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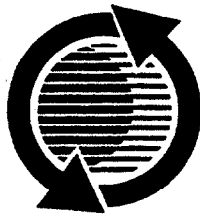
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ABSTRACT

Synthetic diesel fuel can be made from a variety of feedstocks, including coal, natural gas and biomass. Synthetic diesel fuels can have very low sulfur and aromatic content, and excellent autoignition characteristics. Moreover, synthetic diesel fuels may also be economically competitive with California diesel fuel if produced in large volumes.

Previous engine laboratory and field tests using a heavy-duty chassis dynamometer indicate that synthetic diesel fuel made using the Fischer-Tropsch (F-T) catalytic conversion process is a promising alternative fuel because it can be used in unmodified diesel engines, and can reduce exhaust emissions substantially.

The objective of this study was a preliminary assessment of the emissions from older model transit operated on Mossgas synthetic diesel fuel. The study compared emissions from transit buses operating on Federal no. 2 Diesel fuel, Mossgas synthetic diesel (MGSD), and a 50/50 blend of the two fuels. The buses were equipped with unmodified Detroit Diesel 6V92 2-stroke diesel engines. Six 40-foot buses were tested. Three of the buses had recently rebuilt engines and were equipped with an oxidation catalytic converter. Vehicle emissions measurements were performed using West Virginia University's unique transportable chassis dynamometer. The emissions were measured over the Central Business District (CBD) driving cycle.

The buses performed well on both neat and blended MGSD fuel. Three buses without catalytic converters were tested. Compared to their emissions when operating on Federal no. 2 diesel fuel, these buses emitted an average of 5% lower oxides of nitrogen (NO_x) and 20% lower particulate matter (PM) when operating on neat MGSD fuel. Catalyst equipped buses emitted an average of 8% lower NO_x and 31% lower PM when operating on MGSD than when operating on Federal no. 2 diesel fuel

INTRODUCTION

The Energy Policy Act of 1992 (EPACT) was enacted to stimulate the research, development, and accelerated introduction of alternative fuel technologies in the United States. The objective of EPACT is to reduce the nation's dependence on imported petroleum by pursuing renewable and domestically produced energy resources. Under EPACT, DOE has established programs to promote energy diversity and the displacement of crude oil-based motor fuels.

"Gas-to-liquids" (GTL) process technology is one promising approach for achieving energy diversity [1-7]. A brief history of the Fischer-Tropsch GTL synthetic diesel process was given in a previous paper [8]. There has been heightened interest in GTL technology in recent years, as researchers and industrial firms are demonstrating favorable production economics. GTL fuel and chemical plants are emerging in developing countries. GTL pilot plants are also being developed for remote and off-shore applications to liberate remote and stranded natural gas reserves. F-T and other synthetic diesel fuels may be economically competitive with low aromatic California diesel fuel if produced in large volumes. For a

commercial-scale plant, synthetic fuel price estimates range from \$20 to \$25 per barrel of product [2,5-7].

Fischer-Tropsch synthetic diesel fuel is typically synthesized using a three-step procedure [2-6]. First a synthesis gas is produced from the feedstock, F-T catalysis is then used to convert this synthesis gas into liquid hydrocarbons, and finally the resulting synthetic crude is upgraded using standard hydrotreating and isomerization processes and fractionated into middle distillate fuels. This process can be used to create a variety of fuel properties depending on the process technology and streams being blended. Generally, synthetic diesel fuels have favorable characteristics for use in compression ignition engines including:

- Liquid phase at ambient conditions
- Miscible in conventional petroleum-derived diesel
- Good autoignition characteristics (cetane number of 50-75 typically)
- Low sulfur (typically less than 10 ppm)
- Low aromatics (less than 3 vol% possible)
- Energy density comparable to conventional diesel
- Fuel tank flammability similar to conventional diesel
- Suitable for use in unmodified diesel engines
- Transportable as a liquid in existing petroleum infrastructure.

Due in part to the success of previous engine and chassis based testing [9-12], synthetic diesel is being considered as a candidate fuel for the DOE/NREL Alternative Fuel Truck and Bus Evaluation Projects [13].

