., "Effect of Engine Intake-Air Moisture on Exhaust Emission," S. A. E. Paper No. 700107 (1970).

26. Brownson, D. A. and Stebar, R. F., "Factors Influencing the Effectiveness of Air Injection in Reducing Exhaust Emissions," Pt. 2 "Vehicle Emissions," S. A. E. Progr. Technol. 12 (1967).

27. Brubacher, M. L., "Reduction of Diesel Smoke in California," S. A. E. Paper No. 660548 (1966).

28. Bull, M. G., "Development of an Ammonia-Burning Gas Turbine Engine," U. S. Army Eng. Res. Develop. Lab. Rep. AD-671-667. Fort Belvoir, Va., April 1968.

29. Cabal, A. V., Felt, A. E. and Williams, Jr., H. A., "Performance of Leaded LP-Gas in an EMD-567 Dual-Fuel Engine," S. A. E. Paper No. 763A (1963).

30. California Department of Public Health, Technical Report of California Standards for Ambient Air Quality and Motor Vehicle Exhaust. Sacramento, Calif., 1960.

31. California Motor Vehicle Pollution Control Board, California Test Procedure and Criteria for Motor Vehicle Emission Control. Los Angeles, 1964.

32. Campau, R. M. and Neerman, J. C., "Continuous Mass Spectrometric Determination of Nitric Oxide in Automotive Exhaust," S. A. E. Paper No. 660116 (1966).

33. Cantwell, E. N. and Pahnke, A. J., "Design Factors Affecting the Performance of Exhaust Manifold Reactors," Pt. 2 "Vehicle Emissions," S. A. E. Progr. Technol. 12 (1967).

34. Chandler, J. M., Struck, J. H. and Voorhies, W. J., "The Ford Approach to Exhaust Emission Control," S. A. E. Paper No. 660163 (1966).

35. Cole, D. E. and Jones, C., "Reduction of Emissions From the Curtiss-Wright Rotating Combustion Engine With an Exhaust Reactor," S. A. E. Paper No. 700074 (1970).

36. Colucci, J. M. and Barnes, G. J., "Evaluation of Vehicle Exhaust Gas Odor Intensity Using Natural Dilution," S. A. E. Paper No. 700105 (1970).

37. Cornelius, W., Huellmantel, L. W. and Mitchell, H. R., "Ammonia as an Engine Fuel," S. A. E. Trans. 74, 29-44 (1966).

38. Daniel, W. A., "Engine Variable Effect on Exhaust Hydrocarbon Composition (A Single-Cylinder Engine Study With Propane as the Fuel)," S. A. E. Paper No. 670124 (1967).

39. Daniel, W. A., "Why Engine Variables Affect Exhaust Hydrocarbon Emission," S. A. E. Paper No. 700108 (1970).

40. Davis, S. J., "Instruction in Internal Combustion Engines," Proc. Inst. Mech. Eng. 178, No. 26, 719-40 (1963-64).

41. Deeter, W. F., Daigh, H. D. and Wallin, Jr., O. W., "An Approach for Controlling Vehicle Emissions," S. A. E. Paper No. 680400 (1968).

42. Dual Fuel Systems, Inc., Fact Sheet, n. d.

43. Duckstein, L., Tom, M. and Beard, L. L., "Human and Traffic Control Factors in Autombotive Exhaust Emission," S. A. E. Paper No. 680398 (1968).

44. Dunne, J., "Ford's New Smog-Free Engine," Pop. Sci. 55-57 (1970) May.

45. "Du Pont's Exhaust-Manifold Thermal Reactor System" Oil Gas J. 68, 102 (1970) June.

46. Ebersole, G. D., "Hydrocarbon Reactivities of Motor Fuel Evaporation Losses," S. A. E. Paper No. 690089 (1969).

47. Edwards, J. B. and Teague, D. M., "Unraveling the Chemical Phenomena Occurring in Spark-Ignition Engines," S. A. E. Paper No. 700489 (1970).

