Final Project Report

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Development of a Dual Fuel Alcohol/Gasoline Vehicle Using Electronic Fuel Injection

-Submitted by-

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Datsun 200SX Converted by the Denver Research Institute, University of Denver, to Multiple Fuel Methanol/Ethanol/Gasoline Capability.

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1. Project Summary

A 1981 Datsun 200SX automobile was modified to enable it to operate on either methanol, ethanol, or gasoline. The electronic fuel injection system of the vehicle was modified to provide this multiple fuel capability, with optimum operation on each fuel. Two fuel tanks are used; the existing gasoline tank and an alcohol fuel tank which may contain either methanol or ethanol. Selection of either gasoline or alcohol operation is accomplished electronically by simply throwing a switch inside the car. Selection of the kind of alcohol to be used, either methanol or ethanol, is accomplished by turning a selector valve in the engine compartment.

Comparative exhaust emissions and fuel economy tests were performed on the vehicle using each of the three fuels. Best energy efficiency and lowest exhaust emissions were achieved simultaneously using methanol. Ethanol was second in both categories, and gasoline achieved inferior efficiency and emissions compared to both alcohols.

2. Detailed Technical Description

2.1 The Standard Vehicle

A 1981 Datsun 200SX automobile manufactured by Nissan Motor Company of Japan was selected for this conversion. Its selection was based upon several technical criteria:

- It uses a pulse duration controlled, exhaust oxygen sensing feedback controlled electronic fuel injection system (the Bendix/Bosch L-Jetronic System manufactured by JECS in Japan).
- It is the least expensive vehicle using the L-Jetronic injection system (several more expensive vehicles are available, all of foreign manufacture).
- It uses the recently introduced NAPS-Z (Nissan Antipollution System) four cylinder engine which achieves improved fuel utilization by high turbulence, fast burn combustion made possible by the use of two spark plugs per cylinder and a unique combustion chamber geometry.
- The hardtop model of the 200SX easily accommodates the addition of an alcohol fuel tank in the trunk.
- Certain fuel injection system components and engine components were designed for tolerance of water content in the gasoline, which eases the task of ensuring compatibility with alcohol fuels.

Regrettably, a U.S. manufactured automobile was not available with the required technical features to permit the conversion.

The official EPA estimated fuel economy rating of the 200SX is 28 miles per gallon of gasoline, which is an intermediate rating in its vehicle class, ranging from 15 to 42 miles per gallon. Because of its sophisticated fuel injection system and the use of a three-way exhaust catalyst, the standard vehicle exhaust emissions are notably clean and well within both Federal and California emissions standards.

The NAPS-Z (Z20 Type) engine used in the 200SX incorporates a number of features which make it a good candidate for alcohol operation. This engine achieves very rapid combustion by the use of two spark plugs per cylinder, and an intake port and combustion chamber designed for high turbulence. Nissan engineers report a 30% improvement in fuel economy of the Z20 engine compared to its immediate predecessor, the L20B engine. Both engines are in-line overhead cam, four cylinder engines with a displacement of 1,952 cm^3. Both have bore and stroke of 85 and 86 mm respectively and a compression ratio of 8.5. Approximately a 10% improvement in fuel economy is assigned to the improved combustion system, while the remaining 20% is due to the combined effects of the electronic fuel injection system, optimized ignition timing, an advanced exhaust gas recirculation system, and vehicle drivetrain optimization to match the engine characteristics.

Due to the large fuel quantities required and the poor atomization and vaporization characteristics of alcohol fuels, combustion efficiency can be a problem. This is especially true during cold engine operation conditions. The high turbulence, fast burn system of the Z20 engine is advantageous for alcohol in this respect.

The Z20 engine employs a sophisticated feedback controlled EGR (exhaust gas recirculation) system which allows the recirculation of exhaust gas into the intake manifold up to 20% of intake charge composition. Special consideration has been given to ensuring that the cylinder-to-cylinder distribution of the exhaust gas is uniform. In typical engines, a practical EGR limit is only 5%. EGR allows improved thermal efficiency (and thus fuel economy) by effectively reducing pumping losses in the engine, provided that combustion quality is not degraded. The fast-burn features of the engine allow a higher EGR limit before the onset of combustion quality degradation. EGR also reduces NO_x exhaust emissions by decreasing the peak combustion temperatures.

Both methanol and ethanol have wider usable flammability limits than does gasoline. This is notably true of the lower limit which is approximately $\emptyset = 0.7$ for methanol. ($\emptyset$ is defined as the ratio of the actual molar fuel-air ratio to the chemically correct or "stoichiometric" fuel-air ratio.) Although specific data has not been taken, it is assumed that this lower lean-burn limit for alcohol fuels is indicative of a greater tolerance for EGR prior to combustion quality degradation. Thus, the increased EGR flow rate provided on the Z20 engine is considered a positive feature for alcohol operation.

The intake manifold legs (or runners) on the Z20 engine contain water heating passages extending back approximately 6 cm from the intake port, up each leg. These passages are fed by engine coolant that bypasses the thermostat, so they are heated rapidly during the engine warm-up period. This manifold heating feature is definitely advantageous for the improvement of fuel vaporization and the prevention of fuel condensation on the lower manifold legs when using methanol or ethanol. The alcohol fuel injection system (which will be discussed later) injects fuel partially against the back of the intake valves, and partially onto the heated surfaces of the lower manifold legs.

The 200SX uses a JECS (Bendix/Bosch licensed) electronic fuel injection system. Individual electronically actuated fuel injectors are used for each cylinder. A constant fuel pressure is supplied to the injectors, and the fuel quantity is metered by the electronic pulse duration that actuates each injector. All injectors are actuated simultaneously, once every engine revolution. Thus each injector is actuated twice for every intake cycle.

Injection timing is triggered from the same electromagnetic pickup as is the ignition timing, located in the engine distributor. An electronic control unit (ECU) provides the injector actuation pulses, and computes the appropriate pulse duration (and thus fuel quantity) based upon the inputs of several engine transducers. Sensors are used for intake air flow, intake air temperature, coolant temperature, throttle position, and exhaust oxygen content. The exhaust oxygen sensor is a noteworthy feature of the system because it allows feedback control of the injection system in order to maintain a stoichiometric ($\emptyset = 1$) fuel-air ratio under all conditions (except during cold starting and hard acceleration transients). The presence of oxygen in the exhaust indicates that the fuel-air ratio is on the lean side of stoichiometric ($\emptyset < 1$). The ECU corrects for this by increasing the pulse duration sufficiently to restore the $\emptyset = 1$ condition. If no oxygen is present in the exhaust, the ECU begins to shorten the pulse durations, thus leaning the fuel-air ratio until some small oxygen content is detected. In normal operation, the system dithers about the $\emptyset = 1$ mixture with a cycle time of about one second. This feedback control feature ensures that a stoichiometric fuel-air ratio is maintained regardless of variations in the fuel properties, fuel pressure, or air density. This is required for the use of a three-way (oxidation and reduction) type exhaust catalyst, which simultaneously reduces HC, CO and NO_x emissions only if the fuel-air ratio of the engine is precisely maintained at $\emptyset = 1$.

This feedback control feature is advantageous for alcohol operation for the same reasons as for gasoline. A more subtle, but very important advantage of precise fuel-air ratio control, is that it ensures the predictability of the ignition timing characteristics of the engine. Variations in the fuel-air ratio have a significant effect on combustion completion time, and thus on optimum ignition timing. This provides an important advantage for alcohol operation of the engine, since the optimum ignition timing curve must be experimentally determined over a range of engine operational conditions, and then is expected to remain intact thereafter.

2.2 Alcohol Fuel Tank Installation

The existing gasoline tank was retained in its normal location beneath the floor of the trunk in the rear section of the vehicle.

A tank for storage of the alcohol fuel (either methanol or ethanol) was installed in the trunk, above and slightly forward of the location of the gasoline tank. Figure 1 shows the location of the alcohol tank in a phantom view of the vehicle. A racing-type ATL (Aero Tech Laboratories) fuel cell was selected for use as the alcohol fuel tank. It is specifically designed for storage of methanol, which is a popular racing fuel, and it incorporates a number of safety features which allow it to withstand severe accident situations without loss or ignition of the fuel. Its capacity is 22 gallons, which was chosen to provide a range similar to that provided by the 14 gallon gasoline tank. The fuel cell contains an internal bladder which collapses without rupturing in the event of the tank being crushed in an accident. Within the bladder is a semi-rigid, open-cell urethane foam which suppresses fuel sloshing and reduces fuel leakage in the event of a puncture of the bladder. Both the fuel filler neck and the tank vent connection contain gravity check valves which close in the event of vehicle rollover, to prevent fuel leakage.

