EMISSIONS AND ENERGY EFFICIENCY CHARACTERISTICS OF METHANOL-FUELED ENGINES AND VEHICLES

Jeff Alson
Thomas M. Baines

Emission Control Technology Division
Environmental Protection Agency
Ann Arbor, MI

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Jeff Alson, B.S.E.
Environmental Engineer

Thomas M. Baines, M.S.I.O.E.
Research Engineer

Environmental Protection Agency
Ann Arbor, MI 48105

ABSTRACT

This paper summarizes the emissions and energy efficiency results from two recent EPA test programs involving engines designed to utilize methanol fuel. Two methanol-fueled 1981 model year passenger cars and their gasoline-fueled counterparts were tested over the EPA light-duty Federal Test Procedure. The methanol-fueled vehicles emitted greater amounts of methanol and formaldehyde emissions and smaller quantities of hydrocarbons, particulate, and various unregulated pollutants. Carbon monoxide and oxides of nitrogen emission results were mixed. Methanol fueling increased one vehicle's energy efficiency but had little effect on the other. Four heavy-duty engine/catalyst configurations were characterized over the EPA heavy-duty transient and steady-state tests: a conventional diesel engine without a catalytic converter; a version of the same diesel engine modified to utilize dual-injection of methanol and diesel fuels, with and without catalytic aftertreatment; and a pure methanol, direct-injected, spark-ignited engine with catalyst. The engines which utilized methanol fuel emitted higher levels of methanol but lower levels of hydrocarbons, oxides of nitrogen, particulate, smoke and benzo(a)pyrene compared to the diesel engine. Results for carbon monoxide, formaldehyde, and sulfate emissions were varied. The pure methanol engine generally emitted lower emissions than the dual-fueled engine configurations. The energy efficiencies of the methanol-fueled engines were lower than that of the conventional diesel engine. The results from these test programs were compared to those reported in the literature for previous methanol research projects and found to be in general agreement.

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INTRODUCTION

The unforeseen shortages and unstable prices of imported petroleum during the last decade have prompted considerable interest in the development of a long-term domestic fuel supply for our nation's transportation system. Candidate alternative automotive fuels include methanol, ethanol, hydrogen, methane, propane, synthetic gasoline and diesel fuels, broadcut fuels, and shale oil. In order to further our understanding of the impacts of these fuels, the Environmental Protection Agency (EPA) has undertaken a testing program at the Southwest Research Institute to characterize the emissions and energy efficiency capabilities of vehicles and engines that use these fuels.

Because methanol can by synthesized from coal, our most abundant fossil fuel resource, and because it is generally recognized as a viable fuel for spark-ignited, homogeneous charge engines, it has been the subject of much research over the last decade. Unfortunately, such programs have generally involved minor modifications to vehicles which were originally designed and optimized for other fuels (e.g., gasoline). Only recently have manufacturers begun to design engines specifically for methanol combustion.

The purpose of this paper is to present the emissions and energy efficiency results from recent EPA test programs involving light-duty vehicles and heavy-duty engines designed to utilize pure methanol or predominantly methanol fuels. Further, the paper will compare the results of these programs with results from various methanol research projects over the past decade in order to help give the reader a broader understanding of the possible emissions and energy efficiency impacts of broader methanol-fueled vehicle usage.

DESCRIPTION OF THE PROGRAMS

Test Vehicles and Engines

The light-duty vehicles characterized by EPA included two 1981 Ford Escorts and two 1981 Volkswagen Rabbits, with both pairs including one methanol-fueled vehicle and one gasoline-fueled vehicle. Table 1 describes the light-duty vehicles tested. The methanol and gasoline versions of each model are very similar except for the higher compression ratios of the engines

TABLE 1 - LIGHT-DUTY VEHICLES EVALUATED

Vehicle				Engine						
Year	Make	Model	Body Type	Disp.,l	C.R.	Cyl.	Transmission	Odometer Reading (miles)	Fuel Used	Emission Control Devices*
1981	Ford	Escort	Wagon	1.6	8.8:1	4	Manual-4	4872	Gasoline	EGR, PMP, OXD, TWC, CARB
1981	Ford	Escort	Wagon	1.6	11.4:1	4	Auto-3	5976	Methanol	EGR, PMP, OXD, TWC, CARB
1981	VW	Rabbit	4-dr	1.7	8.2:1	4	Auto-3	7919	Gasoline	3CL, MFI
1981	VW	Rabbit	4-dr	1.6	12.5:1	4	Auto-3	1380	Methanol	3CL, MFI

* EGR = Exhaust gas recirculation
PMP = Air pump
OXD = Oxidation catalyst
TWC = Three-way catalyst
3CL = Three-way catalyst with closed-loop fuel system
CARB = Carburetor fuel metering
MFI = Mechanical fuel injection (K-Jetronic)

designed for methanol fuel use. Higher compression ratios are possible because of the higher octane number of methanol fuel. All four vehicles were equipped with factory-installed three-way catalytic converters.

The four heavy-duty engine configurations tested by EPA are described in Table 2. The Volvo TD-100C is representative of current technology diesel engines used in heavy truck applications. The TD-100A is a modified version of this diesel engine and utilizes pilot injection of diesel fuel and primary injection of alcohol fuels (in this program, methanol). The primary fuel is injected through the "original" fuel system with an in-line injection pump while the pilot diesel fuel is injected through a second fuel system consisting of a small distributor-type injection pump. The pilot diesel fuel is used to initiate combustion at all engine operating modes, with the primary fuel then providing the remainder of the necessary energy. Diesel fuel is used exclusively during low loads. (1) The dual-injection TD-100A engine was tested both with and without an oxidation catalyst. The catalyst, manufactured by Unikat AB of Sweden, contained 915 in^3 of catalyst pellets (catalyst content and loading information not supplied by the manufacturer), and was not necessarily optimized for this application.

The M.A.N. D2566 FMUH engine is a modified version of a six-cylinder diesel engine originally developed for bus applications. The primary modification is the addition of a Bosch transistorized pointless ignition system in order to facilitate the combustion of neat methanol fuel. The methanol is injected directly onto the wall of the spherical cavity in the piston which forms the combustion chamber. Mixture formation occurs through the evaporation of the fuel (due to the heat supplied by flame radiation) and the optimized air swirl action. (2) This engine was tested with two catalysts, each handling exhaust from a manifold fed by three cylinders. The catalyst assemblies utilized a Corning substrate with a unit volume of 116 in^3 and a platinum loading of 78 g/ft^3, which is a relatively high noble metal content. The M.A.N. engine is the only one of the four heavy-duty engine/catalyst configurations which utilizes pure methanol fuel. Unfortunately, transient test procedure emissions and energy efficiency data are not available for the diesel version of this engine so direct comparisons between the use of methanol and diesel fuels in almost identical engines will not be possible. The only possible comparisons will be between the pure methanol M.A.N. engine and the diesel-fueled and dual-fueled Volvo engines. Such comparisons must be qualified by the many significant differences between the M.A.N. engine and the Volvo engine configurations as shown in Table 2.