48. El-Mawala, A. G. and Mirsky, W., "Hydrocarbons in the Partial Quench Zone of Flames: An Approach to the Study of the Flame Quenching Process," S. A. E. Paper No. 660112 (1966).

49. Elston, J. C., Andreath, A. J. and Milask, L. J., "Reduction of Exhaust Pollutant Through Automotive Inspection Requirement — The New Jersey Repair Project." Paper presented at the 2nd Int. Clean Air Congress, Washington, D. C., December 1970.

50. Eltinge, L. et al., "Emission Control Requires Good Carburetion and Other Engine Modifications," S. A. E. J. 76, 28-42 (1968) September.

51. Eltinge, L., Marsee, F. J. and Warren, A. J., "Potentialities of Further Emission Reduction by Engine Modifications," S. A. E. Paper No. 680123 (1968).

52. Eyzat, P. and Guibet, J. C., "A New Look at Nitrogen Oxides Formation in Internal Combustion Engines," S. A. E. Paper No. 680124 (1968).

53. Farrar, G. L., "Gas-Liquids Production Up Sharply," Oil Gas J. (1970) July 13.

54. Felt, A. E. and Steele, Jr., W. A., "Combustion Control in Dual-Fuel Engines," S. A. E. Paper No. 437B (1961).

55. Fitch, R. E. and Kilgroe, J. D., "Investigation of a Substitute Fuel to Control Automotive Air Pollution," Final Report of Consolidated Engineering Technology Corporation to National Air Pollution Control Administration. NAPCA Contract CPA-22-69-70, Washington, D. C., February 1970.

56. Fleming, R. D., Allsup, J. R. and Hurn, R. W., "Propane as an Engine Fuel for Clean Air Requirement. Part 1 — A Progress Report." Paper presented at the LP-Gas Engine Fuel Symposium, Detroit, October 1970.

57. Floyd, C. M., "A Comparison of the Performance of Highly Detergent Oils and Highly Dispersant Oils in Natural Gas Engines." S. A. E. Paper No. 680761 (1968).

58. Ford, H. S., Merrion, D. F. and Hames, R. J., "Reducing Hydrocarbons and Odor in Diesel Exhaust by Fuel Injector Design," S. A. E. Paper No. 700734 (1970).

59. Ford, S., Detroit Diesel Div., General Motors Corp., private communication, September 1, 1970.

60. Fox, C. and Peyton, J., Marvel-Schebler Div., Borg-Warner Corp., private communication, December 16, 1970.

61. Fox, C. D., "LPG- 'Torque-Topper' Development," Report No. 4022023 Marvel-Schebler Div., Borg-Warner Corp. (1966) December.

62. Galster, G. M. and Pigott, J. S., "Some Effects of Altitude on LP-Gas Tractor Operation," Paper No. 670057 in S. A. E. Trans. 75, (1968).

63. Garwin, L., "LP-Gas Supplies for the Engine Fuel Market." Paper presented at LP-Gas Engine Fuel Symposium, October 21-22, 1970.

64. Gerstein, M. et al., "Flame Propagation: II. The Determination of Fundamental Burning Velocities of Hydrocarbons by a Revised Tube Method," J. ACS 73, 418-22 (1851) January.

65. Gilbert, L. F. et al., "Oxide of Nitrogen in Engine Exhaust Gas." Paper presented at 132nd A. S. E. Meeting, September 1957.

66. Glass, W., Kim, D. S. and Kraus, B. J., "Synchrothermal Reactor System for Control of Automotive Exhaust Emissions," S. A. E. Paper No. 700147 (1970).

67. Glass, W. et al., "Evaluation of Exhaust Recirculation for Control of Nitrogen Oxide Emissions," S. A. E. Paper No. 700146 (1970).

68. Glasson, W. A. and Tuesday, C. S., "Hydrocarbon Reactivity and the Kinetics of the Atmospheric Photooxidation of Nitric Oxide." Paper presented at the 59th Annual Air Pollution Control Association Meeting, San Francisco, June 1966.