As delivered, the urethane foam in the fuel cell contained a number of volatile substances used as foam plasticizers. In the presence of either methanol or ethanol, these are leached from the foam into solution in the alcohol. Samples of the foam were tested in the laboratory using actual methanol and ethanol fuel samples. Up to 3% of the weight of the foam was found to be removed during alcohol extraction. The presence of these substances in the alcohol can potentially cause the blockage of the fuel injectors, or the formation of gummy deposits in the fuel system. Their effect on the fuel properties of either methanol or ethanol is unknown. Perhaps gummy deposits could form in the upper cylinder of the engine also.

It was found that by pre-conditioning the foam with a week-long alcohol extraction prior to its insertion in the fuel cell, almost all of the soluble materials could be removed. The foam still retained acceptable pliability after this extraction, although the long-term integrity of the foam may be reduced. The laboratory report on the analysis of the foam and fuel samples is included in Appendix I.

A steel support frame was constructed from 1" angle iron for mounting the fuel cell in the trunk of the vehicle. The frame is bolted to the trunk floor in four places, and rubber shock isolation mounts and stress dissipation plates are used at each of the mounting points.

In the unmodified vehicle, the only barriers between the trunk and the rear seat are thin sheets of pressboard. To further ensure the safety of mounting the alcohol fuel tank in the trunk, the trunk was isolated from the passenger compartment by the installation of sheet steel barriers in the forward sections of the trunk. All joints between the sheet steel barriers and the vehicle body and frame panels were sealed with high temperature silicon sealant to ensure against possible fuel vapor intrusion into the passenger compartment in the event of a leak from the alcohol fuel tank or fuel system plumbing.

Refilling the alcohol tanking requires opening the trunk. This is considered a compromise in the original design, but is common practice on several European manufactured cars. The alcohol tank occupies the majority of the trunk area, although approximately five cubic feet of usable trunk area remains between the tank and the rear of the trunk. The spare tire remains in the trunk in its normal location under a panel in the trunk floor, with a conformal recess provided in the gasoline tank beneath it. Since the alcohol tank is located above the forward half of the spare tire, it is necessary to unbolt and slightly lift the alcohol fuel tank frame in order to remove the spare tire. This is very inconvenient and is considered an experimental design compromise.

2.3 Alcohol Fuel Pump and Fuel Supply Components

After evaluation of the alcohol compatibility of several high pressure electric fuel pumps, only one proved to be both reliable in automotive service and capable of handling alcohol fuels. The pump selected is an early-style Bosch rotary vane fuel pump manufactured for only nine months in 1967 and 1968. It was used on the first Bosch fuel injected cars, the 1968 Volkswagen Variant models. The distinction between this fuel pump and all other available pumps is in its "dry motor" construction. Common design practice in all fuel injection type electric fuel pumps is to circulate the fuel around the moving parts of the electric motor. This provides cooling for the motor, which dissipates considerable heat during extended operation. The standard gasoline fuel pump of the Datsun 200SX is of this type. The internal components of the motor are compatible with gasoline. They are not, however, compatible with either methanol or ethanol. Methanol was found to cause swelling of armature windings in several "wet motor" pumps tested. Methanol also causes the formation of a hard black copper oxide coating on the surface of the copper alloy commutator of the motor. This oxide is an insulator which prevents proper electrical contact between the graphite brushes and the commutator. If the methanol contains a considerable percentage of water, it may be electrically conductive enough to internally short the motor. Gasoline, by comparison, will not absorb significant amounts of water and is consistently an insulator. Certain elastomers and plastic components in "wet motor" pumps were also found to be affected by methanol. Some degree of swelling and softening of certain seal materials was noticed.

The use of a "dry motor" pump avoids most of these problems since the fuel does not contact the motor components. Only two "dry motor" pumps were found to meet the pressure and flow rate requirements of the fuel injection system. These were the previously mentioned Bosch pump and a Model V2-303 gear-type pump manufactured by Micropump Corporation. The V2-303 pump incorporates graphite fiber filled Teflon gears rotating against a Type 316 stainless steel sealing plate. After approximately one hour of methanol operation on the test bench, the pump began discharging a black deposit which promptly clogged a fuel filter in the test system.

Analysis was performed on the deposit using an EDAX energy dispersive X-ray analysis system in order to determine the origin of the deposit. The deposit was found to be small particles of type 316 stainless steel which were abraded from the sealing plate by the graphite filled Teflon gears. Apparently, the poor lubrication properties of the methanol aggravated the abrasion of the end grain graphite fiber filaments against the stainless steel. As the sealing plate wore, the pump performance degraded rapidly until it failed to produce adequate pressure after approximately two hours of operation.

The old-style Bosch pump is a rotary vane design in which carbon steel rollers run against anodized aluminum alloy surfaces of the vane chamber. No degradation of pump performance was noticed after eight hours of continuous operation on methanol. Three of these pumps were obtained from auto salvage yards. All were usable, although their previous service records were unknown.

Robert Bosch, Ltd. has not produced this pump since 1968 and could neither supply new units nor provide information on it.

The accumulation of a white granular deposit was observed in the vane chamber of one of these pumps after approximately 24 hours of service on the test bench. EDAX analysis indicated that the deposit was zinc oxide, and was not due to degradation of either the steel rollers or the anodized aluminum walls of the vane chamber. The most probable sources of the zinc are either the galvanized fittings used on the pump (which are removable), or a die-cast zinc fuel filter body used in the test system. Removal of the galvanized coating on the fittings and replacement with an iridite (iridium plate) coating would remove the first source, and substitution of a steel or aluminum filter body would remove the second source, if the amount of the deposits became a problem.

A pulsation dampener is required in the fuel line downstream of the fuel pump for removal of pressure pulses which might affect the fuel metering capability of the fuel injection system. Pulsation dampeners manufactured for gasoline fuel injection by either Bosch or Nissan were found to be acceptable for either methanol or ethanol. No failure has yet been observed in either the test bench apparatus or the actual vehicle, although the synthetic rubber diaphragms used in these units may eventually degrade in alcohol service. A Nissan unit was used in the alcohol circuit of the vehicle.

The fuel pump and the pulsation dampener are installed in a vacant space behind the right rear quarter panel. They are accessible from inside the trunk by removal of a metal cover plate. Also located in this section is a primary fuel filter located in the hose from the alcohol tank drain to the pump inlet. The filter has a glass housing which allows inspection of residue buildup in the filter without disassembly.

Several sheets of polyurethane foam sound insulation material were installed around the alcohol fuel pump to reduce noise transmission.

A drain cock is located at the right rear of the vehicle, below the fuel pump section. It is protected from road dirt buildup by a splash plate. This drain cock facilitates draining the alcohol tank, which may be required when switching from one type of alcohol to another.

Two type 304 stainless steel 5/16" O.D. tubing fuel lines are run parallel to the existing gasoline fuel lines from the tank to the engine compartment. One is used for fuel feed to the alcohol fuel rail of the engine; the other is used for fuel return to the tank. With this type of injection system, fuel recirculates constantly from the tank to the engine and back to the tank.

2.4 Alcohol Fuel Injection System

In order to provide for engine operation on methanol, ethanol, or gasoline, a means for the selective injection of either gasoline or alcohol was required.

In the standard L-Jetronic injection system used on the vehicle, fuel is circulated under pressure through a fuel rail with branches for each of the four fuel injectors. At the end of the fuel rail is a backpressure regulator (BPR) which maintains a constant pressure in the fuel rail, and returns excess fuel to the fuel tank. The flow rate of fuel in the fuel rail is always in excess of the fuel requirements of the engine, so that the fuel pressure is maintained under all conditions, and some fuel is always returned to the tank. The balance port of the BPR is connected to the intake manifold so that actually, the absolute pressure in the fuel rail does not remain constant, but rather the differential pressure between the fuel rail and the intake manifold is held constant. As a result, the differential pressure across each fuel injector is constant, which assures a consistent pulse duration to fuel delivery relationship regardless of variations in the intake manifold pressure.