TABLE 2 - HEAVY-DUTY ENGINES EVALUATED

Manufacturer	Model	Disp., l	C.R.	Cyl.	Injection	Aspiration	Maximum Output	Fuel Used	Emission Control Device
Volvo	TD-100 C	9.6	15:1	6	Direct	Turbocharged	240 hp at 2200 rpm	Diesel	None
Volvo	TD-100 A	9.6	15:1	6	Dual	Turbocharged	253 hp at 2200 rpm	Diesel/Methanol	None
Volvo	TD-100 A	9.6	15:1	6	Dual	Turbocharged	256 hp at 2200 rpm	Diesel/Methanol	Oxidation Catalyst
M.A.N.	D2566 FMUH	11.4	18:1	6	Direct	Naturally Aspirated	198 hp at 2200 rpm	Methanol	Oxidation Catalyst

Test Fuels

The methanol fuel used in these test programs was at least 99.9 percent pure and was used as received. Methanol has a research octane number of approximately 108 and a cetane number of 3. A fuel mixture of 94.5 percent methanol and 5.5 percent isopentane has been recommended by Volkswagen and is being used by the California Energy Commission in that state's Alcohol Fleet Test Program. (3) The purpose of the isopentane is to increase the volatility of the fuel thus aiding cold-starting at low ambient temperatures. Since these programs were conducted at Federal Test Procedure temperatures (68 to 86°F), the isopentane was not necessary. One Federal Test Procedure emissions test was performed with the methanol-fueled Escort using a methanol/isopentane blend. Emissions and subjectively evaluated driveability with the blend were very similar to those with pure methanol with the exception of organic emissions which were slightly higher with the blend.

The gasoline and diesel fuels used in this program met the specifications for EPA test fuels found in the Federal Register. (4) The gasoline fuel had a research octane number of 97.7 and a sulfur content less than 0.01 percent. The diesel fuel had a cetane number of 45 and a sulfur content of 0.24 percent.

Emissions Evaluated

Exhaust from each of the light-duty vehicles and heavy-duty engines tested in these programs were analyzed for each of the currently regulated pollutants: hydrocarbons (HC), carbon monoxide (CO), oxides of nitrogen (NOx), and particulate. Tests were performed for a range of other organic compounds such as methanol, formaldehyde, other aldehydes and ketones, and some individual hydrocarbons. In addition, several other unregulated pollutants (nitrosamines and total organic amines, ammonia, cyanide, and methyl nitrite) were measured during tests with the methanol-fueled Ford Escort. Phenols, smoke, sulfate, and benzo(a)pyrene were also analyzed from the heavy-duty engines. Finally, the energy efficiencies of all of the vehicle and engine configurations were determined.

Test Procedures

Each light-duty vehicle was tested either two or three times over the Federal Test Procedure (FTP). The FTP is the primary basis for EPA emissions and fuel economy certification testing and involves a simulated urban dynamometer driving schedule with both cold and hot start portions and an average speed of 19.5 mph. (5) The light-duty vehicles were also tested over the

Highway Fuel Economy Test (HFET) which involves a relatively high-speed (averaging 48.2 mph) driving cycle and is used primarily for highway fuel economy measurement. (6)

The heavy-duty engines were tested over both steady-state and transient operating cycles. The steady-state tests were based on the 1979 13-mode Federal Test Procedure (FTP) for heavy-duty engines. (7) The steady-state unregulated pollutant measurements were taken over a 7-mode test which is an abbreviated version of the 13-mode FTP. Transient testing was based on the 1984 transient FTP for heavy-duty diesel engines as well as the 1986 proposed FTP, which includes particulate measurement. (8)(9) The transient test involves both hot and cold start operation and generally is a fairly lightly loaded cycle. Because EPA believes that transient testing provides a more realistic assessment of heavy-duty engine emissions in urban environments than does steady-state testing, we will present the transient FTP data in this paper and will report steady-state data only when it differs significantly and is thus of additional interest.

The regulated gaseous pollutants (HC, CO, and NOx) were measured in accordance with standard EPA certification test procedures for light-duty vehicles and heavy-duty engines. (5)(10) The unregulated compounds analyzed in these programs were measured by a variety of different procedures, which are summarized in Table 3. Details of the measurement procedures used for these pollutants have been described elsewhere. (11)(12)

RESULTS OF THE LIGHT-DUTY VEHICLE TEST PROGRAM

The average emission and energy efficiency results for the gasoline and methanol-fueled Escorts and Rabbits are shown in Table 4. The following discussion will focus on these data. In an attempt to put these results into perspective, a literature search has been performed to identify the conclusions of previous research projects utilizing pure methanol in light-duty applications. It will be noted that the EPA light-duty test program focused exclusively on Otto cycle engines. This is convenient for comparative purposes since nearly all previous methanol light-duty vehicle research has involved Otto cycle engines and appropriate since 95 percent of all new passenger cars utilize Otto cycle engines.

TABLE 3 - MEASUREMENT PROCEDURES FOR VARIOUS COMPOUNDS

Compound	Sampling	Method of Analysis
Methanol	Impinger	Gas chromatograph with flame ionization detector.
Aldehydes and Ketones	Impinger	Dinitrophenylhydrazone derivative; gas chromatograph with flame ionization detector.
Individual Hydrocarbons	Bag	Gas chromatograph with flame ionization detector.
Particulate Matter	Filter	Weighed using microbalance.
Nitrosamines (LDV* only)	Trap	Gas chromatograph with TEA detector.
Ammonia (LDV only)	Impinger	Ion chromatograph.
Total Cyanide (LDV only)	Impinger	Cyanogen chloride derivative; gas chromatograph with electron capture detector.