TEST FUELS

Three test fuels were used for the bus tests:

- Federal (49-state) no. 2 diesel fuel
- 100% Mossgas synthetic diesel with fuel lubricity additive
- 50:50% Mossgas synthetic diesel:Federal no. 2 diesel with fuel lubricity additive

The synthetic diesel fuel for this study was produced using the Mossgas conversion of olefins to distillate ("COD") process. Mossgas produces a range of automotive fuel products and chemicals using a natural gas feedstock obtained by pipeline from their off-shore production platform in Mossel Bay, South Africa. The natural gas is reformed to synthesis gas consisting of hydrogen and carbon monoxide. The synthesis gas is chemically converted using high temperature Fischer-Tropsch catalysis to produce olefins and automotive fuel components for commercial markets.

The light olefins that remain from the Fischer-Tropsch conversion, such as propene, butene, pentene and

hexene, were used to synthesize the test fuel used in this study. These light olefins were catalytically oligomerized over a zeolite catalyst to form gasoline and distillate. The resulting product was then hydrotreated. Mossgas uses the COD process to produce commercial specialty fuels and blendstocks.

The properties of the Mossgas synthetic diesel fuel and the Federal no. 2 diesel fuel used in this study are shown in Table 1. The Mossgas fuel had no detectable sulfur, and a cetane number of about 50. The aromatic content was 10% by volume, which is higher than that of a typical Fischer-Tropsch diesel. The cold flow properties of the Mossgas fuel were excellent with a pour point and cloud point below -60 degrees Celsius. A commercially available lubricity improver (Paradyne 655 at 200 ppm treat rate) was added to meet acceptable lubricity levels.

The Federal no. 2 diesel used in the study had a relatively low sulfur content of 0.02% by weight. This is much lower than the standard of 0.05% and lower than the 0.03% to 0.035% sulfur content typically found in Federal diesel.

VEHICLE TESTING

TEST VEHICLES – The buses used for the testing were loaned to the project by the Port Authority of Allegheny County ("PaTransit"). They were removed from revenue service in Pittsburgh, PA for the emissions measurements. The 40-foot buses were 1991 model year made by Orion Bus Industries and equipped with 1991 model year DDC Diesel Corporation (DDC) 6V92 two-stroke diesel engines. One of the test buses is shown in Figure 1.



Figure 1: One of the Pittsburgh transit buses used for the emissions measurements.

Table 1: Test Fuel Properties

Analysis	ASTM	Units	100% MGSD (Mossgas Data) [14]	100% MGSD (SwRI Data) [15]	Federal Diesel Fuel [16]
Flash Point	D93	°C	100	97	
Cloud Point	D2550	°C		<-60	
Water content	D1744	vol%	0.01		
Sediment by extraction	D473	mass%	<0.01		
Water and Sediment	D1796	vol%		0	
Carbon Residue on 10% residue	D4530	wt%	0.09		
Carbon Residue on 10% distillation residue	D524	%		0.1	
Ash	D482	wt%	<0.01		
Distillation	D86	°C			
IBP				229.9	188
10%				235.3	212
50%				254.7	256
90%			321.1	323.7	307
FBP			360.8	361.2	331
Kinematic Viscosity	D445	cSt @ 40°C	2.974	2.98	
Sulfur	D2622	mass%	<0.001		
Sulfur	D5453	ppm		<5	
Sulfur	D4294	wt%			0.02
Corrosion, 100°C for 3 hours	D130	Rating	1A		
Cetane Number	D613		51.4	48.9	
Cetane Index	D4737				48.7
Density @ 20°C	D4052/ D1298	kg/l	0.8007	0.8042	
API Gravity @ 15.6°C	D287	°API		44.0	37.4
Cold Filter Plugging Point	IP309	°C	<-35		
Pour Point	D97	°C		<-60	
SFC Aromatics	D5186	mass%			
Total Aromatics				9.18	
PNA				0.21	
FIA	D1319	vol%			
Aromatic					24.7
Olefins					1.5
Saturate					73.8
Aromatics	IP391	vol%	10.1		
Gum Content	D381	mg/100ml			
Unwashed				8.8	
Washed				0.4	
Lubricity SLBOCLE	D6078	grams			
Neat Fuel				1950	
With Paradyne additive				3800	
Lubricity HFRR	D6079	micron			
Neat Fuel				600	
With Paradyne additive				255	
Oxidation Stability	D2274	mg/100 ml	0.3		
Carbon/Hydrogen	D5291	mass%			
Carbon				83.98	86.11
Hydrogen				14.43	13.37
Nitrogen					<0.03
Residual					
Oxygen (by diff)				1.59	
Heat of Combustion	D240				
Gross		Btu/gal		134,712	137,609
Net				125,878	129,147

The DDC 6V92 is a 2-stroke, vee-configuration, 6 cylinder, 9.05 liter, turbocharged and aftercooled diesel engine with electronic unit fuel injectors. The Pittsburgh bus engines were rated to 253 horsepower (at 2100 rpm) and 880 ft-lb of torque (at 1200 rpm).