It had been originally proposed that a common fuel rail would be used to circulate either gasoline or alcohol. The same fuel injectors would be used for both fuels. Compared to the volume of gasoline delivered by each injector, this volume must be increased by factors of 1.56 for ethanol and 2.17 for methanol. This increased flow rate was to be achieved by increasing the fuel rail pressure for ethanol, and by both increasing the fuel rail pressure and modifying the ECU to increase the pulse duration periods for methanol. The advantage of this approach is that no additional fuel injectors would be required and that no re-routing of existing fuel injection components and lines would be needed.

The disadvantages of this approach were described in the first quarterly report. The pressure increase required to flow ethanol through the gasoline injectors at the required rate would be 95 psi compared to 36 psi for gasoline. The maximum pulse duration that can be generated by the ECU is 10.0 ms. Although under steady state conditions, the engine never requires more than a 7.8 ms pulse duration, the 10.0 ms pulse is required for sharp acceleration transients and for cold starting the engine. Thus, extending the pulse duration by a constant factor for methanol operation would be deleterious to both throttle response and engine cold starting ability. It is possible to modify the ECU to extend the 10.0 ms upper limit, but this causes an engine speed limitation since the maximum time available for injection decreases with increasing engine speed. At 6,000 RPM, the maximum time available for injection is 10.0 ms. Even with the 95 psi fuel pressure, the engine speed would be limited to 4,310 RPM under maximum load conditions for methanol operation.

A transition period would occur when switching from gasoline to alcohol (or the reverse), during which time the fuel rail and fuel injectors are being drained of one fuel and filled with the new fuel. Because of the very low fuel flow rates at engine idle conditions, this transition period might extend for several seconds. During this period, the old fuel would be injected at the rate required for the new fuel. If a gasoline to methanol transition is made, the remaining gasoline in the injectors would be injected at more than double its correct rate. The engine would run extremely rich, or stall. If a methanol to gasoline transition is made, the remaining methanol in the injectors would be injected at less than half its correct rate. This is below its flammability limit, so that the engine would stall. It would be necessary to crank the engine for several seconds until the old fuel is drained from the injectors, and the new fuel is being injected before the engine would restart.

In order to avoid this problem, and to simplify other design requirements (such as the very high fuel pressure), a different design approach was chosen. Separate fuel injectors are used for alcohol and gasoline. Each cylinder now has two fuel injectors, each supplied by a separate fuel rail. Separate BPR's and fuel filters are also used. In this configuration, the vehicle contains two complete and separate fuel injection systems: one for gasoline and one for alcohol. They share a common ECU, and as a result, the fuel injection control strategies are the same regardless of the fuel. Switching from one fuel to the other electronically disconnects one set of four injectors and connects the new set, and also turns off the old fuel pump and turns on the new fuel pump. No modification of the ECU is required. Transition between fuels is instantaneous, except for the time required for the fuel pump to come up to speed, which is under one second. Since the system retains its pressure for several hours after shutdown, switching back to a fuel that was recently used causes no detectable transition period.

A schematic diagram of the dual fuel injection system is shown in Figure 2. In the alcohol circuit of the system, fuel flows from the tank, through the primary fuel filter, into the fuel pump, through the fuel lines up to the engine compartment, through the secondary fuel filter, into the fuel rail to which four fuel injectors are connected, out of the fuel rail into the selector valve where it is directed to one of the two BPR's, and finally returns to the tank via the fuel return line.

Either methanol or ethanol may be used in the alcohol circuit of the fuel injection system. This is accomplished by use of a different fuel rail pressure for each. A selector valve is used to direct the fuel leaving the alcohol fuel rail to either of two BPR's. One is set for 24 psi, the other for 45 psi. This provides a flow ratio of 1.39:1 between methanol and ethanol, which is the required raio for stoichiometric operation on each fuel. Selection of the type of alcohol is accomplished by simply turning the selector valve 90°.

Bosch backpressure regulators from the 1968-73 Volkswagen Type III are used for both the ethanol and methanol BPR's. Bench tests were conducted to determine the alcohol compatibility of this BPR. No failure or degradation in performance has been observed over 50 hours of service on methanol. The regulation capability of the Bosch BPR is excellent and pressure setting drift with time is negligible. By comparison, a Veriflo Type BPR-40 stainless steel and Teflon backpressure regulator demonstrated significant pressure variation with flowrate, although its alcohol compatibility was unquestionable. Since the Bosch units had superior performance and lower cost, they were used for the alcohol circuit of the fuel injection system. Since the diaphragm material in the Bosch units is undetermined, long term alcohol compatibility may be questionable.

The secondary fuel filter selected is a standard gasoline type fuel injection type fuel filter manufactured by JECS for Nissan. It is the same as the gasoline fuel filter on the 200SX. No problems have been encountered with either this fuel filter, or an equivalent Bosch filter, in extensive service on both methanol and ethanol.

Originally, Nissan "Hyprex" fuel hoses were used in the alcohol circuit of the injection system. These are the same high pressure fuel hoses that are used in the gasoline circuit of the system. The inside surfaces of these hoses eventually became gummy and began to secrete a tar-like substance at the hose connections. This was found to be caused by the softening and decomposition of the hose in methanol or ethanol. These were replaced by Weatherhead 6202 hydraulic hose, which contains a nitrile rubber inner hose and a neoprene (chloroprene) rubber outer casing. No problems have been encountered with the new hose, which is considerably less expensive than the Nissan fuel injection hose.

The intake manifold was modified to accept an additional injector for each cylinder. These are located just beneath the gasoline injectors in each manifold leg. Figure 3 is a photograph of the modified manifold with just the alcohol injectors and the alcohol fuel rail in place. The alcohol fuel rail was fabricated from type 304 stainless steel. Figure 4 shows a downstream view of both the gasoline and the alcohol fuel injector nozzles. The spray patterns from both are against the back of the intake valve, although the alcohol injector also sprays some fuel on the final 2 cm of the manifold leg, under which is located the manifold water heating passage. Figure 5 is a photograph of the manifold with both the gasoline and alcohol injection components attached, just prior to installation on the engine.

Figure 6 is a photograph of the engine with all fuel injection components and other accessories installed.

2.5 Fuel Injector Selection

It was necessary to find a fuel injector having a suitable flow coefficient so that either ethanol or methanol could be injected at the required flowrate for each while using the gasoline pulse duration range of the ECU, and reasonable alcohol fuel pressures. An additional requirement was that the injector be compatible with both methanol and ethanol.

All fuel injectors manufactured by Bosch, Bendix, JECS, or Nippon Denso are identical in basic design. They are all essentially the 1967 Bosch-designed injector originally used on the 1968 Volkswagen Type III. Bosch and Bendix have co-licensing agreements between them whereby Bendix may use the Bosch injector, and Bosch may use electronic fuel injection per se, since Bendix produced and patented the first electronic fuel injection system in 1957 (used briefly on the 1958 Chrysler 300 Sedan).

A wide range of flow coefficients are available in Bosch manufactured injectors used on the early (prior to 1975) D-Jetronic type systems. Since the development of the later L-Jetronic system, all Bosch injectors have had the same flow coefficient, and the tailoring of the fuel delivery rate for any given engine has been accomplished by setting of the fuel pressure and pulse duration range generated by the ECU. Since the L-Jetronic injectors had insufficient flow capability for alcohol, several earlier D-Jetronic type injectors were used. Injectors from systems used on Volkswagen, Ford (Lincoln), Volvo and Mercedes-Benz were evaluated on a flow measuring apparatus for this application. The Volkswagen Type III injector tested with the desired flow capability, approximately twice that of the L-Jetronic injectors used in the gasoline circuit on the 200SX. This was fortunate since the Volkswagen injectors are the least expensive available ($30 each compared to as high as $80 each on other cars, even though the parts are identical).

Data on the quantity of fuel delivered vs pulse duration are shown in Figure 7 for the Volkswagen injector flowing alcohol at 24 and 45 psi, and the Datsun 200SX injector flowing gasoline at 36 psi. The 24 and 45 psi fuel pressures were selected for the use of ethanol and methanol respectively. This was based upon the calibration data which is summarized in the graphs of Figure 7.

Compatibility of the injector with methanol and ethanol is an important requirement. Several injectors were cut apart lengthwise and soaked in methanol and ethanol solutions. Bosch injectors manufactured prior to 1978 contained carbon steel parts which corroded rapidly in either alcohol. The same occurs for all Bendix injectors manufactured to date. However, after 1978, Bosch substituted the European equivalent of type 440 stainless steel for the carbon steel parts, and also substituted Viton "O" ring seals for the previous Nitrile rubber seals. Their concern was an acid etching problem due to water absorption in gasoline. Sulfur from the gasoline forms sulfuric acid in the presence of the water, which causes increased wear in the injector moving parts due to corrosion. Fortunately, these new materials are also compatible with both methanol and ethanol, even with substantial water content. The later type Bosch injectors showed no corrosion problems in the alcohol soak tests. The JECS injectors manufactured under Bosch license are also of this new type, which Bosch designated as the Type X injector.