TABLE 3 - MEASUREMENT PROCEDURES FOR VARIOUS COMPOUNDS (CONT'D)

Compound	Sampling	Method of Analysis
Organic Amines (LDV only)	Impinger	Gas chromatograph with ascarite precolumn and nitrogen-phosphorus detector.
Methyl Nitrite (LDV only)	Bag	Gas chromatograph with mass spectrometer.
Phenols (HDE+ only)	Impinger	Gas chromatograph with flame ionization detector.
Sulfate (HDE only)	Filter	Barium chloranilate.
Benzo(a)pyrene (HDE only)	Filter	Liquid chromatograph.
Smoke (HDE only)	—	Smokemeter.
Odor (HDE only)	Trap	Liquid chromatograph.

* LDV = Light-Duty Vehicles
\+ HDE = Heavy-Duty Engines

TABLE 4 - AVERAGE LIGHT-DUTY VEHICLE EMISSION AND ENERGY EFFICIENCY RESULTS

	FTP				HFET			
	Ford Escorts		VW Rabbits		Ford Escorts		VW Rabbits	
	Gas.[a]	Meth.[b]	Gas.	Meth.	Gas.	Meth.	Gas.	Meth.
Hydrocarbons (FID), g/mi	0.37	0.42[c]	0.11	0.39[c]	0.16	0.08[c]	0.11	0.02[c]
Carbon Monoxide, g/mi	4.49	6.03	1.08	0.88	1.69	0.53	1.26	0.23
Oxides of Nitrogen, g/mi	0.55	0.40	0.16	0.68	0.50	0.32	0.06	0.21
Particulate, mg/mi	9.2	6.3	11.8	4.7	2.3	10.1	32.2	11.4
Methanol, mg/mi	ND[d]	407	ND	440	ND	61	ND	2
Total Aldehydes and Ketones, mg/mi	0.2	33.6	ND	10.3	ND	24.3	ND	ND
Formaldehyde, mg/mi	0.2	33.0	ND	10.3	ND	24.0	ND	ND
Total Individual Hydrocarbons, mg/mi	155	50	40	5	75	6	61	1
Methane, mg/mi	96.1	48.3	14.0	4.8	43.8	4.8	27.5	1.0
Ethylene, mg/mi	8.7	0.3	4.8	0.2	5.2	0.2	4.2	ND
Ethane, mg/mi	18.2	0.5	2.6	<0.1	12.2	0.2	6.3	ND
Acetylene, mg/mi	1.4	<0.1	1.8	<0.1	ND	ND	ND	ND
Propane, mg/mi	0.8	0.6	ND	ND	0.3	0.5	ND	ND
Propylene, mg/mi	6.1	ND	4.2	ND	4.7	ND	5.2	ND
Benzene, mg/mi	6.3	<0.1	5.3	ND	3.2	ND	10.5	ND
Toluene, mg/mi	17.2	<0.1	9.2	ND	5.6	ND	7.4	ND

TABLE 4 - AVERAGE LIGHT-DUTY VEHICLE EMISSION AND ENERGY EFFICIENCY RESULTS (CONT'D)

	FTP				HFET			
	Ford Escorts		VW Rabbits		Ford Escorts		VW Rabbits	
	Gas.	Meth.	Gas.	Meth.	Gas.	Meth.	Gas.	Meth.
Nitrosamines, mg/mi	ND	ND	ND	ND	[e]	[e]	[e]	[e]
Ammonia, mg/mi	[e]	10.0	[e]	[e]	[e]	[e]	[e]	[e]
Total Cyanide, mg/mi	[e]	ND	[e]	[e]	[e]	[e]	[e]	[e]
Total Organic Amines, mg/mi	[e]	<0.1	[e]	[e]	[e]	[e]	[e]	[e]
Methyl Nitrite, ppm	[e]	0-0.5	ND	0-1.1	[e]	ND	[e]	[e]
Fuel Economy, mi/gal	24.5	12.6	23.8	13.8	37.9	18.0	30.5	17.2
Energy Efficiency, mi/10^4Btu	2.16	2.25	2.10	2.46	3.35	3.21	2.69	3.06

[a] Gasoline-fueled
[b] Methanol-fueled
[c] Hydrocarbons as measured by the FID (flame ionization detector) and expressed as methanol.
[d] None detected.
[e] Analysis not conducted.

Organic Emissions

Gasoline is composed of various hydrocarbon compounds. One important class of emissions from gasoline-fueled vehicles includes unburned fuel hydrocarbons and their derivatives. Strictly speaking, hydrocarbons are those compounds which include only hydrogen and carbon in their molecular structure. While most fuel-related emissions from gasoline-fueled vehicles are hydrocarbons, derivatives such as oxygenated hydrocarbons are also emitted. Because hydrocarbons dominate these emissions, the custom has been to use the term hydrocarbons to include all unburned gasoline-related emissions as measured by the approved procedure, even those derivatives which are not strictly hydrocarbons. Accordingly, the EPA standard for unburned fuel emissions is a hydrocarbon standard based upon usage of a flame ionization detector (FID). The FID measures most hydrocarbon compounds very accurately. The FID does not measure oxygenated hydrocarbons such as aldehydes and alcohols very accurately.

Since methanol fuel is an oxygenated hydrocarbon itself, the emissions from methanol-fueled vehicles are predominantly oxygenated hydrocarbons such as unburned methanol and aldehydes (specifically, formaldehyde). Thus, reliance upon the term hydrocarbons may not be appropriate, and therefore the term "organic" emissions will be used in this paper to include all unburned fuel and fuel derivative emissions (i.e., all hydrocarbon and oxygenated hydrocarbon emissions). Because of the inability of the FID to accurately measure oxygenated hydrocarbons, the organic compounds in methanol-fueled vehicle exhaust were determined by individual measurement procedures.

Table 4 gives the emission values for various organic species that were measured in this program -- hydrocarbons, methanol, total aldehydes and ketones, formaldehyde, and 8 different individual hydrocarbon compounds. The FID-measured hydrocarbons are presented in the first row. As mentioned above, the hydrocarbons from gasoline-fueled vehicles consist primarily of unburned gasoline-derived hydrocarbons (accurately measured by the FID) and a small quantity of aldehydes (generally not accurately measured by the FID). For each methanol-fueled vehicle, the FID-measured hydrocarbon datum is assumed to be the result of the FID measuring only unburned methanol (which is not strictly correct as there are some hydrocarbons and aldehydes in the exhaust stream). Therefore, the reported FID hydrocarbon values for the methanol-fueled vehicles are based on the molecular weight of the fuel, which includes the oxygen component (i.e., the HC data are reported as methanol). This results in mass emission measurements which are twice as high as they would be if the oxygen were excluded.

