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ABSTRACT

This paper features the results of emission tests conducted on diesel oxidation catalysts, and the combination of diesel oxidation catalysts and water blend fuel (diesel fuel continuous emulsion). Vehicle chassis emission tests were conducted using an urban bus.

The paper reviews the impact and potential benefits of combining catalyst and water blend diesel fuel technologies to reduce exhaust emissions from diesel engines.

INTRODUCTION

Over the past ten years, increasingly more stringent, heavy duty on-highway engine emission regulations have led to the development of engines in which nitrogen oxide (NOx) and diesel particulate matter (PM) emissions have been reduced by as much as 70% and 90% respectively.

Proposed regulations for new heavy duty engines require additional NOx and PM reductions of over 70% from existing emission limits. These emission reductions represent a continuing challenge to engine design due to the NOx-PM and fuel economy tradeoffs associated with most emission reduction strategies.

Emission reductions are also being sought from the on and off-highway in-use fleets. Within the heavy duty engine population, it is becoming more apparent that older engines are contributing a disproportionate amount of emissions toward the overall mobile source emissions inventories. Many of these engines have useful lives of over 15 years. To meet the air quality objectives in many regional areas, reductions in NOx and PM emissions will need to be derived from the in-use, mobile source engine population. In some regional areas, the proposed or required emission reductions from the engines in use potentially represent an even greater challenge than the emission limits proposed for new engines.

It is recognized that the engine, lubricants, fuel, aftertreatment and the engine application must be integrated into a system to maximize the control of emissions.

Recent engine work focuses on improvements or incorporation of new technologies to the power cylinder, air delivery, fuel management, and electronic systems. These improvements typically satisfy the emission requirements of new engines. Some improvements can also be implemented during the engine rebuild process; however, internal engine modifications are not broadly and practically applicable to in-use fleets.

Some new engines require the use of diesel specific oxidation catalysts to meet PM limits. This technology proves to be readily retrofitted.

In the urban environment, health concerns regarding diesel particulates are resulting in thousands of buses being retrofitted with oxidation catalyst technologies. Similarly, natural gas buses frequently employ oxidation catalysts to maintain low particulate, carbon monoxide and hydrocarbon emissions.

In the United States, the implementation of the urban bus rebuild/retrofit requirements increased interest in emission reduction technologies that reduce emissions from in-use heavy duty diesel vehicle fleets [1, 2].

In the United Kingdom and Sweden, many oxidation catalysts are also being installed in retrofit programs [3, 4].

Field trials have been conducted on urban buses and trucks, which were retrofitted with diesel oxidation catalysts, in Ottawa, Canada [5, 6]. In these studies, vehicles were retrofitted and intermittently recovered over a two-year period for full vehicle chassis emission testing over the Central Business District (CBD) and New York Composite Cycles. Test results indicate oxidation catalysts produce reductions in diesel particulate emissions from 19 to >50% with diesel fuel sulfur levels varying from 500 to 1400 ppm.

The retrofitting of heavy duty diesel engines with oxidation catalyst technologies has been utilized for on and off-highway vehicles used in mining, materials handling and other industrial markets. Worker health and safety is the primary reason for these applications.

A rapid series of diesel fuel improvements has been introduced in most parts of the developed world to provide reductions in particulates and NOx from the vehicle fleets in current operation as well as to facilitate the introduction of aftertreatment devices. Reducing the sulfur content and the 'heavy end' of the fuel have been the key changes. In the U.K., government tax incentives have initiated the widespread use of a new grade of diesel termed ultra low sulfur diesel (ULSD), which has a maximum 50 ppm sulfur and T95 <345°C. As well as achieving immediate reductions in particulates and NOx from the current vehicle fleet, the availability of ULSD was intended to encourage the adoption of the latest exhaust oxidation catalysts whose operation is sensitive to higher fuel sulfur levels.

