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ALCOHOL ASSISTED HYDROCARBON FUELS: A COMPARISON OF EXHAUST EMISSIONS AND FUEL CONSUMPTION USING STEADY-STATE AND DYNAMIC ENGINE TEST FACILITIES

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Abstract

This paper presents experimental data which exemplifies the differences in emission level testing on internal combustion engines when dynamic engine tests are used instead of steady-state engine tests. A comparison of the two test methods is made using hydrocarbon fuels with varying amounts of methanol. Emissions measured include the nitric oxides, unburned hydrocarbons and carbon monoxide. Emission levels and fuel consumption are reported for the various volumetric percentages of methanol in the fuel.

Of special significance are the different trends the emission levels establish when subjected to a dynamic engine test as compared to the results for the steady-state tests. Dynamic tests provide a realistic automobile simulation (accelerations and decelerations) while maintaining the laboratory testing accuracy.

1. SUMMARY

Results from the testing program indicate that methanol-gasoline fuels, with up to 15 percent methanol, have a slight decrease in the exhaust emissions CO, NO_x and unburned hydrocarbons. The higher concentrations of methanol further decrease the exhaust emissions but the engine begins to suffer from lean misfire. It is doubtful that the average motorist would accept the automobile's performance under these operating conditions.

Fuel consumption on a total energy usage basis remains unchanged. The methanol has approximately one-half the energy per unit volume which means the engine will consume a greater volume of fuel but the efficiency of the engine will remain constant.

Of prime interest to the motoring public is "Will it have any effect at the gas pump?" Economically the use of methanol stands as the most attractive alternative to gasoline. A 10 percent shortage of petroleum based gasoline could be alleviated with the mixing of 10 percent methanol. Presently technology is available to produce methanol from coal and available figures show methanol can be produced at a cost equivalent to gasoline (1).

2. INTRODUCTION

Considerable attention has been given in recent years to "alternative energy sources." Much of the attention has been to solve the mobile power requirements of a mobile America. Energy sources other than gasoline and diesel fuel have long been neglected because of the low cost and apparently limitless availability of these sources. The relatively recent realization of limitations on the availability of petroleum based fuels has created a flurry of interest and study of non-petroleum based fuels (2 - 9). Michael (2) has made a comparison of various synthetic fuels for use mentioning hydrogen as very attractive for the long term but handling problems dictate immediate attention to a liquid fuel. One suggestion with good potential is methanol or methyl alcohol. It has been predicted by Stiles (1)) that "In addition to using coal-based products in industry, it is my prediction that, within the next five years or so, all of us will be burning a little bit of alcohol in our cars. Within 10 to 15 years we might possibly see a large number of vehicles powered almost completely by methanol alone or in mixtures containing higher alcohols."

Studies of methanol as a fuel have tended to emphasize specific aspects of the fuel but have been limited in general application. As a result, apparently conflicting data have been published. For example, the study of Garrett and Wentworth (3) emphasized the study of methanol as a replacement for natural gas and fuel oil in industrial furnaces and gas turbines. Ebersole's study (4) concerned tests made only in a single-cylinder engine. The studies of Garrett and Wentworth and Ebersole showed lower NO_x concentrations as did an AEC synthetic fuel panel (5). Studies by Pefley (6) indicated no change in NO_x but a significant decrease in unburned hydrocarbons and carbon monoxide. Tests of methanol by Adelman (7) in a Gremlin automobile demonstrated the ability to meet all of the '75 - '76 federal standards. Tests by Lerner (8), using mixtures of gasoline and methanol on unmodified cars were tested and operated. Fuel economy increased by 5 to 13 percent, CO emissions decreased by 14 to 72 percent, and exhaust temperatures decreased from 1 to 9 percent. Acceleration of the automobile was also seen to increase by 7 percent. Conflicting results were obtained by Ninomiya (9) where up to 25 percent methanol was added to gasoline. The addition of the methanol showed no change in the concentration of carbon dioxide, carbon monoxide or nitric oxide. Ninomiya concluded that methanol-hydrocarbon blends do not reduce exhaust hydrocarbons when the engine is operated at a performance level comparable to the methanol-free blend.

3. TEST PLAN AND EQUIPMENT

The cause for the apparent conflicting data reported was attributed to the widely varying conditions of the investigations. A more controlled set of conditions would be necessary to remove the variations caused by manual operators. The test plan must include transient conditions for acceleration as well as steady state driving.

The requirements for an engine test facility can easily be established. A review of the literature, both popular and technical, would indicate the following criteria:

(1) instrumentation for economy and performance

(2) instrumentation for pollution evaluation and study

(3) capability to utilize liquid and gaseous fuels

(4) full manual operation for standard economy and performance testing

(5) capable of testing with accelerations and decelerations typical of actual driving cycles (for example, the California 7 mode cycle, the Federal cycle)

(6) capable of testing engines loaded as in typical vehicles including transmissions, equipment and loading.

The first criterion was established because even with pollution control, performance and economy are still important. In fact, loss of performance and economy with the addition of pollution controls has been a strong complaint of many automobile owners. The growing concern and emphasis on the "energy crisis" indicates not only a desire for economy but a distinct demand for conservation. The remaining criteria were required by the definition of the problem.

Test facilities have been largely concentrated in three types:

(1) dynamometer equipped engine cells with manual control for predominately steady state tests

(2) chassis dynamometer equipment where the full system is tested

(3) standard automobiles used in road tests.

Each of these facilities normally requires the manual control of an operator and one of them would furnish the type of control required for the experiment planned. A computer actuated control system appeared to have the desired features and the system was designed as shown in Figure 1. An EPI 118 minicomputer provides control with feedback from engine speed monitors and dynamometer load monitors. The minicomputer makes any adjustments to the throttle or dynamometer as necessary to bring the engine to the predetermined loading cycle being analyzed. The system is capable of laboratory engine tests for any predetermined loading cycle such as the Federal cycle, and the California 7 mode cycle. It has been shown that with the elimination of driver, vehicle, and chassis dynamometer, test reproducibility with respect to exhaust emissions and engine performance was significantly improved.