Table 5 computes the total organic emissions for the vehicles tested. This is done by adding the actual measurements for hydrocarbon, methanol and formaldehyde (the predominant aldehyde). For the gasoline-fueled vehicles, the hydrocarbon data are the FID measured hydrocarbon results. For the methanol-fueled vehicles, the hydrocarbon data are the sum of the total individual hydrocarbon results.

Certain trends are apparent from Table 5. First, organic emissions from the gasoline-fueled vehicles are nearly all hydrocarbons while the methanol engine exhaust is dominated by unburned methanol but contains small amounts of formaldehyde and low molecular weight hydrocarbons as well. In terms of total organic emissions, both methanol vehicles emitted greater amounts over the FTP but lesser amounts over the HFET compared to the corresponding gasoline vehicles. The total organic emissions from the methanol vehicles are somewhat greater than the level of the current 0.41 g/mi hydrocarbon emission standard for light-duty vehicles.

In this test program, the methanol-fueled vehicles emitted greater amounts of organic emissions over the FTP than did the gasoline-fueled vehicles. A survey of the literature indicates that previous research has resulted in levels of organic emissions from methanol-fueled vehicles ranging from somewhat lower to up to five times higher than organic emissions from gasoline-fueled versions of the same model. (13)(14)(15)(16) These projects all used either an oxidation catalyst or no catalyst at all. Two other projects have been reported which utilized three-way catalysts on Ford Pintos. Both of these projects reported methanol-fueled vehicle emissions to be approximately one-half of the gasoline-fueled vehicle emissions on an <u>ionizable carbon basis</u>, which would result in similar or slightly higher methanol emissions on a mass basis. (17)(18) Thus, the EPA results are within the range of previous data for total organics emissions.

The primary justification for the regulation of organic emissions is their role as oxidant precursors in urban atmospheres. As such, the relative <u>masses</u> of organic emissions in gasoline and methanol exhausts are not as important as the relative <u>photochemical reactivities</u> of the organic species. Formaldehyde is known to be very photochemically reactive, but unburned methanol itself is generally considered to be of low photochemical reactivity. Methanol vehicle exhaust contains almost no alkenes, aromatics, or nonmethane

TABLE 5 - AVERAGE LIGHT-DUTY VEHICLE ORGANIC EMISSION RESULTS (g/mi)

	FTP				HFET			
	Ford Escorts		VW Rabbits		Ford Escorts		VW Rabbits	
	Gas.[a]	Meth.[b]	Gas.	Meth.	Gas.	Meth.	Gas.	Meth.
Hydrocarbons [c]	0.37	0.050	0.11	0.005	0.16	0.006	0.11	0.001
Methanol	0	0.41	0	0.44	0	0.061	0	0.002
Formaldehyde	0.0002	0.033	0	0.010	0	0.024	0	0
Total "Organics"	0.37	0.49	0.11	0.46	0.16	0.09	0.11	0.003

[a] Gasoline-fueled.
[b] Methanol-fueled.
[c] For the gasoline-fueled vehicles, this is the FID value. For the methanol-fueled vehicles, this is the sum of the "individual hydrocarbon" data from Table 4.

alkanes which are the major reactive components of gasoline exhaust. Thus, it is not immediately clear whether methanol exhaust would be more or less reactive than gasoline exhaust.

Probably the only way to compare the relative photochemical reactivities of methanol and gasoline exhausts is to utilize sophisticated smog chamber testing. Bechtold and Pullman performed such a comparison with a 1976 full-size Dodge (with and without an oxidation catalyst) and four 1978 Ford Pintos with three-way-catalysts. Generally, they found that the photochemical reactivity of methanol exhaust was similar to or less than the reactivity of gasoline exhaust under the same vehicle operating conditions. (17) Additional smog chamber work is necessary to quantify the reactivity impacts of methanol vehicles.

A second major issue with methanol-fueled vehicles is formaldehyde emission. As Table 5 shows, the methanol-fueled Escort and Rabbit emitted 33 and 10 mg/mile of formaldehyde, respectively, while the gasoline-fueled Escort and Rabbit emitted 2 and 0 mg/mile, respectively. Past studies confirm that aldehyde emissions are higher from methanol vehicles. (14)(15)(17)(18)(19) These higher emissions are of concern because of formaldehyde's toxicity and possible carcinogenicity, (28) in addition to its high reactivity in the photochemical process. Table 6 gives the formaldehyde emission levels for several different types of gasoline-fueled light-duty vehicles from previous EPA test programs. Table 6 shows that the formaldehyde emissions from the methanol-fueled Escort and Rabbit were much higher than the three-way-catalyst cars but lower than the 1970 non-catalyst cars. Lowering the formaldehyde emissions from methanol-fueled vehicles will likely be a high priority for those manufacturers seeking to introduce such vehicles into the market.

Carbon Monoxide Emissions

As shown in Table 4, CO emissions for the methanol-fueled Escort and Rabbit over the FTP were 6.03 g/mi and 0.88 g/mi, respectively. The methanol-fueled Escort emitted 34 percent more CO and the methanol-fueled Rabbit emitted 19 percent less CO than their gasoline-fueled counterparts over the FTP. Highway CO values were lower for the methanol-fueled vehicles in both cases. Previous studies had indicated that CO levels from methanol-fueled vehicles were similar to those from gasoline-fueled vehicles under stoichiometric conditions. (13)(14)(15)(16) CO levels are primarily a function of air/fuel ratios with more CO formed as the mixture becomes richer. It has been shown that at the leaner air/fuel ratios which are

TABLE 6 - COMPARISON OF AVERAGE FTP FORMALDEHYDE EMISSIONS FOR VARIOUS LIGHT-DUTY VEHICLES

Vehicles	Formaldehyde Emissions (mg/mile)
Previous EPA Projects (20) - All Gasoline-Fueled Vehicles	
1981 3-way-catalyst equipped cars	1
1978, 1979 3-way-catalyst equipped cars	2
1978 oxidation-catalyst equipped cars	3-11
1977 non-catalyst cars	16
1970 non-catalyst cars	51
This Project - All Methanol-Fueled Vehicles	
1981 3-way-catalyst equipped, carbureted car (Escort)	33
1981 3-way-catalyst equipped, fuel injected car (Rabbit)	10

feasible with methanol vehicles, CO emissions are generally lower. (13)(16)

Oxides of Nitrogen Emissions

FTP NOx emissions were 0.40 g/mi and 0.68 g/mi for the methanol-fueled Escort and Rabbit, respectively, compared to 0.55 g/mi and 0.16 g/mi for the gasoline-fueled models (see Table 4). The methanol-fueled Escort emitted 27 percent less NOx but the methanol Rabbit emitted four times more NOx (though still well below the level of the standard of 1.0 g/mi). These mixed results for NOx emissions were unexpected. NOx formation is a function of peak combustion temperatures. As methanol combusts at a lower flame temperature than gasoline, it could theoretically be expected to result in lower NOx levels. This possibility of lower NOx levels was one of the driving forces behind early methanol research projects and was substantiated by several studies showing NOx reductions in the range of 30 to 65 percent. (13)(16)(19)(21) The higher compression ratios of the methanol vehicles would be expected to increase NOx formation somewhat, but higher compression ratios also permit less spark timing advance which decreases NOx emissions. In view of the lower CO and higher NOx emissions (as well as better energy efficiency, which will be discussed below) from the methanol-fueled Rabbit, it seems plausible that the Rabbit was operated leaner than the Escort, which could make successful operation of the reduction catalyst unlikely and lead to higher NOx emissions.

