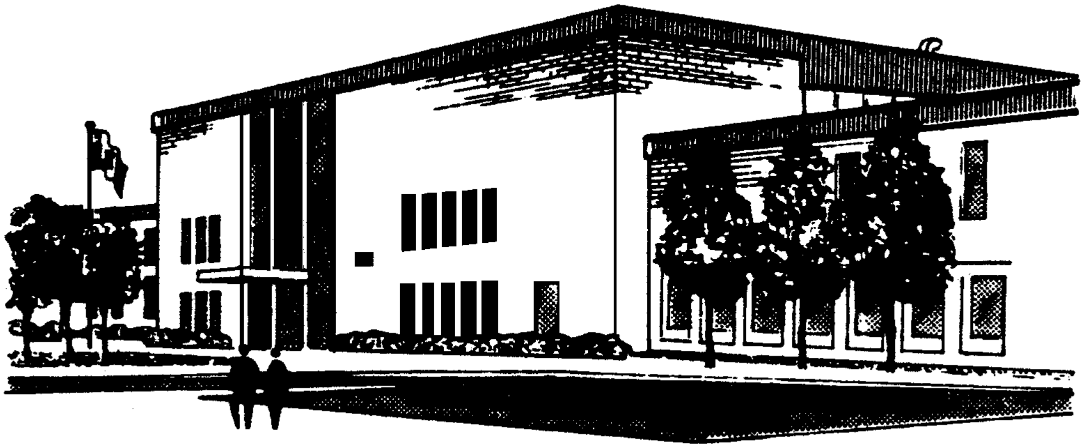
Gaseous and Particulate Matter Emissions from Two In-Use Urban Transit Buses



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Executive Summary

Two in-use urban buses were tested over the Central Business District cycle at two temperatures (20 ˚C and –10 ˚C). The old technology bus was equipped with a 2-stroke diesel engine and was tested in two configurations – with the OEM muffler and with a retrofit oxidation catalyst. This bus was certified to the 1988 heavy-duty diesel engine emission standards. The new technology bus was equipped with a 4-stroke diesel engine with a close-coupled oxidation catalyst and was certified to stringent 1998 urban bus emission standards. Both buses see on-road service with the local public transit authority in Ottawa, Ontario, CANADA.

Emission rates were determined for the gaseous criteria pollutants (CO, NO_X, THC), CO_2, methane and non-methane hydrocarbons, carbonyl compounds, vapour phase organic acids, SO_2, NH_3, $PM_{2.5}$ mass emissions, particle phase organic and inorganic ions, metals, organic and elemental carbon and for particle phase organic compounds.

At the test temperature of 20 ˚C, CO, NO_X and THC emission rates from the old technology bus with the muffler in place were the highest of all configurations. The use of the oxidation catalyst on the old technology bus resulted in a statistically significant decrease in both NO_X and THC emissions, while the CO emissions remained essentially unchanged. In comparing the new technology bus with the old technology bus with the oxidation catalyst, the new bus was found to have statistically significantly lower CO and THC emission rates. There was no difference in the NO_X emission rates. Both buses showed very similar CO_2 emission rates and fuel consumption rates. Cold temperature operation reduced the effectiveness of the oxidation catalyst for both buses, but had no statistically significant effect on the old bus with the muffler in place. NO_X emissions for both of the catalyst equipped bus actually increased with cold temperature operation.

Non-methane hydrocarbon emissions were dominated by ethylene and propylene for all configurations. The n-alkane pattern typical of diesel fuel is readily apparent in the old technology bus emissions, and is less obvious in the new technology emissions.

Toxic organic compound emissions (aromatic hydrocarbons and carbonyl compounds) were 8.5 times higher for the old technology bus with the muffler in place as compared to the new technology bus. The use of the oxidation catalyst on the old technology bus reduced this difference to 7.7 times.

The ozone specific reactivity (mg O_3/mg NMOG) for the new technology bus was slightly higher than for the old technology bus configurations. Operation at cold temperature slightly decreased the specific reactivity for all configurations. When the magnitude of the NMOG emissions was considered, the ozone potential (mg O_3/mile) of the old technology bus with the muffler in place was 9.2 times greater than the new technology bus at standard temperature while the oxidation catalyst on the old technology bus reduced the ozone potential to only 7.1 times greater than the new technology bus.

Vapour phase organic acid emission rates were measured only for the old technology bus and were found to be of the same order of magnitude as the NMHC emission rates. Hydroxymethane sulphonic acid was found in the samples. This is an important finding since sulphur(IV) present in HMSA is more resistant to oxidation in the atmosphere by H_2O_2 and O_3 than is SO_2. This compound is formed by the reaction of aqueous SO_2 with aqueous formaldehyde under acidic conditions, and likely occurs in the condensed water vapour droplets present in cooled, diluted vehicle exhaust.

Particulate matter emissions from the old technology bus with the muffler in place were 15 times greater than the new technology bus. The oxidation catalyst reduced this difference to 5.6 times greater. At cold temperature, PM emissions from the old technology bus were statistically significantly lower as compared to operation at standard conditions. There was no observed change in PM emissions with the new technology bus with operation at cold temperature. The composition of the PM emissions, however, changed significantly. At standard conditions, the old technology bus with the muffler in place had PM emissions that were 76% organic carbon. The oxidation catalyst reduced the organic carbon composition to 24%. The new technology bus had PM emissions that were 13% organic carbon. Operation at cold temperature caused an increase in the OC fraction 78%, 49% and 56% respectively for the old technology bus with the muffler, catalyst and the new technology bus.

Particle phase organic and inorganic ion emissions were low for all configurations (< 1 mg/mile) except for sulphate ion. The new technology bus had the highest sulphate emission rate, likely due to the close-coupled catalyst and the resulting higher exhaust temperatures inside the catalyst. The ammonium ion emission rate was similarly increased.

The oxidation catalyst on the old technology bus had little effect on the sulphate emission rates, likely because the exhaust temperature was not high enough to cause conversion of SO_2 to sulphate. This catalyst was not close-coupled to the engine as it was designed to be an aftermarket retrofit replacement for a standard muffler.

SO_2 emissions were different for the two buses, likely due to a difference in fuel sulphur content as they were tested nearly a year apart, and also the difference in oil consumption between the two engine technologies (2-stroke vs. 4-stroke). Gas phase ammonia emissions were low for all configurations. Most of the ammonia was found in the particle phase due to reaction with particle phase sulphate ion. There was insufficient total ammonia to completely react with the sulphate ion in the particle phase. The sulphate conversion factor (SO_2 to SO_4) for the old technology bus was only about 0.7% while for the new technology bus was 5.7% at standard temperature and only 0.3% at cold temperature. When all oxidized species of sulphur were considered, the total conversion factor for the old technology bus increased from 0.7% to 14%. Results were not available for the new technology bus to compare.

Emissions of trace metals were also low. They were dominated by lube oil components (S, Zn, P, Ca). These emissions were higher with the old technology bus with its 2-stroke engine than with the new technology bus and its 4-stroke engine.

Compounds in the particle phase that could provide source identification fingerprints (n-alkanes, alkylcyclohexanes, petroleum biomarker compounds, PAH, PAsH and NO_2-PAH) were determined. These particle phase organic compound emission rates were very low – mg/mile to µg/mile range, and their emission rates paralleled the changes in OC content with configuration and test temperature. Cold temperature operation increased the emission rates due to greater condensation on the particle phase. The emission profiles normalized to organic carbon emission rate showed strong similarity to the lube oil composition, and in some instances, influence from the fuel could be detected.

These results demonstrate quite convincingly that removing old technology buses from the road can have a dramatic effect on improving urban air quality.

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1. Introduction

For the purposes of developing emission rate data for emissions inventories, two in-use urban diesel buses of different vintages were tested at 20°C and -10°C on a chassis dynamometer. Mass emission rates of CO, CO_2, NO_X, THC, $PM_{2.5}$ were determined. Samples were also collected for determining mass emission rates of methane and non-methane hydrocarbons, carbonyl compounds, particle phase organic and inorganic ions, SO_2, NH_3, vapour phase organic acids and for detailed organic compound analysis. The vehicles were operated over the Central Business District (CBD) test cycle.

The first bus had an older technology 2-stroke engine and was part of an exhaust after-treatment demonstration study conducted by ERMD[1,2]. This bus was tested in two configurations, with the OEM muffler installed and with the aftermarket retrofit oxidation catalyst installed. This particular bus sees in-use service with the local transit authority with the oxidation catalyst installed, but other buses of the same type have no exhaust after-treatment device installed. The second bus was equipped with a new technology 4-stroke diesel engine with an oxidation catalyst and was just recently introduced into service by the local transit authority.

Emissions of both particulate matter and toxic compounds from urban buses are of concern in urban areas, as indicated by the tighter emissions standards of urban bus engines as compared to other diesel engines[3]. The data produced by this series of vehicle tests will be used to help determine the relative contribution of different modes of urban transportation to both toxic organic compound levels and $PM_{2.5}$ levels in Canadian urban areas.

The particulate matter emissions measurements were conducted as part of the PERD funded project "Determination of the concentration, composition and sources of atmospheric carbonaceous particles in Canada" [4]. The detailed gaseous emissions measurements were conducted as part of the TSRI funded project "Measurement and modelling of motor vehicle related air toxics along urban streets" [5].

2. Test Procedure

2.1 Test Vehicles

The buses were tested in as-received condition using the on-board fuel. An inspection for vehicle safety and exhaust system integrity was conducted prior to testing. Details of the two test buses are summarised in Table 1.

Table 1. Vehicle specifications.

	Old Technology Bus 8910	**New Technology Bus 9838**
Powertrain	Detroit Diesel 6V92TA (1989) 2-stroke diesel 1988 HDD engine emission standard Allison 731 transmission	Detroit Diesel Series 50 (1998 DDec 4) 4-stroke diesel 1998 urban bus engine emission standard Allison B4400R transmission
Coach size	40 ft, 1989 MCI	1998 Orion5, 45 passenger
Emission Control / Exhaust After-treatment	Configuration 1: OEM muffler Configuration 2: Engine Control Systems Diesel Oxidation Catalyst	OEM Oxidation Catalyst Waste gate valve ECM smoke control program
Vehicle Weight (kg)		
Empty	10790	12156
Gross	13730	15216
Mileage	765000	201000

The aftermarket (retrofit) oxidation catalyst installed on the old technology bus was designed as a direct replacement for the original muffler. It was located in the exhaust system about 6 feet downstream from the engine. As the exhaust travels through the exhaust system it cools. This retrofit catalyst was unable to take advantage of the exhaust temperature to assist in its operation. The catalyst on the new technology bus was located very close to the engine and was thus able to use the increased exhaust gas temperature to its advantage.

2.2 Chassis Dynamometer

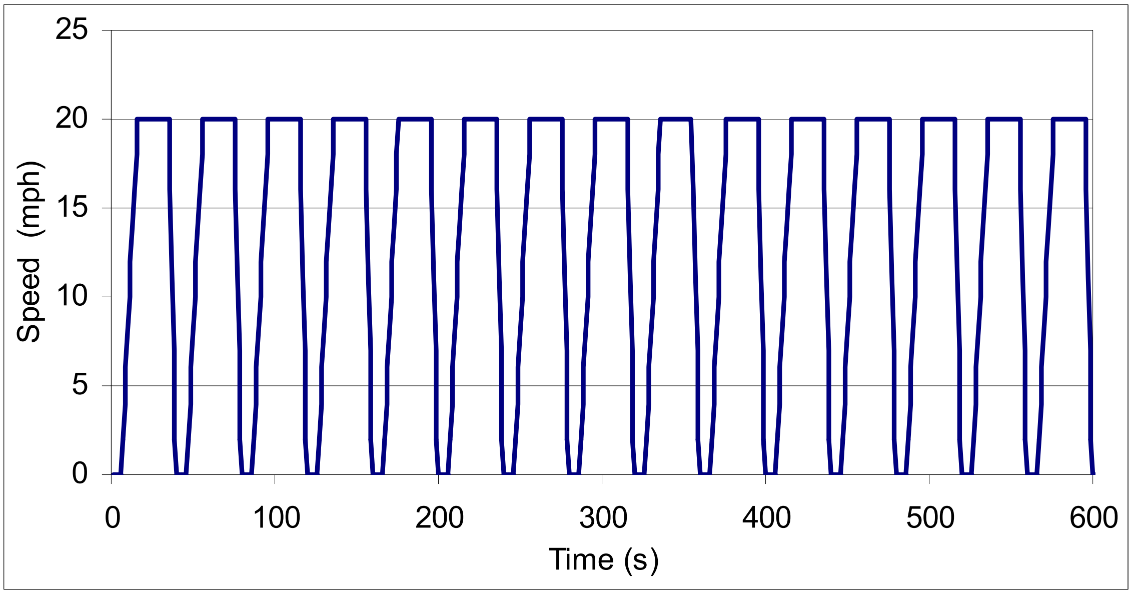
The test procedures that were followed for the exhaust emission testing of these buses were outlined in the US-EPA report entitled "Recommended Practice for Determining Exhaust Emissions from Heavy-Duty Vehicles Under Transient Conditions". The exhaust emission rates and fuel economy were calculated in accordance with the US-EPA Code of Federal Regulation, Schedule 40, Part 86 (CFR).

The buses were driven on a single roll chassis dynamometer system with a 0.61 m (24 inch) diameter roll. The inertia weight and road load were simulated during testing using a 400 Hp General Electric direct current motor. The system has the capability of testing vehicles from 7700 to 35000 kg (18526 to 77161 lb) while the road load is simulated at all vehicle speeds while compensating for the systems internal power losses. The buses were tested at an inertia weight of 28200 lb and a road load of 50 Hp.

2.3 Test Cycle

Each vehicle was tested over 6 repeats of the Central Business District (CBD) test cycle. The first repeat of each set of three was not sampled for particulate matter emissions or detailed gaseous emissions analyses. The criteria pollutants were measured over the first repeat to ensure the vehicle was operating in a repeatable manner. The driving trace for the CBD cycle is shown in Figure 1. This driving cycle is intended to simulate the repetitive acceleration, cruise, deceleration and idle operation of an urban bus moving from one passenger stop to the next and from one intersection to the next in congested urban driving.

Figure 1. Central Business District cycle driving trace.



The buses were tested at two ambient temperatures, 21°C and -10°C. As the buses use only water in their cooling systems and are parked indoors during the winter, the testing at -10°C did <u>not</u> include a cold soak of the vehicle. For the test program the buses were parked inside the test facility, started and then brought into the cold cell for engine warm-up and testing. Emissions testing was not initiated until the vehicle had reached a stable operating temperature and the test cell had reached the desired temperature. This usually required about 30 minutes. Engine start emissions were also not sampled as the vehicle was idled between emissions tests.

Previous experience in testing heavy-duty vehicles on chassis dynamometers has shown that NO_X emissions in particular are quite sensitive to the positioning and securing of the vehicle on the dynamometer[6]. This sensitivity can result in up to a 5% difference in measured NO_X emission rates from the same vehicle under the same conditions except for being repositioned on the dynamometer. For this reason, the testing schedule was designed to minimize the number of times the vehicle was removed from the dynamometer and re-installed. For the old technology bus, the change in configuration between OEM muffler and oxidation catalyst was done with the vehicle in place on the dynamometer. As the catalyst was designed as a retrofit device for installation on in-service vehicles, it was designed to be a direct replacement for the OEM muffler. The changeover was as simple as releasing clamps on the exhaust pipe, dropping out the muffler and securing the catalyst in its place.

2.4 Emissions Sampling

The total exhaust stream produced by the buses was collected and diluted using a constant volume sampling (CVS) dilution system with a total dilute exhaust volume of 2000 scfm. The dilution air was taken from the test cell and was HEPA filtered and passed through activated charcoal to minimize volatile organic compound concentrations. The total volume of raw exhaust was transferred from the buses to the CVS through a six inch diameter flexible, stainless steel pipe that was insulated. The raw exhaust was then diluted with conditioned laboratory air and the mixture directed through a critical flow venturi. During cold temperature testing, the exhaust was diluted with cold air in order to simulate the particulate matter composition that would be found in winter conditions in the ambient air.

2.4.1 Criteria Emissions

Samples of dilute exhaust were collected over each repeat of the CBD cycle for determining emission rates of CO, CO_2, NO_X and THC. Dilute exhaust and dilution air concentrations of CO, CO_2, NO_X and THC were determined using non-dispersive infra-red (CO and CO_2), chemiluminescence (NO_X) and flame ionisation (THC) analysers as described in the CFR.

2.4.2 Particulate Matter Emissions

Particulate matter samples were collected over repeats 2 and 3 of each set of 3 repeats of the CBD cycle. Three probes were installed in the CVS that allowed all samples to be collected at the same point in the system. Sampling was conducted under axial, isokinetic conditions. Attached to two of the probes were 2.5 μm cut point cyclones. Each cyclone operated at 91 lpm to achieve the desired cut point. Both of these cyclones were fitted with 90 mm diameter filter holder containing a single Emfab filter and were sampled at 91 lpm. These samples were collected for detailed organic compound analysis. The third cyclone was fitted with a manifold that allowed four 47-mm diameter filter holders to be connected. Only three filter holders were used. Two of the filter holders were two stage and the third was a three-stage holder. One of the two-stage filter holders had Teflon membrane filter (Gelman Teflo 2 μm pore size) on the first stage for determining mass emission rates and for determining particle phase ions. The second stage was occupied by a fired quartz filter for determining the amount of semivolatile organic carbon adsorbed from the gas stream. The second two-stage filter holder had a fired quartz filter on the first stage for determining elemental and organic carbon content of the PM and a potassium hydroxide coated filter for determining vapour phase organic acids. The third filter holder had a Teflon membrane filter on the first stage for determining mass emission rates and for determining elemental composition. The second stage of this filter holder contained a potassium carbonate coated cellulose filter for determining SO_2 emissions and the third stage contained a citric acid coated cellulose filter for determining NH_3 emissions. Each of the three filter holders was sampled at 30.3 lpm for a total flow through the cyclone of 91 lpm.