Exhaust emissions were measured with a four channel set of Beckman Infrared Analyzers. The exhaust gases of interest and those which can be monitored are NO_x, CO_2, CO and unburned hydrocarbons as N-hexane.

The outputs from the Beckman analyzer were recorded on a six channel brush recorder together with the engine speed and torque level from the dynamometer. Fuel consumption by the engine was measured by a separate weighing and timing device.

The test program was designed to use a conventional automobile engine. A 1970 Ford 302 CID engine as equipped for the general market vehicle was used.

4. COMPUTER CONTROLLED DRIVING CYCLES

The results given in this paper are for a driving cycle modified from the California 7 mode driving cycle. The California cycle is shown in Figure 2.

The first modification was to simplify the cycle by assuming that no shifting occurred so the simulated vehicle would always be operating in high gear. A rear end gear ratio of 3.7:1, and a tire size of H78 x 15 was used. The engine speed deviated from the ideal specified but the same cycle was repeated for each blend of fuel. Figure 3 shows the engine parameters as they vary throughout the modified cycle.

5. RESULTS

The information obtained on the recorder included the simultaneous plotting of the exhaust emission gases, NO_x, CO and unburned hydrocarbons along with the engine RPM and dynamometer torque. Figure 4 is a typical set of test data for the dynamic test runs. The exhaust gas results plotted on the chart are not the instantaneous values, as are the RPM and dynamometer torque, but are subject to a time delay of approximately seven seconds. This time delay is due to the exhaust having to move from the exhaust manifold through the exhaust piping and finally through the Beckman sampling tube.

Five different types of data points were taken from each test for each mixture of methanol and gasoline. These were called the "first acceleration" level, "second acceleration" level, "average power" level, "maximum power" level, and "gas bag" level. Each of these levels and their trends with increasing amounts of methanol are significantly different. An explanation of each of these levels and how they are measured follow.

Observation of the data in Figure 4 shows that during the acceleration and loading of the engine, the pollutants exhibit maximum values. The driving cycle is such that there are two acceleration periods and there corresponds two maximum pollution points.

The maximum pollution values at each of these acceleration periods are used for the "first acceleration" and the "second acceleration" levels.

To obtain a "gas-bag" analysis of the exhaust emissions the curves for instantaneous gas concentrations were integrated using a planimeter. This procedure gives an average concentration for the exhaust gases. The "average power" level was obtained while running the engine steady-state at the average power required for the entire modified California driving cycle. The "maximum power" level was that obtained when running the engine steady-state at the maximum power output needed during the cycle. The average power was 24 hp and the maximum was 47 hp. Concentrations of unburned hydrocarbons, carbon monoxide and nitric oxides as a function of methanol content for the tests are shown in Figures 5, 6, and 7 respectively. Volumetric fuel consumption for the two steady-state power levels and the dynamic tests are shown in Figure 8.

Trends established by the dynamic test results in Figures 5 through 8 indicate that, (1) the volumetric fuel consumption increases by 20 percent as the methanol content increases from 0 to 30 percent, (2) the maximum carbon-monoxide concentration decreases from 4 percent by volume to 1 percent by volume or a decrease of 75 percent when the methanol content is increased to 30 percent, (3) the maximum nitric-oxide concentration decreases by approximately 15 percent as the methanol content increases from 0 to 20 percent. The maximum nitric-oxide concentration then increases by 18 percent when the methanol content increases from 20 percent to 30 percent, (4) the maximum hydrocarbons concentrations exhibit different phenomena with the two accelerations. The first acceleration shows a slight decrease in the maximum concentration of unburned hydrocarbons as the methanol content increases from 0 to 5 percent but then an 80 percent increase is observed as the methanol content is increased from 5 to 30 percent. The maximum concentration during the second acceleration decreases approximately 10 percent while increasing the methanol content from 0 to 30 percent. The "gas bag" analysis shows (1) the unburned hydrocarbons to increase by 40 percent as the methanol fuel percentage is increased from 0 to 30 percent, (2) the carbon monoxide will decrease by 68 percent during the increase of methanol, and (3) the nitric oxides will decrease by 31 percent as the methanol content is raised from 0 to 30 percent.

The dynamic data presented in Figures 5 through 8 represent a total of 98 individual tests. The methanol content was varied in steps of 5 percent volumetric changes from 0 to 30 percent, thus giving 7 distinct data points. Each of these 7 data points represents the average of 14 tests performed at that particular methanol content.

From Figures 5 through 8, the data for the steady-state engine tests suggest the following trends: (1) The nitric oxides, carbon monoxide, and unburned hydrocarbons decrease 72 percent, 75 percent, and 40 percent, respectively, as the methanol content is increased from 0 percent to 40 percent for the 24 hp level; (2) The volumetric fuel consumption increases 20 percent for the same power level as the methanol content increases from 0 to 30 percent; (3) At the 47 hp level the nitric oxides, carbon monoxide, and unburned hydrocarbons decrease 69 percent, 84 percent, and 82 percent, respectively, as the methanol content increases from 0 to 40 percent; and (4) The fuel consumption increased on a weight basis from 7.5 to 9.4 oz/min or an increase of 20 percent as the methanol content increases from 0 to 30 percent.

6. DISCUSSION AND CONCLUSIONS

Explanation of the results shown previously require the use of two factors, the increase in the volumetric percentage of methanol in the fuel and secondly the effect the content of the methanol has on the air:fuel ratio. The theoretical air:fuel ratio for gasoline is 15.1, while that of methanol is 6.4. For the maximum volumetric percentage of methanol in the fuel, that being 30 percent, the theoretical fuel ratio will be 12.5. For equal steps between 0 and 30 percent, methanol content in the fuel, the theoretical air:fuel ratio will vary linearly from 15.1 to 12.5.