Diesel fuel improvements typically involve the reduction of fuel sulfur via hydrotreating to levels as low as 10 ppm (Swedish Mk I fuel). Other fuel parameters such as aromatics and cetane have also been the subject of investigation. Specially manufactured fuels and the incorporation of special fuel components such as biodiesels, Fisher Tropsch blends, dimethyl ether, methanol, and ethanol, are also gaining attention. Advanced diesel fuel formulations offer significant emission reductions to new and older in-use engines every time the fuel tank is filled.

CATALYSTS, CONVERTERS AND CONVERTER MUFFLERS

The AZ diesel oxidation catalyst coating used in these experiments is specifically designed for the effective reduction of the soluble organic fraction contributing to the particulate mass. The catalyst has a loading of platinum on a molecular sieve containing washcoat, which is stabilized against deterioration at elevated temperatures.

The converters used on Metrobus and Routemaster buses were 46.5 cells/cm2, 7L large frontal substrates (LFA) substrates.

The converter muffler used in this study (commercially known as an AZ Purimuffler™) on the Olympian urban bus utilizes two, 46.5 cells/cm^2, 5.05L LFA substrates for a total catalyst volume of 10.1L. The test unit was designed as a direct replacement for the original vehicle muffler and affords comparable exhaust backpressure and sound attenuation. For the purposes of reporting, this technology will be generically referred to as a diesel oxidation converter (DOC).

ADVANCED DIESEL FUELS

Advanced diesel fuel formulations can be further enhanced by their incorporation into water blend diesel fuel technologies. The addition of water to diesel fuel lowers particulate emissions by serving as a diluent to the key combustion intermediates that lead to particulate formation. The incorporation of water also reduces NOx emissions by lowering the peak combustion temperatures through high heat of vaporization.

There are two basic types of emulsions in which water and diesel fuel are combined. Water blend fuel (WBF) is a diesel fuel continuous emulsion (water-in-diesel fuel). A second type is an aqueous or water continuous emulsion (diesel fuel-in-water). When using WBF (diesel fuel continuous), the engine fuel system recognizes the liquid as diesel fuel because the water droplet (less than 1 micron in size) is encapsulated within a diesel fuel [7, 8]. The water contained in the fuel passes through fuel filters readily. Water blend diesel fuel also offers fuel lubricity and corrosion characteristics, which are analogous to commercial diesel fuel. WBF emulsions can be made from selected diesel fuel base stocks and can be used in a wide variety of applications.

The basic explanation for the reduced particulate formation is attributed to a phenomenon known as micro-explosions. Micro-explosions in water blend diesel fuel (diesel fuel continuous emulsion) are the result of instantaneous vaporization of the water droplets within the fuel droplet as the fuel is exposed to increasing in-cylinder temperature during injection. Once the mean temperature of the fuel droplet increases above the boiling point of water, the water quickly and violently evaporates, breaking the droplet into smaller droplets, which results in a more complete vaporization and turbulent mixing of the fuel.

Figure 1 demonstrates how this micro-explosion phenomenon occurs.

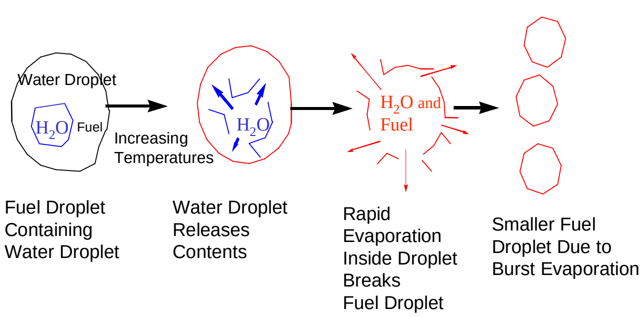


Figure 1. Micro-Explosion Phenomenon in diesel fuel continuous emulsions [7]

Surfactants and other components (e.g. Ethanol or Methanol) enhance the micro-explosion process. Any interaction that reduces the transportation of lower boiling compounds to the surface reduces the rate of diffusion. This process increases the probability of rapid boiling and bubble formation, which leads to enhanced micro-explosion of the fuel droplet.

