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Mossgas "gas-to-liquid" diesel fuels—an environmentally friendly option

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Abstract

This paper presents a brief summary and comparison of heavy vehicle emissions using Mossgas synthetically derived diesel as opposed to a US Regular Federal 49-state number 2 diesel fuel. A series of engine dynamometer and heavy-duty chassis dynamometer tests were performed at West Virginia University early in 1999.

The Mossgas gas-to-liquid (GTL) low sulphur diesel fuel is produced primarily by the conversion of olefins to distillate (COD) process in conjunction with a high temperature Fisher–Tropsch technology process.

Findings were that there were significant emission benefits when using Mossgas GTL diesel fuel. Oxides of nitrogen (NO_x) and particulate matter (PM) emissions were substantially lower when compared to normal fossil fuel-derived diesel. Additionally the benefits have been found to cut across different engine technologies, various test cycles, engine age (1991–1999), as with or without engine aftertreatment catalysts.

The Mossgas GTL diesel meets the world-wide challenge to produce environmentally friendly transportation fuels and sets the benchmark for future diesel specifications. Accordingly Mossgas has petitioned the US Department of Energy to register this fuel as an alternative fuel under its EPACT program [1,2]. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Gas-to-liquid; Particulate matter; Mossgas

1. Introduction

World-wide efforts have been channelled into the formulation of environmentally friendly diesel fuels able of meeting the advanced fuel specifications of the 21st century. Synthetically derived gas-to-liquid (GTL) diesel fuel promises to meet these challenges and spearhead the way into the future.

The benefits of such fuels in reducing emissions over conventional fuels include:

- its zero sulphur specification, implying reduced particulate matter (PM) emissions;
- relatively low aromaticity;
- relatively high cetane rating.

Mossgas (Pty.) Ltd., a South African government-owned company, has 10 years experience in converting offshore natural gas to GTL fuels.

The process to produce the synthetic diesels consists of three basic steps:

- the first step of the GTL process entails the production of synthesis gas in which carbon monoxide and

Abbreviations: CBD, central business district (driving cycle); CO, carbon monoxide; CO_2, carbon dioxide; COD, conversion of olefins to distillate; DDC, Detroit Diesel Corporation; DOE, US Department of Energy; EPA, Environmental Protection Agency; FBP, final boiling point; F–T, Fischer–Tropsch; FTP, federal test procedure; GTL, gas-to-liquids; HC, hydrocarbons; IBP, initial boiling point; MG, Mossgas; NO_x, oxides of nitrogen; NREL, National Renewable Energy Laboratory; PM, particulate matter; WVU, West Virginia University

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hydrogen are produced by steam reforming natural gas;
- the second step involves high temperature Fischer–Tropsch (F–T) conversion to form an olefinic synthetic distillate, synthol light oil (SLO);
- lighter olefinic gasses produced by the F–T process act as feed to the Mossgas conversion of olefins to distillate (COD) unit. Olefins are oligomerised over COD-9 catalyst to form quality distillates and gasoline components [3].

The synthol light oil (SLO) and COD distillates once hydrotreated are distilled to produce quality diesel fuels. This fuel possesses excellent properties for use in compression ignition engines as shown below:

- excellent cold flow properties;
- low sulphur (less than 10 ppm);
- energy content similar to crude fossil fuel-derived diesel;
- cetane number of greater than 48;
- suitable for use in unmodified diesel engines;
- transportable within the existing petroleum infrastructure;
- excellent emission benefits, including in heavy diesel engines;
- excellent compatibility with exhaust gas recirculation (EGR) systems and aftertreatment technologies such as particulate traps and filters, oxidation catalysts, lean NO_x catalysts and selective catalytic reduction devices.

2. Test fuel characteristics

Several fuels were used in this study, utilising a conventional Regular Federal 49-state number 2 diesel fuel as the baseline (D2). The formulations comprise a zero sulphur natural gas-derived fuel (Mossgas 1), an oxygenated blend of Mossgas 1 with 5% volume of Mosstanol 120 heavy alcohols (Mossgas 2), and a proprietary synthetic zero sulphur diesel fuel (Mossgas COD). Table 1 indicates the relative components.