69. GMC Truck & Coach Div., General Motors Corp., A Proposal to Reduce Exhaust Emission and Decrease Vehicle Noise From Existing Diesel Coaches. Detroit, 1970.

70. Golothan, D. W., "Diesel Engine Exhaust Smoke: The Influence of Fuel Properties and the Effect of Using Barium-Contining Fuel Additive," S. A. E. Paper No. 670092 (1967).

71. Graiff, L. B., Legale, C. E. and Robinson, I. C. H., "A Fast-Response Flame Ionization Detector for Exhaust Hydrocarbons," S. A. E. Paper No. 660117 (1966).

72. Gray, Jr., J. T. et al., "Ammonia Fuel — Engine Compatibility and Combustion," S. A. E. Paper No. 660156 (1966).

73. Groth, R. H. and Calabro, D. S., "Evaluation of Saltzman and Phenoldisulfonic Acid Methods for Determining NO_x in Engine Exhaust Gas," J. Air Pollut. Contr. Ass. 19, 884-87 (1969) November.

74. Hahn, A. V., Petrochemical Industry Market and Economics, 33-39. New York: McGraw-Hill 1970.

75. Hardison, L. C., "Techniques for Controlling the Oxides of Nitrogen," J. Air Pollut. Contr. Ass. 20, 377-82 (1970) June.

76. Harkins, J. and Goodwine, J. K., "Oxides of Nitrogen in Diesel Exhaust," J. Air Pollut. Contr. Ass. 14, No. 1, 34-37 (1964) January.

77. Harris, W. L. and Hummel, J. W., "Effects of Inlet-Air Temperature and Humidity on Performance of an LP-Gas Engine." Paper No. 670056 in S. A. E. Trans. 75, 1968.

78. Hittler, D. L. and Hamkins, L. R., "Emission Control by Engine Design and Development." S. A. E. Paper No. 680110 (1968).

79. Huls, T. A. and Nickols, H. A., "Influence of Engine Variables on Exhaust Oxides of Nitrogen Concentrations From a Multi-Cylinder Engine," S. A. E. Paper No. 670482 (1967).

80. Huls, T. A., Myers, P. S. and Uyehara, O. A. "Spark-Ignition Engine Operation and Design for Minimum Exhaust Emission," S. A. E. Paper No. 660405 (1966).

81. Institute of Gas Technology, Seminar on Natural-Gas-Fueled Vehicles (December 4, 1969) Chicago, 1970.

82. Jackson, M. W., "Effects of Some Engine Variables and Control Systems on Composition and Reactivity of Exhaust Hydrocarbons," S. A. E. Paper No. 660404 (1966).

83. Jackson, M. W. and Nebel, G. J., "Some Factors Affecting the Concentration of Oxides of Nitrogen in Automobile Exhaust Gases," J. Air Pollut. Contr. Ass. 8, 213-19 (1958) November.

84. Johnson, D. R., "Free World Supply/Demand of LP-Gas and Natural Gas." NLPGA Times, 18-21 (1969) Summer.

85. Kaleskas, E. W., "Performance of a Low-Emission Vehicle Operating on Propane." Paper presented at the LP-Gas Engine Fuel Symposium, Detroit, October 1970.

86. Karim, G. A., "The Ignition of a Premixed Fuel and Air Charge by Pilot Fuel Spray Injection With Reference to Dual-Fuel Combustion," S. A. E. Paper No. 680768 (1968).

87. Karim, G. A., "On the Emission of Carbon Monoxide and Smoke From Compression Ignition Engines: Including Natural Gas-Fueled Engines." Paper presented at the 2nd Int. Clean Air Congress, Washington, D. C., December 1970.

88. Kaufman, F. and Kelso, J. K., "Thermal Decomposition of Nitric Oxide," J. Chem. Phys. 23, 1702-07 (1955) September.

89. Khan, J. M., "Formation and Combustion of Carbon in a Diesel Engine," S. A. E. Paper No. 700735 (1970).

90. Klosterman, D. L. and Sigsby, Jr., J. E., "Application of Subtractive Techniques to the Analysis of Automotive Exhaust." Presented at the National ACS Meeting, Atlantic City, September 1965.