Particulate Emissions

As shown in Table 4, particulate levels over the FTP were lower for both methanol-fueled vehicles than for the corresponding gasoline-fueled vehicle. The methanol-fueled Rabbit also emitted less particulate over the HFET, although the methanol-fueled Escort emitted more particulate over the HFET. All of the particulate levels were well below the level of the 0.20 g/mi standard which is planned for 1985 light-duty diesel vehicles.

Other Unregulated Pollutants

Ammonia, cyanide, and organic amine emissions were measured from the methanol-fueled Escort over the FTP. The resulting emissions were 10 mg/mi, 0 mg/mi, and 0.02 mg/mi, respectively. These levels are somewhat lower than the average levels of 13 mg/mi ammonia, 3 mg/mi cyanide, and 0.05 mg/mi organic amines measured from three-way-catalyst gasoline-fueled vehicles in a previous project. (22) All four vehicles were tested for nitrosamines over the FTP and none were detected.

Very low levels of methyl nitrite were detected under certain testing conditions with the methanol-fueled vehicles. A more detailed discussion of the nitrosamine and methyl nitrite testing and results is presented elsewhere. (20)

Energy Efficiency

The fuel economy and energy efficiency results are also given in Table 4. The fuel economy values for the methanol-fueled vehicles are low, due to the volumetric heating value of methanol being about one-half that of gasoline. But fuel economy is usually not as important as energy efficiency. Accordingly, the fuel economy results have been translated into miles per 10^4 Btu, a measure of how far a fuel can propel a vehicle on 10,000 Btu. On this basis, the gasoline-fueled Escort had a value of 2.16 mi/10^4 Btu over the FTP while the methanol-fueled Escort had a value of 2.25 mi/10^4 Btu, an improvement of 4 percent. On the HFET, the methanol-fueled Escort was 4 percent less efficient. Overall, then, the efficiencies of the gasoline and methanol-fueled Escorts were similar. The methanol-fueled Rabbit was 17 percent more efficient over the FTP and 14 percent more efficient over the HFET, for an overall efficiency increase of approximately 15 percent. One reason why the use of methanol fuel increased the efficiency of the Rabbit but not that of the Escort may be that Ford made a more concerted effort to maintain very low NOx levels which could have resulted in some detrimental energy efficiency tradeoffs (more spark timing retard, possibly not as lean, etc.).

There are several reasons why methanol-fueled vehicles would be expected to have higher energy efficiencies than their gasoline-fueled counterparts: methanol's high octane number allows the usage of higher compression ratios, its wider flammability limits and higher flame speeds provide acceptable engine performance at leaner operation, and its high heat of vaporization acts as an internal coolant reducing the mixture temperature during the compression stroke and allowing a larger charge to be inducted. (16) Improvements in energy efficiency as high as 25 to 30 percent have been hypothesized, (29) but only recently have entire vehicles been assembled to operate on pure methanol which can be evaluated against these expectations. In view of the above discussion, Volkswagen's 15 percent energy efficiency improvement is not unexpected.

Summary of Light-Duty Vehicle Test Program

Total mass organic emissions were somewhat higher for both methanol-fueled vehicles over the FTP (though lower over the HFET), but resulting impacts on urban atmosphere photochemical reactivities cannot be predicted at this time. Formaldehyde emissions were higher for both of the methanol-fueled vehicles under all testing conditions. Both CO and NOx results were mixed, with methanol fueling sometimes increasing and sometimes decreasing these emissions. Theoretical expectations and previous data both indicate that methanol-fueled vehicles should emit lower levels of NOx emissions compared to equivalent gasoline-fueled vehicles. Emissions of particulate and unregulated compounds such as ammonia, cyanide, and organic amines were consistently lower from the methanol-fueled vehicles than from similar gasoline-fueled vehicles. The energy efficiency results were also mixed. The methanol-fueled Escort showed no overall improvement while the methanol-fueled Rabbit was approximately 15 percent more efficient than the gasoline-fueled Rabbit. A more extensive discussion of this light-duty vehicle testing program is presented elsewhere. (20)

RESULTS OF THE HEAVY-DUTY ENGINE TEST PROGRAM

The average emission and energy efficiency results for the heavy-duty engines evaluated over the transient FTP are shown in Table 7. The following discussion will focus on these data, but the results of steady-state testing will also be discussed when they are of additional interest. Diesel engines have always dominated the most demanding heavy truck applications, but there are indications that diesels will soon dominate nearly all classes of heavy-duty vehicles. Thus, one of EPA's interests in the heavy-duty area has been engines which utilize methanol and which could replace existing diesel engines. Attempts will be made to compare these results to past projects found in the literature, but this is the first program to be publically reported that characterizes the emissions of methanol-fueled diesel-cycle engines over the EPA heavy-duty transient test procedure. Thus, comparisons to a large data base are not possible.

Organic Emissions

As discussed above in the section on light-duty vehicle results, the issue of organic emissions from gasoline and methanol-fueled vehicles can be somewhat confusing because of the different types of exhaust products and measurement procedures. Diesel fuel, like gasoline, is composed of hydrocarbons and a diesel engine's unburned fuel-related emissions are dominated by hydrocarbons. Thus, there is the same difficulty in comparing diesel and methanol-fueled engine organic emissions as there is with gasoline and methanol-fueled vehicle organic emissions.