Table 1
Components by percentage volume of Mossgas formulations

Composition	Mossgas 1	Mossgas 2	Mossgas COD
COD syndiesel	63	60	100
SLO syndiesel (F–T)	30	28	0
Straight run diesel	7	7	0
Mosstanol 120 (heavy alcohols)	0	5	0

COD syndiesel forms the majority component (greater than 60%) in each of the three proposed formulations, while the SLO syndiesel component from the F–T process forms the second largest component. Portions of mixed heavy alcohols were used in the Mossgas 2 blend. These anhydrous alcohols are synthetically derived products as part of the Mossgas GTL process. The basic fuel specifications are highlighted in Table 2.

The fuels boil in the typical diesel distillation range from approximately 220–365 °C as tested by ASTM D86. Due to the presence of heavy alcohols in the Mossgas 2 blend the initial boiling point (IBP) is lowered to 81.3 °C. The alcohols were added specifically for applications where ultra-low PM emissions are of importance, and for their excellent compatibility with aftertreatment devices.

The ultra-low sulphur content of less than 10 ppm mass is seen as one of the Mossgas fuel's greatest at-

Table 2
Basic fuel specifications

	Units	Mossgas 1	Mossgas 2	Mossgas COD	D2
Density at 20 °C	kg/l	0.8088	0.8065	0.8007	0.8337
Distillation IBP	°C	222	81.3	229	188
90% (v/v) recovery	°C	322	318	323	307
Final boiling point	°C	360	363	361	331
Total sulphur	% m/m	<0.001	<0.001	<0.001	0.035
Cetane number		53.0	49.3	51.4	48.7
Aromatic content	% v/v	16.4	15.9	10.1	24.7

tributes. The fuel has good ignition performance characteristics, with a minimum cetane number of 48 as tested by ASTM D613.

Due to the large portion of iso-paraffins present in the diesel fuel the low temperature operability is exceptional and provides fuel flow well below sub-zero temperatures. Cold flow plugging point (CFPP) (IP 309) is used to characterise low temperature operability of diesel, the Mossgas fuels CFPP values are typically in the range of $-20\,^{\circ}$C and lower.

The relatively low aromatic (IP 391) content specification is less than 18% by volume. The bulk of the aromatics are single ring mono-aromatics, with no detectable hazardous poly-aromatic species.

The level of aromatics is approximately half that of crude derived fuel and has been selected to ensure a balance between low emissions and vehicle operability. In the case where diesels containing less than 10% volume aromatics have been used to substitute crude derived diesel markets, diesel fuel pump failures were experienced.

3. Experimental

The emissions reduction potential of Mossgas natural gas-derived diesel fuels was determined in a series of engine dynamometer and heavy-duty chassis dynamometer tests. West Virginia University's Engine and Emissions Research Center [4,5] conducted this work in early 1999. Four sets of full emissions measurement tests were conducted, namely:

1. Transient engine dynamometer testing on a 1998 Navistar T444 diesel engine (typical of medium heavy-duty truck engines in use today) over the federal test procedure (FTP), as used for engine certification in the US.
2. Transient engine dynamometer testing on a 1992-specification Detroit Diesel Corporation (DDC) 6V-92TA two stroke-cycle engine (typical of engines in use in 1990–1998 era transit buses) over the FTP.
3. Transient chassis dynamometer testing on two 40-foot transit buses with DDC 6V-92TA turbocharged, aftercooled engines (owned by the Port Authority of Allegheny County, Pittsburgh, PA) over the central business district (CBD) cycle. One bus was typical of an in-use unmodified bus, while the other bus had been remanufactured to 1998 EPA Urban Bus Retrofit Standards.
4. Transient chassis dynamometer testing on a 1999-specification 40-foot transit bus with a DDC Series 50 four stroke-cycle engine (owned by the New York City Transit Authority, New York). This bus was tested over three different transient heavy-duty chassis dynamometer test cycles:
   - CBD cycle;
   - New York City Bus Cycle (NY Bus);
   - Route 22; a driving cycle developed from actual in-use bus testing in New York city.