Three of the six buses used in this study used engines with high mileage accumulation (typically over 350,000 miles) and were not equipped with exhaust gas aftertreatment. The other three buses had engines that were recently rebuilt according to the Environmental Protection Agency's Urban Bus Retrofit/Rebuild Program and were fitted with an oxidation catalytic converter manufactured by Engine Control Systems Ltd. Bus number 2029 was tested early in the study without a catalyst. It was then fitted with a rebuilt engine and a catalytic converter and retested. The test buses were not modified in any way for the Moss gas synthetic diesel fuel.

CHASSIS EMISSIONS TESTING - West Virginia University (WVU) measured emissions for this study using one of its transportable emissions laboratories located at the WVU home site in Morgantown, WV. The transportable laboratory consists of a heavy-duty chassis dynamometer and an emissions measurement facility. Design details of the laboratory and previous emissions measurements using the laboratory have been presented in several previous reports [17-25].

Chassis Dynamometer - The dynamometer equipment is mounted on a fifth wheel semi-trailer for portability. Upon arriving at the test site, the wheels of the trailer are removed and the trailer is lowered to the ground. The test vehicle is driven onto two sets of free running rollers mounted in the trailer bed. Power is transferred from the test vehicle to the dynamometer through hub adapters that are bolted to the drive wheels. The inertia weight of the bus is simulated by a set of flywheels. The road load is applied to the test vehicle using air-cooled eddy current power absorbers. Figure 2 shows one of the test buses mounted on the dynamometer.

Emissions Measurements - The emissions measurement system uses a 45.7 cm (18 in.) diameter, 6.1 m (20 ft.) long exhaust dilution tunnel mounted atop the box trailer that houses the emissions measuring equipment. Two fans and critical flow venturis control the flow rate in the dilution tunnel.

Carbon monoxide (CO), carbon dioxide (CO₂), oxides of nitrogen (NO_x), and total hydrocarbons (THC) are measured continuously throughout the test. Particulate matter (PM) is captured on a filter and weighed. Bag samples are collected and analyzed for background correction.

Test Method - The buses were tested using the Central Business District (CBD) driving cycle described in SAE Recommended Practice J1376. The CBD driving cycle was developed by the Federal Transit Administration to represent the operation of a transit bus in a downtown business district. The cycle, shown in Figure 3, consists of

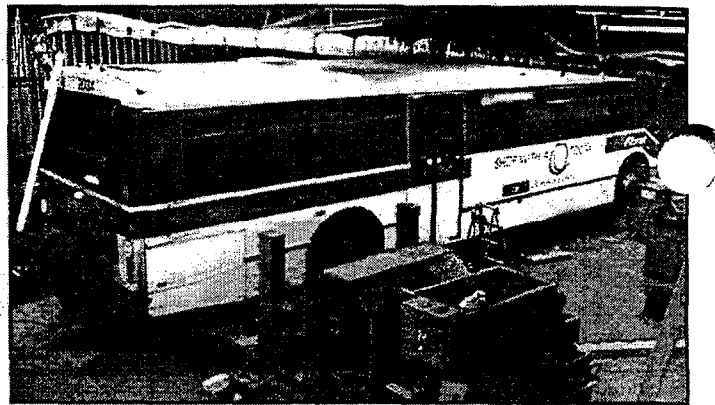


Figure 2: One of the PaTransit buses on the WVU transportable chassis dynamometer

fourteen identical acceleration, cruise, and deceleration cycles. A short idle time was added before and after the vehicle activity to aid data gathering in the light of sampling delay times [26]. The cruise sections occur at 32 km/hr (20 mph). Transit bus emissions measurements using this driving cycle have been reported in many previous papers [for example, 22, 27-29].