Dilution air samples were collected without the use of a cyclone as the dilution air was HEPA filtered. One set of dilution air samples was collected over all tests conducted on a given day. Four 47-mm diameter filter holders were used. One filter holder contained two quartz filters for elemental and organic carbon analysis. The second filter holder contained a Teflon filter followed by a potassium carbonate filter and a citric acid coated filter, the third filter holder contained a Teflon filter followed by a quartz filter and the fourth filter holder contained an Emfab filter for detailed organic carbon analysis**.**

The samples collected for detailed particulate matter emissions characterization are summarized in Table 2.

Table 2. Particulate matter sampling scheme.

Dilute Exhaust Samples			
Target Compounds	**Analytical Technique**	**Filter Media**	**Equipment Needed**
Organic Carbon / Elemental Carbon Organic acids	NIOSH 5040 IC/CE	Quartz (1) KOH quartz (2)	47mm filter (2-stage) 30.33 lpm Channel 1 of 91 lpm, 2.5 μm cyclone
Gravimetric Trace Metals OC/EC correction	Mettler MT-5 XRF NIOSH 5040	Teflo (1) Quartz (2)	47mm filter (2-stage) 30.33 lpm Channel 2 of 91 lpm, 2.5 μm cyclone
Ions SO_2 NH_3	IC	Teflo (1) Carbonate (2) Citric (3)	47mm filter (2-stage) 30.33 lpm Channel 3 of 91 lpm, 2.5 μm cyclone
Detailed Organic Carbon Analyses	GC-MS	Emfab (1&2)	90 mm filter (2-stage) 91 lpm 2.5 μm cyclone
Dilution Air Samples			
Target Compounds	**Analytical Technique**	**Filter Media**	**Equipment Needed**
Organic Carbon / Elemental Carbon	NIOSH 5040	Quartz (1&2)	47mm filter (2-stage) 22.75 lpm Channel 1 of 91 lpm, 2.5 μm cyclone
Gravimetric, Ions and SO_2 and NH_3	Mettler MT-5 IC / CE	Teflo (1) Carbonate (2) Citric (3)	47mm filter (2-stage) 22.75 lpm Channel 2 of 91 lpm, 2.5 μm cyclone
Trace Metals and OC/EC correction	IC / CE	Teflo (1) Quartz (2)	47 mm filter (2-stage) 22.75 lpm Channel 3 of 91 lpm, 2.5 μm cyclone
Detailed Organic Carbon Analyses	GC-MS	Emfab (1)	47 mm filter (2-stage) 22.75 lpm Channel 4 of 91 lpm, 2.5 μm cyclone

2.4.3 Gaseous Emissions

Samples were collected for determining emission rates of methane, non-methane hydrocarbons, carbonyl compounds.

For the old technology bus, dilute exhaust was drawn through a glass tube packed with Tenax adsorbent then delivered to a Tedlar bag. This sample was analysed for methane and non-methane hydrocarbons (NMHCs, C_2-C_{26}). One dilute exhaust sample was collected as an average over two repeats of the CBD. Samples for carbonyl compound analysis were collected on 2,4-dinitrophenylhydrazine (DNPH) coated silica cartridges. One dilute exhaust sample was collected as collected as a single sample over two repeats of the CBD cycle.

One dilution air sample for methane and non-methane hydrocarbons was collected over all 4 of the sampled repeats. The Tenax tube was not used on the dilution air sample as the air was conditioned using activated carbon. One dilution air sample for carbonyl compounds collected over all 4 of the sampled repeats.

For the new technology bus, the Tenax adsorbent was not used upstream of the Tedlar bag. Hydrocarbon emission rates from this bus were expected to be very low as it was designed to meet much lower emissions standards than the older bus and was equipped with an oxidation catalyst. The current sample collection and analysis method for C_{12}-C_{26} NMHCs does not have sufficiently low detection limits to produce high quality data for these low-emitting buses. The Tedlar bag sample was analysed for methane and non-methane hydrocarbons in the range C_2-C_{12}. One dilute exhaust sample was collected as an average over the two repeats of the CBD. Samples for carbonyl compound analysis were collected on DNPH coated silica cartridges. One dilute exhaust sample as collected as a single sample over two repeats of the CBD cycle. Dilution air samples for methane and non-methane hydrocarbons and for carbonyl compounds were collected as single samples over all 4 of the sampled repeats.

2.5 Analytical Methods

A wide variety of analytical methods are employed to give the emission data set for this project. Each method is briefly outlined below.

2.5.1 Gravimetric Analysis

Initial and final masses for the 47 mm and 90 mm diameter Emfab filters were determined using a Mettler AE240 semi-microbalance capable of 10 µg mass resolution. Filters were humidity equilibrated for a minimum of 8 hours at 50% RH before each mass determination. Constant mass to within 0.00002 g was obtained for both initial and final mass determinations. The quantitation limit for $PM_{2.5}$ mass emission rate using the 90 mm filter was 10 mg/mile.

Initial and final masses for the 47 mm Teflon membrane filters were determined using a Mettler MT-5 microbalance capable of 1 µg mass resolution. Filters were humidity equilibrated for a minimum of 8 hours at 40 ± 10% RH before each mass determination. Constant mass to within 0.000002 g was obtained for both initial and final mass determinations. The quantitation limit for $PM_{2.5}$ mass emission rate using the low flow 47 mm filter was 3 mg/mile.

Gravimetric measurements were performed by Environment Canada – ERMD.

2.5.2 Organic and Inorganic Ions

One of the two Teflon membrane filters collected on each repeat was submitted for determining particle phase organic and inorganic ions by ion chromatography and capillary electrophoresis. The potassium carbonate and citric acid coated cellulose filters and the potassium hydroxide coated quartz filter were submitted for sulphate ion, ammonium ion and organic acid anion analyses respectively. These analyses were performed by the Analysis and Air Quality Division at the Environmental Technology Centre of Environment Canada.

The Teflon filter samples were first wetted with 120 µL isopropanol and then extracted into 12 mL deionised water by ultrasonication for 30 minutes. The extracts were analysed by three methods: gradient ion chromatography for inorganic and organic anions, isocratic ion chromatography for inorganic cations and capillary electrophoresis for organic acid anions. Both ion chromatography methods used suppressed conductivity detection while the capillary electrophoresis method used indirect UV detection at 214 nm[7,8]. Table 3 summarises the complete suite of organic and inorganic ions determined from the Teflon filters using these three methods and their respective detection limits.

The potassium carbonate coated filters were extracted into 50 mL 0.09% H_2O_2 in deionised water and ultrasonicated for 30 min. The peroxide was necessary to ensure the complete oxidation to sulphate ion. The extracts were analysed by isocratic ion chromatography with suppressed conductivity detection. The detection limit for this method is approximately 0.2 mg/mile.

The citric acid coated filters were extracted into 10 mL deionised water and ultrasonicated for 30 minutes. The extracts were analysed by isocratic ion chromatography with suppressed conductivity detection. The detection limit for this method is approximately 0.07 mg/mile.

The potassium hydroxide coated filters were extracted into 10 mL deionised water with ultrasinication for 30 minutes. The extract was then passed through an ion exchange cartridge to exchange the excess potassium ions for hydrogen ions in the solution to permit better chromatography. These extracts were analysed by capillary electrophoresis using indirect UV detection[7]. Table 4 summarises the complete suite of organic acid anions determined using this method and their respective detection limits.

Table 3. Particle phase organic and inorganic ions and their detection limits (mg/mile).

Particle Phase Organic Anions			Particle Phase Inorganic Anions			Particle Phase Inorganic Cations		
	DL mg/mile	QL mg/mile		DL mg/mile	QL mg/mile		DL mg/mile	QL mg/mile
Pyruvate	0.08	0.3	Methane sulphonate (MSA)	0.1	0.4	Lithium	0.02	0.06
Glyoxylate	0.08	0.3	Chloride	0.05	0.2	Sodium	0.06	0.2
Benzoate	0.1	0.4	Nitrite	0.1	0.4	Ammonium	0.06	0.2
Oxalate	0.02	0.08	Bromide	0.1	0.5	Potassium	0.05	0.2
Phthalate	0.04	0.1	Nitrate	0.06	0.2	Magnesium	0.03	0.1
Malonate	0.009	0.03	Sulphate	0.05	0.2	Manganese	0.04	0.1
Formate	0.01	0.04	Phosphate	0.07	0.2	Calcium	0.06	0.2
Malate	0.01	0.03				Strontium	0.06	0.2
Succinate	0.009	0.03						
Glutarate	0.007	0.02						
Adipate	0.02	0.08						
Pimelate	0.01	0.03						
Hydroxymethane sulphonate (HMSA)	0.02	0.06						
Acetate	0.03	0.1						
Azelate	0.02	0.08						
Lactate	0.03	0.1						

Table 4. Gas phase organic acids and their detection limits (mg/mile).

Measured Organic Acid Anion	Corresponding Organic Acid	DL mg/mile	QL mg/mile
Formate	Formic	0.3	0.9
Succinate	Succinic	0.2	0.6
Glutarate	Glutaric	0.3	0.8
Phthalate	Phthalic	0.2	0.6
Adipate	Adipic	0.3	0.9
Hydroxymethane sulphonate	Hydroxymethane sulphonic (HMSA)	0.3	1.0
Acetate	Acetic	0.5	1.5
Lactate	Lactic	0.2	0.8

2.5.3 Elemental Analysis

The second Teflon membrane filter was submitted to the Analysis and Air Quality Division at the Environmental Technology Centre of Environment Canada for x-ray fluorescence analysis for 47 elements using their standard method for aerosol samples on Teflon filters. An x-ray fluorescence spectrometer equipped with a silicon-lithium detector was used for all measurements. As this analysis is non-destructive, these samples can be archived for later analysis for platinum group elements. Table 5 summarises the target elements and their detection limits for the XRF analysis.

Table 5. Target analytes for the XRF analysis of trace metals and their detection limits (mg/mile).

	mg/mile		mg/mile
Na	0.01	Rb	0.0009
Mg	0.002	Sr	0.0008
Al	0.003	Y	0.0009
Si	0.004	Zr	0.0009
P	0.003	Nb	0.0009
S	0.002	Mo	0.001
Cl	0.006	Pd	0.001
K	0.009	Ag	0.001
Ca	0.009	Cd	0.001
Sc	0.01	In	0.001
Ti	0.01	Sn	0.002
V	0.009	Sb	0.002
Cr	0.006	Te	0.002
Mn	0.005	I	0.003
Fe	0.006	Cs	0.003
Co	0.003	Ba	0.003
Ni	0.002	La	0.002
Cu	0.004	Ce	0.002
Zn	0.002	Pr	0.002
Ga	0.003	Nd	0.002
Ge	0.002	W	0.02
As	0.002	Hg	0.004
Se	0.001	Pb	0.004
Br	0.001		

2.5.4 Total Organic and Elemental Carbon

The two quartz filters (one primary particulate matter filter and one secondary adsorbed carbon filter) were submitted for analysis of total organic and elemental carbon using NIOSH Method 5040 "Thermal/Optical Transmittance (TOT) method. This analysis was performed by NRCan – Mining and Mineral Technology Laboratory. The method is described as follows.

A 1.5 cm^2 punch is taken from each filter sample. This filter punch is heated sequentially to temperatures of 300, 600 and 900 °C in a pure helium atmosphere to evolve volatile carbon. The sample is then cooled to 600 °C, the atmosphere is changed to 2% oxygen in helium and the sample is heated further to 600, 750 and 940 °C. The carbon evolved in the helium or helium/oxygen stream is first quantitatively catalytically oxidized to carbon dioxide, then quantitatively reduced to methane. The methane content of the stream is quantified using a flame ionisation detector. The transmittance of laser light by the filter sample is monitored throughout the analysis. This transmittance decreases during the volatilization in a helium atmosphere owing to the pyrolysis of organic material. When oxygen is added, the transmittance increases as the light absorbing carbon is combusted and removed. Organic carbon is defined as that which evolves prior to re-attainment of the reflectance and elemental carbon as that material that evolves after the original transmittance has been attained.

This analysis method requires samples to be collected on pure quartz filters. During sample collection, the quartz sample media adsorbs vapour phase organic carbon from the sample stream. This adsorption results in a positive artifact in the organic carbon analysis as there is organic carbon present on the filter that is not part of the particulate matter. A negative artifact also occurs during sampling when a small fraction of the organic carbon adsorbed to the particulate matter is desorbed as a result of the pressure drop across the filter. The positive artifact is usually quite large while the negative artifact is usually small and is often ignored. In order to effectively correct for the positive artifact, a second quartz filter is located downstream of a Teflon membrane filter. The Teflon membrane filter does not adsorb organic carbon from the vapour phase leaving the downstream quartz filter exposed to a particle-free sample stream. In ambient air studies and in previous emissions studies[9,10], the secondary quartz filter was placed downstream of the primary quartz filter. This placement has been shown to inadequately correct emissions samples for the adsorbed organic carbon artifact as the secondary quartz filter is exposed to a depleted vapour phase organic carbon sample stream. With emissions samples, the vapour phase organic carbon concentration is much higher than seen in ambient air samples and the difference in the method of correction is significant.

Detection limits for organic and elemental carbon for samples collected in this study are approximately 1.3 mg/mile.

2.5.5 Particle Phase Organic Compounds

The 90 mm diameter Emfab filters were combined into composite samples for each vehicle and configuration. Considering level of effort required and the cost involved in this type of analysis, and the amount of sample required to provide valid results, composite samples were deemed necessary. Table 6 and Table 7 summarize the target compounds for each analysis. Detection limits for these compounds are given in Table 8 and Table 9.

The sample extraction, cleanup and fractionation procedures were performed by NRCan-CETC. The sample analyses were performed by NRCan-CETC and Environment Canada – AAQD.

Table 6. Target PAH, NO_2-PAH and PAsH.

PAH	NO_2-PAH	PAsH
Acenaphthylene	2- Nitrofluorene	thionaphthene
Acenaphthene	9-Nitroanthracene	dibenzothiophene
Fluorene	2-Nitroanthracene	naphtho(2,1-b)thiophene
2-Me-Fluorene	9-Nitrophenanthrene	2-methyldibenzothiophene
Phenanthrene	2-Nitrofluoranthene	8-methylnaphtho(2,1-b)thiophene
Anthracene	3-Nitorfluoranthene	5-methylnaphtho(2,1-b)thiophene
Fluoranthene	4-Nitropyrene	4,6-dimethyldibenzothiophene
Pyrene	1-Nitropyrene	1,8-dimethyldibenzothiophene
Retene ()	2-Nitropyrene	1,3-dimethyldibenzothiophene
Benzo(a)Fluorene	7-Nitrobenz(a)anthracene	phenanthro(4,3-b)thiophene
Benzo(b)Fluorene	6-Nitrochrysene	phenanthro(3,4-b)thiophene
1-Me-Pyrene	1-Nitrobenzo(e)pyrene	phenanthro(2,1-b)thiophene
Benzo(g,h,i)Fluoranthene	6-Nitrobenzo(a)pyrene	phenanthro(2,3-b)thiophene
Benzo(a)Anthracene	4-Nitrobenzo(e)pyrene	anthra(2,3-b)thiophene
Triphenylene	3-Nitrobenzo(e)pyrene	10-methylbenzo(b)naphtho(2,1-d)thiophene
Chrysene	3-Nitrobenzo(a)pyrene	2-methylbenzo(b)naphtho(2,1-d)thiophene
7-Me-Benzo(a)Anthracene	1-Nitrobenzo(a)pyrene	8-methylbenzo(b)naphtho(1,2-d)thiophene
Benzo(b)Fluoranthene	2-Nitrobenzo(a)pyrene	5-methylbenzo(b)naphtho(2,1-d)thiophene
Benzo(k)Fluoranthene	9-Nitrodibenzo(a,c)anthracene	6-methylbenzo(b)naphtho(2,1-d)thiophene
Benzo(e)Pyrene	1,3-Dinitropyrene	8-methylbenzo(b)naphtho(2,3-d)thiophene
Benzo(a)Pyrene	1,6-Dinitropyrene	11-methylbenzo(b)naphtho(2,3-d)thiophene
Perylene	1,8-Dinitropyrene	
2-Me-Cholanthrene	6-Nitro-3,4-Benzocoumarin	
Indeno(1,2,3-cd)Pyrene	7-Nitro-12-Methylbenzo(a)anthracene	
Dibenzo(a,c)&(a,h)Anthracene	12-Ethyl-6-Nitrochrysene	
Benzo(b)Chrysene		
Benzo(g,h,i)Perylene		
Anthanthrene		

Table 7. Target alkanes, alkylcyclohexanes and petroleum biomarker compounds.

Alkanes	Terpanes	Steranes
n-C11	C19 tricyclic terpane	C20 aaa-sterane
n-C12	C20 tricyclic terpane	C21 Baa-sterane
n-C13	C21 tricyclic terpane	C21 aBB-sterane
n-C14	C22 tricyclic terpane	C21 aaa-sterane
n-C15	C23 aB-dimethyl-a-butylpodocarpane	C22 aBB-sterane
n-C16	C25 tricyclic terpane	C27 20S-Ba-diasterane
n-C17	C26 tricyclic terpane	C27 20R-Ba-diasterane
Pristane (2,6,10,14-tetramethylpentadecane)	C26 tricyclic triterpane 22R	C27 20S-aB-diasterane
n-C18	C26 tricyclic triterpane 22S	C27 20R-aB-diasterane
Phytane (3,7,11,15-tetramethylhexadecane)	C27 tetracyclic terpane 22R	C28 20S-Ba-diasterane
n-C19	C27 tetracyclic terpane 22S	C28 20R-Ba-diasterane
n-C20	C28 tetracyclic terpane 22R	C28 20R/S?-Ba-diasterane
n-C21	C28 tetracyclic terpane 22S	C28 20R/S?-Ba-diasterane
n-C22	C27 aB-Trisnorneohopane	C28 20S-Ba-diasterane
n-C23	C27 aaB-Trisnorhopane	C27 20R-Baa-cholestane
n-C24	Trisnorhopane	C27 20S-aaa-cholestane
n-C25	C30 Tricyclic terpane 22R	C27 20R-aBB-cholestane
n-C26	C30 Tricyclic terpane 22S	C27 20S-aBB-cholestane
n-C27	C28 aaB-Bisnorhopane	C27 20R-aaa-cholestane
n-C28	C29 aB-25-norhopane	C29 20S-Ba-diasterane
n-C29	aB-norhopane	C29 20S-Ba-diasterane
n-C30	C29 aB-Norneohopane	C28 20S-aaa-methylcholestane
n-C31	Ba-norhopane	C28 20R-aBB-methylcholestane
n-C32	aB-hopane	C28 20S-aBB-methylcholestane
n-C33	Ba-hopane	C29 20R-aB-diasterane
n-C34	22S-aB-homohopane	C28 20R-aaa-methylcholestane
n-Alkylcyclohexanes	22R-aB-homohopane	20S-aaa-ethylcholestane
n-C13 - cyclohexane	C32 22S-aB-bishomohopane	20R-aBB-ethylcholestane
n-C14 - cyclohexane	C32 22R-aB-bishomohopane	20S-aBB (20R-Baa)-ethylcholestane
n-C15 - cyclohexane	C33 22S-aB-trishomohopane	20R-aaa-ethylcholestane
n-C16 - cyclohexane	C33 22R-aB-trishomohopane	
n-C17 - cyclohexane	C34 22S-aB-tetrakishomohopane	
n-C18 - cyclohexane	C34 22R-aB-tetrakishomohopane	
n-C19 - cyclohexane	C35 22S-aB-pentakishomohopane	
n-C20 - cyclohexane	C35 22R-aB-pentakishomohopane	

Table 8. Detection limits for particle phase organic compounds.