The carburetor used in the experiments was a standard model from Ford Motor Company and was jetted for use with paraffin fuels such as gasoline and was not adjusted to the specifications required by the alcohol fuels. Using this carburetor with the methanol loaded fuels produced a lean fuel mixture. The increased concentration of methanol increased the excess air from 0 to approximately 20 percent.

Combustion products from common fuels include carbon monoxide and at higher combustion temperatures the oxides of nitrogen. As the amount of excess air is increased, certain trends regarding the concentration of these gases are followed. The amount of carbon monoxide found in the exhaust gases will decrease while the amount of nitric oxides will increase initially then decrease as the temperature drops. Examining the results from both steady-state and dynamic tests, the concentration of the carbon monoxide is seen to decrease as predicted by Stinson and Smith (11). However, the percentage of decrease found in the experimental test was much higher than predicted for constant mixtures of fuels. The additional decrease shown by these tests can be attributed to the fact that less carbon is actually entering the engine. The gasoline structure shows eight carbon atoms per molecule while the methanol molecule has only one atom.

The increase in nitric oxides as the excess air increases as shown by Smith and Stinson (11) is caused by the additional oxygen associating with the free nitrogen radicals. To lower the concentration of nitric oxides requires lowering the combustion temperature and pressure. Other experiments (8) have shown that methanol, with its relatively high mass for its heating value does have the ability to decrease the charge temperature. This factor and the lower temperature from a lean air:fuel mixture are responsible for the lower nitric oxides as the methanol content is increased. The results from these experiments validate previous work in showing that the methanol does have a cooling effect and does in turn decrease the concentration of the nitric oxides in the exhaust from an internal combustion engine. There is one exception, however, and it is shown in Figure 7. At a concentration of 20 percent methanol by volume the nitric oxide concentration reverses its downward trend.

To explain this phenomenon first consider the performance of the carburetor. The carburetor is adjusted to deliver fuel and air under a constant fuel:air ratio except at two positions, (1) closed for idle, or (2) when the throttle is wide open and the power valve is opened. When the throttle is wide open, the engine will induct essentially a constant and limiting amount of air, controlled primarily by the piston displacement, while the amount of liquid fuel to be added is increased by the power valve opening. As the restricted air flow and the power valve opening allows the fuel mixture to become richer, this increase in fuel flow and corresponding increase in fuel:air ratio will increase the MEP and the temperature of the combustion process (11). The increase in temperature and pressure are the prerequisites for the formation of the nitric oxides. In observing the action of the throttle during the two acceleration periods of the modified California driving cycle, the throttle was never driven to a wide open position until the higher concentrations of methanol in the fuel were tested. The initial downward slope of the curve in Figure 7 is caused by the lean air:fuel mixtures and also by the cooling effects of the methanol. The reversal and upward slope is caused by the engine trying to follow the acceleration of the driving cycle. The fuel mixture is too lean to supply adequate power for the engine to follow the acceleration curve, hence the throttle is pushed wide open and remains there in a fuel rich condition until the dynamometer load is dropped. The temperature increase due to the fuel-rich burning in the cylinder will offset the cooling effects of the methanol. The increase in the maximum point for the concentration for nitric oxides at high methanol content would not have been noticed in a steady-state test or in a driving test where a gas bag analysis of the exhaust emissions was used.

The concentrations of unburned hydrocarbons with an increase of methanol in the fuel were generally observed to decrease. The decrease in unused fuel is directly attributable to the addition of methanol which produced a lean mixture. The excess air contributed to a more complete combustion process. The one exception to this general trend is observed in Figure 5 where a large increase in the unburned hydrocarbons is observed when the volumetric percentage of methanol in the fuel increases from 10 to 30 percent. The large increase is seen to occur only for the initial acceleration, which is twice as severe as the second acceleration in the modified California driving cycle. The first acceleration also has to start the engine from an idle condition while the second starts at a higher RPM. As additional methanol is added to the fuel using the standard carburetor, the power output is seen to drop off, a fact which is directly attributed to the lean fuel mixture. When the driving cycle requires the engine to perform this acceleration, the carburetor produces a highly fuel-rich condition and a degradation of the combustion process results, hence the higher concentrations of unburned hydrocarbons.

The corresponding gas bag analysis for the unburned hydrocarbons indicates the increase in unburned hydrocarbons. These trends would not have been determined by a steady-state engine test.

Examination of Figure 6 shows the concentration of carbon monoxide to decrease as the volumetric percentage of methanol in the fuel increases. The maximum concentration of the CO during the dynamic testing is shown to be approximately five times as great as the steady-state test run at 24 hp. An examination of the CO concentration during the dynamic testing shows the concentration to be a factor of ten greater when the engine is running at constant speed. The dynamic testing provides this type of result that would not be detected in a steady-state test.

The curves for nitric oxide concentration show that the gas bag analysis for the dynamic tests are approximately 65 percent less than for the average power steady-state run. The difference can be attributed to excessive nitric oxides which are produced for only 15 to 20 seconds of the total 140 second duration of the driving cycle while during a steady-state test, the nitric oxides are produced the full time. Leaner fuel mixtures cause the decrease in unburned hydrocarbons that are shown in Figure 5, but an increase in the fuel:air ratio caused by a maximum throttle condition causes the one dynamic test plot to increase, another trend unrecognized in steady-state testing.

Fuel consumption for all the dynamic and steady-state tests was seen to increase on a volumetric basis as shown in Figure 8. This would be expected since the heating value of the methanol is approximately 50 percent that of the gasoline. Reducing the volumetric fuel consumption to a total BTU usage showed no significant change in total energy consumption, hence no change in efficiency of the engine.

Qualitatively speaking, the author has used methanol blends of up to 10 percent in his personal automobile and has observed no adverse performance problems. In fact, the methanol seems to have a smoothing effect on engine performance similar to the addition of tetra ethyl lead.