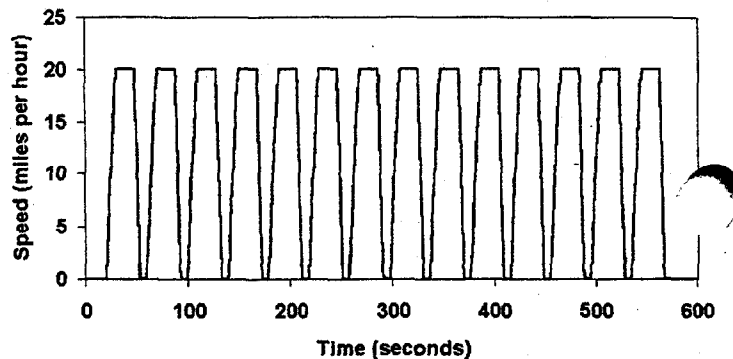


Figure 3: The Central Business District (CBD) driving cycle.

Tests Performed - Three buses with rebuilt engines and equipped with catalytic converters and three buses without catalytic converters were tested. The emissions from each bus were measured while the bus operated on each of the three test fuels. Between measurements with different fuels, the bus' fuel system was emptied and flushed with the new fuel type. The emission tests performed are summarized in Table 2.

Table 2: Summary of Emissions Tests Performed

	Fuel	Number of Tests
Buses with rebuilt engines and catalytic converters	No. 2 Diesel	3
	100% MGSD	3
	50% MGSD	3
Buses without catalytic converters	No. 2 Diesel	3
	100% MGSD	3
	50% MGSD	3
		Total = 18

RESULTS

Drivers could not detect a performance difference between buses operating on the Mossgas synthetic diesel and the Federal no. 2 diesel fuel over the CBD driving cycle. The average emissions results are summarized in Table 3. At least three measurements were taken and averaged for each result presented in the table.

EFFECT OF TEST FUEL - Three buses equipped with rebuilt engines and catalytic converters were tested on the three test fuels. The results of these tests are shown in the bar charts of Figure 4. Each chart shows results for each bus and the average of all three buses. Substituting 100% MGSD fuel in place of no. 2 diesel fuel led to lower average levels of all four emissions measured. NO_x was

reduced by an average of 8%, PM was reduced by an average of 31%, CO was reduced by an average of 49%, and HC was reduced by an average of 35%. The average NO_x reduction with a 50:50 blend of no. 2 diesel and MGSD was substantially more than half of the reduction with 100% MGSD fuel. The PM reduction with the blend was approximately half of the reduction measured with 100% MGSD fuel.

With the exception of the hydrocarbon emissions from bus 2029, all buses followed the same trend of progressively decreasing emissions with 50% and 100% Mossgas synthetic diesel.

Table 3: Average emissions (in grams per mile) and fuel mileage from buses tested on federal No. 2 diesel, Mossgas synthetic diesel (MGSD), and a 50:50 blend of the two fuels.

	Fuel	Bus Number	CO	NO _x	HC	PM	CO ₂	MPG*	Btu/mile
Buses with rebuilt engines and catalytic converters	No. 2 Diesel	2025	1.96	34.51	0.75	1.23	4355	2.33	55713
	No. 2 Diesel	2029	1.07	26.91	0.39	1.89	4458	2.28	56995
	No. 2 Diesel	2048	2.11	29.71	0.75	1.12	3451	2.94	44159
	Averages:		1.71	30.38	0.63	1.41	4088	2.52	52289
	50% MGSD	2025	1.34	31.93	0.54	1.14	4360	2.20	57589
	50% MGSD	2029	0.81	26.40	0.40	1.59	4346	2.21	57391
	50% MGSD	2048	1.51	27.69	0.59	0.83	3381	2.84	44672
	Averages:		1.22	28.67	0.51	1.19	4029	2.42	53217
	100% MGSD	2025	1.02	31.37	0.44	1.01	4206	2.19	56272
	100% MGSD	2029	0.75	26.10	0.29	1.16	4181	2.21	55928
	100% MGSD	2048	0.82	26.53	0.49	0.76	3338	2.77	44659
	Averages:		0.87	28.00	0.41	0.97	3908	2.39	52286
	Buses without catalytic converters	No. 2 Diesel	2029	11.73	35.85	1.82	1.79	4328	2.34
No. 2 Diesel		2030	6.65	34.88	2.11	1.18	4149	2.44	53221
No. 2 Diesel		2034	40.42	26.26	1.31	9.03	4900	2.05	63468
Averages:			19.60	32.33	1.75	4.00	4459	2.28	57429
50% MGSD		2029	10.33	32.23	1.88	1.52	4348	2.20	57601
50% MGSD		2030	6.26	33.93	2.03	1.13	4099	2.34	54244
50% MGSD		2034	37.91	26.02	0.99	8.61	4704	2.02	62887
Averages:			18.16	30.72	1.63	3.75	4383	2.18	58274
100% MGSD		2029	11.02	33.37	1.72	1.34	4392	2.09	58963
100% MGSD		2030	5.73	32.92	1.75	1.16	4133	2.23	55391
100% MGSD		2034	26.52	25.64	0.72	7.07	4639	1.97	62596
Averages:			14.42	30.64	1.40	3.19	4388	2.10	58984