	Old Technology Bus	New Technology Bus
n-alkanes (mg/mile)	0.001	0.0004
alkylcyclohexanes (mg/mile)	0.005	0.0001
Terpanes/hopanes (mg/mile)	0.0008	0.0002
Steranes/cholestanes (mg/mile)	0.001	0.0004

Table 9. Detection limits for particle phase organic compounds.

PAH (mg/mile)	Old Technology Bus	New Technology Bus	PAsH (μg/mile)	Old Technology Bus	New Technology Bus	NO_2-PAH (μg/mile)	Old Technology Bus	New Technology Bus
Acenaphthylene	0.0001	0.00003	thionaphthene	0.003	0.0008	2- Nitrofluorene	0.003	0.0008
Acenaphthene	0.0001	0.00003	dibenzothiophene	0.007	0.002	9-Nitroanthracene	0.003	0.0008
Fluorene	0.0001	0.00003	naphtho(2,1-b)thiophene	0.007	0.002	2-Nitroanthracene	0.003	0.0008
2-Me-Fluorene	0.0002	0.00006	2-methyldibenzothiophene	0.001	0.0004	9-Nitrophenanthrene	0.003	0.0008
Phenanthrene	0.0003	0.00008	8-methylnaphtho(2,1-b)thiophene	0.003	0.0008	2-Nitrofluoranthene	0.003	0.0008
Anthracene	0.0003	0.00008	5-methylnaphtho(2,1-b)thiophene	0.001	0.0004	3-Nitorfluoranthene	0.006	0.002
Fluoranthene	0.0003	0.00008	4,6-dimethyldibenzothiophene	0.01	0.004	4-Nitropyrene	0.012	0.003
Pyrene	0.0003	0.00008	1,8-dimethyldibenzothiophene	0.01	0.004	1-Nitropyrene	0.003	0.0008
Retene	0.002	0.0005	1,3-dimethyldibenzothiophene	0.008	0.002	2-Nitropyrene	0.003	0.0008
Benzo(a)Fluorene	0.0003	0.00008	Phenanthro (4,3-b)thiophene	0.03	0.008	7-Nitrobenz(a) anthracene	0.003	0.0008
Benzo(b)Fluorene	0.0003	0.00008	Phenanthro (3,4-b)thiophene	0.03	0.008	6-Nitrochrysene	0.003	0.0008
1-Me-Pyrene	0.0003	0.00008	Phenanthro (2,1-b)thiophene	0.03	0.008	1-Nitrobenzo(e) pyrene	0.006	0.002
Benzo(g,h,i)Fluoranthene	0.0009	0.0002	Phenanthro (2,3-b)thiophene	0.03	0.008	6-Nitrobenzo(a) pyrene	0.006	0.002
Benzo(a)Anthracene	0.001	0.0003	anthra(2,3-b)thiophene	0.03	0.007	4-Nitrobenzo(e)pyrene	0.012	0.003
Triphenylene	0.001	0.0003	10-methylbenzo(b) naphtho(2,1-d)thiophene	0.03	0.008	3-Nitrobenzo(e)pyrene	0.003	0.0008
Chrysene	0.0007	0.0002	2-methylbenzo(b) naphtho(2,1-d)thiophene	0.03	0.008	3-Nitrobenzo(a)pyrene	0.009	0.002
7-Me-Benzo(a)Anthracene	0.002	0.0005	8-methylbenzo(b) naphtho(1,2-d)thiophene	0.03	0.008	1-Nitrobenzo(a)pyrene	0.006	0.002
Benzo(b)Fluoranthene	0.002	0.0005	5-methylbenzo(b) naphtho(2,1-d)thiophene	0.03	0.008	2-Nitrobenzo(a)pyrene	0.003	0.0008
Benzo(k)Fluoranthene	0.002	0.0005	6-methylbenzo(b) naphtho(2,1-d)thiophene	0.02	0.004	9-Nitrodibenzo(a,c) anthracene	0.017	0.005
Benzo(e)Pyrene	0.001	0.0004	8-methylbenzo(b) naphtho(2,3-d)thiophene	0.03	0.008	1,3-Dinitropyrene	0.006	0.002
Benzo(a)Pyrene	0.002	0.0005	11-methylbenzo(b) naphtho(2,3-d)thiophene	0.01	0.004	1,6-Dinitropyrene	0.003	0.0008
Perylene	0.002	0.0004				1,8-Dinitropyrene	0.006	0.002
2-Me-Cholanthrene	0.003	0.0008				7-Nitro-12-Methylbenzo(a)anthracene	0.003	0.0008
Indeno(1,2,3-cd)Pyrene	0.007	0.002				12-Ethyl-6-Nitrochrysene	0.003	0.0008
Dibenzo(a,c)&(a,h)Anthracene	0.006	0.002						
Benzo(b)Chrysene	0.007	0.002						
Benzo(g,h,i)Perylene	0.005	0.001						
Anthanthrene	0.006	0.002						

2.5.5.1 Sample Extraction and Clean-up

Sodium sulphate and distilled chromatographic grade solvents including acetone, cyclohexane, toluene, dichloromethane (DCM) and methanol were used without further purification.

Silica gel (Aldrich;100-200 mesh, pore size 150Å, pore 1.2cm^3/g, and active surface 320 m^2/g), was washed and activated prior to use according to the following procedure. A batch of 200-300 g silica gel was placed in a 900 × 41-mm id. chromatography column with a coarse porosity fritted disk. The column was serially rinsed with 2 volumes of methanol followed by 2 volumes of DCM. The silica gel was dried overnight at 110°C, then activated at 250°C for 24 hours and kept in an oven at that temperature until used.

Aliphatic standards (greater than 99% purity) from n-C_8 to n-C_{34} – including deuterotetracosane, pristane, phytane and 5-α-androstane - were purchased from Chiron Laboratories (Trondheim, Norway), Chromatographic Specialties, Ultra Scientific/VWR and Aldrich (Milwaukee, WI). The biomarker standards (greater than 96% purity, 0.1mg/mL) were purchased from Chiron Laboratories (Trondheim, Norway). They included cholestanes, steranes and hopanes.

High purity PAH standards were purchased from many suppliers including Supelco (US), Eastman Kodak (US), Ultra Scientific (US), Koch-Light Lab (US), K & K Lab (US), and Aldrich (US). Nitro-PAH standards were purchased from NIST (US) and PAsH standards were supplied by McMaster University. Isotope-labelled surrogates were purchased from MSD Isotopes, Canada and CDN Isotopes, Canada.

The particulate-loaded filters were placed in the extraction tube of the pressurized solvent extractor ASE 200 from DIONEX (hereafter referred to as ASE) after being spiked with appropriate recovery standards. The filters were extracted sequentially with DCM followed by methanol. The operating conditions used in this work were as follows:

- Cell pressure and temperature: 2000 psi at 100°C
- Extraction time: 5-min heat up and 5-min static
- Nitrogen purge at 100 psi for 240 seconds

The DCM extract was subjected to solvent exchange to cyclohexane by adding an excess of solvent and concentrating to ~1mL in an automated solvent evaporator from Zymark. This extraction scheme is illustrated in Figure 2.

For analysis of lube oil samples, 50 µl of the lube was dissolved in 1.0 mL of cyclohexane and processed in the same manner as the filter extracts using the following procedures. The lube oil samples were spiked with the alkane, biomarker and alkylcyclohexane recovery standard but not the PAH suite recovery standard. The PAH suite recovery standard was prepared in toluene and would have interfered with the column chromatography used for fractionation if added.

Figure 3 shows the column separation scheme used in this work. Approximately 5 g of 5% deactivated silica was prepared by adding 5 % water to activated silica (w/w) and shaking vigorously until no clumps were observed. Next, the deactivated silica was transferred to a 1.5 cm (id) × 25 cm chromatography column packed at the bottom with glass wool and topped with approximately 1 g of sodium sulphate. The height of the deactivated silica gel bed was ~4.5 cm. The column was pre-cleaned with 15 mL of cyclohexane.

A vial was placed under the column and the sample loaded onto the column with approximately 2 mL of cyclohexane rinses. An additional 13 mL of cyclohexane was added to collect paraffins and biomarkers in the first vial (Fraction 1). Prior to the column bed going dry the first vial was removed and replaced with a second one. The column was immediately eluted with 15 mL of cyclohexane/acetone (50/50 v:v). This fraction contained the PAH suite of compounds (Fraction 2). Just as the column bed went dry, the second vial was removed and the column eluted with two 15 mL aliquots of methanol collected in two separate vials (Fractions 3 and 4).

Fraction 1 was concentrated to 1 mL or less using the automated solvent evaporator. These fractions were further concentrated to a preinjection volume of 0.1 mL using nitrogen blowdown in a precalibrated vial or Kuderna-Danish concentrator. Fraction 2 was transferred to AAQD for further handling and PAH analysis. Fractions 3 and 4 were archived.

Figure 2. Filter sample extraction scheme.

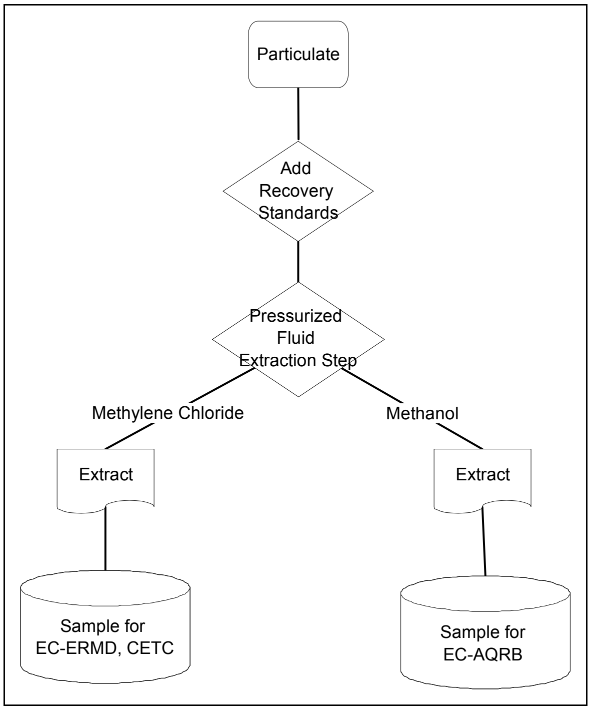
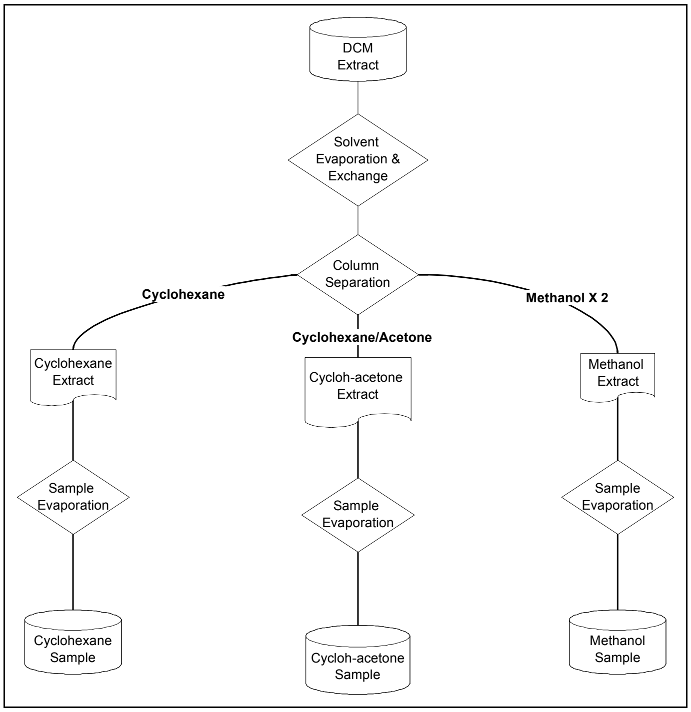


Figure 3. Separation scheme - column chromatography of DCM extracts



2.5.5.2 Analysis of Alkanes, Alkylcyclohexanes and Petroleum Biomarkers

The analysis for *n*-paraffins, pristane, phytane and biomarkers was performed on a HP 6890GC equipped with a 5972A mass selective detector (MSD). System control and data acquisition was achieved with a HP MS Chemstation (Windows95 series).

The MSD was operated in scan mode to evaluate the chromatography and in the selected ion monitoring mode (SIM) for quantitative analysis of target compounds:

- m/z 85 ions for *n*-paraffins, pristane and phytane
- m/z 177 and 191 ions for hopanes/triterpanes
- m/z 217 and 218 ions for steranes

Alkylcyclohexanes were analyzed in scan mode through extraction of the m/z 82 ion chromatogram.

Quantitative measurements of alkanes and biomarkers were achieved using the external standard method. Paraffin concentrations were obtained using the HP Chemstation software. Biomarker concentrations were determined using peak integration listings of m/z ion pairs 177/191 and 217/218 from the HP Chemstation software as input data for BIOMQUANT, a dedicated software package written in Visual Basic at CETC to handle standard calibration curves and concentration calculations for samples.

A SP-B5 (5% Phenyl methyl siloxane) fused silica capillary column, 30 m × 0.25-mm id. (0.25 μm film) was used. The chromatographic conditions were as follows:

- carrier gas, helium (1.5 mL/min)
- injection mode: splitless
- injector & detector temperatures: 275°C, 280°C

The following temperature program was used:

- initial temperature 50°C, no hold
- ramp to 300°c at 6°C/min
- 10 min hold at 300°C

2.5.5.3 Analysis of PAH, PAsH and NO_2-PAH

Fraction F2 was delivered to AAQD from CETC. F2 contains PAH, NO_2-PAH, PAsH and some polar compounds. The F2 fraction was split in half. One half was analysed for PAH and PAsH while the other half was analysed for NO_2-PAH.

PAH/PAsH Fraction:

The extract was concentrated to approximately 450 μL using a gentle stream of nitrogen. 50 μL of d10-Floranthene was added as a recovery standard and the extract was made up to a final volume of 500 μL. The extract was analysed for PAH using low resolution GC/MS equipped with a 30m DB-XLB column. The details of the analytical conditions are given in Table 10. Following PAH analysis the extract was concentrated to less than 50 μL and to remove polar interferences it was injected onto a HPLC system with a 250 x 4.6 mm silica column. The column was eluted with 5% dichloromethane in hexane at 1mL/min. The fraction containing PAsH was collected between 2 and 13 minutes. The extract was concentrated to 30 μL before 20 μL of d8-DBT was added as a recovery standard. The extract was then analysed for PAsH using low resolution GC/MS equipped with a 30m DB-XLB column as indicated in Table 10.

NO_2-PAH Fraction:

The extract was blown down just to dryness using a gentle stream of nitrogen and then dissolved in 1 mL of DMSO. Aliphatic compounds were removed by extracting the DMSO with 3, 1 mL aliqouts of hexane. The DMSO was then diluted with 3 mL of water before the NO_2-PAH were extracted with 3, 3 mL aliquots of cyclohexane. The extract was then concentrated and made up to a final volume of 100 μL which was then injected onto a 250 x 4.6 mm silica column contained in an HPLC system. The extract was then separated using a solvent gradient of 5 % dichloromethane in hexane to 100 % dichloromethane. The NO_2-PAH were collected over a 17 minute window while the gradient was maintained at 45 % DCM. The gradient program may be extended to change 100 % DCM to

100 % acetonitrile. This fraction could be collected for the analysis of polar compounds which were eluted on the deactivated silica column. The NO_2-PAH fraction was concentrated to approximately 0.5 mL using a TurboVap before being blown down just to dryness under a gentle stream of nitrogen. 50 µL of the recovery standard containing d7-2-nitrodibenzodioxin and d11-nitrobenzo(a)anthracene was added just before analysis. The samples were analyzed using HRGC/HRMS operating in the negative chemical ionization mode. Methane was used as the reagent gas. The GC is equipped with a DB-5 column. The analytical conditions are summarized in Table 11.

Table 10. PAH and PAsH analytical conditions

Instrument	HP 5890 Series II GC interfaced with HP 5970 MSD.
Injection	on-column, 1 µL for PAH, 2 µL for PAsH
Column	30 m DB-XLB fused silica, 0.25 mm ID and 0.25 µm film thickness
Oven Program	PAH: 90°C for 1 min, to 200°C at 20 °C/min, to 250°C at 2.5 °C/min, then to 280°C at1.5 °C/min and hold for 10 min PAsH: 90 °C for 2 min, to 200 °C at 25 °C/min, to 280 °C at 1.5 °C/min and hold for 6 min
Detection Mode	Electron Impact (EI), Selected Ion Monitoring (SIM); Scan time 1 s or less, dwell time 50-100 ms/ion A minimum of two characteristic ions per compound are monitored.