This comprehensive emissions study was designed to include:

- both heavy-duty engine dynamometer and vehicle dynamometer transient emissions testing;
- both two and four stroke-cycle heavy-duty engines from two different engine manufacturers;
- a range of engine technologies and ages;
- a range of transient chassis dynamometer test cycles;
- the effect of catalytic exhaust gas aftertreatment on engine emissions using these fuels.

4. Test equipment and engine testing procedures

The Engine and Emissions Research Laboratory (EERL) at WVU is equipped with state-of-the-art engine test equipment capable of operating light and heavy-duty engines over both transient and steady state cycles. The WVU transportable laboratory used similar equipment used in the EERL. Several technical papers [6–12] have been published on the design of the transportable laboratories and on emissions data collected from both conventional and alternatively fuelled vehicles.

4.1. Engine and vehicle exhaust emissions testing

Engine exhaust emissions, including unburned hydrocarbons (HC), carbon monoxide (CO), carbon dioxide (CO_2), oxides of nitrogen (NO_x) and PM, were measured with a 400 kW GE transient engine dynamometer using a full scale dilution tunnel system.

Sampling and analysis of the exhaust stream was performed on a continuous basis. Table 3 lists the anal-

Table 3
Gaseous and particulate emissions analysers used at the WVU EERL

Exhaust emission component	Acronym	Method	Manufacturer	Model
Carbon monoxide	CO	Non-dispersive infra red	Rosemount analytical	880A
Hydrocarbons	HC	Heated flame ionisation	Rosemount analytical	402
Oxides of nitrogen	NO_x	Chemiluminescent	Rosemount analytical	955
Carbon dioxide	CO_2	Non-dispersive infra red	Beckman industrial	868
Particulate matter	PM	Tapered element oscillating microbalance	Rupprecht & Patashnik	1105

Table 4
Engines used in engine dynamometer testing

Manufacturer	Model	Power rating	Configuration	Control
Navistar	T444E	230 hp at 2200 rpm	V8, turbocharged, intercooled, direct injection, four stroke	Electronic EEC-IV (injection timing and injection pressure control)
DDC	6V-92TA	253 hp at 2000 rpm	V6, turbocharged, intercooled, direct injection, two stroke	Electronic DDEC-II (injection timing control)

ysers employed for the testing. The equipment and procedures used meet the requirements of the United States Code of Federal Regulations (CFR 40) requirements to perform engine certification. Table 4 illustrates the details of the two engines used for the transient engine dynamometer testing.

5. Results and discussion

All results are graphically illustrated as a percentage reduction over the D2 base case fuel in Figs. 1–4.

5.1. Engine dynamometer FTP transient emissions results for 1998 Navistar T444E engine

Table 5 lists the FTP emission test results for the 1998 Navistar T444E engine dynamometer trials. The percentage emissions reductions over the D2 fuel are indicated in parenthesis (Fig. 1). A NO_x reduction of 10% was achieved for the Mossgas 1 fuel over the D2 fuel. Further, by addition of 5% volume heavy alcohol to Mossgas 1 fuel the NO_x emissions were further reduced to 13% for the Mossgas 2 fuel. Increased hydrocarbon emissions are recorded for the Mossgas 2 fuel, this is attributed to the presence of the alcohol that lengthens the delay period before ignition. Effectively the time for complete combustion prior to the opening of the exhaust valve is reduced resulting in higher hydrocarbon emissions. It should be noted that the HC and CO emissions remained well below the regulated emission levels. PM reductions of up to 15% were achieved over the D2 fuel indicating that the low sulphur content of the synthetic fuel has a positive effect on reducing this emission parameter.

It should be noted that the engine was unmodified, and that injection timing modifications could be used to obtain significantly lower PM emissions for the same overall NO_x emissions.