* Miles per liquid gallon (not corrected for energy content)

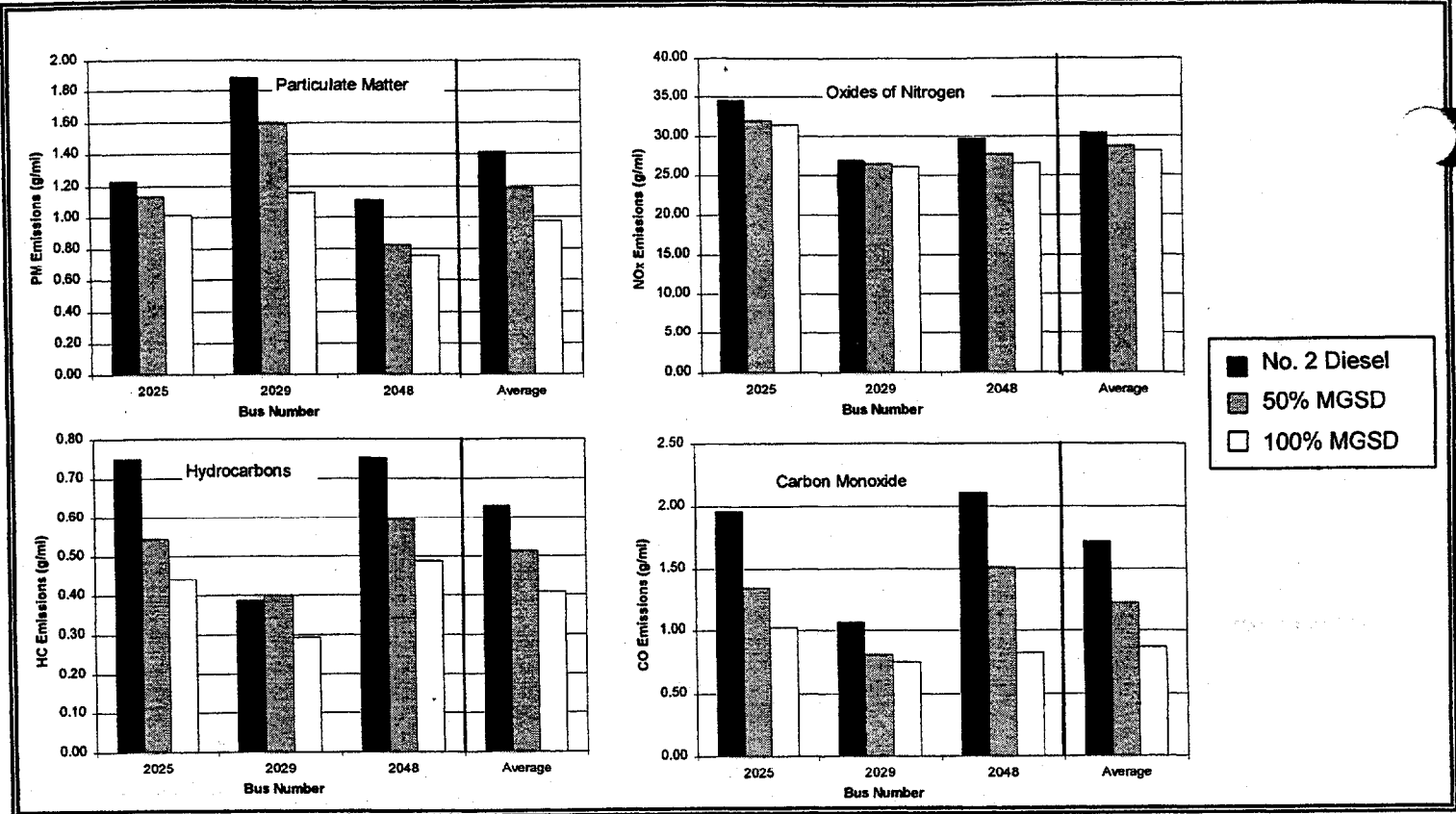


Figure 4: Emissions results from buses with rebuilt engines and catalytic converters