As the water blend fuel enhances fuel atomization, it leads to the selective reduction of the insoluble carbon fraction of the particulate, which correlates to a reduction in opacity. Particulate reductions of 20-50% have been reported [7,8]. Table 1 presents the 8-Mode emission summary data reported from an 8 cylinder, 34.5L engine [7].

The data in Table 1 summarize two test condition — Fill and Go and Reset Power. Fill and Go represents the use of a 20% water blend fuel with no engine re-calibration. Use of the water blend fuel causes the power output to be reduced up to 15%. A 15% reduction in NOx and 50% reduction in particulate emissions were achieved. When the engine power was reset to the original power level, NOx was reduced by 16.6% and particulate reduced by 52%. Resetting power is only a possibility for non-regulated engines.

Table 1. 8 Mode Emission Results for 8 Cylinder, 34.5L Engine, Fill and Go and Reset Power [7]

	Emissions % Reduction **Fill and Go**	Emissions % Reduction **Reset Power**
NOx	15.0%	16.6%
HC	13.9%	18.8%
NOx + HC	15.0%	16.6%
CO	8.6%	17.1%
CO_2	6.3%	4.4%
Particulates	50.5%	52.3%

COMBINING TECHNOLOGIES

By combining water blend diesel fuel with advanced diesel oxidation catalyst technologies, greater particulate reductions should be obtained. The combination of water blend emulsified diesel fuels and oxidation catalysts could prove to offer particulate reductions similar to trap systems but without the need for trap regeneration or maintenance.

DIESEL FUEL – An ultra low sulfur diesel (ULSD) with a fuel sulfur level of less than 50 ppm was used to conduct the tests. The fuel is typical of commercially available ULSD in the United Kingdom.

WATER BLEND DIESEL FUEL – The water blend diesel fuel used in this study, know as PuriNOx™ Performance Systems fuel, is currently under market evaluation. PuriNOx™ is a registered trademark of The Lubrizol Corporation representing a system that combines diesel fuel, water, and a proprietary additive package in a proprietary blending unit to produce water blend fuel. The fuel formulation contains the additive blend and is composed of approximately 20% de-mineralized water and 80% ULSD. In these tests, the fuel was run in the engine without any modification or re-calibration.

VEHICLE DESCRIPTIONS – The vehicles tested were as follows:

a. Pre-Euro 0, Routemaster, mechanically fuel injected 8.1L normally aspirated engine, with an automatic gearbox. The vehicle was tested after an initial catalyst break-in period.
b. Pre-Euro 0, Metrobus, mechanically fuel injected, 10.5L normally aspirated engine with an automatic gearbox. The vehicle was tested after an initial catalyst break-in period.
c. Euro II Olympian B10A bus, mechanically fuel injected with an automatic gearbox. Maximum rated power was 183 kW at 2000 rpm, 1050 Nm torque at 1450 rpm.

HEAVY DUTY CHASSIS DYNAMOMETER TESTS –

The chassis dynamometer set-up has been previously described in reference [3]. Figure 2 shows the vehicle installation on the chassis dynamometer and the direction of the wind flow in the Variable Temperature Emissions Chamber (VTEC). Each vehicle was tested at curb weight with an additional load value simulating a typical passenger load. As an example, the Olympian urban bus tests were conducted at a dynamometer road load of 13,723 kg, which represented the vehicle weight plus a nominal passenger load of 75%.

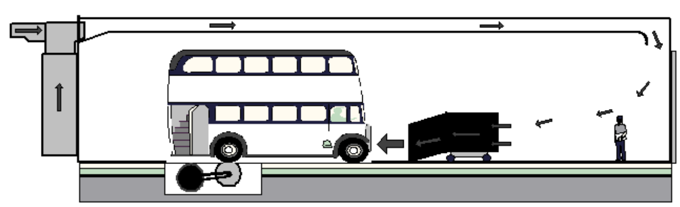


Figure 2. Diagram of VTEC Chassis Dynamometer and Airflow [3]

TEST DESCRIPTIONS – The vehicles were tested over the Millbrook London Transport Bus (MLTB) Cycle. The MLTB test cycle is an actual driving cycle, which was developed from monitoring an actual in-service bus operating in London, England. The cycle represents London Transport Bus Route 159, from Brixton Station via Lambeth Bridge to Trafalgar Square to Oxford Circus along Oxford Street and finally to the end of Baker Street. The overall length of the cycle is 2281 seconds representing a total distance traveled of 8.92 km.