Table 5
Engine dynamometer FTP transient emissions results for 1998 Navistar T444E[a]

	HC (g/bhp h)	CO (g/bhp h)	CO_2 (g/bhp h)	No_x (g/bhp h)	PM (g/bhp h)
D2	0.183	1.091	669.81	3.848	0.112
Mossgas 1	0.169 (−7.8%)	0.890 (−18.5%)	647.37 (−3.4%)	3.459 (−10.1%)	0.096 (−14.8%)
Mossgas 2	0.327 (+78%)	1.016 (−6.9%)	643.38 (−3.9%)	3.339 (−13.2%)	0.096 (−14.3%)
1998 EPA emission regulations	1.3	15.5	–	4.0	0.10

[a] All test results that are reported in this table were repeated in triplicate. The range of the standard deviations for the various fuels was 0.003–0.013 for HC, 0.009–0.040 for CO, 2.746–5.511 for CO_2, 0.017–0.067 for NO_x and 0.001–0.004 for PM.

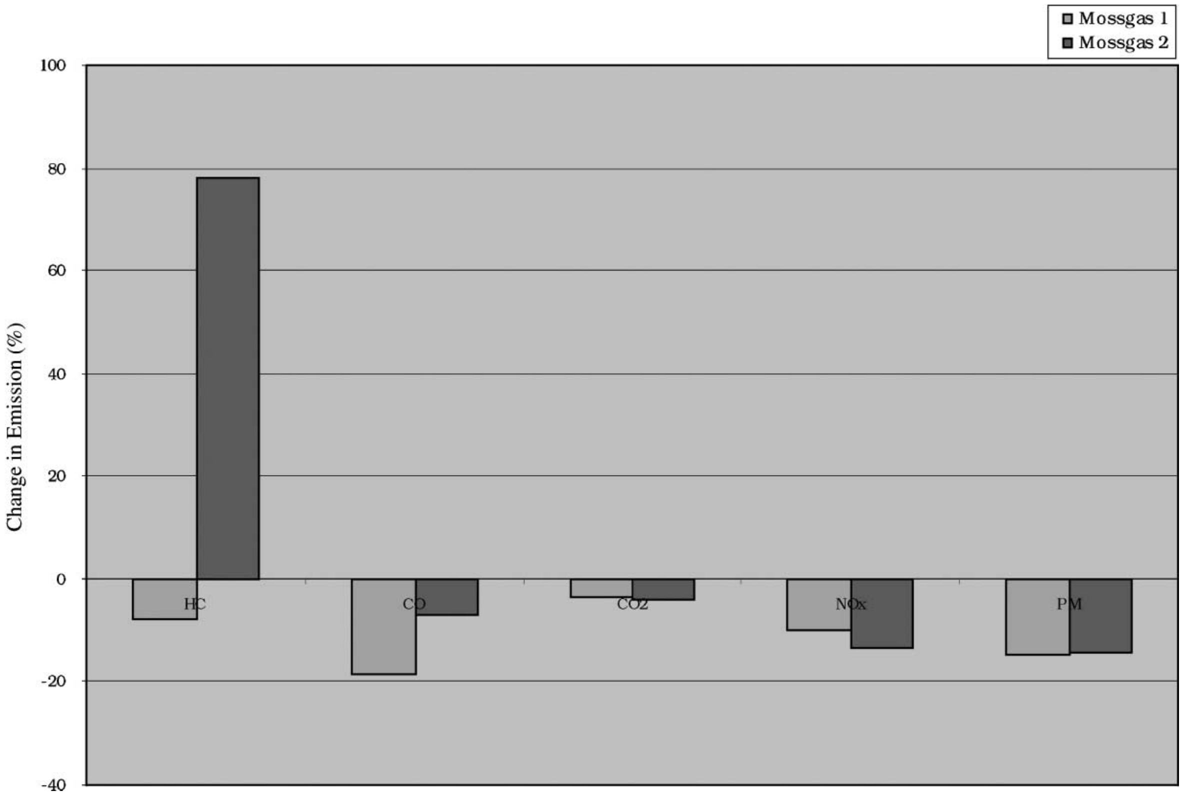

Fig. 1. Percentage reduction—increase in emissions over base D2 fuel for 1998 Navistar T444E engine.