91. Kopa, R. D., "Control of Automotive Exhaust Emission by Modification of the Carburetion System," S. A. E. Paper No. 660114 (1966).

92. Kiuvanen, G. J., Westra, R. O. and Lien, D. G., "Engine-Fuel Relationships With LPG and Natural Gas," S. A. E. Paper No. 670054 (1966).

93. Landen, E. W., "Nitrogen Oxides and Variables in Precombustion Chamber Type Diesel Engines," S. A. E. Paper No. 714B (1963).

94. Lee, J. J., "Ammonia Line Has Unusual Features," Oil Gas J. 66, 103-108 (1968) November 4.

95. Lee, R. C. and Wimmer, D. B., "Exhaust Emission Abatement by Fuel Variations to Produce Lean Combustion," S. A. E. Paper No. 680769 (1968).

96. Levedahl, W. J., "Multistage Autoignition of Engine Fuels," Fifth Symposium (Int.) on Combustion, 372-85, Reinhold 455.

97. Linden, H. R., "U. S. Natural Gas Supply and Demand," Public Util. Fortn. 81, 13-18 (1968) February 1.

98. Linnell, R. H. and Scott, W. E., "Diesel Exhaust Composition and Odor Studies," J. Air Pollut. Contr. Ass. 12, 510-14, 545 (1962) November.

99. Littler, D. L. and Hamkins, L. R., "Emission Control by Engine Design and Development," S. A. E. Paper No. 680110 (1968).

100. "LP-Gas Industry Future Up to Refiners," Oil Gas J. 68, 40-41 (1970) May 18.

101. Maga, J. A. and Hass, G. C., "Present and Future Emission Standards for Heavy-Duty Vehicles," S. A. E. Paper No. 690765 (1969).

102. Maga, J. A. and Kinosian, J. R., "Motor Vehicle Emission Standards Present and Future," S. A. E. Paper No. 660104 (1966).

103. Manning, J., Stewart & Stevenson Services, Inc., private communication and letter of September 17 and December 16, 1970.

104. Marshall, W. F. and Hurn, R. W., "Factors Influencing Diesel Emissions," S. A. E. Paper No. 680528 (1968).

105. Matsumoto, K., Toda, T. and Nohira, H., "Oxides of Nitrogen From Smaller Gasoline Engine," S. A. E. Paper No. 700145 (1970).

106. McConnell, G., "Oxide of Nitrogen in Diesel Engine Exhaust Gas: Their Formation and Control," Proc. Inst. of Mech. Engrs. 178, Pt. I, No. 38, 1001-13 (1963-64).

107. McJones, R. W. and Corbeil, R. J., "Natural Gas-Fueled Vehicles Exhaust Emission and Operational Characteristics," S. A. E. Paper No. 700078 (1970).

108. McLaughlin, E. J., Pinotti, P. L. and Sigworth, H. W., "Power Booster Fuels for Diesel Engines." Paper presented at the S. A. E. Natural Fuels and Lubricants Meeting, Chicago, October 1951.

109. Mehne, J. T. and Carufel, L. D., "LP-Gas Engines for the 1970's." Paper presented at the LP-Gas Engine Fuel Symposium, Detroit, October 1970.

110. Mengelkamp, R. A. and Hudson, A. C., "LP-Gas Fuel System Affects Engine Performance," Paper No. 670052 in S. A. E. Trans. 75, (1968).

111. Merrion, D. F., "Effect of Design Revisions on Two-Stroke Cycle Diesel Engine Exhaust," S. A. E. Paper No. 680422 (1968).

112. Merrion, D. F., Detroit Diesel Div., General Motors Corp., private communication, December 16, 1970.

113. Meurer, J. S., and Urlaub, A., "Man Modified M Combustion System Burns Any Grade of Gasoline Efficiently and Without Knock," S. A. E. J. 77, 36-41 (1969) June.