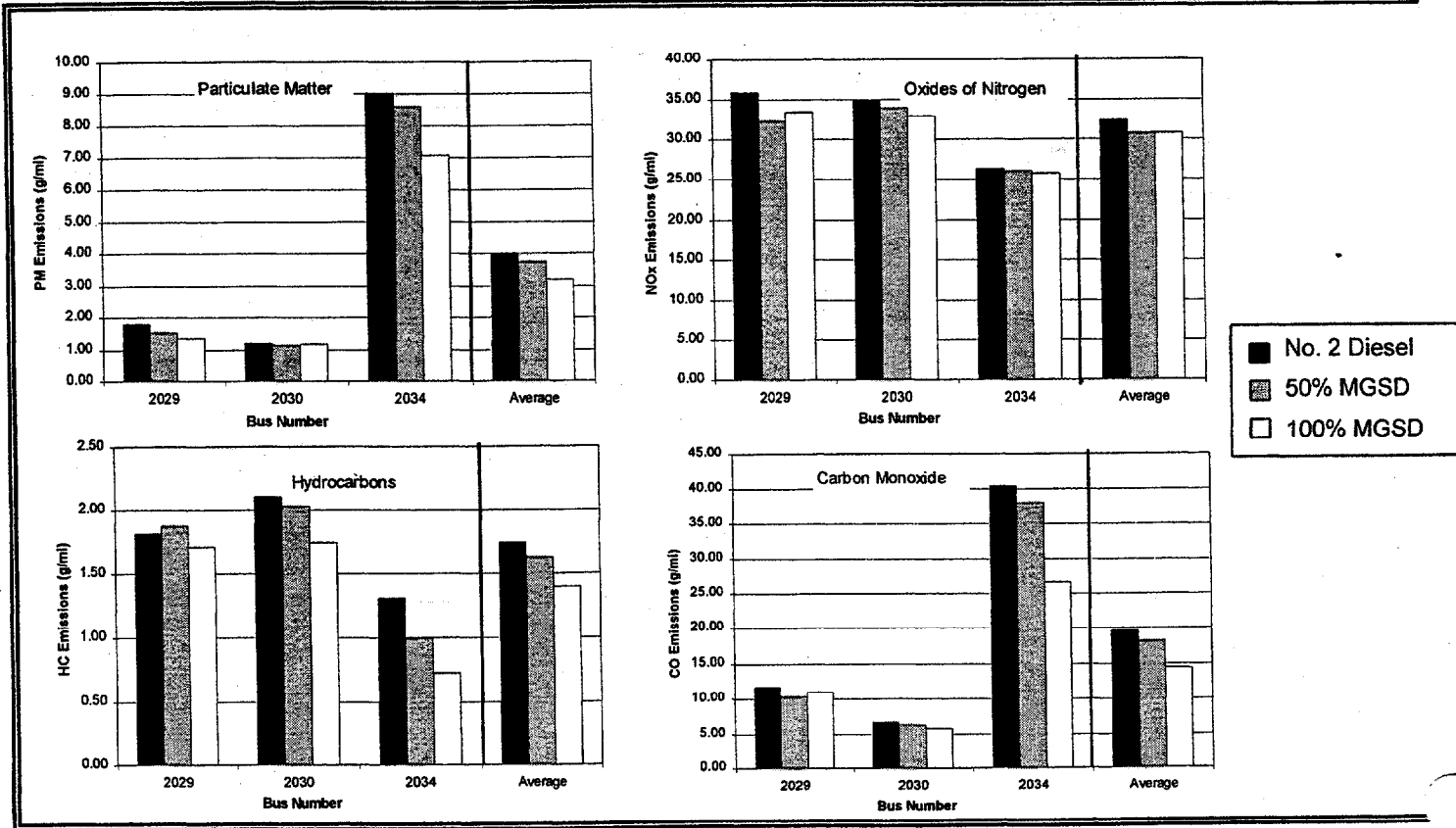


Figure 5: Emissions results from buses without catalytic converters

Three buses with high mileage engines and no catalytic converters were also tested. The results of these tests are shown in the bar charts of Figure 5. Substituting 100% Moss gas synthetic diesel fuel in place of Federal no. 2 diesel fuel in these buses also led to lower average levels of all four emissions measured. NO_x was reduced by an average of 5%, PM was reduced by an average of 20%, CO was reduced by an average of 26%, and HC was reduced by an average of 20%. In this case, The average NO_x reduction with a 50:50 blend of no. 2 diesel and MGSD was nearly identical to the reduction with 100% MGSD. This result agrees with an earlier study by the authors on class 8 trucks using Shell Middle Distillate F-T fuel [8]. In contrast, the PM reduction with the blend was only about a quarter of the reduction measured with 100% MGSD fuel.