Another fortunate break was that replacement injectors manufactured by Bosch after 1978 for the early D-Jetronic injection systems also employ the new materials. Thus it was possible to obtain an early type injector which had the desired flow coefficient, and also have the benefit of the new alcohol tolerant materials. A standard replacement part for a 1968-78 Volkswagen Type III was perfect for the alcohol fuel injection system.

3. Emissions, Fuel Economy and Power Output Test Results

Following completion of the injection system and related vehicle modifications, the engine was first operated on gasoline in order to verify that it was fully operational in its standard configuration. The alcohol tank was filled with methanol (VWR technical grade) and the alcohol fuel circuit was primed by briefly switching on the fuel pump override switch located in the trunk of the vehicle. The methanol back pressure regulator was adjusted for a 45 psig rating on the fuel pressure gauge located in the engine compartment. While the engine was operating on gasoline, the fuel selector switch was thrown to the "alcohol" position. A slight increase in the engine idle speed was noticed. Engine operation on methanol was undiscernible from gasoline operation. With no special adjustments made, the vehicle performed impressively well on methanol.

First engine operation on ethanol followed a few days later, after substituting ethanol for methanol in the alcohol tank, and setting the ethanol backpressure regulator to 24 psig. The initial results were the same as with methanol; excellent driveability and a slightly increased idle speed.

A preliminary evaluation of exhaust emissions on each of the three fuels was performed at engine idle conditions, and no-load "rev-up" transients. Nitrogen dioxide (NO) concentrations in the exhaust were measured with a Thermoelectron Corp. Series 10A Chemiluminescence NO_x analyzer. Carbon monoxide (CO) concentrations were measured with a Beckman Type 865 infrared absorption CO analyzer. These tests were performed in order to roughly assess the comparative emissions on each fuel, and to preliminarily determine the effect of ignition timing variation on emissions for methanol and ethanol operation.

CO emissions for methanol or ethanol were undetectable for any no-load steady-state condition, either at idle or higher engine speeds. Ignition timing had no effect on this. These observations verified that, indeed, the electronic control system was preventing over-rich excursions of the fuel-air ratio during steady state operation. Laboratory data of other researchers (1) has shown that CO emissions on either ethanol or methanol only occur for $\emptyset > 1$. The lack of detectable CO emissions during these steady state tests indicated that $\emptyset$ was not noticeably greater than 1.0.

Exhaust oxygen concentration was measured with a Beckman Model F3 magnetic deflection oxygen analyzer. No more than 1% oxygen appeared in the exhaust during these tests. The lack of significant exhaust oxygen verified that $\emptyset$ was not noticeably lean ($\emptyset < 1$). The combined information from the CO and O_2 concentration measurements verified that, indeed, the oxygen sensing feedback control injection system was operating according to its gasoline design strategy during alcohol operation. That is, it maintained $\emptyset \cong 1$ during steady state conditions.

During no-load "rev-up" tests, in which the throttle was opened fully for approximately two seconds, the electronic control unit temporarily ignores the oxygen feedback signal, and provides an over-rich fuel-air mixture in order to improve the throttle response. CO emission concentrations as high as 2.6% were observed during these tests using methanol. This figure was compared with the 4.1% CO maximum concentration observed on "rev-up" tests using gasoline. These observations indicated that the acceleration enrichment feature of the electronic control system was correctly operating during use of methanol or ethanol, and also provided the first indication that CO emissions might be lower on methanol than on gasoline.

NO_x emissions data were also taken during these tests, but due to the no-load test conditions, provided little usable information. It was hoped that the idle ignition timing might be optimized for lowest NO_x emissions. The NO_x concentrations measured at various ignition timing settings only verified the expected trend that retarding the ignition timing produced lower NO_x emissions, but with a concomitant (and unmeasured) reduction in engine efficiency and power output.

Idle NO_x exhaust concentrations were measured at 5 ppm on methanol and 15 ppm on gasoline. "Rev-up" NO_x maximum concentrations were 90 ppm on methanol and 180 ppm on gasoline.

A further observation was that variation of the fuel rail pressure for either methanol or ethanol seemed to have no effect (except for very wide variations) on either the emissions or driveability of the vehicle. Clearly, the ECU was automatically compensating for the reduced fuel delivery that occurs with lower fuel pressures by extending the injection pulse duration accordingly. A similar shortening of the pulse duration occurred for increased fuel pressure.

Overall, it was concluded that the electronic feedback controlled injection system was doing everything it was designed to do (for gasoline) during alcohol operation.

Since little could be learned about optimum ignition timing during no-load tests, the ignition timing was nominally set to the manufacturer's recommended setting for gasoline. This was 16° BTDC at 700 RPM, with all vacuum advance lines connected. It should be noted that the NAPS-Z engine is unique in its use of a high advance setting at idle conditions.

No other adjustments were made, so that the engine was optimally set up for gasoline operation according to the manufacturer's specifications. In this configuration, complete EPA standard emissions and fuel economy certification tests were performed on the vehicle using each of the three fuels. These tests were performed by Environmental Testing Corporation (ETC) in Aurora, Colorado. The EPA Full Test Procedure (FTP) was run on gasoline and methanol. The EPA Highway Fuel Economy Test (HWFET) was run on gasoline, ethanol, and methanol. The results of these tests are summarized in Table 1. A vehicle inertial weight setting of 2,875 lbs was used for these tests, in agreement with the manufacturer's information on the certification procedures that were used by the EPA on their U.S. certification vehicle.

A carbon balance method is used for determination of fuel consumption during the EPA standard tests. This is described by SAE specification number J1094a, SS 5.4. Use of this method (which was programmed into ETC's computers) generates erroneous fuel consumption data when using alcohol fuels. This is due to the assumption in the SAE specification, that the fuel is entirely hydrogen and carbon. The oxygen content of alcohol fuels does not allow this assumption. A correction to the SAE specified procedure was derived from the correct chemical mass balance, and this was used to determine fuel consumption on either methanol or ethanol. The complete derivation is listed in Appendix II. It is noted that without this correction, EPA FTP and HWFET tests will generate erroneous fuel consumption figures for alcohol fuels. A copy of the revised method was requested by and has been sent to the EPA Vehicle Emissions laboratories in Ann Arbor, Michigan.

As indicated in the data summary of Table 1, emissions of CO and unburned hydrocarbons were significantly lower on either methanol or ethanol, compared to gasoline, during both the city and highway driving cycles. It is noted that no correction factors were applied to the HC response of the Flame Ionization Detector (FID) used to measure exhaust HC concentrations during these tests.

No reliable correction factor has yet been arrived at for the decreased response of an FID to the primarily alcohol composition of HC emissions from alcohol fuels, although 0.65 has been used by some other researchers (1)(3). If the 0.65 response factor were applied to the HC data of Table 1, each grams per mile figure would be increased by a factor of 1.54. This would not affect the trend shown by these data compared to the gasoline HC figures, with either methanol or ethanol producing lower HC emissions than gasoline.

The most significant improvement in emissions was for CO. In the HWFET test, CO emissions on either methanol or ethanol were 23% of the CO emissions on gasoline. No correction factors are necessary for analyzer response to CO or NO_x.

NO_x was slightly higher on the alcohols compared to gasoline. This was later found to be due to the non-optimum ignition timing and poor exhaust catalyst efficiency during alcohol operation. It was found after these tests, that as little as a 2° retarding of the ignition timing brought NO_x emissions on methanol or ethanol below the gasoline NO_x figures. Exhaust emissions were sampled at the tailpipe (after the catalyst) by the CVS (Constant Volume Sampling) procedure (2) during all these tests.

For comparison, emissions and fuel economy data provided by Nissan, the vehicle manufacturer, are also shown in Table I. These data were taken at near sea level, using gasoline, in a similar 1981 Datsun 200SX at the EPA laboratory in Ann Arbor, Michigan. A small reduction in fuel economy is observed between the high altitude (5,300 ft.) data from our vehicle and the low altitude Nissan data. However, a significant worsening in emissions is noted at the high altitude in all categories except NO_x, which is lower in the high altitude data. This is predictable considering the 20% reduction in atmospheric oxygen available at Denver altitude compared to Ann Arbor.