A summation of the experiment falls in three general areas:

(1) The driving cycle used in making fuel tests and pollution studies has a significant effect on the fuel economy and exhaust emissions of the internal combustion engine and will give different and more

relevant data than a steady-state test.

(2) The use of a computer-controlled engine-dynamometer system is highly feasible and necessary to define operation of engine add-on devices and the performance of fuels, and will give the controlled testing environment needed.

(3) The use of methanol-blends of up to 10 percent can be used with no modification to existing engines and drivers should experience no performance losses.

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8. BIOGRAPHIES

8.1 Dr. John Simonsen

Dr. John Simonsen received his B.S. degree at the University of Utah and his M.S. and Ph.D. degrees at Purdue University. Upon completion of the Ph.D. degree he joined the engineering faculty at Brigham Young University where he served as Department Chairman for 9 years. Presently he is on a leave of absence from his teaching assignments and is serving as Vice-President of Engineering for Valtek Corporation.

8.2 Dr. Dwight Bushnell

Dr. Dwight Bushnell received his B.S. and M.S. degrees from the University of Utah. Leaving the University he was employed by Hercules, Inc. as a Development Engineer where he was involved in finite element stress analysis and later, moving to Bio-Logics, Inc., he was involved with design engineering and had responsibilities as a Design Group Manager.

Returning to school he received his Ph.D. degree from Brigham Young University and then joined the faculty at the University of Missouri - Rolla. Currently he is teaching in the area of Engineering Mechanics and is involved in research with the Rock Mechanics and Explosives Research Center.

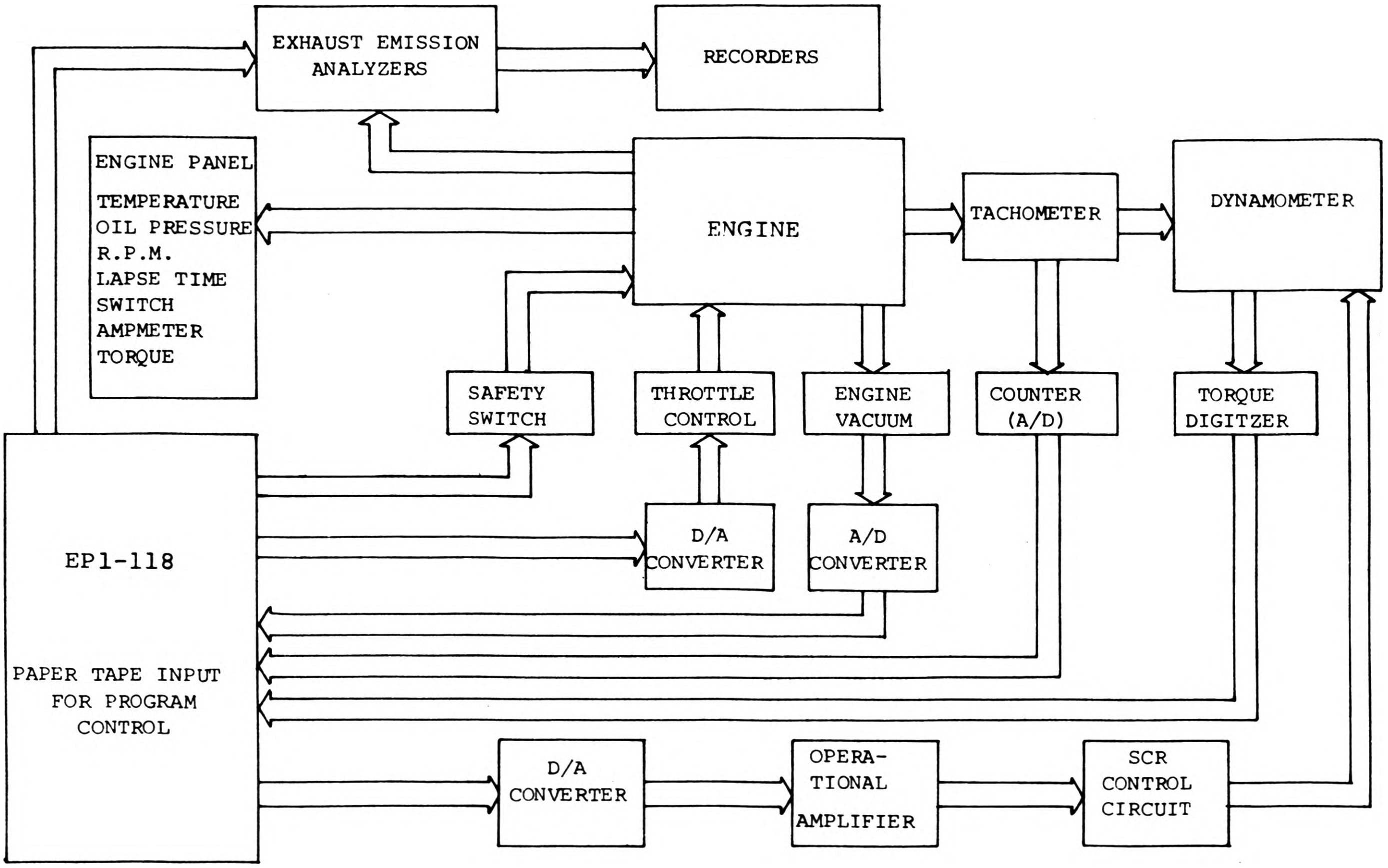

Figure 1. Computer controlled engine and dynamometer.