Bus number 2034 had dramatically higher PM and CO emissions and somewhat lower NO_x and HC emissions than buses 2029 and 2030. Although buses 2029 and 2030 had similar fuel consumption (within about 4%), the fuel consumption of bus 2034 on Federal no. 2 diesel was somewhat higher (about 16% higher than the average of buses 2029 and 2030). The higher fuel consumption and lower NO_x indicates that the injection timing in bus 2034 may be retarded relative to manufacturer specifications. Note that much of the average PM reduction with MGSD in this set of buses is due to the large reduction in PM from bus 2034.

When tested on 50% MGSD, the emissions trends of bus number 2029 (without a catalyst) were different than the other two non-catalyst buses for NO_x, HC, and CO. These trends can be seen clearly in Figure 5. The cause of this anomaly is unknown.

EFFECT OF REBUILT ENGINES AND CATALYST - The average emissions from buses with rebuilt engines and catalytic converters are compared to emissions from buses with older engines and no catalytic converters in Figures 6 and 7. The buses with rebuilt engines and catalysts had dramatically lower CO, HC and PM emissions than those with older engines and no catalyst. Most of this reduction is likely due to the oxidizing effect of the catalyst on CO, HC, and the soluble organic fraction of the PM emissions.

Also apparent from Figures 6 and 7 is that NO_x emissions were reduced somewhat in the buses with rebuilt engines and catalytic converters. The NO_x reduction cannot be attributed to the catalyst. The emission reductions from buses with rebuilt engines and catalysts followed the same trends in all buses with both MGSD and Federal no. 2 diesel.

Continuous gaseous emission rates were measured during the tests. Although not directly relevant to the comparison of fuels, an interesting trend in the continuous data warrants mentioning. Buses with oxidation catalytic converters had decreasing HC and CO emissions over the course of the CBD test cycle. Typical continuous HC and CO for a catalyst-equipped bus are shown in Figures 8

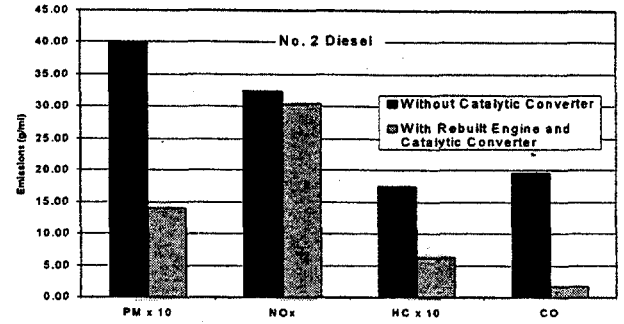


Figure 6: Average emissions results from buses with rebuilt engines and catalytic converters compared to buses without catalytic converters while operating on no. 2 diesel fuel.

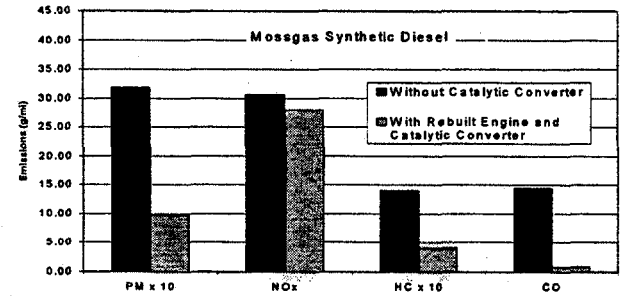


Figure 7: Average emissions results from buses with rebuilt engines and catalytic converters compared to buses with out catalytic converters while operating on Moss gas synthetic diesel fuel.

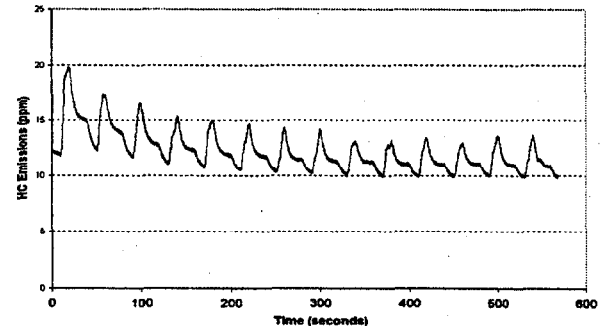


Figure 8: Continuous HC emissions over the CBD cycle from a bus with rebuilt engine and catalytic converter.