Table 11. NO_2PAH analytical conditions

Instrument	HP 5890 Series II GC interfaced with VG Autospec HRMS
Injection	1 µL, Splitless, 280°C
Column	30 m DB-5 fused silica, 0.25 mm ID and 0.25 µm film thickness
Oven Program	100°C for 2 min, to 200°C at 25 °C/min, hold 1 min., 10 °C/min to 240°C, 5 °C/min to 300 °C and hold for 5.4 min
Ionisation Mode	NCI using UHP argon as reagent gas, Selected Ion Recording Source pressure: 2-4 x 10^{-5} torr Source temperature: 260 °C

Identification and Quantitation:

A total of three ion masses (one quantitation ion and two confirmation ions) were monitored for each PAH and PAsH analytes. The presence of a target compound in the sample extract was confirmed when all of the following criteria were satisfied:

- Response for the two most abundant characteristic ions must exceed the background noise level by a minimum ratio of 3:1.
- The abundance ratio of the two major characteristic ions must be within ±40% of the corresponding compound in the external standard solution.
- The third qualifying ion must be present unless the ion is masked by high background interference.
- The peak maxima for the specified characteristic ions must be coincident within 2 scan units.
- Analyte's retention time relative to the closest eluting surrogate must be within 0.1 min of the relative retention time of the corresponding standard mixture components.

Quantitative measurement of PAH and PAsH were achieved using the external standard calibration method. PAH concentrations were reported along with surrogate recovery data. No surrogate recoveries were available for PAsH results.

Two characteristic ions, molecular $(M)^-$ ion and $(M + 1)^-$ ion, were monitored for each of the nitro-PAH analytes. At 10,000 mass resolution, analytes were measured using the negative ion chemical ionization (NICI) and selective ion recording (SIR) techniques. Confirmation criteria are similar to PAH except that ion ratio must be within ±30%. Nitro-PAH compounds were quantified using the Internal Standard (Isotope Dilution) method.

2.5.6 Methane and Non-methane Hydrocarbons

Samples were collected for analysis of methane and non-methane hydrocarbons (NMHC) in the range of C_1 to C_{26}. To collect this sample, the dilute exhaust is drawn through a Tenax adsorbent tube and delivered to a Tedlar bag. The heavier hydrocarbons are collected on the Tenax and the lighter compounds either not retained or partially retained by the Tenax are collected in a Tedlar bag. The results from the two samples are converted to dilute exhaust concentrations, compounds appearing in both samples have the results added and the emission rates are calculated from the composite dilute exhaust concentrations.

Approximately 165 volatile non-methane hydrocarbons were determined in the Tedlar bag samples by high-resolution gas chromatography with a flame ionisation detector following cryogenic preconcentration. An Entech M7000 cryogenic concentrator, operating in the microscale purge and trap mode, was used as an inlet to the GC, allowing a sample volume of 50 mL to be used. This method is referred to as the NMHC method.

A Hewlett Packard 5890 Series II gas chromatograph with a flame ionisation detector was used for the analysis. Data was acquired and sample concentrations were calculated using the Hewlett Packard ChemStation software.

The analytical method was calibrated using external standards on a per component basis. Compound identification was confirmed on selected samples by GC-FTIR analysis. The hydrocarbon gas phase standards used were prepared in-house using a permeation tube gas standard generator (Kin-Tek Laboratories, LaMarque, Texas).

The preconcentrator system does not allow for the determination of methane and sometimes the C_2 hydrocarbons are not well retained on the trap. Methane must be determined using an alternate method and in certain instances, confirmation of the C_2 and C_3 hydrocarbon concentrations determined using the preconcentrator method is required. The methane analysis and the C_2 and C_3 hydrocarbon confirmation were accomplished by simple gas loop injection onto a capillary column. The sample loop was flushed with sample and the contents of the loop were injected directly onto the capillary column. This method is referred to as the light hydrocarbon (LHC) method. A Hewlett Packard 5890 Series II gas chromatograph with a flame ionisation detector was used for the analysis. Data was acquired using the Hewlett Packard ChemStation software. This system was also calibrated using external standards generated from the Kin-Tek bench.

Approximately 165 compounds are determined in a pentane extract of the Tenax adsorbent. Many of these compounds are common to the volatile NMHC method. Hydrocarbon compounds trapped on the Tenax adsorbent tubes are recovered by solvent desorption with pentane and analyzed by GC-FID. Samples are introduced to the GC by automated splitless liquid injection. This method is known as the Semivolatile NMHC method.

These analyses were performed by Environment Canada – ERMD. Detection limits for these two methods are given in Table 12.

Table 12. Detection limits (mg/mile) for target compounds in the detailed hydrocarbon analyses.

Compound	**Detection Limit (mg/mile)**
Methane	28
Volatile NMHCs ($<C_{12}$)	0.3
Semivolatile NMHCs (C_{12}-C_{26})	5

2.5.7 Carbonyl Compounds

During sampling, dilute exhaust is drawn through silica gel Sep-Pak cartridges coated with 2,4-DNPH. The carbonyl compounds selectively react with the 2,4-DNPH forming hydrazones that are retained on the cartridge. The hydrazones are removed from the cartridge using a solvent and the liquid sample that results is analysed by high performance liquid chromatography (HPLC). The DNPH coated silica cartridges were prepared in-house by ERMD. No cartridge blank correction was necessary for these samples.

After sample collection, the 2,4-DNPH-carbonyl hydrazones were eluted from each Sep-Pak cartridge and the solution was made up to volume in a graduated centrifuge tube with HPLC grade Acetonitrile (J.T. Baker). An aliquot of this solution was analyzed by reverse phase HPLC with UV-Visible detection. A Hewlett Packard 1090M HPLC with a diode-array detector, 100 vial autosampler and the HPLC-3D ChemStation software was used for sample analysis. The ratio of transmitted light intensity at two wavelengths is used as the signal for quantitation. The method reports 24 carbonyl compounds, though 8 of the 24 individual compounds are reported as pairs as they co-elute. External calibration standards were purchased from Radian International (Austin, Tx.). Where commercial standards were not available, the hydrazones were synthesized in house and standards prepared. A calibration check mix was run after every 10th sample to monitor detector response and retention time drifts. Near baseline resolution was obtained for the acrolein-acetone-propionaldehyde triplet. This analysis was performed by Environment Canada – ERMD.

Detection limits for the target carbonyl compounds are given in Table 13.

Table 13. Detection limits (mg/mile) for target carbonyl compounds.

Compound	**Detection Limit (mg/mile)**
Formaldehyde	1.0
Acetaldehyde	1.4
2-3 butandione	2.3
Acrolein	1.7
Acetone	1.7
Propionaldehyde	1.6
Methoxyacetone	2.3
Crotonaldehyde	2.0
Methyl Vinyl Ketone	2.0
Methacrolein	2.0
Methyl Ethyl Ketone	2.0
Isobutyraldehyde & Butyraldehyde	2.0
Benzaldehyde	2.6
Isovaleraldehyde	2.3
Trimethylacetaldehyde & 3m2-Butanone	2.3
Valeraldehyde	2.3
Acetophenone	2.8
o-Tolualdehyde	2.8
m&p-Tolualdehyde	2.8
Methyl isobutyl Ketone	2.5
Pinacolone	2.5
Hexanaldehyde	2.5
2,5-Dimethylbenzaldehyde	3.0

3. Results and Discussion

3.1 Gaseous Emissions

3.1.1 Criteria Emissions

Emission rates of the criteria pollutants (CO, NO_X and THC) and of CO_2 were determined for the old technology bus in both configurations and for the new technology bus at two different ambient temperatures. These results are summarized in Table 14 and presented graphically in Figure 4. Analysis of variance was used to determine whether changes in emission rates were statistically significant. A 95% confidence limit was used.

The use of the oxidation catalyst on the old technology bus results in a statistically significant reduction in NO_X and THC emissions at standard temperature as compared to the same vehicle operated with the OEM muffler installed. A small increase in CO emissions was observed but the increase was not statistically significant. In comparing the emissions of the old technology bus with exhaust aftertreatment to the new technology bus, the new bus showed significantly reduced CO and THC emissions but no change in NO_X emissions.

The decrease in NO_X emissions from the old technology bus with the use of the oxidation catalyst may be as a result of the catalyst using the NO_2 present in the exhaust to assist with the oxidation of hydrocarbons both in the gas phase and particle bound.

At cold temperatures, the emissions reductions seen in using the oxidation catalyst on the old bus as compared to the OEM muffler were not statistically significant. The oxidation catalyst appears to lose its effect during cold temperature operations. This loss of effectiveness is aggravated by the placement of the catalyst quite far downstream from the engine.

The effect of cold temperature operations on emissions can be seen in comparing the emissions measured for each bus configuration at the two test temperatures. For the old technology bus with the OEM muffler in place, a significant reduction in CO emissions was observed during operation at cold temperature while the increases in NO_X and THC were not statistically significant. For the old technology bus with the oxidation catalyst installed, the reductions observed in CO, NO_X and THC during cold temperature operation were not statistically significant. For the new technology bus, statistically significant increases in both NO_X and CO emissions were seen during cold temperature operation while the reduction observed in THC emissions was not significant.

Fuel consumption rates were determined from the emissions data and are summarized in Table 14 and compared in Figure 5. Cold temperature operation has little effect on fuel consumption rates for either bus.

Table 14. Mass emission rates (g/mile) and fuel consumption (L/100 km) results.

		g/mile				L/100 km
20 ˚C		**CO**	**CO_2**	**NO_X**	**THC**	**FC**
Muffler	avg	7.56	2787	26.9	2.62	64.1
	stdev	0.68	42	0.4	0.08	1.1
OxyCat	avg	7.86	2734	20.2	1.88	63.5
	stdev	0.31	5	0.9	0.03	0.4
New	avg	4.61	2704	20.3	0.40	62.5
	stdev	0.07	176	0.2	0.11	2.8
-10 ˚C						
Muffler	avg	6.40	2714	27.3	2.69	62.3
	stdev	0.24	88	0.4	0.06	1.8
OxyCat	avg	5.25	2712	25.3	2.66	62.7
	stdev	1.03	87	3.3	0.06	1.6
New	avg	5.82	2538	33.2	0.36	60.5
	stdev	0.05	64	0.3	0.06	0.7

Figure 4. Comparison of criteria pollutant emission rates.

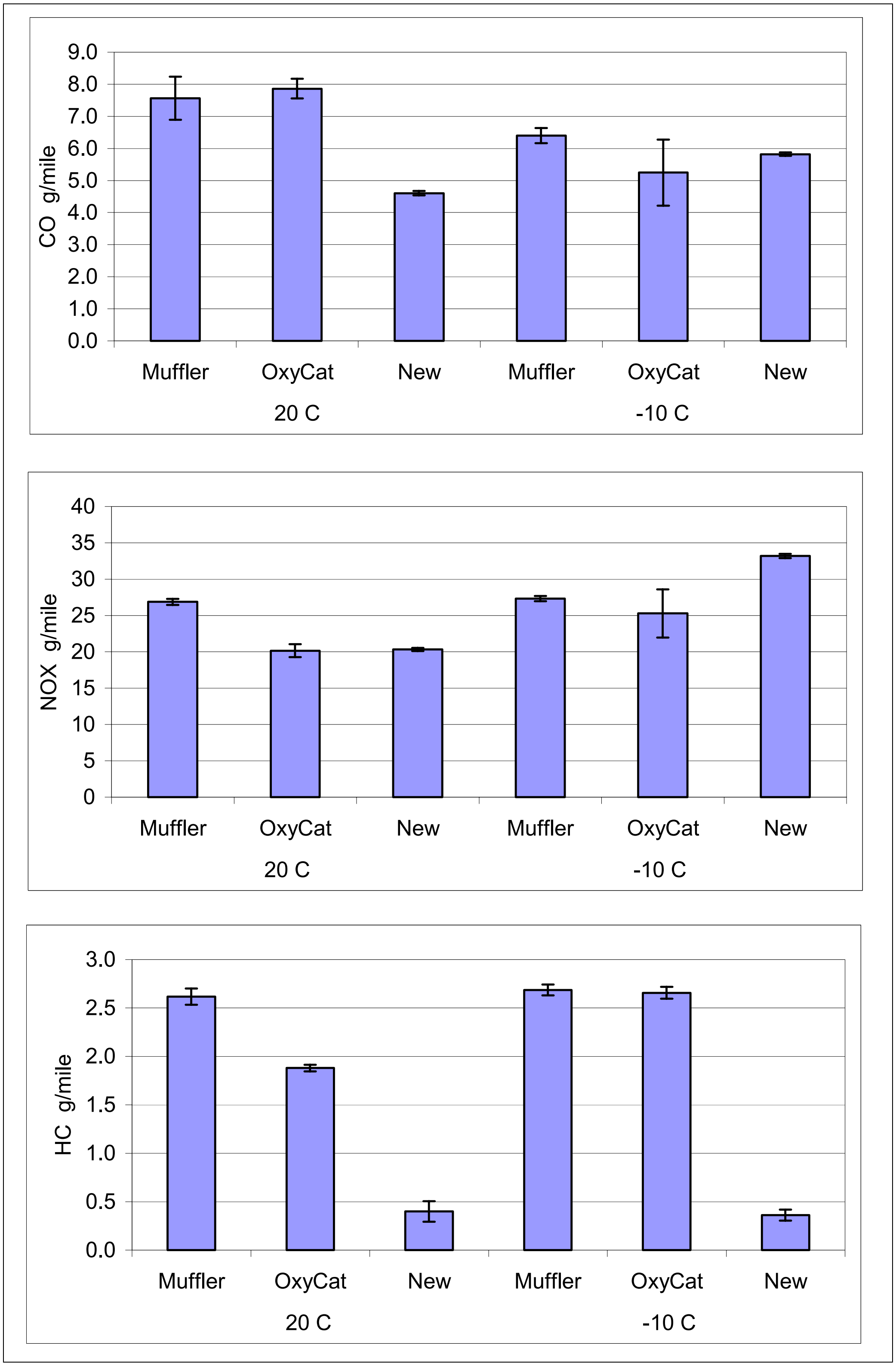
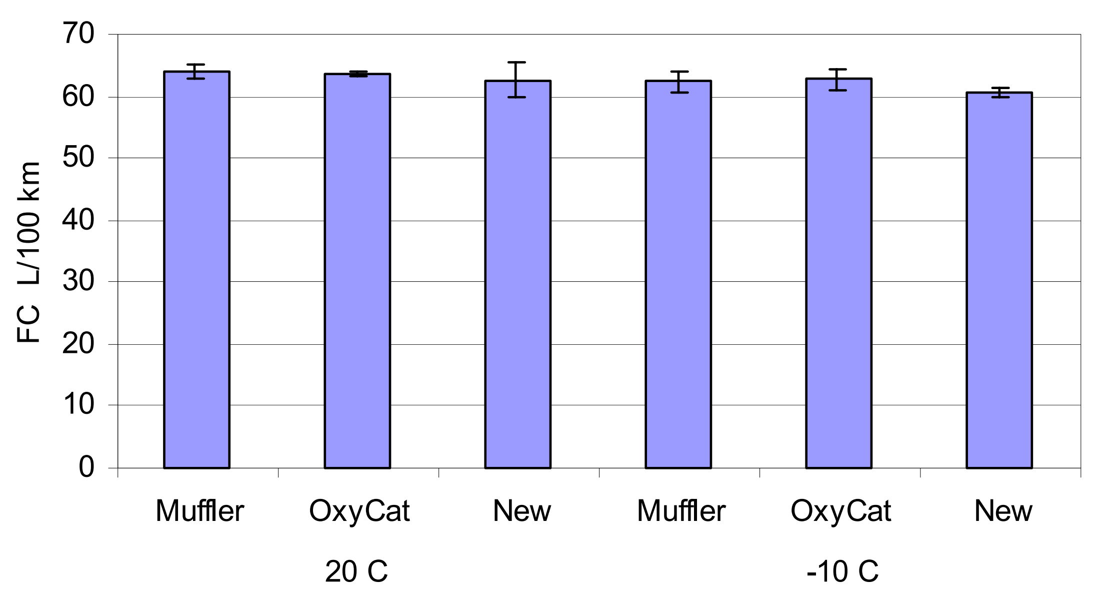


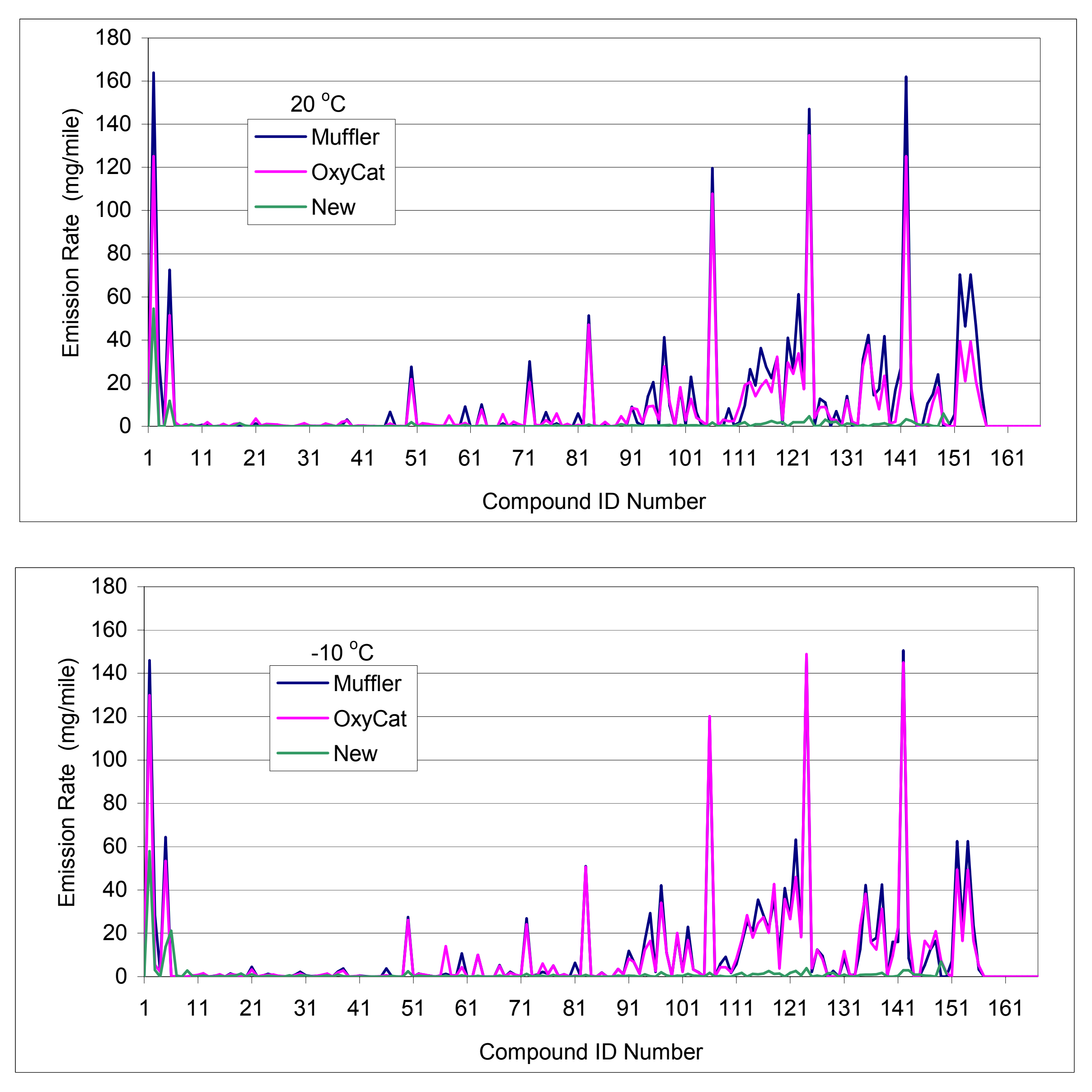
Figure 5. Comparison of fuel consumption (L/100 km).