114. Mick, S. H. and Clark, Jr., J. B., "Weighting Automotive Exhaust Emissions," S. A. E. Paper No. 690523 (1969).

115. Minkoff, G. J. and Tipper, C. F. H. Chemistry of Combustion Reactions, 3, 153. London: Butterworths, 1962.

116. Milks, D. et al., "Studies and Analysis of Diesel Engine Odor Production." Paper presented at the 2nd Int. Clean Air Congress, Washington, D. C., December 1970.

117. Miller, C. O., "Diesel Smoke Suppression by Fuel Additive Treatment," S. A. E. Paper No. 670093 (1967).

118. Moody's Investors Service, Inc., Moody's Public Utility Manual. New York, 1970.

119. Mrochek, J. E., "The Economics of Hydrogen and Oxygen Production by Water Electrolysis and Competitive Processes," in Abundant Nuclear Energy. U. S. Atomic Energy Commission Rep. No. CONS-680810. Oak Ridge, Tenn.; Oak Ridge National Laboratory, 1969.

120. National Energy Board of Canada, Annual Report: Energy Supply and Demand in Canada and Export Demand for Canadian Survey. Ottawa, 1969.

121. "New Engines are Designed for Use of Natural Gas," Prod. Eng., 62-4 (1970) March 2.

122. Newhall, H. K., "Control of Nitrogen Oxides by Exhaust Recirculation — A Preliminary Theoretical Study," S. A. E. Paper No. 670495 (1967).

123. Newhall, H. K., "Kinetics of Engine Generated Nitrogen Oxide and Carbon Monoxide," in Proceedings of the 12th Int. Symposium on Combustion, 603, Pittsburgh: Combustion Institute (1969).

124. Newhall, H. K. and El Messiri, I. A., "A Combustion Chamber Designed for Minimum Engine Exhaust Emissions," S. A. E. Paper No. 700491 (1970).

125. Newhall, H. K. and Starkman, E. S., "Direct Spectroscopic Determination of Nitric Oxide in Reciprocating Engine Cylinders," S. A. E. Paper No. 670122 (1967).

126. New York City Department of Air Resources, information supplied to the Institute of Gas Technology, August 1970.

127. "New York State Motor Vehicle Emission Program," Final Report. Division of Motor Vehicles, Department of Air Resources, City of New York, August 1968.

128. Nichols, J. E., El Messiri, I. A. and Newhall, H. K., "Inlet Manifold Water Injection for Control of Nitrogen Oxides — Theory and Experiment," S. A. E. Paper No. 690018 (1969).

129. 1968 LP-Gas Market Facts, National LP-Gas Association. Chicago, 1969.

130. 1970 National Petroleum News Factbook Issue. New York: McGraw-Hill, May 1970.

131. Pahnke, A. J. and Conte, J. F., "Effect of Combustion Chamber Deposits and Driving Conditions on Vehicle Exhaust Emissions," S. A. E. Paper No. 690017 (1969).

132. Papa, L. J., "Gas Chromatography — Measuring Exhaust Hydrcarbons Down to Parts Per Billion," S. A. E. Paper No. 670494 (1967).

133. Patterson, D. J., "Cylinder Pressure Variations, A Fundamental Combustion Problem," S. A. E. Paper No. 660129 (1966).

134. Pattison, J. N. et al., "New Jersey's Rapid Inspection Procedures for Vehicular Emissions," S. A. E. Paper No. 680111 (1968).

135. Pearsall, T. J. and Garabedian, C. G., "Combustion of Anhydrous Ammonia in Diesel Engine," S. A. E. Paper No. 670947 (1967).

136. Pecsok, D. A., "News Release — Pollution Emission Results." St. Louis County Health Department, Clayton, Mo., June 1970.

137. Perez, J. M. and Landen, E. W., "Exhaust Emission Characteristics of Precombustion Chamber Engines," S. A. E. Paper No. 680421 (1968).