5.2. Engine dynamometer FTP transient emissions results for 1992 DDC 6V-92TA

Table 6 lists the FTP emission test results for the heavy-duty two stroke, diesel engine (1992 DDC 6V-92TA) dynamometer trials. The percentage reduction over the D2 fuel is indicated in parenthesis. Fig. 2 illustrates the percentage reductions in regulated emissions. Simultaneous reductions of 1–2% NO_x emissions were noted while PM emission levels were reduced by up to 15% over the D2 fuel. Similar reductions were reported for the Mossgas COD diesel fuel.

5.3. Transient chassis dynamometer testing—effect of rebuilt engines and oxidation catalyst

Table 7 illustrates emissions from two 40-foot transit buses equipped with DDC 6V-92TA engines as measured the WVU transient chassis dynamometer.

Table 6
Engine dynamometer FTP transient emissions results for 1992 DDC 6V-92TA[a]

	HC (g/bhp h)	CO (g/bhp h)	CO_2 (g/bhp h)	NO_x (g/bhp h)	PM (g/bhp h)
D2	0.50	1.60	723.8	4.97	0.24
Mossgas COD	0.50 (0.0%)	0.94 (−41.1%)	695.9 (−3.8%)	4.77 (−4.0%)	0.20 (−14.5%)
D2	0.67	1.58	726.4	5.00	0.24
Mossgas 1	0.59 (−12.3%)	1.32 (−16.4%)	700.0 (−3.6%)	4.93 (−1.4%)	0.20 (−15.5%)

[a] All test results that are reported in this table were repeated in five times. The range of the standard deviations for the various fuels was 0.015–0.062 for HC, 0.065–0.253 for CO, 1.417–8.712 for CO_2, 0.070–0.855 for NO_x and 0.006–0.029 for PM.