TABLE 7 - AVERAGE HEAVY-DUTY ENGINE EMISSION AND ENERGY EFFICIENCY RESULTS OVER THE TRANSIENT FEDERAL TEST PROCEDURE

	Volvo TD-100 C Conventional Diesel No Catalyst	Volvo TD-100 A Methanol/Diesel Dual-Injection No Catalyst	Volvo TD-100 A Methanol/Diesel Dual-Injection With Catalyst	MAN D2566 FMUH Spark-Ignited Methanol With Catalyst
Hydrocarbons,[a] g/hp-hr	0.85	1.45	0.12	0.04
Carbon Monoxide, g/hp-hr	3.01	7.67	2.69	0.31
Oxides of Nitrogen,[b] g/hp-hr	8.34	5.45	5.51	6.61
Particulate, g/hp-hr	0.52	0.30	0.27	0.04
Methanol, mg/hp-hr	[c]	3700	670	680
Total Aldehydes and Ketones, mg/hp-hr	10	190	200	<1
Formaldehyde, mg/hp-hr	10	170	200	<1
Total Phenols, mg/hp-hr	26	18	36	0
Total Individual Hydrocarbons, mg/hp-hr	97	130	50	1
Methane, mg/hp-hr	11	26	22	1
Ethylene, mg/hp-hr	78	71	23	<1
Ethane, mg/hp-hr	<1	1	<1	<1
Acetylene, mg/hp-hr	2	<1	<1	<1
Propylene, mg/hp-hr	6	30	4	<1
Benzene, mg/hp-hr	1	5	1	<1

TABLE 7 - AVERAGE HEAVY-DUTY ENGINE EMISSION AND ENERGY EFFICIENCY RESULTS OVER THE TRANSIENT FEDERAL TEST PROCEDURE (CONT'D)

	Volvo TD-100 C Conventional Diesel No Catalyst	Volvo TD-100 A Methanol/Diesel Dual-Injection No Catalyst	Volvo TD-100 A Methanol/Diesel Dual-Injection With Catalyst	MAN D2566 FMUH Spark-Ignited Methanol With Catalyst
Sulfate, mg/hp-hr	28	12	73	Not Run
Benzo(a)pyrene, μg/hp-hr	2.8	1.3	0.2	0.01
Brake Specific Fuel Consumption				
lb fuel/hp-hr	0.476	0.878	0.856	1.171
lb diesel equivalent/hp-hr	0.476	0.492	0.487	0.538
Smoke, peak percent opacity	33	23	7	0

[a] Hydrocarbons as measured by the HFID (heated flame ionization detector) and expressed as diesel-like species.
[b] No NOx correction factor used.
[c] Does not apply.

Table 8 simplifies the organic emissions results from four of the heavy-duty engines evaluated in this program. The total organic emissions are the sum of the hydrocarbon, methanol, total aldehydes and ketones, and total phenols measured by the specific testing procedures used for each pollutant or class of pollutants. Only the hydrocarbon values in Table 8 need explanation. The hydrocarbon value for the conventional diesel engine is the value in Table 7 for the heated flame ionization detector (HFID) minus the value for total phenols. This is appropriate since the HFID detects and measures phenols very accurately. The hydrocarbon values for the dual-injection Volvo and the pure methanol M.A.N. engines are based on the individual hydrocarbon measurements in Table 7. Propane and toluene are not listed in Table 7 nor included in the data in Table 8, the former because it was not detected in any of the tests and the latter because of suspected chromatographic interferences.

As Table 8 shows, the dual-injection Volvo without catalyst emitted 4.04 g/hp-hr of organics, a level 4 to 6 times higher than the other three engine/catalyst configurations tested. The dual-injection Volvo engine with catalyst emitted 0.96 g/hp-hr, the conventional diesel Volvo engine emitted 0.86 g/hp-hr, and the pure methanol M.A.N. engine emitted 0.68 g/hp-hr. The emissions from these three configurations are all under the level of the 1.3 g/hp-hr standard scheduled for future heavy-duty engines. The organics from the conventional diesel engine were nearly all hydrocarbons, while the organics from the dual-fuel engine (with and without catalyst) were primarily methanol but also included significant amounts of aldehydes and ketones and hydrocarbons. The organic emissions from the pure methanol engine were almost all unburned methanol with only trace amounts of aldehydes and hydrocarbons detected. The pure methanol M.A.N. engine emitted even less aldehydes than the conventional diesel engine over the transient FTP cycle.

As a check on the M.A.N. aldehyde results during transient operation, we will report the aldehyde results for the 7-mode steady-state tests. The pure methanol engine emitted negligible amounts of aldehydes over five of the seven modes of the steady-state test, but did emit very significant amounts during the two 2-percent load speeds. In terms of the 7-mode composite, the pure methanol M.A.N. engine emitted 48 mg/hp-hr; this compares to 14 mg/hp-hr for the conventional diesel engine, 64 mg/hp-hr for the dual-fuel Volvo engine without catalyst, and 110 mg/hp-hr for the dual-fuel Volvo engine with catalyst. (23) Note that the use of the catalyst on the dual-injection engine actually increased aldehyde emissions for both the transient and steady-state

TABLE 8 - AVERAGE HEAVY-DUTY ENGINE ORGANIC EMISSION RESULTS OVER THE TRANSIENT FTP (g/hp-hr)

	Volvo TD-100 C Conventional Diesel No Catalyst	Volvo TD-100 A Methanol/Diesel Dual-Injection No Catalyst	Volvo TD-100 A Methanol/Diesel Dual-Injection With Catalyst	MAN D2566 FMUH Spark-Ignited Methanol With Catalyst
Hydrocarbons	0.82[a]	0.13[b]	0.05[b]	0.001[b]
Methanol	0	3.70	0.67	0.68
Total Aldehydes and Ketones	0.01	0.19	0.20	0.001
Total Phenols	0.03	0.02	0.04	0
Total "Organics"	0.86	4.04	0.96	0.68

[a] From Table 7, hydrocarbons less phenols.
[b] From Table 7, total individual hydrocarbons.

testing. This is likely due to the partial oxidation of unburned methanol to formaldehyde. A larger or more efficient catalyst might solve this problem.

Thus, the pure methanol engine emitted over 3 times more aldehydes than the conventional diesel engine over the composite 7-mode test, but less aldehydes than the conventional diesel over the transient test. The high level of aldehydes during the steady-state 2-percent load speeds and the likelihood of aldehyde formation due to partial oxidation in the catalyst indicates that more research into aldehyde control is necessary and that improvements may be possible.