138. Pratt, D. T. and Starkman, E. S., "Gas Turbine Combustion of Ammonia," S. A. E. Paper No. 670938 (1967).

139. "Propane Demand Will Outrun Supply," Oil Gas J. 68, 44 (1970) March 2.

140. Quick, S. L. and Kittredge, G. K., "Control of Vehicular Air Pollution Through Modifications to Conventional Power Plants and Their Fuels." Paper presented at the 2nd Int. Clean Air Congress, Washington, D.C., December 1970.

141. Reid, R. S., Mingle, J. G. and Paul, W. H., "Oxides of Nitrogen From Air Added in Exhaust Ports," S.A.E. Paper No. 660114 (1966).

142. Robinson, E. and Robbins, R. C., "Sources, Abundance, and Fate of Gaseous Atmospheric Pollutants," American Petroleum Institute Final Report SRI Project PR-6755, 69, 99. Huntsville, Ala.: Stanford Research Institute, February 1968.

143. Robison, J. A., "Humidity Effect on Engine Nitric Oxide Emissions at Steady-State Conditions," S.A.E. Paper No. 700467 (1970).

144. Santo, J. O., Fagley, W. S. and Hunter, W. A., "Chrysler Evaporation Control System; The Vapor Saver for 1970," S.A.E. Paper No. 700150 (1970).

145. Sawyer, R. F. et al., "Oxides of Nitrogen in the Combustion Products of an Ammonia Fueled Reciprocating Engine," S.A.E. Paper No. 680401 (1968).

146. Scheffler, C. E., "Combustion Chamber Surface Area, A Key to Exhaust Hydrocarbons," S.A.E. Paper 660111 (1966).

147. Schneider, H. T. and Tooker, R. S., "The 1970 General Motors Emission Control Systems," S.A.E. Paper No. 700149 (1970).

148. Schwing, R. C., "An Analytic Framework for the Study of Exhaust Manifold Reactor Oxidation," S.A.E. Paper 700109 (1970).

149. Schwochert, H. W., "Performance of a Catalytic Converter on Unleaded Fuel," S.A.E. Paper 690503 (1969).

150. Shelef, M., Otto, K. and Gandhi, H., "The Heterogeneous Decomposition of Nitric Oxide on Supported Catalysts," Atmos. Environ. 3, Pergamon Press, 107-22 (1969).

151. Sigsby, Jr., J. E. and Rose, Jr., A. H., "Evaluation of a Subtractive Method in Auto Exhaust Analysis." Presented at the National ACS Meeting, New York, September 1966.

152. Sneed, M. C. and Brasted, R. C., Comprehensive Inorganic Chemistry. Princeton, N.J.: D. Van Nostrand, 1956.

153. Spindt, R. S. et al., "Nitrogen Oxides, Combustion and Engine Deposits," S.A.E. Trans. 64, 797 (1956).

154. Squibb, C. E., "An Observation by a Carburetion Equipment Manufacturer and Distributor." Paper presented at the LP-Gas Engine Fuel Symposium, Detroit, October 1970.

155. Stahman, R. C., Kittredge, G. D. and Springer, K. L., "Smoke and Odor Control for Diesel-Powered Trucks and Buses," S.A.E. Paper No. 680443 (1968).

156. Starkman, E. S. and Newhall, H. K., "Characteristics of the Expansion of Reactive Gas Mixtures as Occurring in Internal Combustion Engine Cycles," Paper No. 650509, S.A.E. Trans. 74, (1966).

157. Starkman, E. S. and Newhall, H. K., "Thermodynamic Properties of Methane and Air, and Propane and Air for Engine Performance Calculation," S.A.E. Paper No. 670466 (1967).

158. Starkman, E. S. et al., "Ammonia as a Spark-Ignition Engine Fuel: Theory and Application," S.A.E. Paper No. 660155 (1966).

159. Starkman, E. S. et al., "Alternative Fuels for Control of Engine Emission," J. Air Pollut. Contr. Ass. 20, 87-92 (1970) February.