The MLTB test cycle compares favorably to other European transient urban driving cycles such as The Netherlands Organization for Applied Scientific Research (TNO) cycle and The European Transient Cycle (ETC). Figure 3 provides a comparison of the speed and time characteristics of these three test cycles.

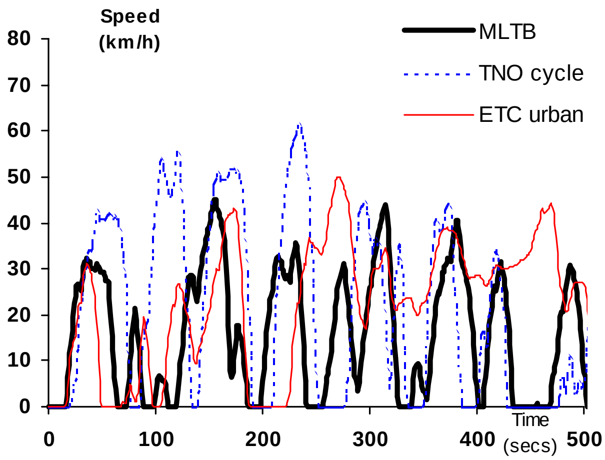


Figure 3. Comparison of Millbrook London Bus (MLTB) Cycle to other chassis driving cycles. (modified from [3])

RESULTS

EMISSION TEST RESULTS FOR VEHICLES EQUIPPED WITH OXIDATION CATALYSTS RUNNING ON ULSD FUEL – Figures 4 and 5 illustrate the emission results for the Routemaster and Metrobus chassis tests over the MLTB cycle. Results indicate that the diesel oxidation catalyst reduced diesel particulate emissions by an average of 45%, hydrocarbons by 86% and carbon monoxide by 92%. In both vehicle tests, slight reductions of NOx were also observed.

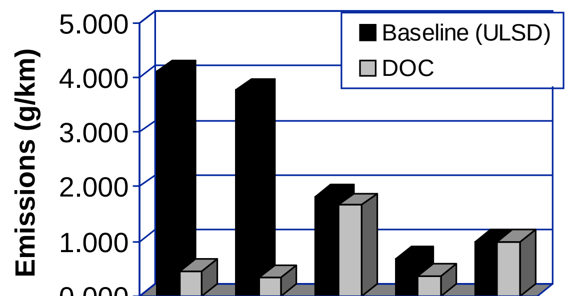
Baseline (ULSD) results for the Routemaster bus, which was equipped with a 8.1L naturally aspirated engine, indicate volatile organic fraction (VOF) accounts for 32% of the particulate--the oil component contributes 22% and the fuel component contributes 10%. With the catalyst installed, the VOF decreased to 6%, shared equally between oil and fuel components. In terms of mass, the oil component decreased by 93% and the fuel component decreased by 82% with the catalyst fitted.

Baseline (ULSD) results for the Metrobus, which was equipped with a 10.5L naturally aspirated engine, indicates VOF accounts for 40% of the particulate mass without the catalyst installed--the oil component contributes 36% and the fuel contributes 4%. With the catalyst fitted, the VOF accounts for 15% of the total particulate with the oil accounting for 12%.

The older pre-Euro 0 vehicles with relatively high percentage VOF levels, indicate oxidation catalysts yield excellent PM emission reductions. However, the upper limit for particulate reduction was found to be approximately 45-50% with little potential to reduce NOx emissions. These results compare favorably to those found in the Ottawa field trials [5, 6].