In comparing the organic emission results of the four engine/catalyst configurations in Table 8, two conclusions seem apparent. The first is that the pure methanol engine, with catalyst, actually produces lower organic emissions than the conventional diesel without catalyst (catalysts are difficult to utilize with diesel engines because of particulate matter buildup and subsequent blockage). This improvement was even more apparent over the steady-state testing where the organic emissions with the conventional diesel engine were nearly twice those from the pure methanol M.A.N. engine. (23) The second is that dual-injection of methanol and diesel fuel increases organic emissions significantly without an oxidation catalyst and increases them slightly with an oxidation catalyst. The use of dual-injection did not provide the same organic emission reductions as did the use of pure methanol fuel.

Of course, this discussion has centered on the mass organic emissions and not the effects on urban atmosphere photochemical reactivities. Again, research needs to be performed on the relative reactivity impacts of methanol and diesel exhausts.

Carbon Monoxide Emissions

The carbon monoxide emissions for each of the configurations evaluated are shown in Table 7. They were 3.01 g/hp-hr for the Volvo diesel engine, 7.67 g/hp-hr for the dual-injection Volvo engine without catalyst, 2.69 g/hp-hr for the dual-injection Volvo engine with catalyst, and 0.31 g/hp-hr for the pure methanol M.A.N. engine. All of these levels are well below the levels of present and future heavy-duty CO standards. The M.A.N. engine's very low CO emissions are due both to very low engine-out emissions and effective catalytic aftertreatment.

Oxides of Nitrogen Emissions

As Table 7 indicates, the transient NOx emissions were 8.34 g/hp-hr for the conventional diesel engine, 5.45 g/hp-hr for the dual-fueled engine without catalyst, 5.51 g/hp-hr for the dual-fueled engine with catalyst, and 6.61 g/hp-hr for the pure methanol engine. The heavy-duty NOx standard is currently 10.7 g/hp-hr, but the Clean Air Act Amendments of 1977 require EPA to promulgate a new standard representing a 75 percent reduction from baseline values. It might be expected that the utilization of methanol, with its lower flame temperature, would lower NOx emissions. Previous dual-fuel, single-cylinder testing had shown NOx reductions as high as 50 percent. (24)(25) The dual-fuel Volvo, both with and without catalyst, produced 38 percent less NOx than the Volvo diesel engine, while the pure methanol M.A.N. engine emitted 21 percent less than the conventional diesel engine. Reductions during steady-state testing were even larger, ranging from 23 percent for the pure methanol engine to 56 percent for the dual-injection engine without catalyst, all compared to the conventional diesel engine. Thus, these results do agree with both the theoretical expectation of lower NOx emissions and previous results.

Particulate and Related Emissions

Methanol has no carbon-carbon bonds and generally has not been observed to form carbonaceous particles. In addition, methanol does not typically contain inorganic materials like sulfur or lead which can also be sources of solid particulate. For these reasons, it has been hypothesized that pure methanol usage in diesel engines would result in zero or near zero particulate emissions. (26) If true, this would be a primary advantage for methanol usage as particulate emissions from diesel engines have become a major environmental concern.

The data in Table 7 confirm the hypothesis that methanol produces little or no particulate. The conventional diesel engine produced 0.52 g/hp-hr of particulate during transient testing. The dual-fuel Volvo engine, which on average used approximately 20 percent diesel fuel by weight, emitted 0.30 and 0.27 g/hp-hr of particulate, respectively, for the non-catalyst and catalyst versions (decreases of 42 and 48 percent). The pure methanol M.A.N. engine emitted just 0.04 g/hp-hr, a reduction of 92 percent from the conventional diesel engine. The particulate values under steady-state testing were similar, with an even lower level for the pure methanol engine. The M.A.N. engine results were the only data below the level of the proposed EPA particulate standard of 0.25 g/hp-hr.

No carbon (soot) particulate was visible on any of the filters taken from the pure methanol engine. These results suggest that methanol combustion may inherently produce low particulate emissions and that the particulate emitted by the dual-injection engine was likely due to diesel fuel combustion.

Smoke is a measure of the visible fraction of particulate matter. As such, smoke levels do not necessarily correlate with particulate mass emission values. In this program, acceleration, lug, and peak smoke measurements were taken with the FTP smoke procedure. Table 7 gives the peak opacity readings. Generally, the diesel engine produced the highest smoke levels, followed by the dual-fuel engine without catalyst, the dual-fuel engine with catalyst, and the pure methanol engine. There was essentially no smoke opacity for the M.A.N. engine at any time. Note that these smoke levels do correlate directionally with the particulate values discussed above.

Sulfate is frequently one component of particulate matter. It is formed by the oxidation of fuel sulfur to sulfate. Because chemical-grade methanol contains no sulfur, the use of methanol should reduce sulfate emissions. The conventional diesel engine emitted 28 mg/hp-hr of sulfate. The dual-fuel engine without catalyst emitted 12 mg/hp-hr, a reduction of 57 percent. But the addition of the oxidation catalyst increased the sulfate emissions of the dual-fuel engine to 73 mg/hp-hr, an increase of six times compared to the non-catalyst dual-fuel configuration and an increase of 2.6 times compared to the diesel engine. It is well known that catalysts increase sulfate formation. (30) It was assumed that because the methanol contained no sulfur, the sulfate emissions from the pure methanol engine would be zero. Therefore, the test was not even run for the M.A.N. engine.

Benzo(a)pyrene is a polynuclear aromatic hydrocarbon and a known carcinogen. (31) Table 7 shows that the use of pure methanol as a fuel produces very little benzo(a)pyrene. As with total particulate, the data suggest that the more you displace diesel fuel with methanol, the less benzo(a)pyrene is emitted.

Energy Efficiency

As shown in Table 7, the actual fuel consumption in kilograms of fuel per horsepower-hour is much higher for those engines which used methanol; this is to be expected since methanol has a much lower volumetric heating value than diesel fuel. Table 7 also gives the fuel consumption results in terms of diesel fuel equivalent per horsepower-hour, utilizing the different

Btu contents of the fuels to develop a measure of energy efficiency. This calculation was straightforward for the pure methanol engine, but for the dual-injection configurations it was necessary to determine the relative proportions of methanol and diesel fuel that were consumed over the transient test cycle. It was found that approximately 80 percent of the total fuel used (by weight) by the dual-fuel engine was methanol and 20 percent was diesel fuel.