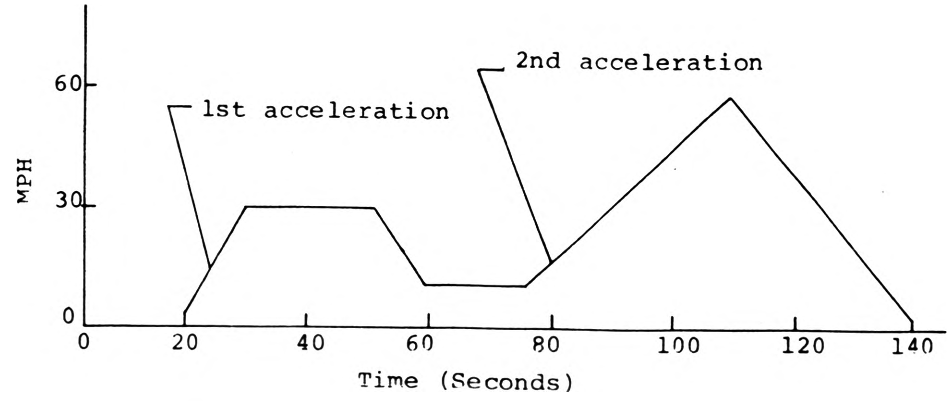

Figure 2. California driving cycle.

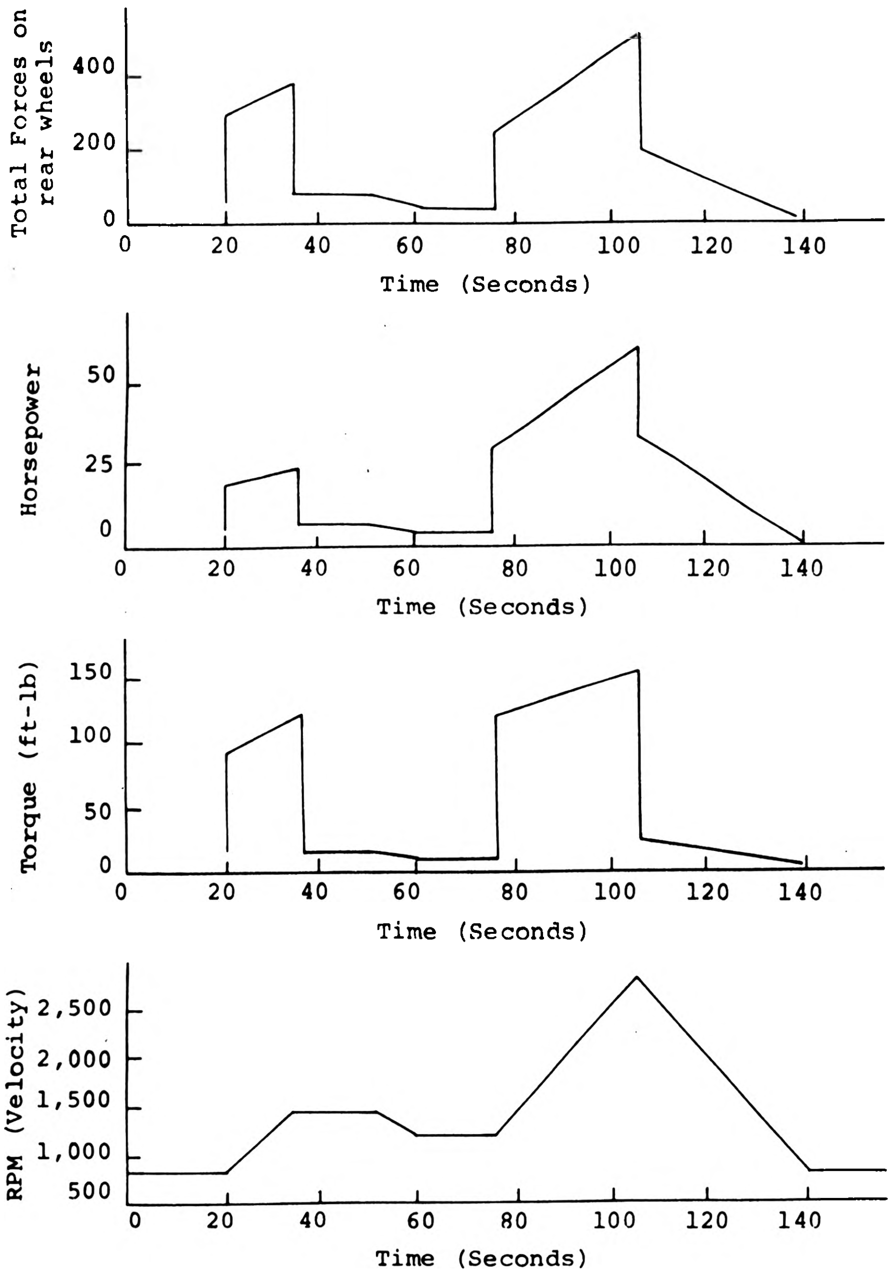

Figure 3. Total force, horsepower, dynamometer load and RPM diagrams for modified California driving cycle (no gear shifting).