3.1.2 Methane and Non-methane Hydrocarbons

Emission rates of methane and non-methane hydrocarbons were measured for each bus configuration at two operating temperatures. These results are given in Table 26 in Appendix 1. Total non-methane hydrocarbon emission rates are summarized in Table 15. The results are compared in Figure 6. The compound ID numbers are listed in Table 26 in Appendix 1. For the old technology bus, the oxidation catalyst causes a reduction in the hydrocarbon emissions as compared to those measured with the muffler in place. The reduction appears to be consistent across the range of hydrocarbons determined. A smaller reduction is apparent in the cold temperature results. The difference in emission profiles between the new technology bus and the old technology bus is dramatic. Emissions of the heavier hydrocarbon emissions are nearly eliminated and substantial reductions in the lighter hydrocarbons are also evident.

Figure 6. Comparison of hydrocarbon emission rates.

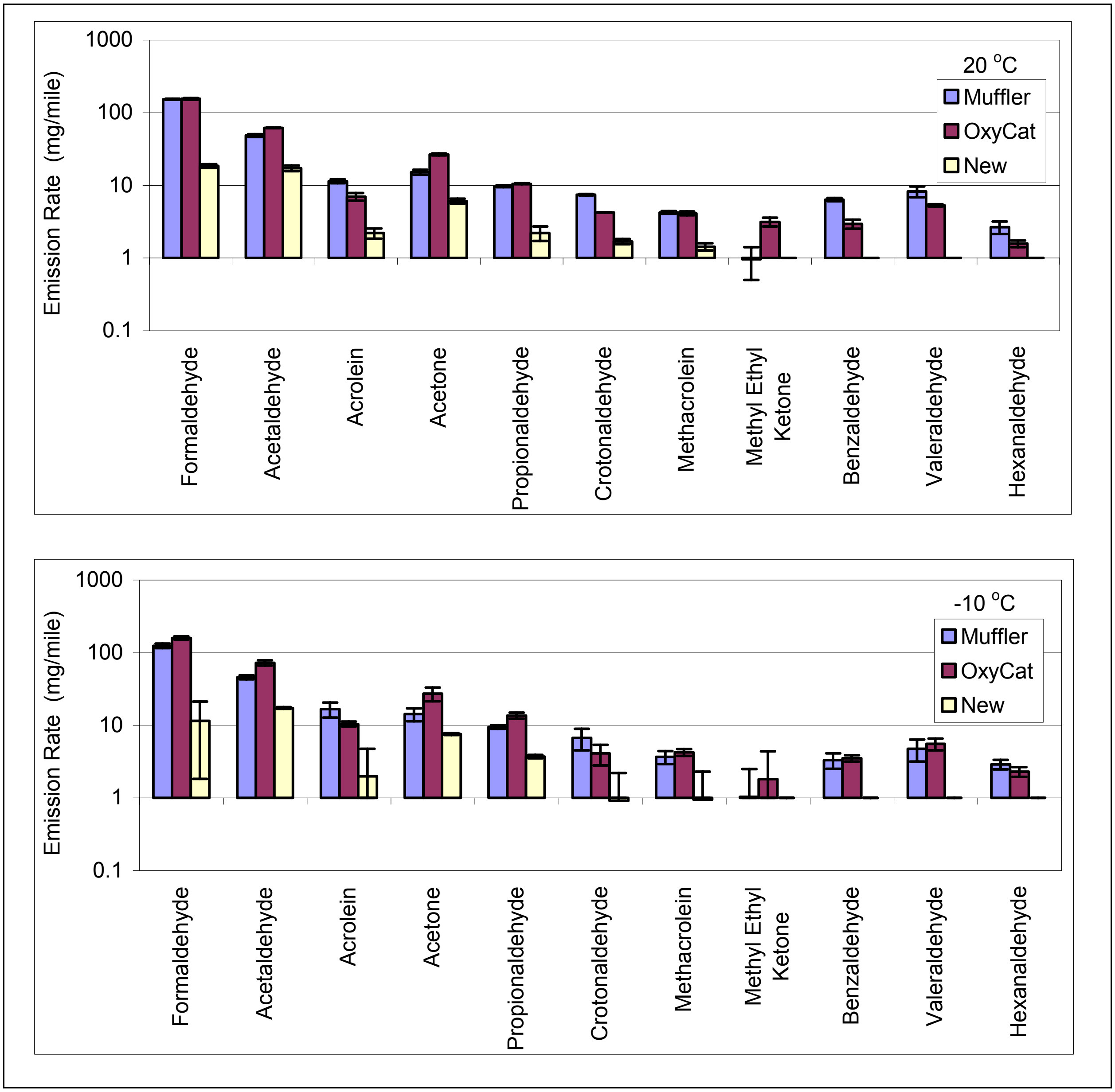


3.1.3 Carbonyl Compounds

Emission rates of carbonyl compounds were measured for each bus configuration at two operating temperatures. These results are given in Table 27 in Appendix 1. The total carbonyl emission rates are summarized in Table 15. The results are compared in Figure 7. In order for the emissions from the new technology bus to be visible in the graphs, a logarithmic emission rate scale is used in Figure 7.

For the old technology bus, the oxidation catalyst causes slight increase in the total carbonyl emission rate as compared to the rate measured with the muffler in place. The increase is observed at both operating temperatures, but is greater under cold temperature operation. This effect may again be due to the placement of the catalyst in the exhaust stream and the lower exhaust temperature inside the catalyst resulting in less complete oxidation of hydrocarbons. There are no substantial changes in the carbonyl profile between the oxidation catalyst and muffler configurations. The total carbonyl emission rate for the new technology bus is substantially lower than the old bus and does not appear to change with operating temperature. As was seen with the non-methane hydrocarbon profile, the carbonyl profile shows significant reductions in the emission rates of the heavier carbonyl compounds.

Figure 7. Comparison of carbonyl compound emission rates.



3.1.4 Ozone Reactivity and Toxicity

One of the reasons motivating the detailed measurements of the composition of the emissions is to evaluate the relative contributions to ground level ozone and to the emissions of toxic compounds. Different organic gases have different relative reactivities towards forming ground level ozone. One measure of this difference in reactivity is the maximum incremental reactivity (MIR) value[11]. The mass emission rate of a compound is multiplied by its MIR value to obtain an estimate of the amount of ground level ozone that would be produced by the emission of that amount of the compound in question if it were emitted into an urban airshed to undergo photochemical reactions. The sum of all of these ozone emission rates gives the ozone forming potential of the exhaust. Dividing this total by the total mass of organic emissions gives the specific reactivity of the exhaust. These specific reactivities can be used to compare the emissions from different vehicles or different configurations or test conditions. The calculated ozone forming potential and specific reactivity for each bus configuration and each test temperature are summarized in Table 15 and compared in Figure 9 and Figure 8. The emissions from the old technology bus whether operated with or without the oxidation catalyst, though lower in specific reactivity have the potential to produce significantly greater amounts of ground level ozone, just due to the greater amount of material emitted. Based on these results, it would take 8 new buses produce the same amount of ground level ozone (due to non-methane organic gas emissions) as one old bus. The caveat to this statement is that both CO and NO_X emissions also play a role in ground level ozone formation. Their role is not reflected in this analysis.

Table 15. Total carbonyl, NMHC and NMOG emission rates, ozone forming potential and specific reactivity.

		Total Carbonyl (mg/mile)	Total NMHC (mg/mile)	Total NMOG (mg/mile)	Ozone Potential (mg O_3/mile)	Specific Reactivity (mg O_3/mg NMOG)
20 °C						
Muffler	avg	268	1892	2160	9686	4.48
	stdev	8	66	74	247	0.004
OxyCat	avg	283	1457	1740	7517	4.31
	stdev	5	107	111	473	0.005
New	avg	49	138	187	1051	5.61
	stdev	4	22	26	157	0.07
-10 °C						
Muffler	avg	237	1814	2050	8874	4.33
	stdev	6	64	70	254	0.02
OxyCat	avg	305	1663	1968	8392	4.26
	stdev	12	119	131	438	0.07
New	avg	44	174	218	1105	5.10
	stdev	10	31	41	36	0.66

Figure 8. Comparison of the specific reactivities of the bus emissions.

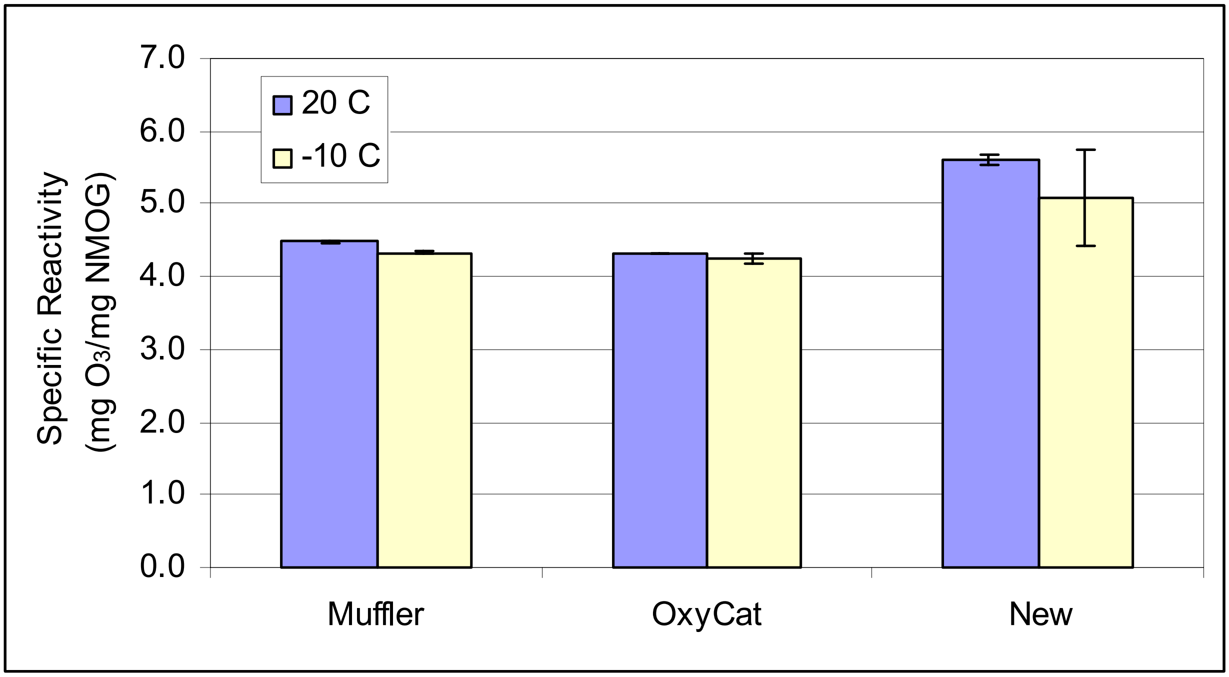
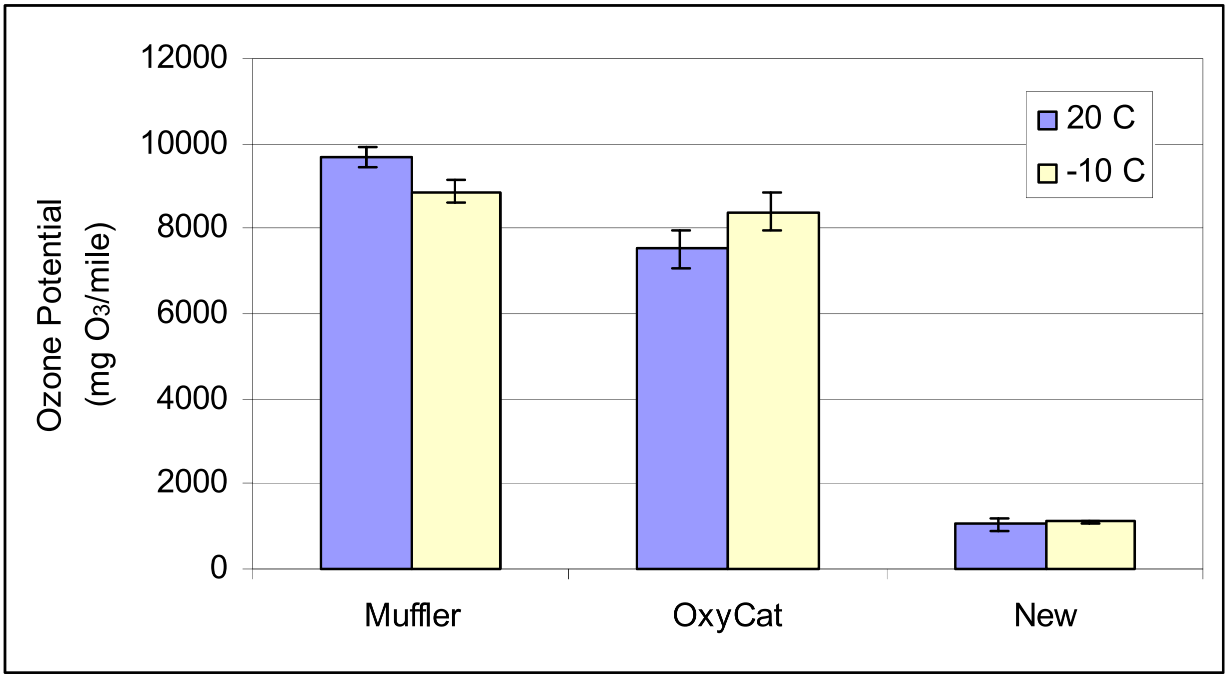


Figure 9. Comparison of the ozone forming potential of the bus emissions.

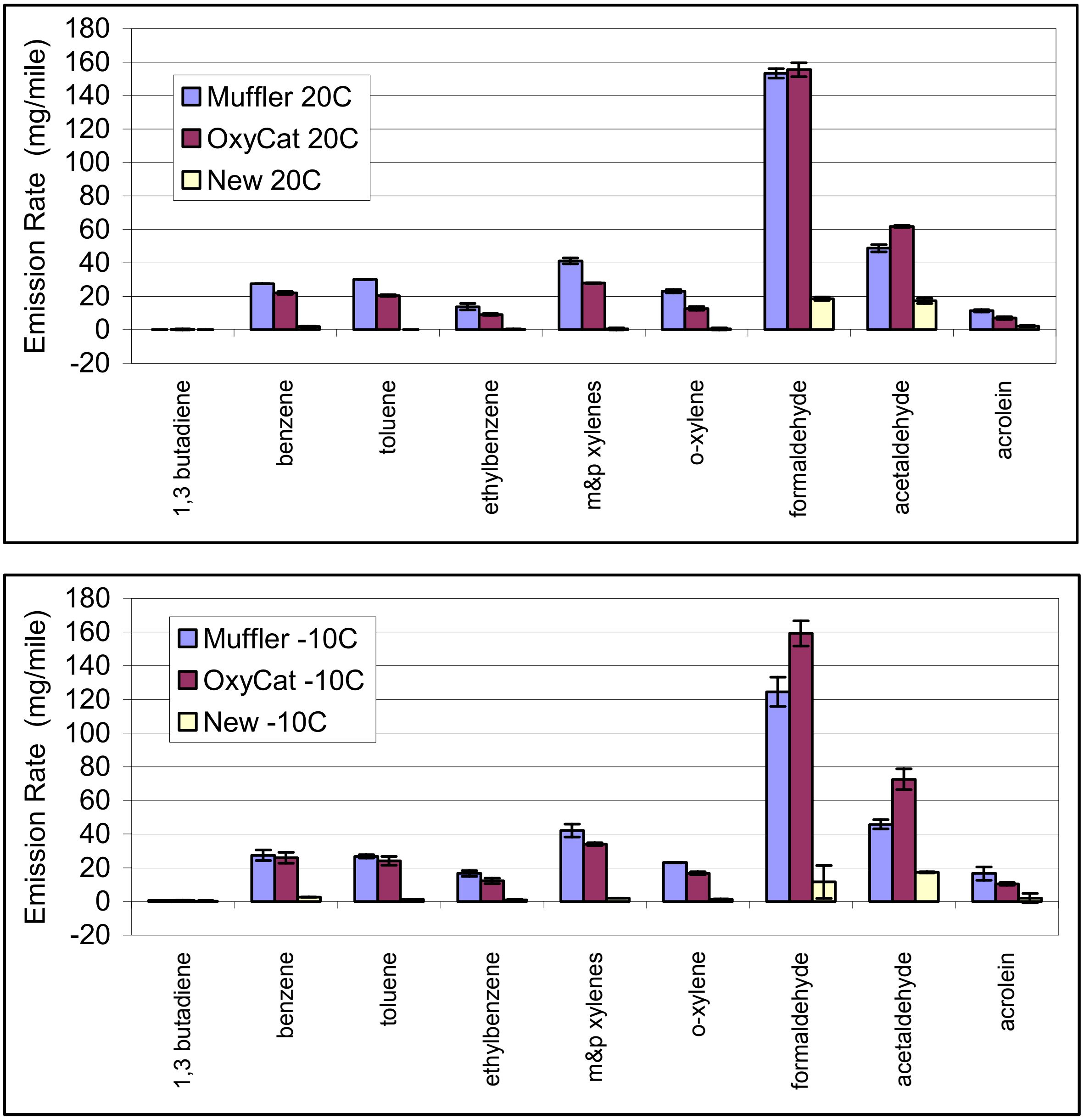


Compounds emitted from diesel buses appear on the Canadian Environmental Protection Act (CEPA) Priority Substances List (PSL). These compounds and their measured emission rates are summarized in Table 16 and compared in Figure 10. Formaldehyde is clearly the toxic compound emitted in the largest amount, contributing to between 30% and 50% of the total toxic emissions. The new bus emits approximately one-eighth the toxic emissions of the old technology bus in either configuration.