Although not a normal part of the standard EPA tests, the exhaust stream was also sampled prior to the catalytic converter in an effort to determine the effectiveness of the three-way-catalyst (TWC) during alcohol operation. Modal (real-time) plots of certain emissions were plotted during the course of each test, with samples taken both prior to and after the catalytic converter. These are included in Appendix III.

These modal data clearly indicated that the catalyst effectiveness during either methanol or ethanol operation was significantly lower than during gasoline operation. This was true for all species sampled. These data indicated that, contrary to the trend of the tailpipe emissions data, NO_x emissions measured prior to the catalyst were actually lower on both alcohols compared to gasoline. The reduction capability of the catalyst was significantly diminished during alcohol operation compared to gasoline operation. Thus, although NO_x emissions leaving the engine itself were higher on gasoline, they appeared lower at the tailpipe when compared to alcohol operation.

No reason for this was determined, although the problem has been discussed with other researchers who have made similar observations (4). A thermocouple was installed in the exhaust stream immediately prior to the catalyst bed in order to determine if exhaust gas temperature differences between gasoline and alcohol, which might cause different catalyst bed temperatures, might account for the efficiency difference. Exhaust gas temperatures on either methanol or gasoline were almost exactly the same as on gasoline. Under no circumstances did they differ within limits of experimental error. The most varied case occurred between methanol and gasoline under high load conditions, when the methanol exhaust temperature appeared to be approximately 100°C lower than the gasoline exhaust temperature. This slight temperature difference could not account for the radical difference in catalyst effectiveness between gasoline and alcohol. This is an obvious area for further study.

Fuel economy data were taken during the EPA tests using the corrected carbon balance method previously described. The "gasoline equivalent" fuel economy results of Table 1 were arrived at by equilibration of the lower heating values of either methanol or ethanol, to the lower heating value of Indolene (standard gasoline used in the EPA tests). This technique provides a fair standard of comparison of each fuel on an "equal energy" basis. The supporting equations for this conversion appear in Appendix IV.

Clearly, the engine efficiency (and thus fuel economy) was higher on either alcohol compared to gasoline. A 9.0% improvement in effective fuel economy was realized by methanol over gasoline in the EPA FTP. It should again be noted that the ignition timing was set for optimum gasoline operation, and unchanged between the gasoline and alcohol tests. Ignition timing was, therefore, not optimum for methanol or ethanol.

The complete computer printouts generated for each of the EPA tests are contained in Appendix V. These provide the raw emissions concentrations data taken from both the bag samples and during modal analysis during the tests.

Following the EPA standard tests, an effort was made to determine optimum ignition timing on methanol. Due to budgetary constraints, it was not possible to re-run the EPA tests parametric with different ignition timing settings, although this would have to be the best approach. It was necessary to assume that best fuel economy occurs with Minimum Best Torque (MBT) ignition timing. Torque is a directly measurable parameter using a dynamometer.

Using a chassis dynamometer at Spitzer Automotive Electric Co. in Denver, full power/variable RPM tests were performed on methanol at various ignition timing settings. An identical test was run on gasoline with the standard ignition timing setting. Data generated in these tests is shown in Figure 8. It must be noted that the timing was varied simply by rotation of the distributor. This method retains the shape of the ignition advance curve (functional with RPM and manifold vacuum), which is optimum for gasoline. It is probably not optimum for either methanol or ethanol, although nothing could be done about this due to budget limitations in this limited scope project. Using maximization of torque as the sole criterion, the optimum ignition timing on methanol appeared to be 2° retarded from the gasoline setting (14° idle advance vs 16° on gasoline).

These tests also revealed another attractive benefit to alcohol operation: a maximum road horsepower output of 59 BHP on methanol compared to 53 BHP on gasoline, an 11.3% improvement.

With the ignition timing at the new setting, the vehicle competed in the 1981 Society of Automotive Engineers (SAE) Clean Air and Fuel Economy Rally, held July 9 and 10, 1981. Vehicles were evaluated for emissions using the third phase (hot, stabilized) of the EPA FTP. They then were driven over a 181 mile road course consisting of city, highway, and mountain driving. The total Rally score was based upon the weighted summation of fuel economy, emissions, and rally performance (time and distance technique) scores. Greatest emphasis was assigned to fuel economy, then to emissions, and least to rally performance. A summary of the rally scoring criterion appear in Appendix VI.

No special preparation was done to the vehicle for the rally, other than the inflation of the tires to 48 psi pressure, and decreasing the idle speed to 600 RPM. Methanol was used exclusively. The gasoline tank was drained. A summary of the rally performance of the car is shown in Table II, which is the official rally score sheet for the entry. The car achieved a total score of

884 out of 1,000 possible, which was the highest in the rally. The closest competitor was a 837 point score. The car won the "Overall Champion" award, as well as six other awards for fuel economy and emissions. A total of 21 vehicles competed in the rally. The majority of these were diesel powered, although three other methanol powered vehicles competed. This car won best fuel economy, best emissions, and best overall awards in the special "renewable fueled vehicle" class, in addition to the overall award, and all awards in the 3-4 passenger vehicle class. Emissions and fuel economy data taken on the car by the SAE officials during the rally is also summarized in Table 1. The significantly higher CO and HC emissions might be explained by the use of a higher inertial load during the Rally emissions test (3,250 vs 2,875 lbs used in previous tests). The lower NO_x emissions were an expected result of the retarded ignition timing compared to the previous tests. All emissions were significantly below the proposed Federal high altitude emissions standards.

As a further comparative evaluation, the car has been entered in the "Future Fuels Challenge Rally," to be held October 17-23, 1981. This is a fuel economy competition for renewable fuel vehicles which will run from Los Angeles to New York.

4. Vehicle Service Record

Since its completion in July, the vehicle has been in constant daily use. To date, 4,920 miles have been logged. Approximately 60% of this use has been on gasoline, primarily as a matter of convenience. The remaining 40% has been on methanol. Only approximately 200 miles of operation on ethanol have been logged, specifically for tested purposes only. This is due to the high cost of ethanol compared to either gasoline or methanol. Methanol is purchased in 55 gallon drum quantities for 65 cents per gallon from Alternative Fuels, Inc. in Broomfield, Colorado, or for 75 cents per gallon from Mountain Chemical Company in Golden, Colorado. Alternative Fuels actually purchases methanol from Mountain Chemical Company, but buys in 3,000 gallon lots at a reduced price, such that it can resell the methanol in small quantities for less than Mountain Chemical Company. This methanol is actually recycled industrial solvent which contains a small (less than 2%) water content. Actual tests for water content indicate that the methanol we have purchased from either supplier has varied from 0.2% to 0.6% water.

There are at least five other methanol suppliers in the Denver area, from which high purity methanol can be obtained, at a somewhat higher cost.

The vehicle is capable of operating on methanol with substantial water content without degradation in engine performance, although the actual water tolerance limit has not been determined. The small water content of the methanol we have been using has no detectable effect on either fuel economy, emissions or driveability.

Using the EPA FTP test data on methanol and gasoline fuel economy, it is determined that with methanol at 65 cents per gallon, a vehicle fuel cost of 4.7 cents per mile is realized. By comparison, unleaded gasoline at $1.40 per gallon yields a vehicle fuel cost of 5.4 cents per mile. Consequently, operation of the vehicle on methanol is 13% less expensive than operation on gasoline. This has been an incentive for methanol operation, and has made the inconvenience of local refueling more acceptable. The large 22 gallon capacity of the alcohol fuel tank has also been a valuable asset. Using the EPA highway fuel economy test data on gasoline, methanol, and ethanol, the vehicle range using only the alcohol tank is 421 miles on methanol or 557 miles on ethanol. The vehicle range on gasoline using the standard 14 gallon gasoline tank is 513 miles. The total vehicle range using both the gasoline tank and the alcohol tank filled with ethanol is 1,070 miles. This long range capability has been particularly valuable on long trips. In August a trip from Denver to Los Angeles and back was made using ethanol and gasoline on the Denver to Los Angeles leg, and methanol and gasoline on the return leg.

There have been no failures of any components related to the alcohol fuel injection system or fuel tank during normal vehicle operation. Two of the alcohol fuel injectors failed immediately after the engine of the vehicle was washed. This was caused by the entry of water into a connector between the injectors and their dropping resistors. The water in the connector caused the short circuit of the dropping resistors on the two injectors, which caused excessive current to flow resulting in the burn-out of the injector solenoid coils. Replacement of the two failed injectors completely repaired the problem. The connector has since been weather sealed to ensure against water penetration.