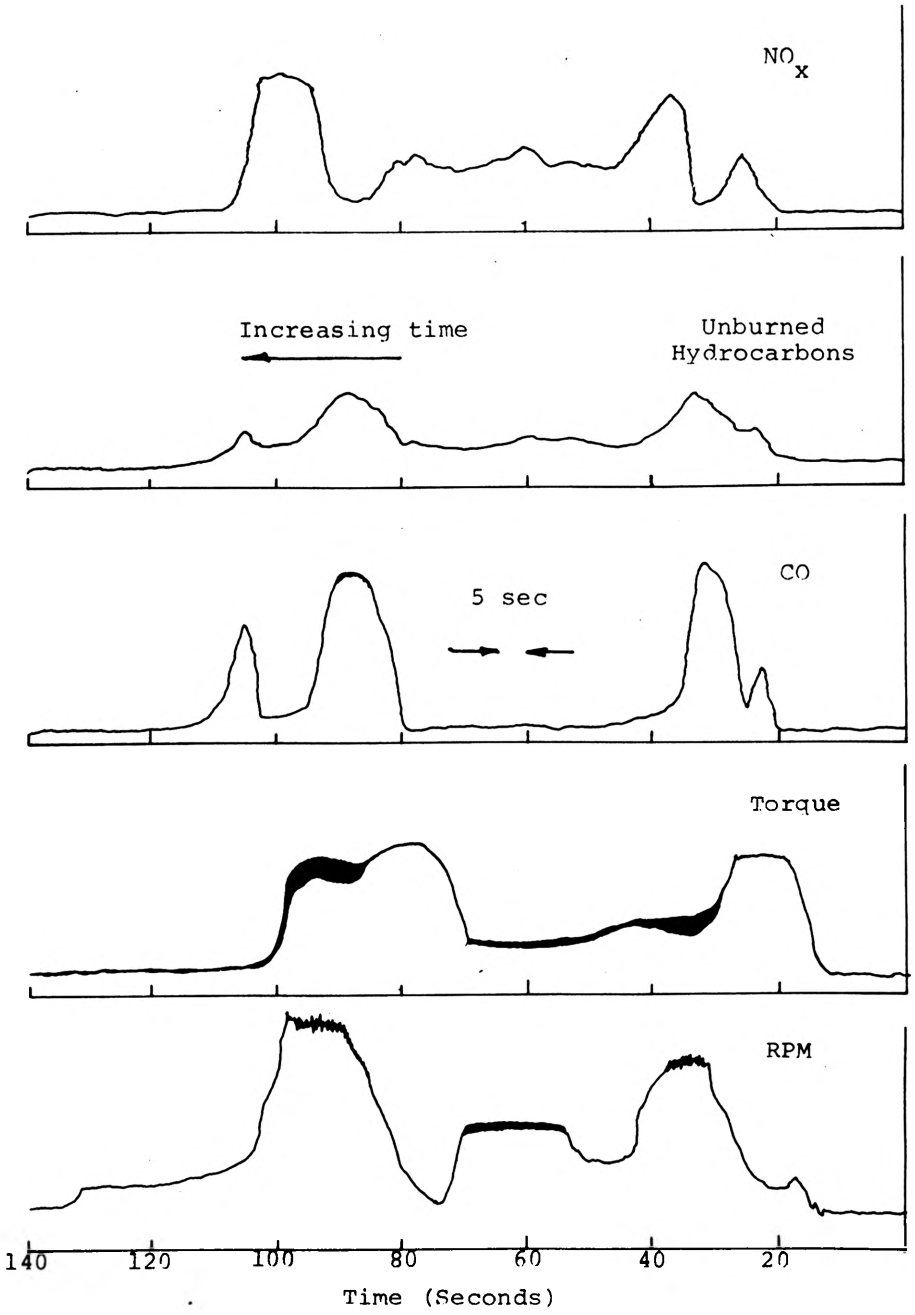

Figure 4. Test data from recorder output.

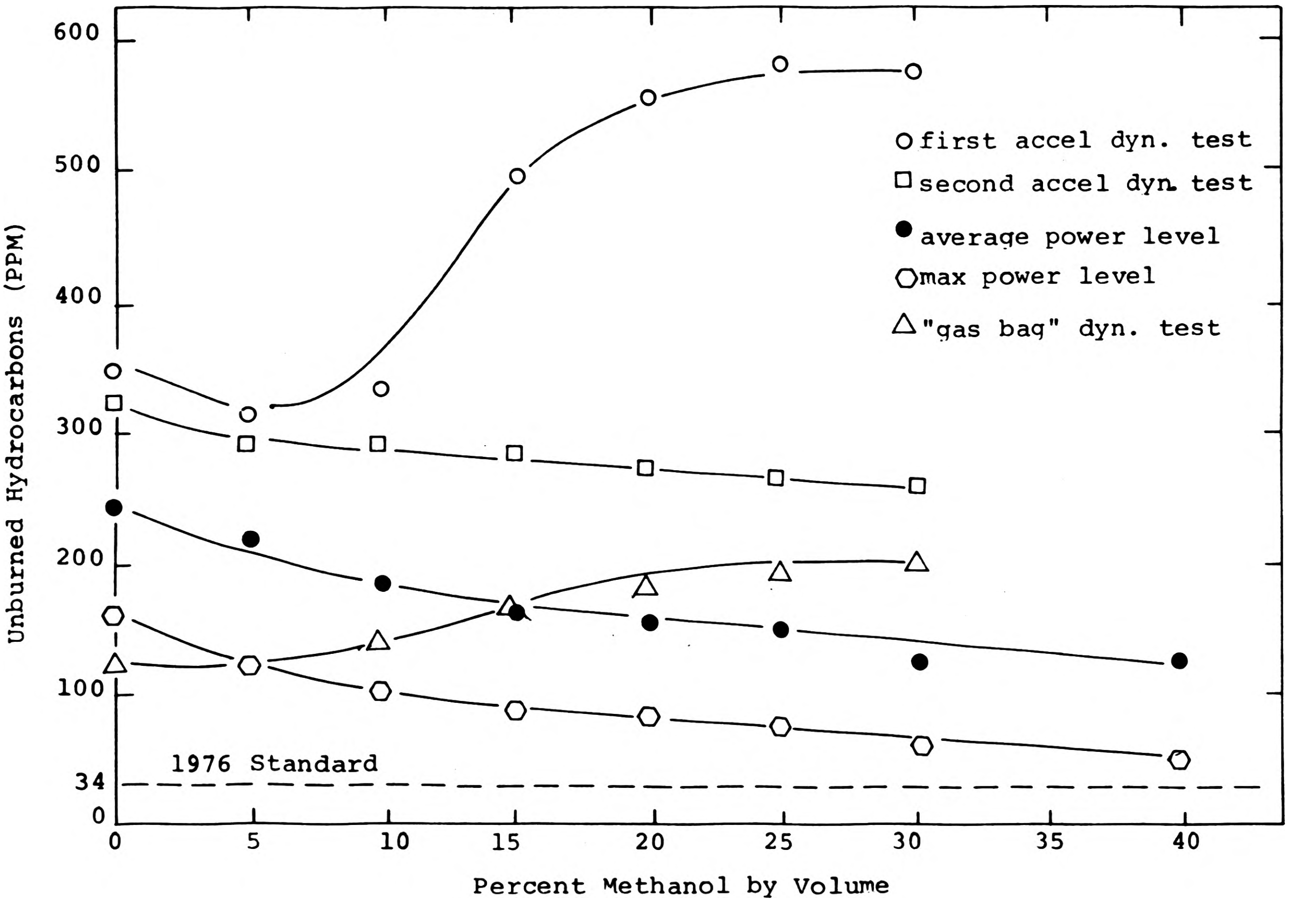

Figure 5. Unburned hydrocarbon concentration for steady-state, dynamic and gas bag test methods.