The data indicate that the dual-fuel configurations were about 3 percent less efficient than the diesel engine, while the pure methanol engine was approximately 13 percent less efficient during the transient testing. The higher fuel consumption for the M.A.N. engine is likely due to the higher fueling rates at low speeds. (32) The transient test cycle is a fairly lightly loaded cycle. Over the steady-state cycle, the dual-fuel Volvo and pure methanol M.A.N. engines were both 10 percent less efficient than the conventional Volvo diesel engine. The energy efficiency comparisons between the M.A.N. engine and the Volvo engine configurations must be qualified in view of the significant design differences between the engines. The much higher efficiency of the Volvo diesel engine compared to the pure methanol M.A.N. engine may not be due exclusively to the different fuels used. There is some evidence in the literature that methanol is less efficient than diesel fuel at lower loads but equal to or more efficient at heavier loads, though it must be noted that this is based predominantly on dual-fuel engines and steady-state testing. (1)(24)(25)(27)

Summary of Heavy-Duty Engine Test Program

Table 7 summarizes the average emission and energy efficiency data over the EPA transient test cycle for the four heavy-duty engine configurations evaluated in this program. The conventional Volvo diesel engine produced results typical of heavy-duty diesel engines: fairly low organic and CO emissions, fairly high NOx, particulate, and smoke values, measurable amounts of benzo(a)pyrene, and low brake specific fuel consumption. The conventional diesel's organics were nearly completely hydrocarbons, with small quantities of aldehydes and phenols.

The dual-fuel Volvo engine utilized approximately 80 percent methanol and 20 percent diesel fuel over the transient test cycle. Without the oxidation catalyst, the dual-fuel engine emitted nearly 5 times more organics than did the conventional diesel engine, with over 90 percent of the organics being unburned methanol. Aldehyde emissions were much higher than from the conventional diesel design, and measurable amounts of hydrocarbons were also detected. CO emissions were over twice as high, but significant reductions of NOx, particulate, smoke, and benzo(a)pyrene levels were found. Fuel consumption, on an energy equivalent basis, was slightly higher for the dual-fuel engine than for the Volvo diesel engine.

Addition of an oxidation catalyst to the dual-injection Volvo engine reduced organic emissions by a factor of four, and resulted in total organic levels similar to those of the diesel engine. The organics were composed almost entirely of unburned methanol and aldehydes. The catalyst reduced CO levels below those of the diesel engine, and reduced smoke and benzo(a)pyrene values even further. NOx, particulate, and energy efficiency were not affected much by the catalyst.

The emissions from the pure methanol, spark-ignited M.A.N. engine with catalyst were generally much lower than the emissions from the other three engine/catalyst configurations. Total organic emissions were lower than those from the diesel engine, and were nearly all unburned methanol with only trace amounts of aldehydes during transient operation. Somewhat greater amounts of aldehydes were observed during steady-state testing. CO values were very low, nearly a 90 percent reduction compared to the diesel engine. NOx emissions were lower than from the diesel engine, but somewhat higher than from the dual-fuel engine. Particulate, smoke, and benzo(a)pyrene values were all zero or near zero. However, the energy efficiency of the M.A.N. engine was 13 percent lower over transient operation and 10 percent lower during steady-state testing compared to the diesel engine. A more detailed presentation of the data from the heavy-duty testing programs is available elsewhere. (23)

CONCLUSIONS

Light-Duty Program

At this time it is not possible to conclude whether methanol-fueled passenger cars would be environmentally preferable to current gasoline-fueled models. EPA's testing of two of the more advanced methanol-fueled designs produced mixed results. Total organic emissions were higher from the methanol-fueled Escort and Rabbit compared to their gasoline-fueled counterparts, although the overall impacts on urban atmosphere photochemical reactivities cannot be predicted because of the different compounds emitted. The methanol-fueled vehicles emitted primarily unburned methanol and formaldehyde while the gasoline-fueled vehicles produced almost exclusively hydrocarbons.

More research is needed to determine the relative public health impacts of these various pollutants. Because of its high photochemical reactivity and possible human carcinogenicity, formaldehyde emission is probably the most critical public health issue associated with widespread methanol-fueled vehicle introduction. CO and NOx emission results were mixed in this program, though there is good agreement in the literature that methanol combustion should reduce NOx formation. Particulate and unregulated pollutant emissions were consistently lower for the methanol-fueled vehicles. The two Escorts had similar energy efficiencies, while the methanol-fueled Rabbit was about 15 percent more efficient than its gasoline-fueled counterpart. Many researchers have predicted even greater energy efficiency improvements.

Although conclusions at this time would be premature, some comments on the results of this program can be made. First, it must be noted that one of the two vehicles used in this program for comparative purposes, the gasoline-fueled Volkswagen Rabbit, is one of the lowest emitting vehicles on the market today. Second, it would appear that much optimization is possible for methanol-fueled vehicles. Until now, the methanol-fueled vehicles which have been developed have involved modifications of designs intended and optimized for gasoline fuel. Emissions and fuel economy of gasoline-fueled vehicles have been studied for many years. It is plausible that continued research and development will lead to future methanol-fueled vehicles which will provide both emissions and energy efficiency improvements.

Heavy-Duty Program

Compared to the conventional diesel Volvo engine, the dual-fuel Volvo engine, which utilized approximately 80 percent methanol fuel, produced mixed emission results. Without an oxidation catalyst, the dual-fuel Volvo emitted much more organic and CO emissions, but considerably less NOx, particulate, smoke, and benzo(a)pyrene emissions. The addition of catalytic aftertreatment reduced the organic and CO emissions to levels similar to those of the conventional diesel engine, and maintained the lower NOx, particulate, smoke, and benzo(a)pyrene values. The organic emissions from the dual-fuel engine configurations were mostly unburned methanol and aldehydes, while the diesel engine emissions were largely hydrocarbons. The energy efficiencies of the dual-fuel engine configurations were slightly less than that of the conventional diesel engine. These results generally compare well with results reported in the literature.

The pure methanol, spark-ignited M.A.N. engine, with catalyst, emitted zero or near zero CO, particulate, smoke, and benzo(a)pyrene. It also emitted less NOx and organic emissions than the conventional diesel engine, with the organics being composed almost exclusively of unburned methanol and very low levels of aldehydes. The energy efficiency of the M.A.N. engine was 10 to 13 percent less than that of the conventional diesel engine, although the design differences between the M.A.N. and Volvo engines may account for part of the latter's efficiency advantage. These results, and data reported in the literature, indicate that methanol utilization in heavy-duty diesel engines would produce significant environmental benefits, especially with respect to NOx and particulate emissions which are particularly difficult to control from diesel engines. The primary concern involves energy efficiency, which is critical in the trucking industry. Again, it is possible that further research will result in improvements with respect to the energy efficiency of methanol-fueled heavy-duty engines.

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