160. Steffensen, R. J., Agnew, J. L. and Olsen, R. H., "Combustion of Hydrocarbons Property Table," Engineering Bulletin of Purdue University, Eng. Extension Series 122. Lafayette, Ind., May 1966.

161. Swartz, D. N., Wilson, K. W. and King, W. J., "Merits of Liquefied Petroleum Gas Fuel for Automotive Air Pollution Abatement," Report Nos. 61-55, Los Angeles: University of California, August 1961.

162. Sweeney, N., "Here's What Users Pay for Ammonia," Hydrocarbon Process. 47, 265-268 (1968) September.

163. Taylor, R. E. and Campau, R. M., "The IIEC — A Cooperative Research Program for Automotive Emission Control," Proc. Amer. Petrol. Inst. 49, 309-27 (1969).

164. Teague, D. M., Lesniak, Jr., E. J. and Loeser, E. H., "A Recommended Flame Ionization Detector Procedure for Automotive Exhaust Hydrocarbons," S. A. E. Paper No. 700468 (1970).

165. Thomas, H. R. and Grothusen, H. D., "LP-Gas Sales far Outstrip Production in Setting New Records in 1969," Butane-Propane News (1970) January.

166. Thomas, H. R. and Wetzel, O. K., "Propane Supply and Demand." Panel presentation presented at National LP-Gas Association Convention, May 3-6, 1970.

167. Thomson, J. C., "NAPCA Findings on Gaseous Fuels." Paper presented at the LP-Gas Engine Fuel Symposium, Detroit, October 1970.

168. U. S. Bureau of Census, Inorganic Chemicals and Gases Summary for 1968. Washington, D. C.: U. S. Department of Commerce, 1969.

169. U. S. Department of Health, Education, and Welfare, "Control of Air Pollution From New Motor Vehicles and New Motor Vehicle Engines," Federal Register 31, No. 61 (1966) March.

170. U. S. Department of Health, Education, and Welfare, "Control of Air Pollution From New Motor Vehicles and New Motor Vehicle Engines," Federal Register 33, No. 2 (1968) January.

171. U. S. Department of Health, Education, and Welfare, "Control of Air Pollution From New Motor Vehicles and New Motor Vehicles Engines," Federal Register- Part III 35, No. 219, 17,288-313 (1970) November.

172. U. S. Office of Business Economics, Surv. Curr. Bus. 50, No. 11. Washington, D. C.: U. S. Department of Commerce, November 1970.

173. U. S. Public Health Service, Environmental Health Service, National Air Pollution Control Administration, Air Quality Criteria for Carbon Monoxide. Washington, D. C.: U. S. Department of Health, Education, and Welfare, 1970.

174. U. S. Public Health Service, Environmental Health Service, National Air Pollution Control Administration, Control Techniques for Carbon Monoxide, Nitrogen, and Hydrocarbon Emissions From Mobile Sources. Washington, D. C.: U. S. Department of Health, Education, and Welfare, 1970.

175. U. S. Public Health Service, Environmental Health Service, National Air Pollution Control Administration, Control Techniques for Particulate Air Pollutants, AP-51. Washington, D. C.: U. S. Department of Health, Education, and Welfare, 1970.

176. Walsh, A. D., "The Knock Rating of Fuels." Ninth Int. Symposium on Combustion, 1046-55. Academic Press, 1963.

177. Wentworth, J. T., "Piston and Ring Variables Affect Exhaust Hydrocarbon Emissions," S. A. E. Paper No. 680109 (1968).

178. Wimmer, D. B. and McReynold, L. A., "Nitrogen Oxides and Engine Combustion," S. A. E. Paper No. 380E (1951).

179. Wise, H. and Frech, M. F., "Kinetics of Decomposition of Nitric Oxide at Elevated Temperatures, I. Rate Measurement in a Quartz Vessel," J. Chem. Phys. 20, 1724 (1952).