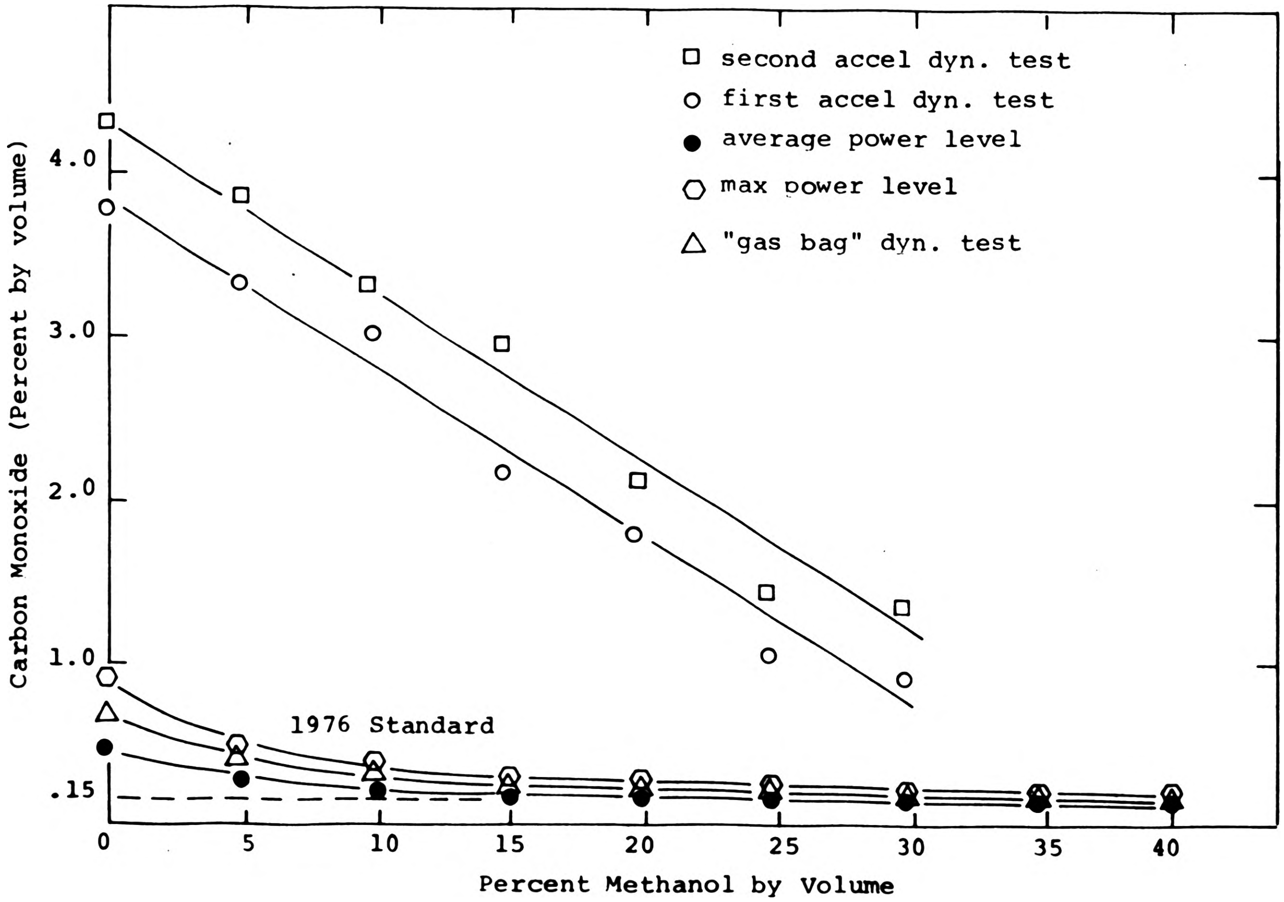

Figure 6. Carbon monoxide concentrations for steady-state, dynamic and gas bag test methods.