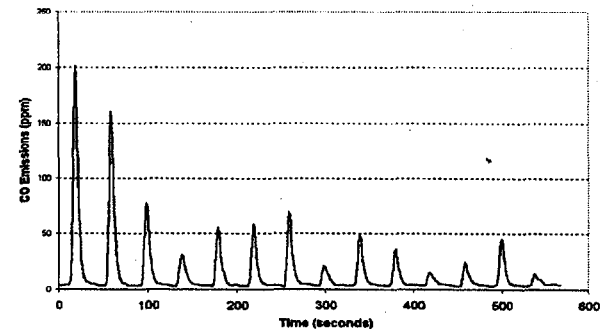


Figure 9: Continuous CO emissions over the CBD cycle from a bus with rebuilt engine and catalytic converter.

and 9. This trend was not observed in buses without catalyts.

Figures 8 and 9 clearly illustrate that the HC and CO drop progressively over the cycle. The WVU protocol for the CBD test cycle includes three additional peaks of the CBD just prior to the actual test data shown here, so the catalyst has already seen some exhaust warming. These results indicate that a test facility that did not employ the warm-up ramps would see higher average HC and CO emissions than measured in this study. This suggests a need for more precisely defined heavy duty vehicle chassis testing protocols to avoid measurement differences between facilities.

FUEL CONSUMPTION – For each of the buses tested, the fuel consumption (in Btu/mile) was not strongly affected by the fuel type. No more than a 3% deviation from the average fuel consumption occurred on any bus. The trends in this small variation were mixed – the MGSD lead to higher fuel consumption in four buses and lower fuel consumption in two buses. The bus-to-bus variability was much greater than the fuel effect. Fuel consumption of no. 2 diesel fuel differed by as much as 23% between catalyst equipped buses and 16% between buses without catalyts.

CONCLUSIONS

- The use of Mossgas synthetic diesel fuel and the use of rebuilt engines and catalyts according to the EPA Urban Bus Retrofit/Rebuild Program both show promise for reducing emissions from older transit buses using Detroit Diesel 6V92 engines.
- The Mossgas synthetic diesel fuel had properties conducive to low emissions, including no detectable sulfur, and an aromatic content of about 10% by volume. The Mossgas synthetic diesel also had excellent cold flow properties.
- Drivers could not detect a performance difference between buses operating on the Mossgas synthetic diesel and the Federal no. 2 diesel fuel over the CBD driving cycle.
- Use of Mossgas synthetic diesel in place of Federal no. 2 diesel in the test buses led to lower levels of all four regulated emissions measured. For the buses with rebuilt engines and oxidation catalytic converters, oxides of nitrogen were reduced by an average of 8%, particulate matter was reduced by an average of 31%, carbon monoxide was reduced by an average of 35%, and total hydrocarbon emissions were reduced by an average of 49%.
- The variation of fuel consumption with test fuel was less than 3% and was much smaller than the bus-to-bus fuel consumption variation.

- More precisely defined heavy-duty vehicle chassis dynamometer testing protocols are needed to avoid measurement differences between facilities due to catalyst warm-up.

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

CBD – Central Business District (driving cycle)
 CO – Carbon Monoxide
 COD – Conversion of Olefins to Distillate
 DDC – Detroit Diesel Corporation
 DOE – U.S. Department of Energy
 EPA – Environmental Protection Agency
 EPACT – Energy Policy Act of 1992
 FBP – Final Boiling Point
 FIA – Fluorescent Indicator Adsorption
 F-T diesel – Fischer-Tropsch diesel
 FTP – Federal Test Procedure
 GTL – Gas-to-liquids
 HC – Hydrocarbons
 HFRR – High Frequency Reciprocating Rig
 IBP – Initial Boiling Point
 MGSD – Mossgas synthetic diesel
 NO_x – Oxides of Nitrogen
 NREL – National Renewable Energy Laboratory
 PM – Particulate Matter
 ppm – parts per million
 SFC – Supercritical Fluid Chromatography
 SLBOCLE – Scuffing Load Ball On Cylinder
 Lubricity Evaluator
 THC – Total Hydrocarbons
 WVU – West Virginia University