180. Witzky, J. E. and Clark, Jr., J. M., "A Study of the Swirl Stratified Combustion Principle," S. A. E. Paper No. 660092 (1966).

181. Yagi, S. et al., "A Study in the Development of Exhaust Emission Controls for Small Displacement Honda Engines," S. A. E. Paper No. 680527 (1968).

182. Yumlu, V. S. and Carey, Jr., A. W., "Exhaust Emission Characteristics of Four-Stroke, Direct Injection, Compression Ignition Engines," S. A. E. Paper No. 680420 (1968).

183. Agnew, J. T., "Unburned Hydrocarbons in Closed Vessel Explosions, Theory Vs. Experiment Applications to Spark-Ignition Engine Exhaust," S. A. E. Paper No. 670125 (1967).

184. Brinkman, W., "The Use of Natural Gas in Spark-Ignition Engines." Paper presented at the Institute of Marine Engineers, London, February 15, 1968.

185. Svoboda, E. J., "Exhaust Emissions on Fork Lift Applications — The Motivations, the Controls, the Benefits." Paper presented at the LP-Gas Engine Fuel Symposium, Detroit, October 1970.

186. Weil, N. A., Jenney, A. F. and Garrett, J. H., "Development of the New Family of Cummins Natural Gas Engines," ASME Publication 65-OGP-13 (1965).

8929

187. Hopkins, H. H., "Feasibility of Utilizing Gaseous Fuels for Reducing Emissions From Motor Vehicles," Environmental Protection Agency, Ypsilanti, Michigan.

188. "Profile of Air Pollution Control in Los Angeles County," Air Pollution Control District, January 1969.

189. "1969 LP - Gas Market Facts," National LP - Gas Association, 1970.

190. Murray, R. G. and Schoeppel, R. J., "Emission and Performance Characteristics of an Air-Breathing Hydrogen-Fueled-Internal Combustion Engine," unpublished information, 1971.

STANDARD TITLE PAGE FOR TECHNICAL REPORTS

1. Report No. APTD-0698

2. Govt. Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle Emission Reduction Using Gaseous Fuels for Vehicular Propulsion

5. Report Date June 1971

6. Performing Organization Code

7. Author(s)

8. Performing Organization Rept. No.

9. Performing Organization Name and Address
Institute of Gas Technology
3424 South State Street
IIT Center
Chicago, Illinois 60616

10. Project/Task/Work Unit No.

11. Contract/Grant No. EPA-APCO-70-69

12. Sponsoring Agency Name and Address
Air Pollution Control Office
Environmental Protection Agency
Cincinnati, Ohio 45227

13. Type of Report & Period Covered Final

14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstracts - The findings of a study are presented as they relate to each of the following objectives: 1. To provide a comprehensive vehicular pollution emissions by using gaseous fuels in commercially available engine systems. 2. To examine the logistics of gaseous fuels to assess the availability, cost, storage and handling methods and safety requirements of gaseous fuels. 3. To determine the feasibility of using natural gas as a supplementary fuel in a two stroke cycle, diesel powered intercity bus as a means of reducing exhaust pollution while operating in urban areas and bus terminals. 4. To recommend specific research and development programs necessary to confirm or establish the low emission characteristics and economic feasibility of selected gaseous fueled vehicular engine systems.

17. Key Words and Document Analysis. (a). Descriptors

Air pollution
Exhaust emissions
Ground vehicles
Internal combustion engines
Natural gas
Liquified natural gas
Availability
Natural resources
Fuel consumption
Fuel storage
Costs
Feasibility
Bus (vehicles)
Diesel engines
Urban areas

17b. Identifiers/Open-Ended Terms

Air pollution control

17c. COSATI Field/Group 13B

18. Distribution Statement Unlimited

19. Security Class (This Report) UNCLASSIFIED

20. Security Class. (This Page) UNCLASSIFIED

21. No. of Pages 268

22. Price

FORM NBS-867(1-70)

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Institute of Gas Technology
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IIT Center
Chicago, Illinois 60616

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