Table 16. CEPA PSL compounds emitted from the buses.

	20 °C						**-10 °C**					
	Muffler		**OxyCat**		**New**		**Muffler**		**OxyCat**		**New**	
	avg	stdev	avg	stdev	avg	stdev	avg	stdev	avg	stdev	avg	stdev
1,3 butadiene	0.10	0.03	0.22	0.31	0.03	0.04	0.53	0.11	0.50	0.23	0.20	0.28
benzene	27.53	0.11	21.90	0.80	1.88	0.33	27.42	3.15	26.01	3.19	2.54	0.02
toluene	30.09	0.08	20.42	0.51	0.00	0.00	26.81	1.04	24.09	2.64	1.23	0.08
ethylbenzene	13.72	1.90	9.07	0.49	0.35	0.08	16.61	1.69	12.29	1.62	1.04	0.33
m&p xylenes	41.13	1.73	27.81	0.35	0.45	0.64	42.08	3.78	34.10	0.80	1.97	0.06
o-xylene	22.96	0.96	12.75	1.17	0.48	0.65	23.05	0.10	16.78	0.92	1.20	0.47
formaldehyde	153.26	2.87	155.42	4.16	18.47	1.00	124.58	8.65	159.26	7.52	11.56	9.72
acetaldehyde	48.68	2.21	61.73	0.68	17.25	1.52	45.80	2.72	72.64	6.14	17.31	0.42
acrolein	11.40	0.71	7.01	0.83	2.20	0.35	16.65	3.91	10.42	0.79	1.98	2.80
total toxics emissions	**349**		**316**		**41**		**324**		**356**		**39**	

Figure 10. Comparison of CEPA PSL toxic emissions from the buses.



3.1.5 Ammonia and Sulphur Dioxide

Emissions of ammonia and sulphur dioxide contribute to the photochemical formation of aerosols in the atmosphere. Sulphur dioxide is emitted as a result of oxidation of the sulphur in the fuel and lubrication oil. Ammonia tends to be formed under fuel-rich combustion conditions. Ammonia emissions are expected to be low for diesel vehicles as the engines operate under very lean combustion conditions.

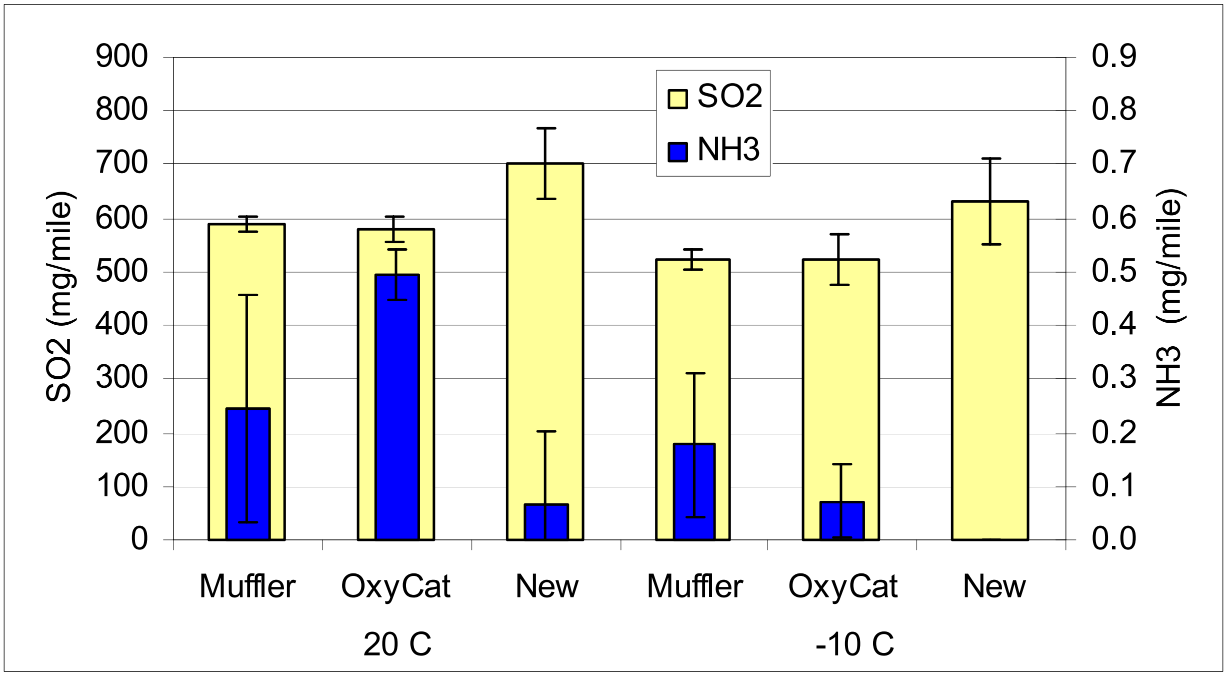
The measured ammonia and sulphur dioxide emission rates are summarized in Table 17 and compared in Figure 11. As expected, the ammonia emission rates are very low. The sulphur dioxide emission rates are not affected by the presence of the oxidation catalyst on the old technology bus, but they do appear to be lower under cold temperature operating conditions. The difference in the sulphur dioxide emissions from the two buses is likely due to a difference in fuel composition as they were tested nearly a year apart. A fuel sample was collected from the new technology bus and was analysed for sulphur content, with a result of 400 ppm.

The increase in ammonia emissions observed with the old technology bus in changing from the muffler to the oxidation catalyst is not statistically significant. The reaction of ammonia with citric acid during sample collection requires a minimum level of moisture on the filter in order to be quantitative. In examining the individual sample results, the possibility of the filters not having sufficient moisture content must be considered. The 20˚C Muffler tests were conducted at the end of the measurement schedule for the old technology bus and these measurements show the greatest variation. One of the four measurements results in a similar NH_3 emission rate as seen with the oxidation catalyst in place while the other three results are much lower.

Table 17. Ammonia and sulphur dioxide emission rates (mg/mile).

20 °C		**SO_2**	**NH_3**
Muffler	avg	591	0.24
	stdev	14	0.21
OxyCat	avg	579	0.49
	stdev	24	0.05
New	avg	703	0.07
	stdev	66	0.13
-10 °C			
Muffler	avg	522	0.18
	stdev	19	0.13
OxyCat	avg	523	0.07
	stdev	49	0.07
New	avg	632	ND
	stdev	81	

Figure 11. Comparison of ammonia and sulphur dioxide emission rates.



3.1.6 Vapour Phase Organic Acids

Due to sample collection difficulties, vapour phase organic acids were determined for the old technology bus only. Emissions of vapour phase organic acids contribute to the photochemical formation of aerosols in the atmosphere. They are also intermediates in the photo-oxidation of hydrocarbon and carbonyl compound emissions, so in order to understand the atmospheric chemistry and to interpret measurements of the relative contributions of various compounds to photochemical aerosol formation, the emission rates of these compounds are needed. The emissions of these compounds, though small, are on the same order of magnitude as other individual hydrocarbons and carbonyls.

HMSA is hydroxymethane sulphonic acid, $CH_2(OH)SO_3H$. It is an adduct that is formed in acidic aqueous solution by the reaction of dissolved and hydrated sulphur dioxide and formaldehyde[12]. These conditions can occur in diluted vehicle exhaust where the water is present in liquid form as tiny droplets. HMSA is an important species in fog and cloud water as it is an important source of acidity and may play a role in long-range transport of SO_2.[13]. Sulphur (IV) present as HMSA becomes resistant to oxidation by H_2O_2 and by O_3[14]. The implication of finding significant emissions of HMSA from vehicles is that the reaction rates and emission rates of sulphur dioxide implemented in atmospheric chemistry models used to predict aerosol formation will need to be revised to consider the role of this compound in the atmosphere, potentially affecting the results of these models.

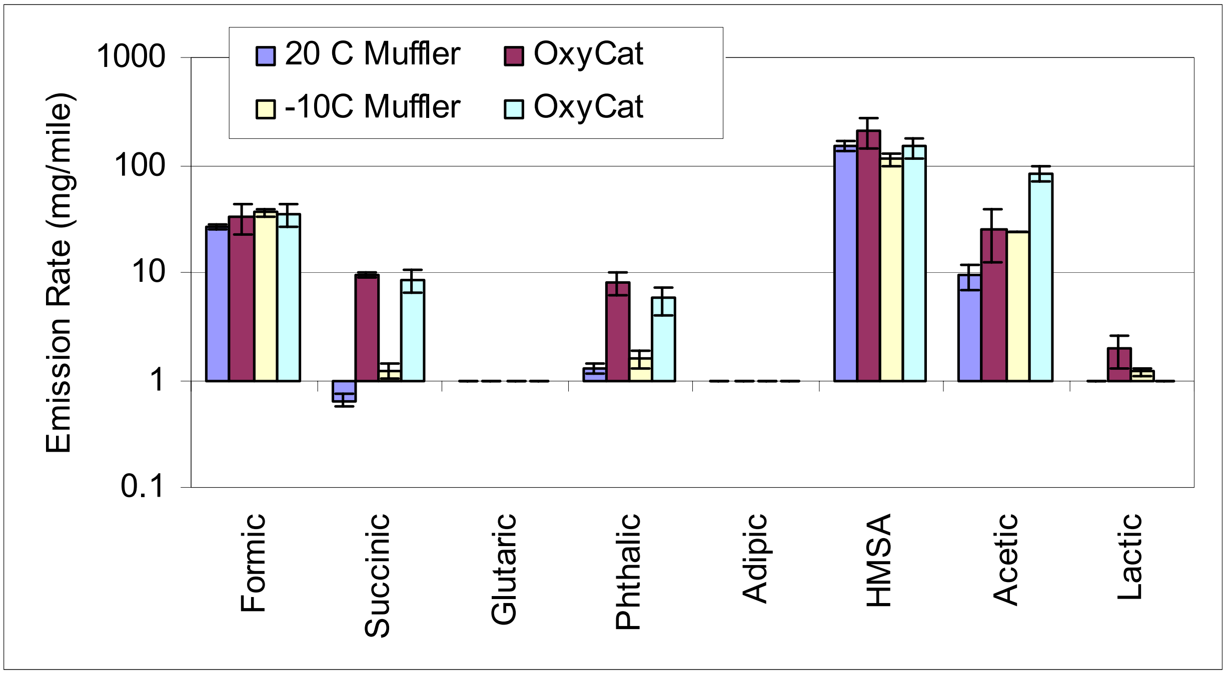
The measured vapour phase organic acid emission rates are summarized in Table 18 and compared in Figure 12. Note the logarithmic scale on the emission rate axis in this figure.

The presence of the oxidation catalyst produces increased emission rates of all acids. In some instances, the increase is dramatic, in others, less significant. Emission rates also tend to be higher during cold temperature operation.

Table 18. Vapour phase organic acid emission rates (mg/mile).

		mg/mile							
20 °C		**Formic**	**Succinic**	**Glutaric**	**Phthalic**	**Adipic**	**HMSA**	**Acetic**	**Lactic**
Muffler	avg	26.8	0.64	<MDL	1.29	<MDL	149	9.49	<MDL
	stdev	1.3	0.08	<MDL	0.14	<MDL	16	2.57	<MDL
OxyCat	avg	33.0	9.46	<MDL	8.11	<MQL	208	25.3	1.93
	stdev	10.7	0.28	<MDL	2.11	<MQL	69	13.2	0.69
-10 °C									
Muffler	avg	36.6	1.24	<MDL	1.55	<MDL	113	23.7	1.18
	stdev	3.1	0.19	<MDL	0.28	<MDL	16	0.41	0.11
OxyCat	avg	34.5	8.32	<MDL	5.69	<MDL	146	83.8	<MDL
	stdev	7.5	1.99	<MDL	1.67	<MDL	30	13.2	<MDL

Figure 12. Comparison of vapour phase organic acid emission rates.



3.2 Particulate Matter Emissions

Particulate matter emissions were characterized for mass, organic and elemental carbon composition, metals, ions and a suite of organic compounds useful for tracing the sources of emissions in atmospheric samples.

3.2.1 $PM_{2.5}$ Mass Emissions

Particulate matter mass emission rates were determined from three filter samples collected simultaneously. These results are summarized in Table 19 and compared in Figure 13. The results from the different filter media are not statistically significantly different.

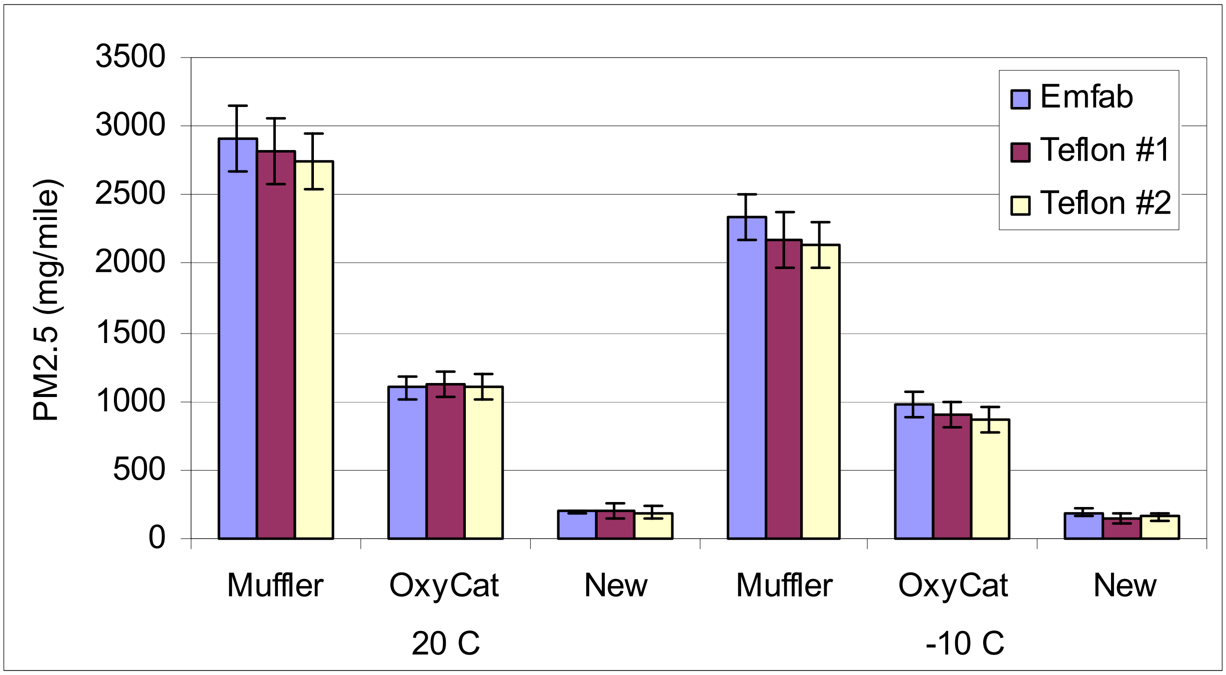
The use of the oxidation catalyst on the old technology bus causes a statistically significant reduction in $PM_{2.5}$ emissions at both test temperatures. A reduction of greater than 60% in mass is achieved. The new technology bus achieves a mass emission rate reduction of greater than 90% as compared to the old technology bus equipped with the muffler and greater than 80% compared to the same bus with an oxidation catalyst.

PM emissions are lower during cold temperature operation for both configurations of the old technology bus, but only slightly lower for the new technology bus. The reduction is statistically significant for only the old technology bus equipped with the muffler.

Table 19. $PM_{2.5}$ mass emission rates (mg/mile).

20 °C		**$PM_{2.5}$ Emfab 90mm**	**$PM_{2.5}$ Teflon 47mm #1**	**$PM_{2.5}$ Teflon 47mm #2**
Muffler	avg	2916	2817	2746
	stdev	236	242	197
OxyCat	avg	1101	1129	1107
	stdev	82	94	87
New	avg	195	203	193
	stdev	13	51	38
-10 °C				
Muffler	avg	2341	2172	2131
	stdev	172	202	165
OxyCat	avg	975	902	872
	stdev	97	86	92
New	avg	190	152	158
	stdev	25	35	21

Figure 13. Comparison of $PM_{2.5}$ mass emission rates.



3.2.2 Organic and Elemental Carbon

The organic and elemental carbon composition of the particulate matter may be a useful characteristic in tracing the source of PM emissions. The measured emission rates are summarized in Table 20. The emission rates and relative composition of the PM are compared in Figure 14 and Figure 15 respectively.

The use of the oxidation catalyst on the old technology bus has an overall effect of reducing the PM mass emission rate. The organic carbon mass emission rate is significantly reduced and the elemental carbon mass emission rate is slightly increased causing the relative composition of the PM to be substantially changed. The emissions measured with the oxidation catalyst in place are less than 25% organic carbon while those measured with the muffler in place greater than 75% organic carbon. The oxidation catalyst appears to reduce PM mass emission rates by reducing the organic carbon fraction of the PM. The reduction of organic carbon contribution is not as dramatic during cold temperature operation. The PM composition under these conditions is about half organic and half elemental carbon.