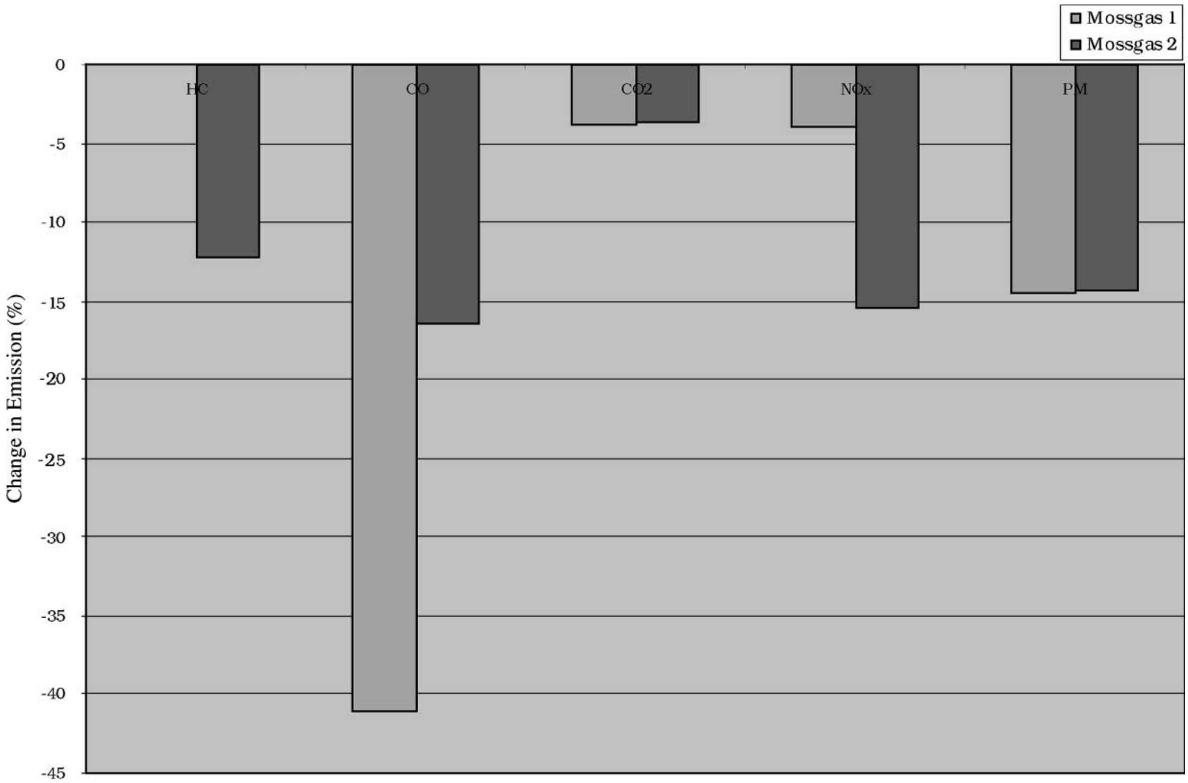

Fig. 2. Percentage reduction in emissions over base D2 fuel for DDC 6V-92TA engine.

Table 7
Transient chassis dynamometer testing over the CBD cycle—transit bus testing—port authority of Allegheny County[a]

Cycle	Fuel	Emission results (g/mile)					Fuel economy	
		HC	CO	CO_2	NO_x	PM	mile/gal	BTU/mile
Unmodified Bus #1								
CBD	D2	1.02	39.4	5059	27.5	10.0	1.99	65456
CBD	Mossgas 1	0.90	32.5	4908	26.5	8.86	1.86	66365
CBD	Mossgas 2	0.96	21.8	5034	26.9	7.45	1.82	67820
CBD	D2	1.33	39.9	4896	26.3	8.93	2.05	63398
CBD	Mossgas 1	1.07	33.2	4771	24.8	8.56	1.91	64549
Percentage reduction	Mossgas 1 over D2	−16.2	−17.2	−2.8	−4.7	−8.0		
Percentage reduction	Mossgas 2 over D2	−18.3	−45.0	1.1	0.0	−21.3		
Catalytic converter equipped Bus #2								
CBD	D2	0.43	1.72	4356	26.8	1.69	2.33	55705
CBD	Mossgas 1	0.40	0.38	4347	25.2	1.27	2.12	58157
CBD	Mossgas 2	0.42	0.27	4367	26.6	0.97	2.11	58424
CBD	D2	0.35	1.07	4458	26.9	1.89	2.28	56995
Percenatagr reduction	Mossgas 1 over D2	2.6	−72.8	−1.4	−6.2	−29.1		
Percentage reduction	Mossgas 2 over D2	7.7	−80.7	−0.9	−0.9	−45.8		

[a] All test results that are reported in this table were repeated in triplicate. The range of the standard deviations for the various fuels across the test cycles was 0.01–0.02 for HC, 0.11–0.26 for CO, 27–221 for CO_2, 0.07–1.60 for NO_x and 0.01–0.06 for PM.