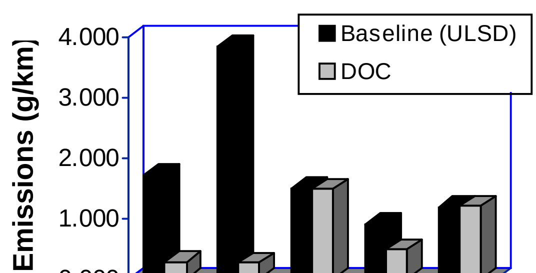
Figure 6 illustrates the emission results for the Euro II Olympian chassis test, comparing baseline (ULSD) with ULSD combined with DOC. The test results showed that particulate emissions were reduced by 22%. Gaseous performance was high, showing reductions of 92% and 96% respectively for HC and CO emissions. The addition of the DOC, had a negligible effect on NOx emissions.

This engine is believed to produce a lower VOF level in the particulate. Consequently, application of the DOC to this engine was expected to result in less particulate reduction. Particulate emissions for the DOC equipped Olympian bus were less than half of those of the pre-Euro 0 vehicles. Particulate reduction due to the oxidation catalyst for the Euro II Olympian (22%) was also about half the level of the pre-Euro 0 bus (45%).



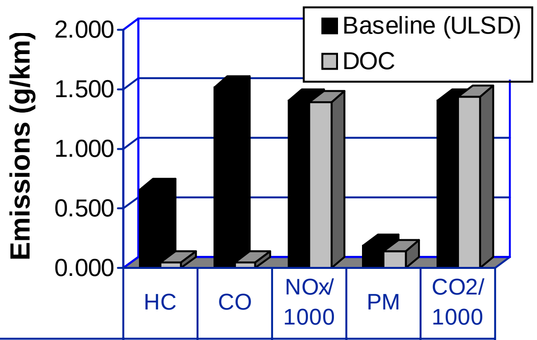
	HC	CO	NOx/ 1000	PM	CO2/ 1000
Baseline (ULSD)	4.102	3.757	1.826	0.685	1.002
DOC	0.457	0.350	1.660	0.379	1.000

Figure 4. Pre-Euro 0 Routemaster Emissions (g/km) The Millbrook London Transport Bus Cycle



	HC	CO	NOx/ 1000	PM	CO2/ 1000
Baseline (ULSD)	1.721	3.833	1.503	0.910	1.198
DOC	0.277	0.272	1.488	0.489	1.207

Figure 5. Pre-Euro 0 Metrobus Emissions (g/km) The Millbrook London Transport Bus Cycle

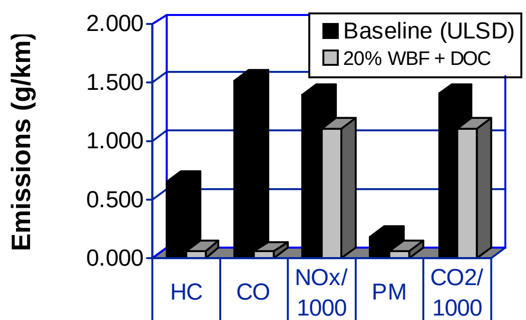


	HC	CO	NOx/ 1000	PM	CO2/ 1000
Baseline (ULSD)	0.654	1.516	1.400	0.182	1.404
DOC	0.054	0.053	1.388	0.142	1.440

Figure 6. Euro II Olympian Emissions (g/km) The Millbrook London Transport Bus Cycle

EMISSION TEST RESULTS FOR VEHICLES UTILIZING COMBINED TECHNOLOGIES – Figure 7 illustrates the emission results of the Euro II Olympian chassis test, baseline (ULSD) with a 20% water blend ULSD and DOC. The combined technologies reduced total particulate by 70% compared to the baseline. In addition, a reduction of 21% was attained in NOx emissions. Gaseous emission reductions (HC and CO) were equivalent or slightly better than DOC alone.

Although the 20% water blend fuel slightly reduces power, there was no reported effect on the vehicle's ability to follow the test cycle as prescribed.