Though the mass of PM emissions is significantly decreased, almost no change in relative carbon composition is observed due to cold temperature operation of the old technology bus with the OEM muffler in place. This could be due to changes in combustion due to the more dense cold air taken in by the engine as CO emissions are also similarly reduced.

The PM from the new technology bus tested at standard temperature is nearly 90% elemental carbon. During cold temperature operations, the organic carbon contribution is increased to about 55%, again likely due to the less efficient catalyst operation at reduced ambient temperatures.

Table 20. Organic and elemental carbon emission rates (mg/mile)

20 ˚C		**OC corrected**	**EC corrected**	**TC corrected**	**%TC of $PM_{2.5}$**
Muffler	avg	1790	543	2333	80
	stdev	240	31	266	
OxyCat	avg	250	790	1039	94
	stdev	4	60	56	
New	avg	31	213	244	125
	stdev	7	30	28	
-10 ˚C					
Muffler	avg	1484	424	1908	82
	stdev	171	55	211	
OxyCat	avg	402	420	822	84
	stdev	92	15	81	
New	avg	113	90	203	106
	stdev	20	29	46	

Figure 14. Comparison of organic and elemental carbon emission rates.

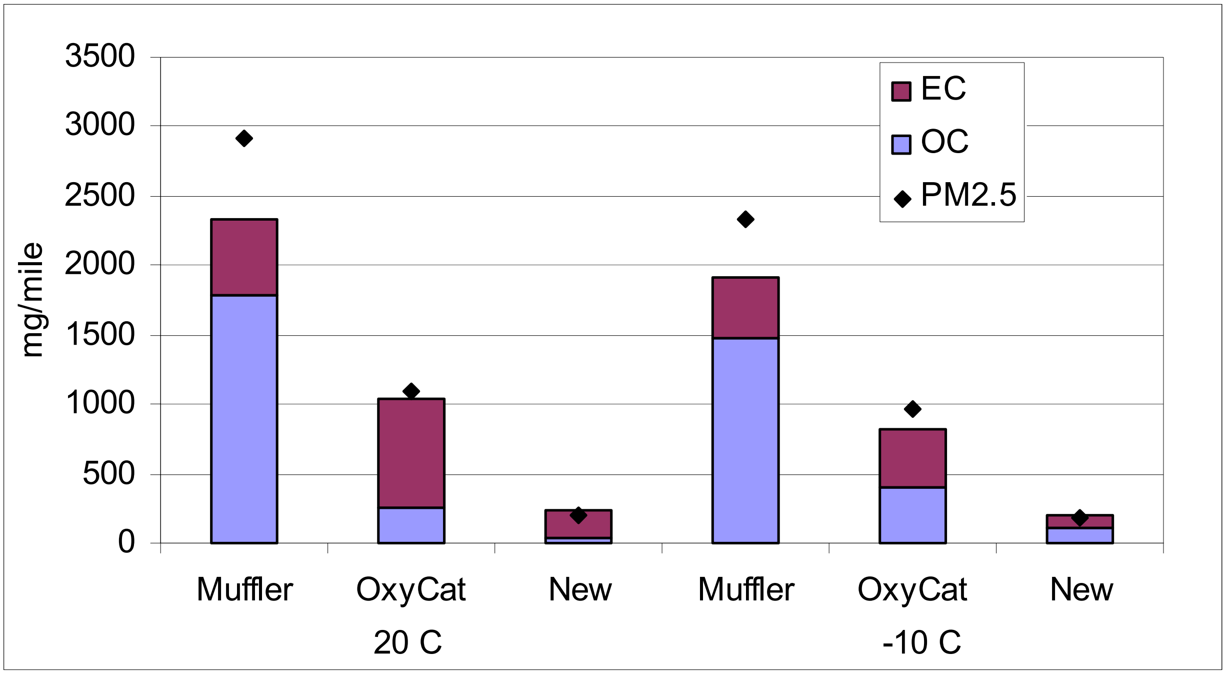
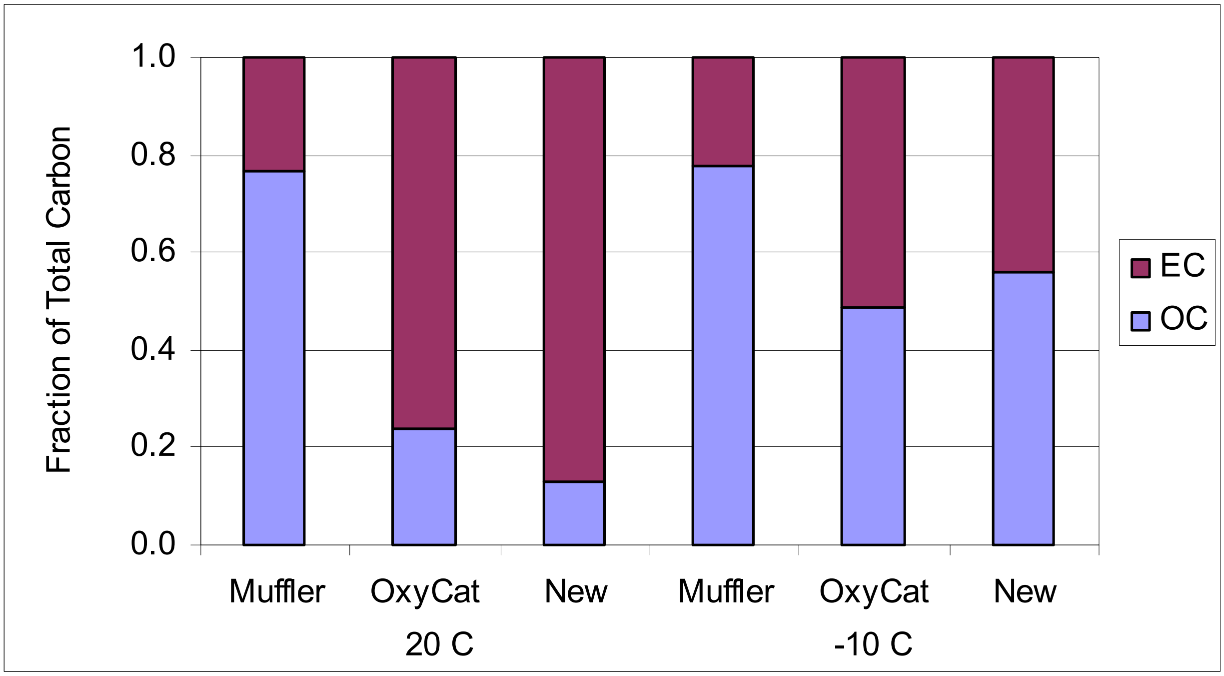


Figure 15. Comparison of the relative carbon composition of $PM_{2.5}$ emissions.



3.2.3 Particle Phase Ions

Emission rates of particle phase ions are summarized in Table 21 through Table 23. The results are compared in Figure 16 through Figure 18.

Emissions of particle phase ions are generally low. Ammonium ion is present in the particle phase due to reaction of ammonia with condensed sulphuric acid present in the particle phase. Whether the ammonium sulphate is directly emitted or formed during sample collection cannot be determined from these results. A molar balance of particle phase ammonium and sulphate ions would show a 2:1 ratio of ammonium to sulphate if all of the particle phase sulphate ion had reacted with ammonia to form ammonium sulphate. This mole ratio is shown in Figure 19. The broken line indicates a 2:1 molar ratio. The highest sulphate emission rates were measured for the new technology bus operated at 20˚C. Clearly there is insufficient total ammonia emitted to completely react with the sulphate emitted by this bus under these conditions. In fact the amount of gaseous ammonia remaining unreacted is a small fraction of the total ammonia emitted for this bus. Even for the lower sulphate emission rates, there is insufficient ammonia emitted to react with the sulphate emitted, as shown in the scale expansion of Figure 19. The data points above the 2:1 line are approaching the quantitation limits of the methods and therefore have larger uncertainties than the other measurements. The regression line shows the correlation of particle phase ammonium ion with particle phase sulphate ion.

The oxidation catalyst on the old technology appears to reduce emissions of particle phase inorganic ions, including sulphate ion but results in an increase in organic ions including hydroxymethane sulphonate. The new technology bus shows fairly high emissions of particle phase sulphate ion but operation at cold temperature substantially reduces these emissions. It is not clear from these measurements whether the catalyst on this vehicle is responsible for the sulphate emissions and whether a change in operating temperature of the catalyst decreases the production of sulphate at cold ambient temperatures.

Particle phase organic ions were determined only for the old technology bus. The oxidation catalyst appears to increase both the variety of ions and their emission rates as compared to operation with the muffler.

Table 21. Particle phase cation emission rates (mg/mile).

20 C		**Lithium**	**Sodium**	**Ammonium**	**Potassium**	**Magnesium**	**Manganese**	**Calcium**	**Strontium**
Muffler	avg	<MDL	<MQL	2.07	0.33	0.04	<MDL	nd	<MDL
	stdev	<MDL	<MQL	0.06	0.03	0.01	<MDL	nd	<MDL
OxyCat	avg	<MDL	<MQL	1.74	0.38	0.06	<MDL	nd	<MDL
	stdev	<MDL	<MQL	0.23	0.05	0.01	<MDL	nd	<MDL
New	avg	<MDL	0.39	9.99	0.19	0.12	<MDL	0.67	<MDL
	stdev	<MDL	0.23	1.81	0.02		<MDL	1.19	<MDL
-10 C									
Muffler	avg	<MDL	0.20	1.18	0.98	0.01	<MDL	nd	<MDL
	stdev	<MDL		0.19	0.66	0.00	<MDL	nd	<MDL
OxyCat	avg	<MDL	0.82	1.13	0.96	0.05	<MDL	nd	<MDL
	stdev	<MDL	0.96	0.07	1.07	0.03	<MDL	nd	<MDL
New	avg	<MDL	<MQL	1.45	0.72	<MQL	<MDL	0.48	<MDL
	stdev	<MDL	<MQL	0.62		<MQL	<MDL	0.17	<MDL

Figure 16. Comparison of particle phase cation emission rates.

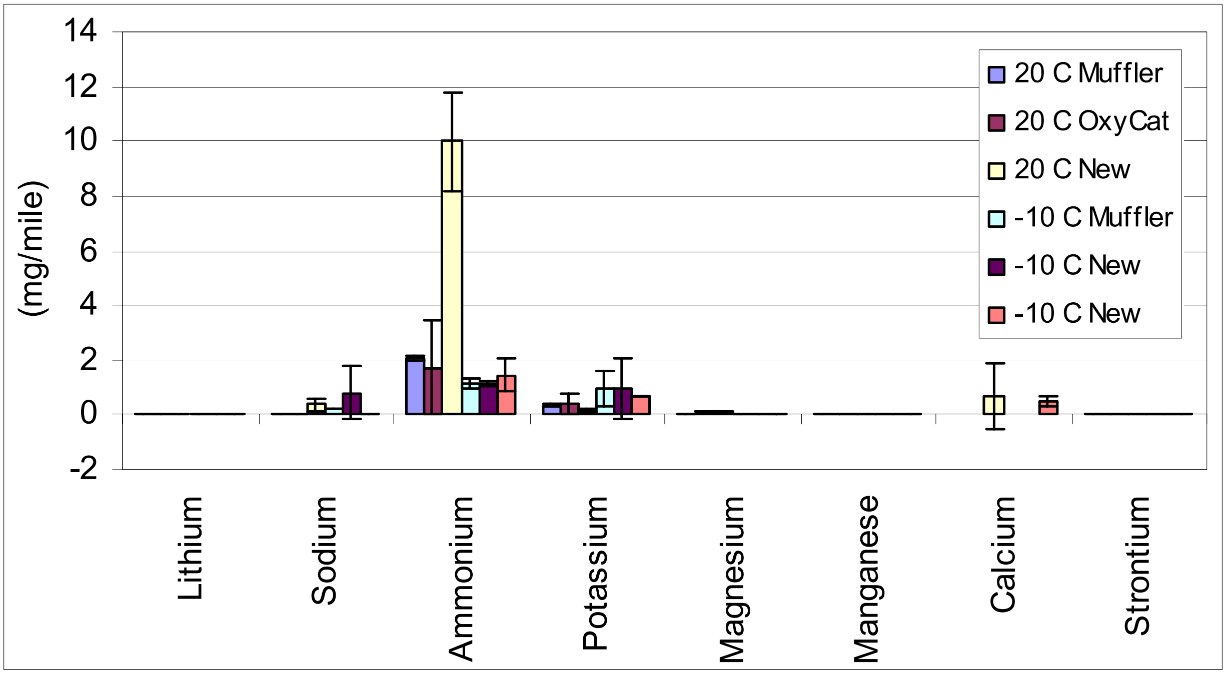


Table 22. Particle phase anion emission rates (mg/mile).

20 °C		**MSA**	**Chloride**	**Nitrite**	**Nitrate**	**Benzoate**	**Sulphate**	**Oxalate**	**Phosphate**
Muffler	avg	<MDL	<MQL	0.19	0.48	0.47	7.81	0.15	2.12
	stdev	<MDL	<MQL	0.03	0.10	0.04	0.45	0.01	0.12
OxyCat	avg	1.53	<MQL	0.09	0.31	<MDL	0.95	0.12	0.53
	stdev		<MQL		0.07	<MDL	0.62		0.10
New	avg	0.81	0.20	<MQL	0.11	<MDL	59.6	<MDL	0.99
	stdev	0.51	0.21	<MQL	0.01	<MDL	21.5	<MDL	0.15
-10 °C									
Muffler	avg	0.24	<MQL	0.20	0.72	0.36	8.32	0.18	2.59
	stdev		<MQL	0.01	0.08	0.07	0.86	0.00	0.14
OxyCat	avg	<MDL	0.55	0.17	1.18	0.27	6.08	0.18	1.64
	stdev	<MDL		0.03	0.31	0.06	1.29	0.03	0.14
New	avg	<MDL	0.37	<MQL	0.22	<MDL	3.33	0.52	0.39
	stdev	<MDL	0.27	<MQL	0.14	<MDL	0.76	0.16	0.09

Figure 17. Comparison of particle phase anion emission rates.

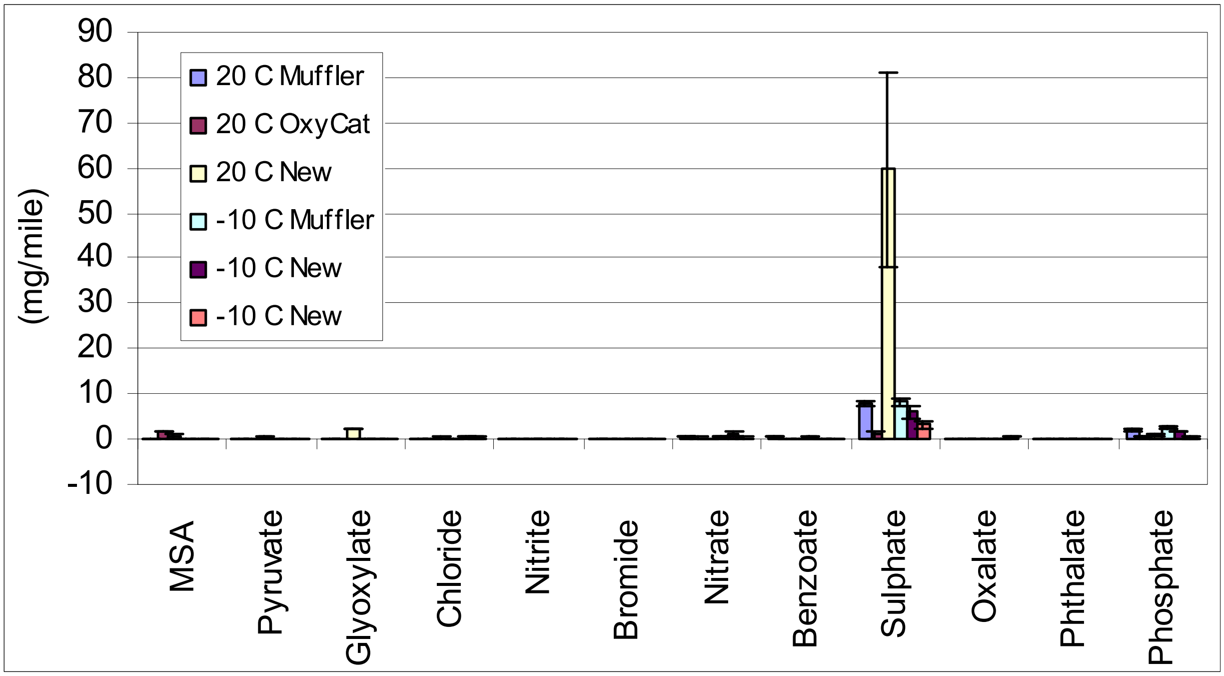


Table 23. Particle phase organic ion emission rates (mg/mile).

20 °C		**Formate**	**Malate**	**Succinate**	**Glutarate**	**Adipate**	**Pimelate**	**HMSA**	**Acetate**	**Lactate**
Muffler	avg	0.30	0.05	0.05	<MDL	<MQL	<MDL	<MQL	0.35	0.33
	stdev	0.11	0.01	0.00	<MDL	<MQL	<MDL	<MQL	0.22	0.09
OxyCat	avg	0.53	0.08	0.09	0.06	0.08	<MDL	0.07	0.37	0.48
	stdev	0.29	0.00	0.01	0.01		<MDL		0.50	0.10
-10 °C										
Muffler	avg	0.38	0.09	0.07	<MQL	<MDL	<MDL	0.14	0.29	0.28
	stdev	0.22	0.00	0.01	<MQL	<MDL	<MDL	0.09	0.16	0.10
OxyCat	avg	0.56	0.19	0.16	0.16	0.14	0.09	0.55	0.55	0.37
	stdev	0.15	0.17	0.09	0.13	0.07		0.47	0.37	0.30

Figure 18. Comparison of particle phase organic ion emission rates.