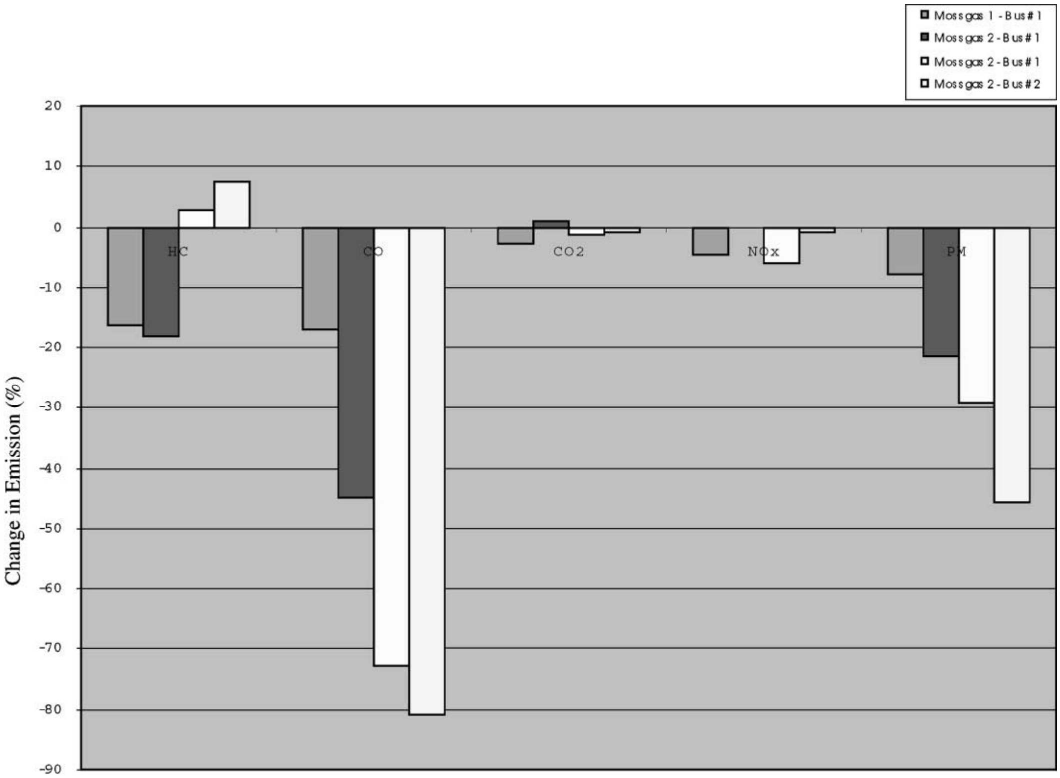

Fig. 3. Emission increase—reductions over D2 fuel catalytically equipped bus versus non-modified bus as tested over the CBD bus cycle.

One of the buses was rebuilt according to the Environmental Protection Agency's Urban Bus Retrofit Program and was fitted with an oxidation catalytic converter. Fig. 3 illustrates the percentage reduction over the D2 fuel. Testing was performed over the CBD cycle, used for transit bus testing.

The neat Mossgas fuel (Mossgas 1) and the heavy alcohol-containing blend (Mossgas 2) displayed significant reductions for NO_x, PM and CO in the unmodified bus as well as the bus equipped with an oxidation catalyst. The fuel effect was carried over from the uncatalysed bus (8–15% PM reduction) to the catalysed bus (30–40% PM reduction) and is independent of the level of emissions of the exhaust constituent. The catalytically equipped bus running on the Mossgas 2 heavy alcohol-containing blend (5%) displayed the highest level of PM reduction.

For each of the buses tested the fuel consumption (BTU/mile) was not significantly affected by fuel type, although the fuel consumption of the synthetic fuels is lower on a mile per gallon basis due to their lower density.

5.4. Transient chassis dynamometer testing—effect of test cycle

Transient chassis dynamometer tests evaluating the effect of test cycles on a 1999 model year 40-foot transit bus, using a four stroke DDC Series 50 direct injection engine are reported in Table 8. The Mossgas COD fuel was compared to a Regular Federal 49-state number 1 diesel fuel (D1) on the WVU chassis dynamometer. Fig. 4 illustrates the percentage reductions in emissions over the D1 fuel.

Fuel consumption results highlighted the fact that the Mossgas fuel demonstrates similar consumption to that of the Regular Federal 49-state number 1 diesel, while substantial emission benefits were demon-

Table 8
Transient chassis dynamometer testing over three different transient driving cycles—transit bus testing—New York city transit authority (CBD: central business district cycle; NY Bus: New York city bus cycle; Route 22: a driving cycle developed from actual in-use bus testing in New York city)

Fuel	Fuel cycle	Emission results (g/mile)					Fuel economy	
		HC	CO	CO_2	NO_x	PM	mile/gal	BTU/mile
D1	CBD	0.0	2.3	2837	36.9	0.15	3.39	37120
Mossgas COD	CBD	0.1	1.0	2816	32.2	0.30	3.28	37684
Percentage reduction over D1		25.0	−54.6	−0.7	−12.7	−43.3		
D1	NY Bus	0.1	15.5	7639	85.7	0.73	1.26	100162
Mossgas COD	NY Bus	0.2	6.6	7272	72.3	0.37	1.27	97399
Percentage reduction over D1		25.0	−57.7	−4.8	−15.6	−49.3		
D1	Route 22	0.1	2.6	2506	32.9	0.130	3.84	32809
Mossgas COD	Route 22	0.2	2.6	2386	26.9	0.097	3.87	31952
Percentage reduction over D1		50.0	0.0	−4.8	−18.2	−25.4		