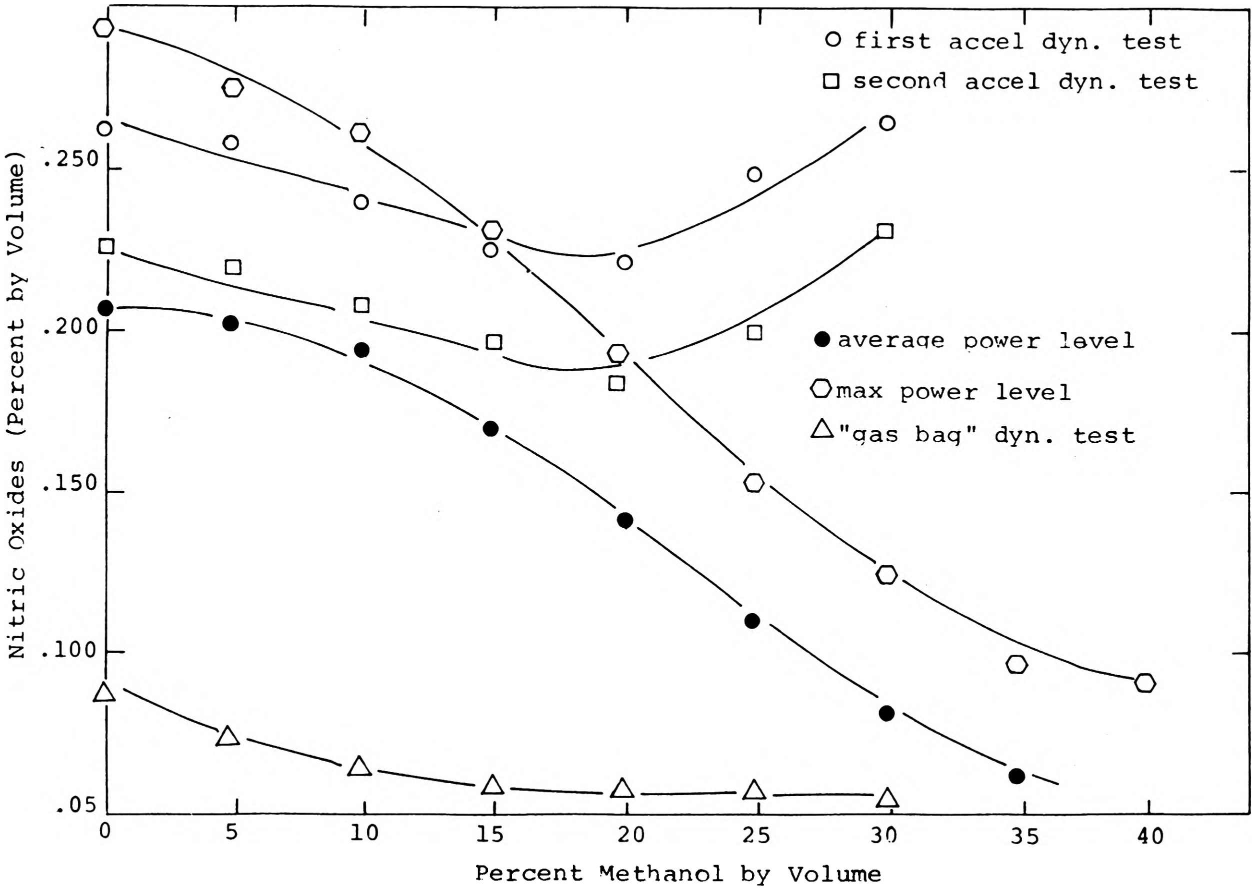

Figure 7. Nitric oxides concentration for steady-state, dynamic and gas bag test methods.

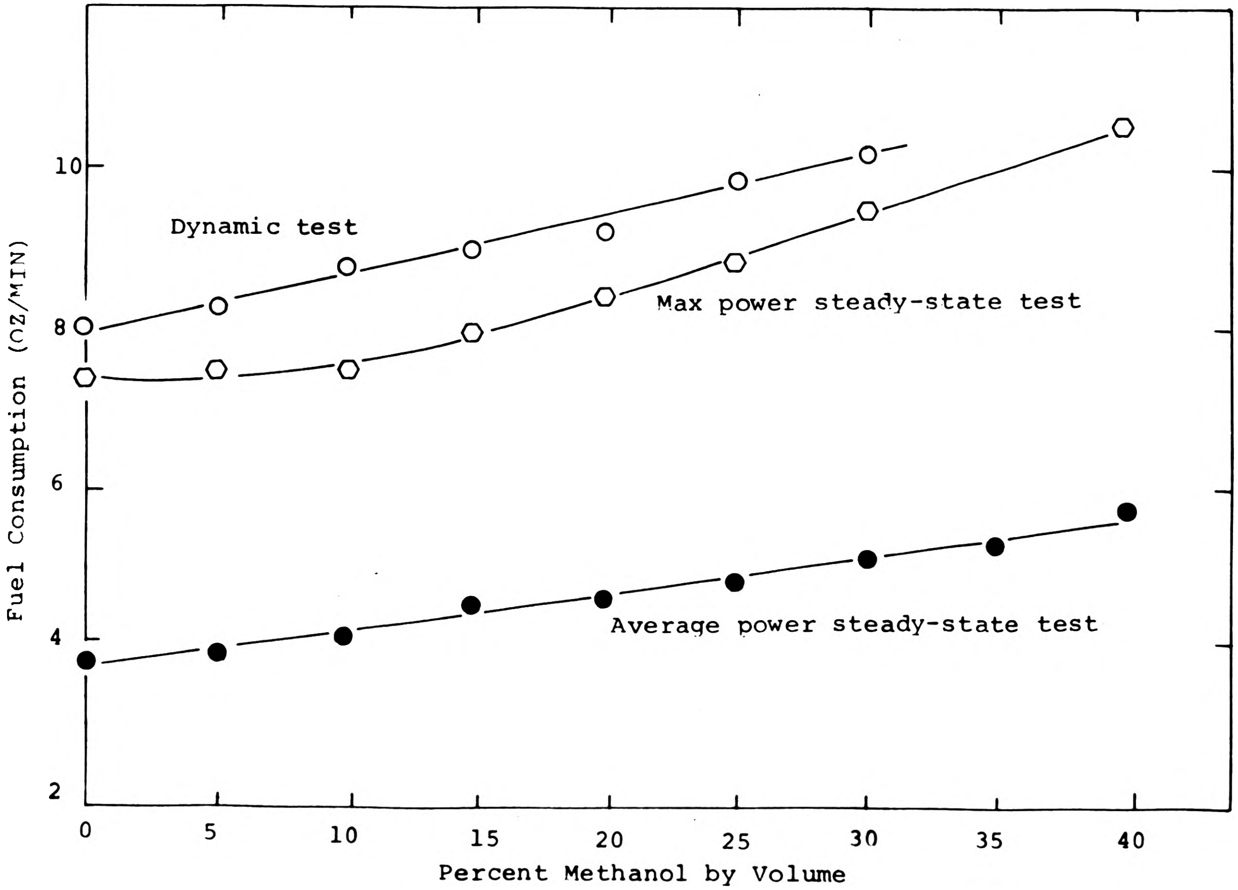

Figure 8. Fuel consumption as a function of methanol content for dynamic and steady-state engine tests.