The only other repairs performed on the car to date are the replacement of one rear shock absorber (under warranty), and the replacement of one low beam headlight. Preventive maintenance was performed at 2,200 miles. This included an oil change, oil filter replacement, and sparkplug replacement.

In preparation for the upcoming "Future Fuels Challenge Rally" a number of modifications are being made to minimize fuel consumption. These include use of narrow, hard compound tires and the installation of a fuel consumption rate meter and electronic throttle positioner system.

Since the vehicle has only been in operation since July, it has been difficult to ascertain the improvement in cold startability on alcohol that the injection system is expected to allow. To date, the coldest starting condition was 40°F. The engine started on methanol after approximately five seconds of cranking. With winter approaching, there will be ample opportunity to further assess cold starting capability on methanol and ethanol.

At some appropriate time in the future, it is anticipated that the engine will be disassembled for an evaluation of the long-term wear of frictional surfaces and an observation of possible corrosion problems.

5. Areas For Future Study

During the course of this project several problem areas and possible improvements have been identified for future study and development.

Catalyst Efficiency

As previously described, modal test data during the EPA FTP and EPA HWFET tests indicated that the three-way exhaust catalyst currently used for gasoline engines suffers as much as a 80% reduction in conversion efficiency for all emissions when used on an alcohol engine. This is not due to either incorrect stoichiometry or a reduced exhaust temperature during alcohol operation. No information has been found in current literature on exhaust catalyst efficiency for alcohol engines.

This is an important area for further study since, with an effective catalyst, the already notably clean emissions of an electronically fuel injected alcohol engine could be made exceptionally clean.

Optimal Fuel Injection Control Strategy for Alcohol

In the present work, the fuel injection control strategies of an ECU designed for optimum gasoline operation were used for methanol and ethanol with good results. However, it is doubtful that these are truly optimum for either alcohol. No previous work has been found in published form which investigates optimum alcohol fuel injection control strategies using a feedback controlled electronic fuel injection system. The construction and testing of an EFI system of this type specifically optimized for alcohol might yield further improvements in effficiency and emissions.

Optimization of Ignition Timing on the Fast-Burn Alcohol Engine

The standard timing curve of the NAPS-Z engine was retained, but shifted slightly by rotation of the distributor. Partial throttle power output tests have indicated that the MBT (Minimum Best Torque) timing curve during methanol operation differs significantly from the gasoline curve. More advance is needed at idle, and less advance at higher RPM's, compared with the gasoline curve. The effect of manifold vacuum on ignition advance is less pronounced on methanol than on gasoline. Further study is needed to fully define the timing control functions for methanol operation, and a means for implementing the different curve must be installed. An electronic dual-advance curve generator has been devised for this purpose. With knowledge of the desired timing dependency on RPM and vacuum, optimum ignition timing during alcohol operation could be implemented, without compromising the optimum ignition timing for gasoline operation.

Increasing Compression Ratio

The theoretical thermal efficiency of an Otto cycle engine increases with increased compression ratio. Compression ratio is limited in gasoline engines by the rather low octane rating or "knock resistance" of gasoline. Methanol has a significantly higher octane rating than gasoline (109 RON compared to 91 RON respectively). This allows the use of much higher compression ratios without encountering knock. Typically, alcohol engines are modified to increase the compression ratio by milling the cylinder head and/or installing high compression pistons. This was not done on this project since it was necessary to retain the capability for operation on gasoline. Higher efficiency could be realized during methanol operation with the increased compression ratio.

If the compression ratio were increased, it may be possible to still operate on gasoline if an electronic detonation sensor is used to retard the ignition timing at the onset of a knocking condition. This could be made interactive with the alcohol fuel injection system such that alcohol fuel injection would be engaged automatically under knocking conditions. Several other variations of this approach have been suggested by colleagues.

Turbocharging

Due to the low octane rating of gasoline, turbocharger boost pressure must be limited to avoid knocking in turbocharged gasoline engines. Methanol or ethanol are tolerant of much higher boost pressures due to their high octane ratings. Turbocharged methanol engines are the rule rather than the exception in many forms of competitive racing.

In a dual-fuel alcohol/gasoline vehicle such as this, the electronic control of the waste-gate setting (which limits boost pressure) is possible, thus allowing different boost limits for gasoline and alcohol. Since turbocharging produces an efficiency advantage during high load engine operation, the use of a "selective boost" turbocharger installation on an alcohol/gasoline dual fuel vehicle might further increase efficiency during alcohol operation.

Materials Compatibility with Alcohol

Considerable analysis of fuel system materials was required in order to specify alcohol tolerant components in the fuel injection system. All indications to date are that the selected components are compatible with methanol and ethanol, since no materials related problems have been encountered other than initial ones which have since been corrected. Inevitably, some compromises must be made in most alcohol engine conversions, since automotive fuel system components are specifically designed for gasoline compatibility, and alcohol compatibility is ignored. We were fortunate in locating alcohol compatible critical components for the system such as the fuel pump, back pressure regulators, pulsation dampener and fuel injectors. It must be noted though, that no currently manufactured versions of any of these parts are actually designed for alcohol use. The fact that the only available fuel pump for use with electronic fuel injection that is tolerant of alcohol service was last manufactured in 1968 is an example of this problem.

The production of alcohol fueled vehicles, whether using fuel injection or carburetors, will require the manufacture of components specifically for alcohol service. Even in Brazil, where carbureted alcohol vehicles are being produced by four major manufacturers, fuel system components are often compromise solutions and materials compatibility problems are still present (5). Surprisingly, little information was found in a literature search on this subject. The few alcohol compatibility papers available simply review known facts in this area, but do not report on new developments. The most useful information was obtained from the producers of the various plastics, elastomers and metals, and from experimental analysis.

It does not appear that there is any lack of alcohol tolerant materials available; the problem is that these materials are not being used for the manufacture of automotive fuel system components. There is still insufficient incentive for manufacturers to do so, considering the very limited market for such components.

The long term effects of alcohol operation on engine reliability have been studied, but have been constrained to carbureted engines with known problems of poor fuel/air ratio control and poor cold operation characteristics (6). It is suggested that with the more sophisticated fuel management made possible with electronic fuel injection many of the previous indications of poor engine reliability on alcohol fuel might be contradicted.

These are clearly areas for further study and development.

6. Acknowlegments

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8. Tables and Figures

TABLE I. Summary of Emission Test Data

Multiple Fuel Experimental Datsun 200 SX

gms/mi.:	HC	CO	NO_x	F/E (mpg)	F/E (gasoline equiv.)
Gasoline					
EPA 1978 FTP:					
Phase I	.994	13.131	1.011	24.847	
Phase II	.055	.192	.427	25.342	
Phase III	.244	6.113	.622	28.859	
Weighted Average	.301	4.502	.602	26.108	
EPA HWFET	.082	.382	.738	36.624	
Nissan data: (sea level)					
EPA 1978 FTP (weighed average)	.156	1.35	0.58	28	
EPA HWFET	.023	0.18	0.31	37	
Methanol					
EPA 1978 FTP:					
Phase I	.522	7.420	1.252	13.066	27.052
Phase II	.034	.155	.803	13.343	27.625
Phase III	.028	1.138	1.089	15.188	31.445
Weighed Average	.133	1.930	.974	13.741	28.449
EPA HWFET	.012	.087	1.130	19.146	39.640
SAE Rally data:					
EPA 1978 FTP (Phase III)	.214	2.978	.838	15.872	32.861
Road Course mileage				25.52	54.33
Ethanol					
EPA HWFET	.021	.087	1.021	25.339	38.510

Note: All tests independantly performed by Environmental Testing Corporation, Aurora, CO (except Nissan data)

TABLE II, COMPARATIVE FUEL PROPERTIES

	Unleaded Gasoline	Methanol (Methyl Alcohol)	Ethanol (Ethyl Alcohol)
Molecular Formula	C_8H_{17}*	CH_3OH	C_2H_5OH
Density (22°C, 1 Atm) (kg/L)	~.73	.79	.79
Boiling Point (°C)	25-210	65.0	78.0
Lower Heating Value (MJ/kg)	43.5	19.7	26.8
Research Octane Number	93	115	107
Latent Heat of Vaporization (MJ/kg)	~0.440	1.110	0.904
Ignition Limits in Air at 22°C, 1 Atm (% volume vapor in air)			
lower	~0.6	5.5	3.5
upper	~8.0	26.0	15.0

*Gasoline is a blend of various hydrocarbons ranging from C_4H_{10} through $C_{12}H_{26}$. Average values are shown for formula and physical properties.