	HC	CO	NOx/ 1000	PM	CO2/ 1000
Baseline (ULSD)	0.654	1.516	1.400	0.182	1.404
20% WBF + DOC	0.055	0.046	1.106	0.055	1.106

Figure 7. Euro II Olympian Emissions (g/km) The Millbrook London Transport Bus Cycle

DISCUSSION

The DOC technology utilized in these studies in conjunction with the older pre-Euro 0 vehicles (Routemaster and Metrobus) offered reductions of PM, HC and CO emissions of approximately 45%, 86% and 92%, respectively. The results compare favorably to other results previously published [5, 6].

Due to the PM emissions level of the older vehicles, the addition of a DOC offers an attractive and practical means to reducing PM emissions. The results indicate when the DOC technology is applied to older engines, it offers reductions of 15-21 kg over a 50,000 km period. Due to the high engine-out PM emissions of older urban bus engines, they remain a challenge to commercially available, passively regenerating, diesel particulate filter systems.

The results for the newer Euro II Olympian bus indicate that an advanced DOC system can offer high gaseous emission reductions of over 90% and moderate particulate reductions of 22%. Over a 50,000 km interval, the DOC would lead to a PM reduction of approximately 2.0 kg.

More importantly, the combination of water blend diesel fuel and DOC technologies dramatically enhances the reduction of diesel particulate and nitrogen oxides (NOx). The combination of 20% WBF and DOC technologies result in a 70% reduction of PM and a 21% reduction in NOx emissions. Over a 50,000 km interval, this results in a reduction of approximately 6.35 kg of particulate and 147 kg of NOx.

Table 2. Particulate (PM) and NOx Emission Reductions over a 50,000 km Interval for a Euro II Olympian bus

Emissions System	PM Reduction (kg)	NOx Reduction (kg)
DOC	2.0	-na-
20% WBF + DOC	6.35	147.0
Particulate Filter System	8.19	-na-

Compared to DOC, approved NO2 regenerative diesel particulate trap systems can produce ≥80% reductions in PM but little reduction in NOx emissions. Over a 50,000 km interval, a trap system would produce an approximate particulate reduction of 8.2 kg (assuming a 90% filtration efficiency).

Of particular note, water blend fuels can be made from various 50 cetane fuel base stocks. Therefore, on and off-highway blends can be produced. The DOC system employed in these tests has produced consistent emission results over a variety of vehicle types where fuel sulfur has ranged from <50 ppm to 500 ppm to as much as 1400 ppm [6]. These fuel sulfur levels are not acceptable to currently available NO_2 regenerative diesel particulate trap technologies.

The combined water blend diesel fuel and DOC system option offers a viable means to significantly reduce emissions with relatively low capital investment on a per vehicle basis. The investment is equivalent to the installation of an appropriate DOC system.

CONCLUSIONS

1. Advanced diesel oxidation converters (DOCs) prove to offer approximately 45% PM reduction on the pre-Euro 0 vehicles tested over the Millbrook London Transport Bus Cycle (MLTB). Hydrocarbon and carbon monoxide reductions of over 85% were also achieved.
2. An advanced diesel oxidation converter muffler proves to offer 22% PM reduction on a Euro II, Olympian bus over the MLTB cycle. Hydrocarbon and carbon monoxide reductions over 90% were achieved.
3. An advanced diesel oxidation converter muffler combined with the use of water blend diesel fuels proves to offer particulate and NOx reductions of up to 70% and 21% respectively over the MLTB cycle.

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NOMENCLATURE

TPM or PM:	Total Particulate Matter
THC or HC:	Total Hydrocarbons
CO:	Carbon Monoxide
NO_x:	Nitrogen Oxides
SOF:	Soluble Organic Fraction
SO4:	Sulphate
C or °C:	Degrees Celsius
kph:	Kilometers / Hour
g/km:	Grams / Kilometer
kg:	Kilogram
kW:	Kilowatts
km/L:	Kilometers / Liter
km:	Kilometers
VOF:	Volatile Organic Fraction