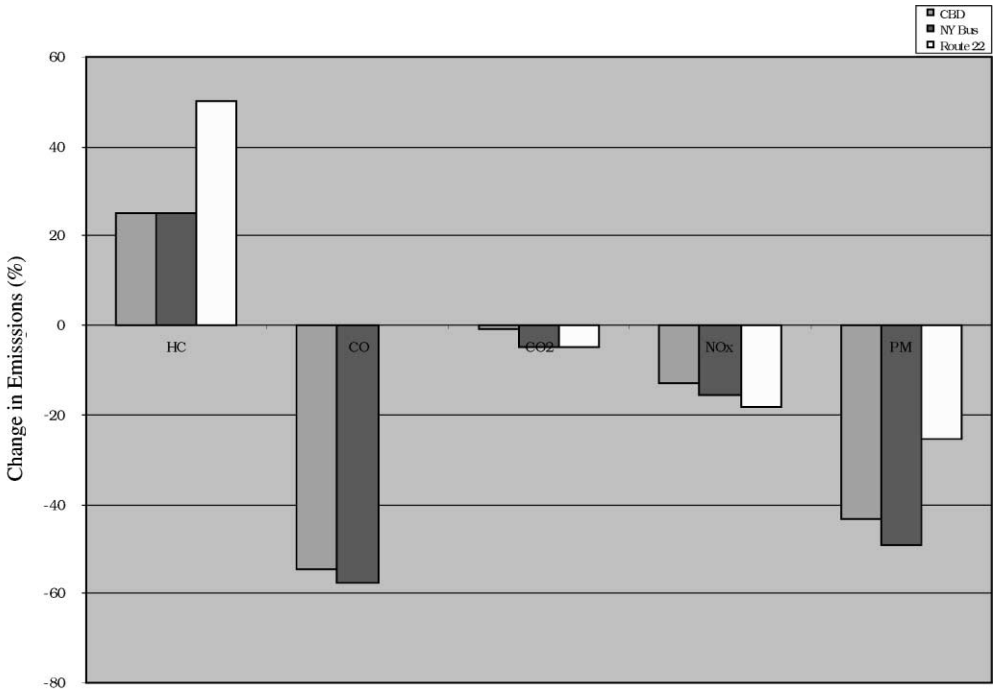

Fig. 4. Emission percentage increase—reductions of transit bus driving cycles over D2 fuel.

strated with the Mossgas fuel. NO_x was reduced by 12–18% across the three different transient cycles employed, while PM was reduced to an even greater extent of 25–50%. This bus represents currently prevailing emissions certification standards, and demonstrates the emission reduction benefits of the Mossgas diesel even for relatively low emitting four stroke engines.

6. Conclusions

This study has clearly demonstrated that Mossgas synthetically derived diesel fuel offers significant emission reduction benefits over normal fossil fuel-derived diesel fuels without any loss in performance over all expected conditions and applications as covered by the following cases:

- both heavy-duty engine dynamometer and vehicle transient emissions;
- both two and four stroke heavy-duty engines from different engine manufacturers;
- over a range of different engine technologies and ages;
- over range of various transient chassis dynamometer testing cycles;
- the presence or absence catalytic exhaust gas aftertreatment devices.

These test cases were contrived by acknowledged researchers in the field and cover practically all in-service conditions that can be put to test.

Mossgas synthetic diesel fuels are characterised by zero sulphur contents and relatively high cetane number both with and without oxygenates. Thus significant reductions in nitrous oxides and PM are realised offering measurable and perceptible contributions to a healthier environment. We believe that Mossgas GTL diesel sets the benchmark for future diesel fuel specifications.

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