Conversion factors for S.I. Units:

1 MJ/kg = 430 Btu/lb
1 kg/L = 8.35 lb/gal (U.S.)

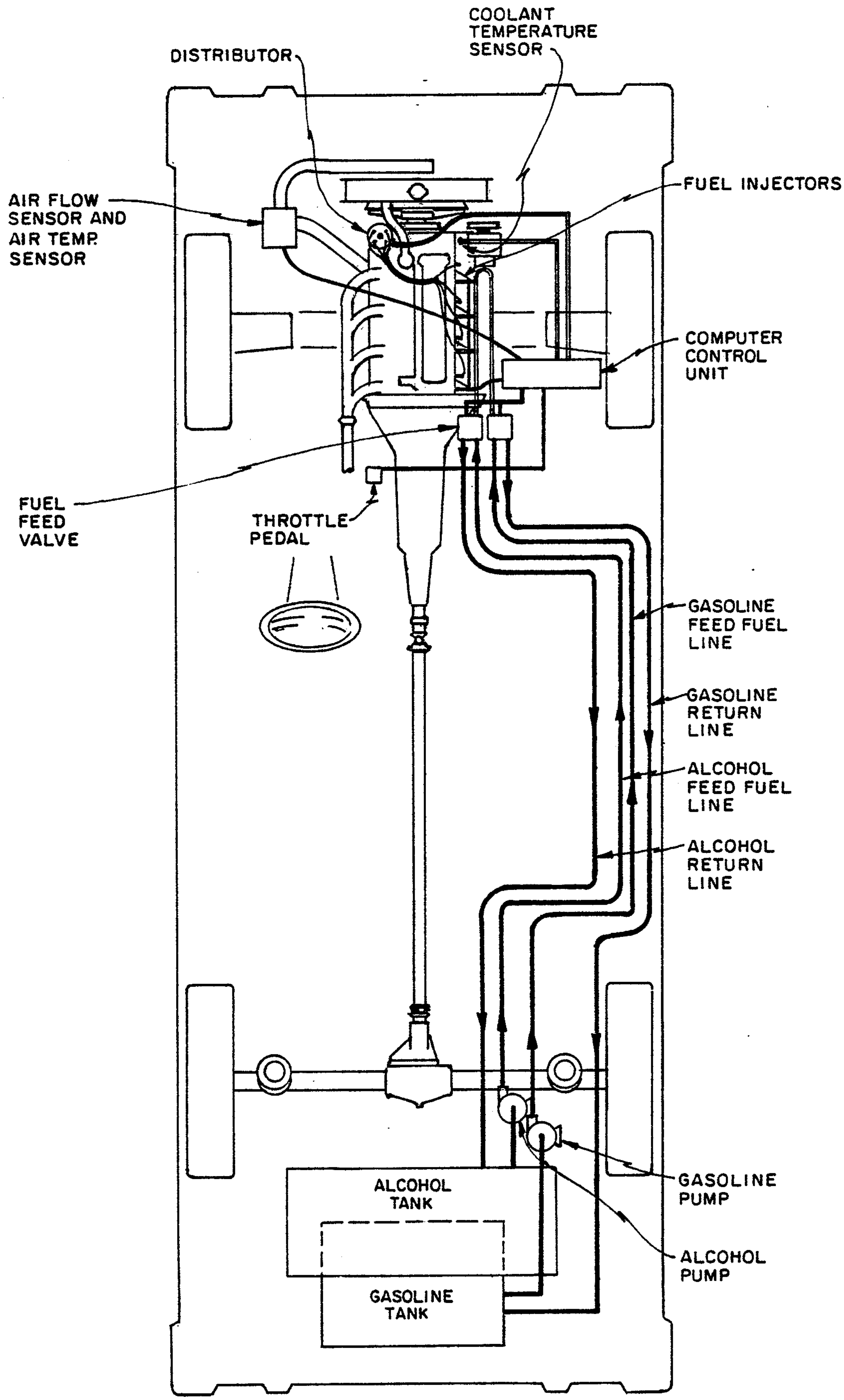

FIGURE 1. DIAGRAM OF MULTIPLE FUEL SYSTEM IN VEHICLE

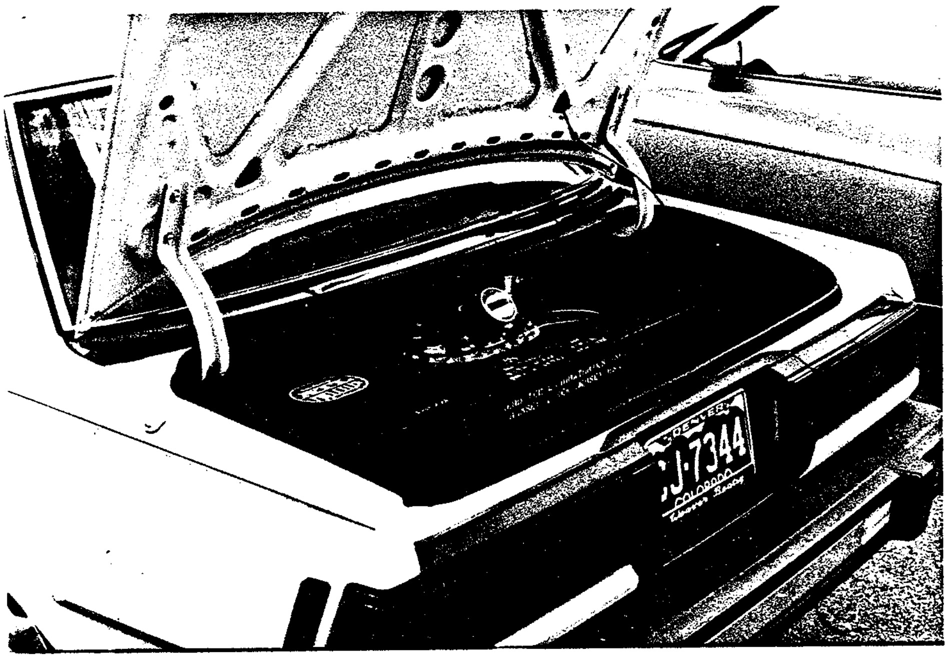

Figure 1a. Alcohol Fuel Tank Installed in Trunk of Vehicle.

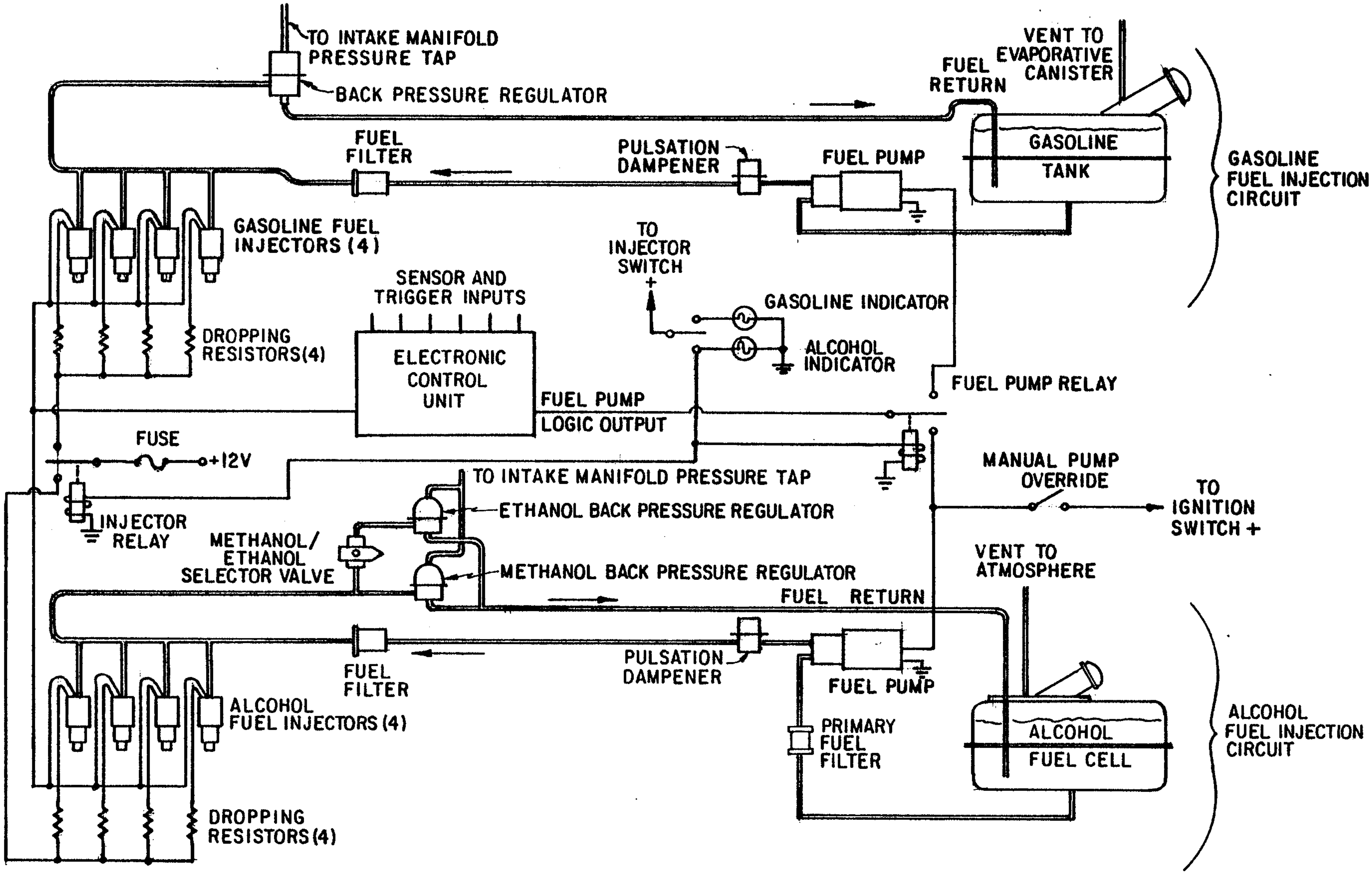

FIGURE 2. SCHEMATIC DIAGRAM OF DUAL ALCOHOL/GASOLINE ELECTRONIC FUEL INJECTION SYSTEM INSTALLED IN DATSUN 200SX.

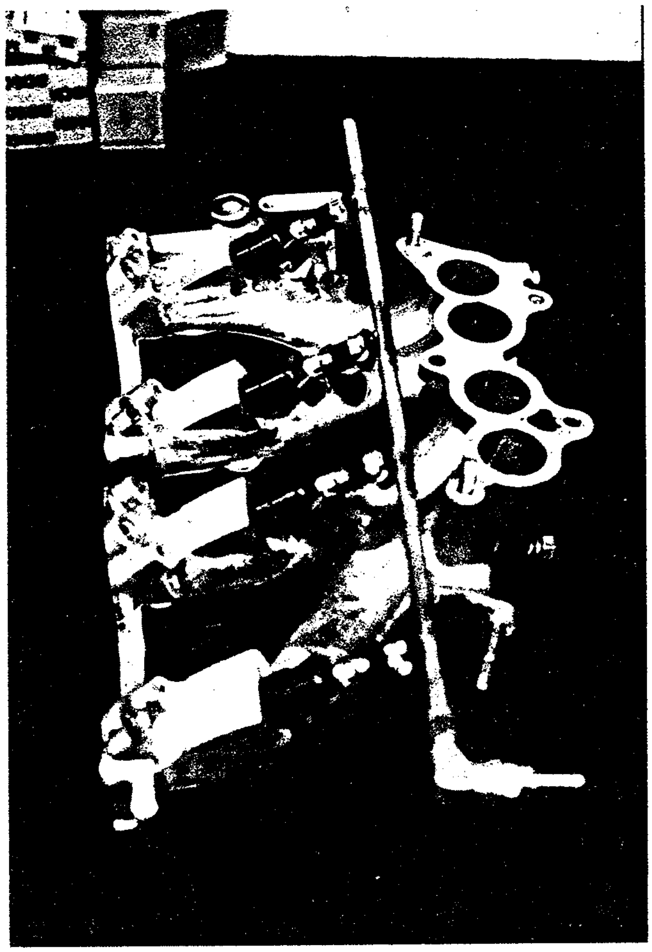

Figure 3. Intake Manifold with Alcohol Fuel Injectors in Place.

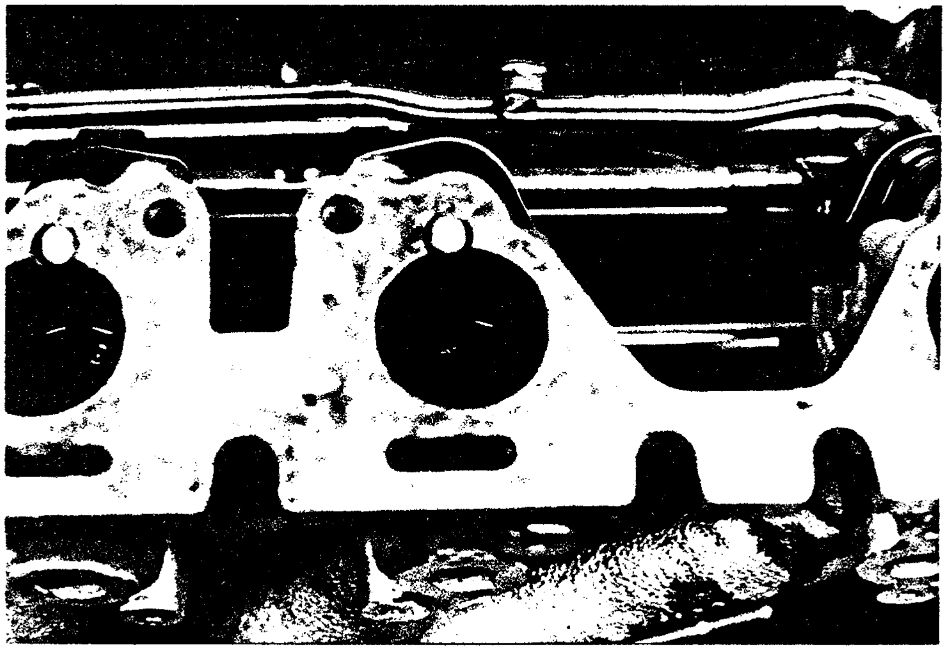

Figure 4. Port View of Intake Manifold with Gasoline and Alcohol Fuel Injector Nozzles Visible

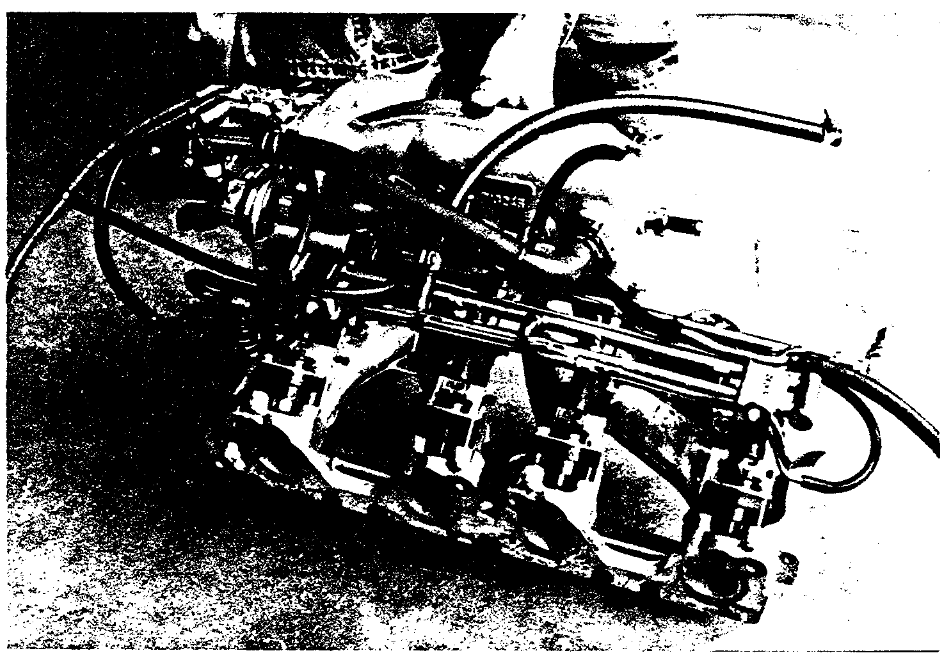

Figure 5. Intake Manifold with All Fuel Injection Components Installed.