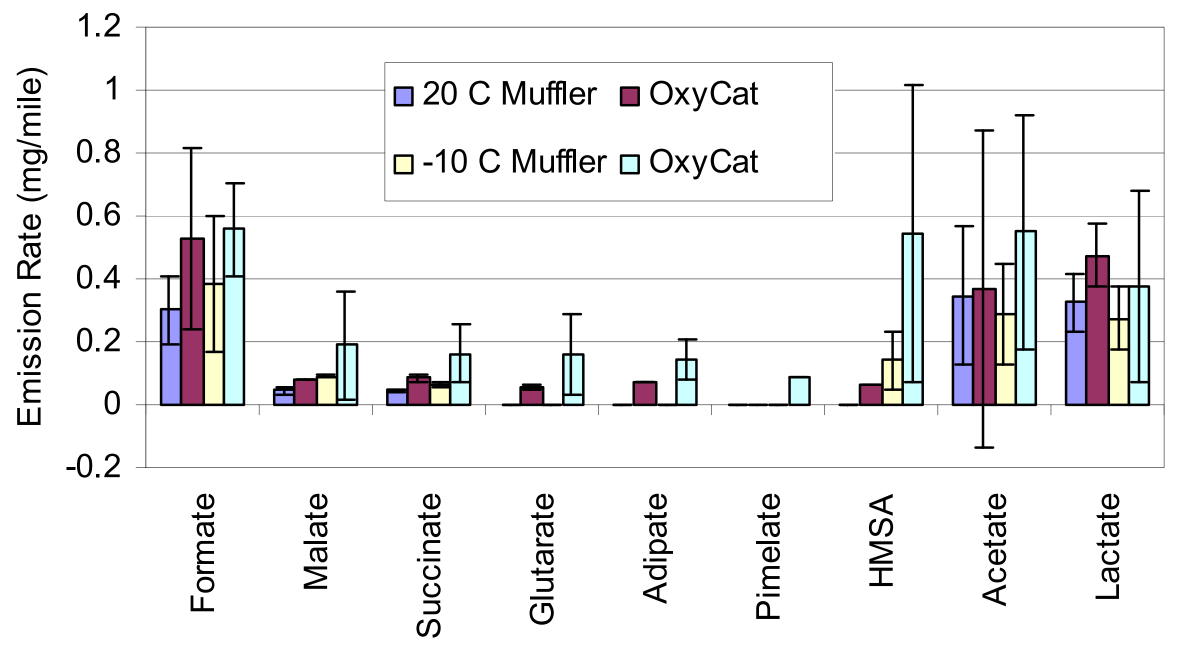
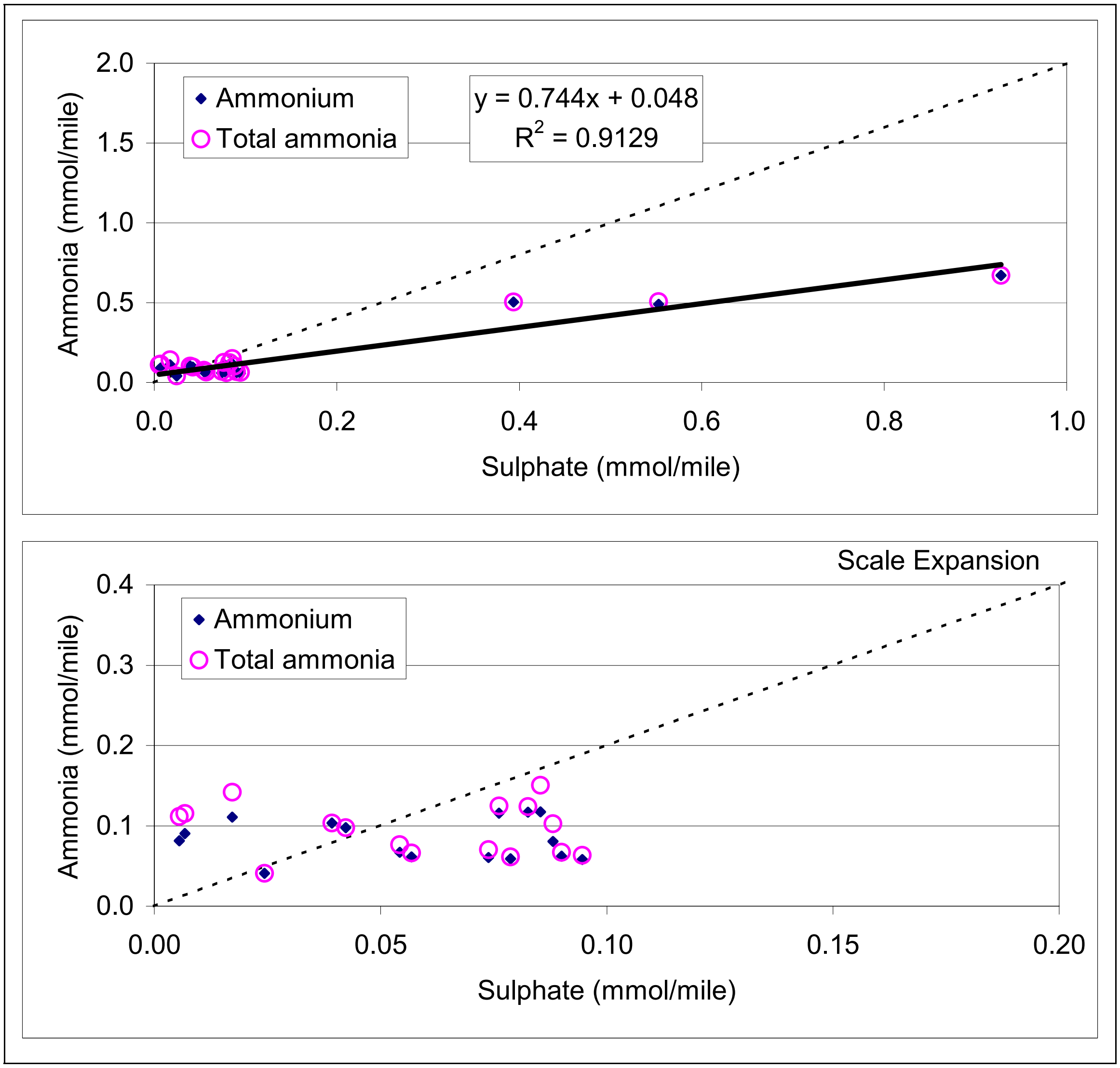


Figure 19. Molar ratio of particle phase ammonium ion, total ammonia and particle phase sulphate ion.



A sulphur balance of the measured emissions is presented in Table 24. The calculated fuel sulphur level assumes all the sulphur found in the emissions is due to the fuel sulphur content (average 383 ppm for the old technology bus and average 419 ppm for the new technology bus). Some of the sulphur is, however, due to the lubrication oil, but there is no reliable way to estimate it from the emissions. A recent heavy-duty diesel engine emissions studies conducted by the U.S. Department of Energy (DECSE Program) suggested that sulphur emissions decrease linearly with fuel content down to approximately 30 ppm fuel sulphur, where they level off with decreasing fuel sulphur. Conventional lubrication oils were used in the U.S. study and are not expected to differ from those used in the buses of this study.

The results in Table 24 show that for the old technology bus, approximately 13% of the sulphur emitted is in the form of gas phase HMSA. A conversion factor often used in photochemical modelling is defined as the mass of sulphur emitted as sulphate divided by the mass of sulphur in the fuel (assumed to be emitted entirely as SO_2). This conversion factor is called the Sulphate Conversion Factor is on average 0.85% for the old technology bus with the muffler in place and 0.38% with the catalyst. Results are not available to calculate a conversion factor for the new bus. If one calculates a sulphur dioxide to sulphate conversion factor, based on actual emissions, these conversion factors become 0.97% for the old bus with the muffler, 0.44% with the catalyst. For the new technology bus, the sulphate conversion factor is 5.35% at standard temperature but decreases at cold temperature to 0.35%.

Table 24. Sulphur balance on measured emissions (mg/mile).

		S from SO_2	S from SO_4	S from HMSA (gas phase)	S from MSA (particle phase)	S from HMSA (particle phase)	Total S	Calculated Fuel S (ppm)
20 ˚C	Muffler	296	2.61	42.7	ND	ND	341	399
	OxyCat	290	0.32	59.6	0.52	0.019	350	414
	New	352	19.9	NM	NM	NM	372	446*
-10˚ C	Muffler	261	2.78	32.4	0.08	0.041	296	356
	OxyCat	262	2.03	41.8	ND	0.158	306	365
	New	316	1.11	NM	NM	NM	317	393*

ND = not detected, NM = not measured, *does not include HMSA or MSA emissions.

3.2.4 Elements

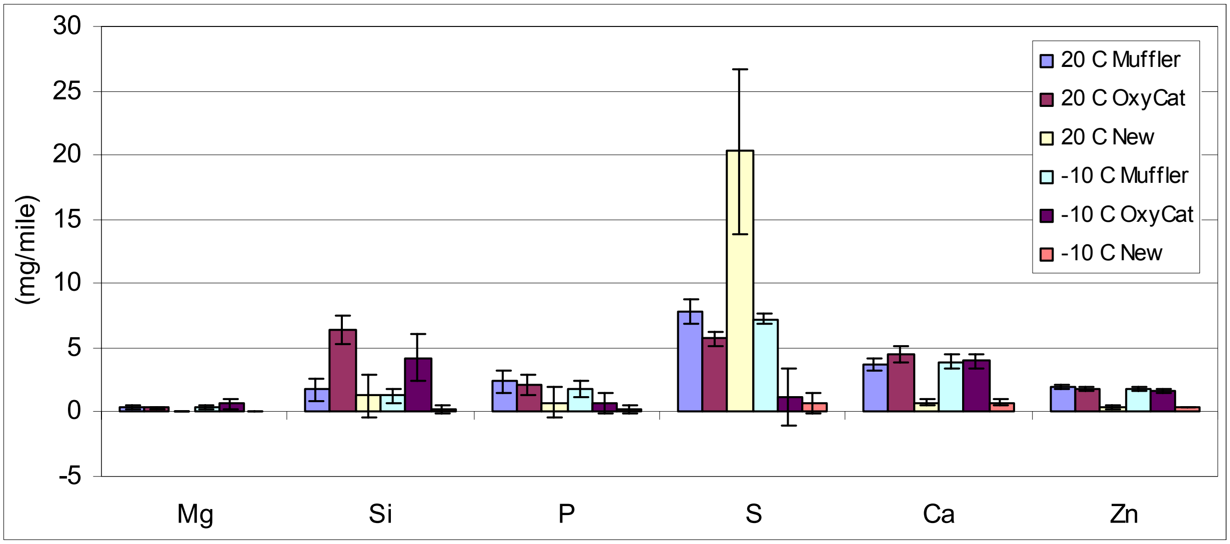
Emissions of elements were determined from Teflon membrane filters. The measured emission rates for selected elements are given in Table 25 and compared in Figure 20. Complete emission rate data is given in Table 28 in Appendix 1. Emissions of sulphur dominate the elemental profile. Sulphur can be present in several forms in the particulate matter (sulphate, organic sulphur, elemental sulphur). Calcium, phosphorus and zinc are present in the particulate matter from the lubricating oil. Other metals arise due to engine wear and trace components in both the fuel and lubricating oil.

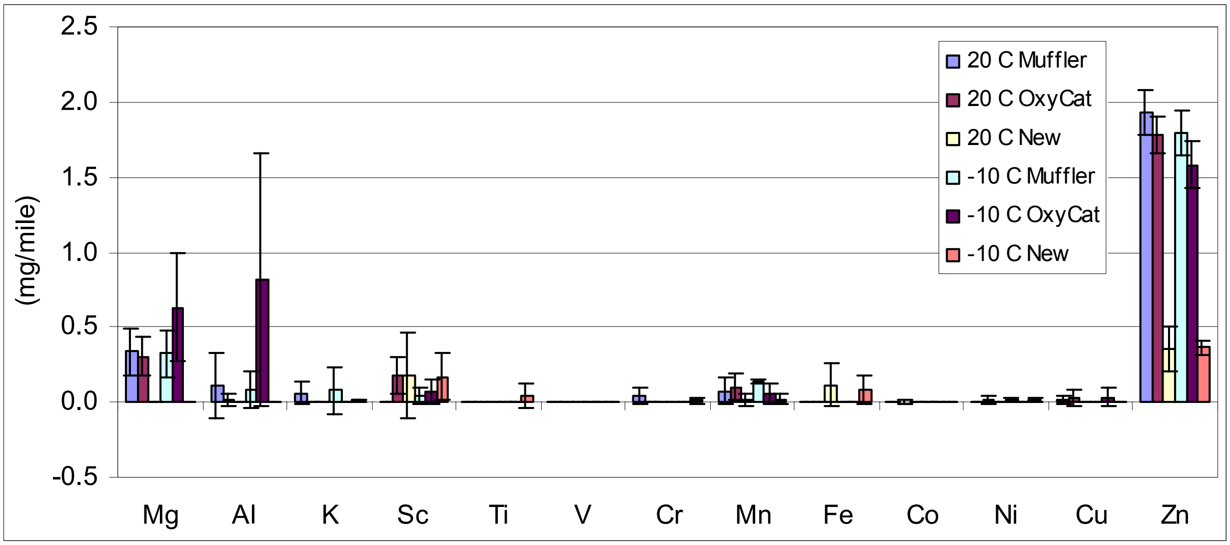
Emissions of metals are generally low. A dramatic decrease in lubrication oil related elements (Ca, Zn, P) is observed for the new technology bus over the old technology bus. This is a direct result of the different engine technology (4 stroke vs. 2-stroke). Increases in silicon emissions for the old technology bus with oxidation catalyst installed over the same bus with the muffler installed can be attributed to attrition of the catalyst monolith. Note that the increased sulphur emissions for the new bus at standard temperature correlate with the increased particle phase sulphate emissions observed earlier.

Table 25. Emission rates for selected elements (mg/mile).

20 °C		**Mg**	**Si**	**P**	**S**	**Ca**	**Zn**
Muffler	avg	0.34	1.74	2.39	7.88	3.70	1.93
	stdev	0.16	0.84	0.86	0.98	0.41	0.15
OxyCat	avg	0.31	6.44	2.12	5.74	4.49	1.78
	stdev	0.13	1.10	0.79	0.55	0.69	0.12
New	avg	0.00	1.26	0.78	20.27	0.76	0.36
	stdev	0.00	1.67	1.12	6.42	0.28	0.14
-10 °C							
Muffler	avg	0.33	1.33	1.83	7.27	3.95	1.80
	stdev	0.16	0.55	0.67	0.46	0.51	0.15
OxyCat	avg	0.63	4.26	0.63	1.11	3.99	1.58
	stdev	0.36	1.87	0.78	2.22	0.57	0.15
New	avg	0.00	0.20	0.21	0.69	0.76	0.37
	stdev	0.00	0.37	0.29	0.80	0.20	0.05

Figure 20. Comparison of emission rates of selected elements.


30
25
20
15
10
5
0
-5
(mg/mile)
Mg
Si
P
S
Ca
Zn
20 C Muffler
20 C OxyCat
20 C New
-10 C Muffler
-10 C OxyCat
-10 C New


2.5
2.0
1.5
1.0
0.5
0.0
-0.5
(mg/mile)
Mg
Al
K
Sc
Ti
V
Cr
Mn
Fe
Co
Ni
Cu
Zn
20 C Muffler
20 C OxyCat
20 C New
-10 C Muffler
-10 C OxyCat
-10 C New

3.2.5 Detailed Organic Composition

Emissions of n-alkanes, alkylcyclohexanes, petroleum biomarker compounds, PAH, NO_2-PAH and PAsH were determined in the particle phase samples. The measured emission rates are given in the Appendix in Table 29 through Table 34 and compared in Figure 21 through Figure 26. The compound identifiers for the target analytes used in these figures are found in the corresponding data tables in the Appendix. The alkanes are the largest contributor to the organic carbon content, followed by the petroleum biomarker compounds, the alkylcyclohexanes, PAH, PAsH and NO_2-PAH. The PAsH and NO_2-PAH emission rates are about an order of magnitude lower than the PAH emission rates. The PAH suite sample for the old technology bus in with the muffler in place was lost during sample preparation and therefore results are not available.

For the old technology bus, the effect of the oxidation catalyst can clearly be seen in reducing the emission rate of most measured compounds as was indicated in the reduced organic carbon content of the PM. The exceptions to this observation were the NO_2-PAH emission rates which increased for the old technology bus with the use of the oxidation catalyst over the muffler configuration. The NO_2-PAH emission rates from the new technology bus were similar to those of the old technology bus with the oxidation catalyst in place.

The temperature dependence of the emission rates is also apparent in these figures. For the alkanes, the cold temperature operation increases the contribution of the lighter compounds to the particulate matter samples for all bus configurations. At warmer temperatures, these compounds are partitioned more towards the vapour phase, but at lower temperatures, they appear condensed on the particle phase. In the particulate matter samples, the C_{11}-C_{13} remain in the vapour phase at both temperatures. Similar trends with operation temperature are seen with the petroleum biomarker compounds and the alkylcyclohexanes, PAH, PAsH and NO_2-PAH

The same suite of compounds was determined in the fuel and lubrication oil samples collected from the new technology bus. The concentrations of these compounds in the fuel and lubrication oil samples are given in the Appendix in Table 35 through Table 40. These compositions are compared in Figure 27 and Figure 28. Note the very low concentrations of petroleum biomarker compounds in the diesel fuel sample where only the lowest molecular weight terpanes and steranes are found in measurable quantities. Only the lowest molecular weight PAH, PAsH and NO_2-PAH are present in the fuel. There is a broader distribution of PAH in the lube oil sample, but only the lightest PAsH and NO_2-PAH were found in the lube oil. The lube and fuel oil PAH suite concentrations were not corrected for recovery as the recovery standard mixture would have interfered with the column chromatography during clean-up. The comparisons of PAH suite compounds can therefore be semiquantitative at best. This is apparent with the PAsH comparison of the lube and PM compositions. These compounds do arise in the PM due to the lube oil. The presence of NO_2-PAH in the PM samples is due to formation during combustion or over the catalyst.

Figure 21. Comparison of n-alkane emission rates (mg/mile).

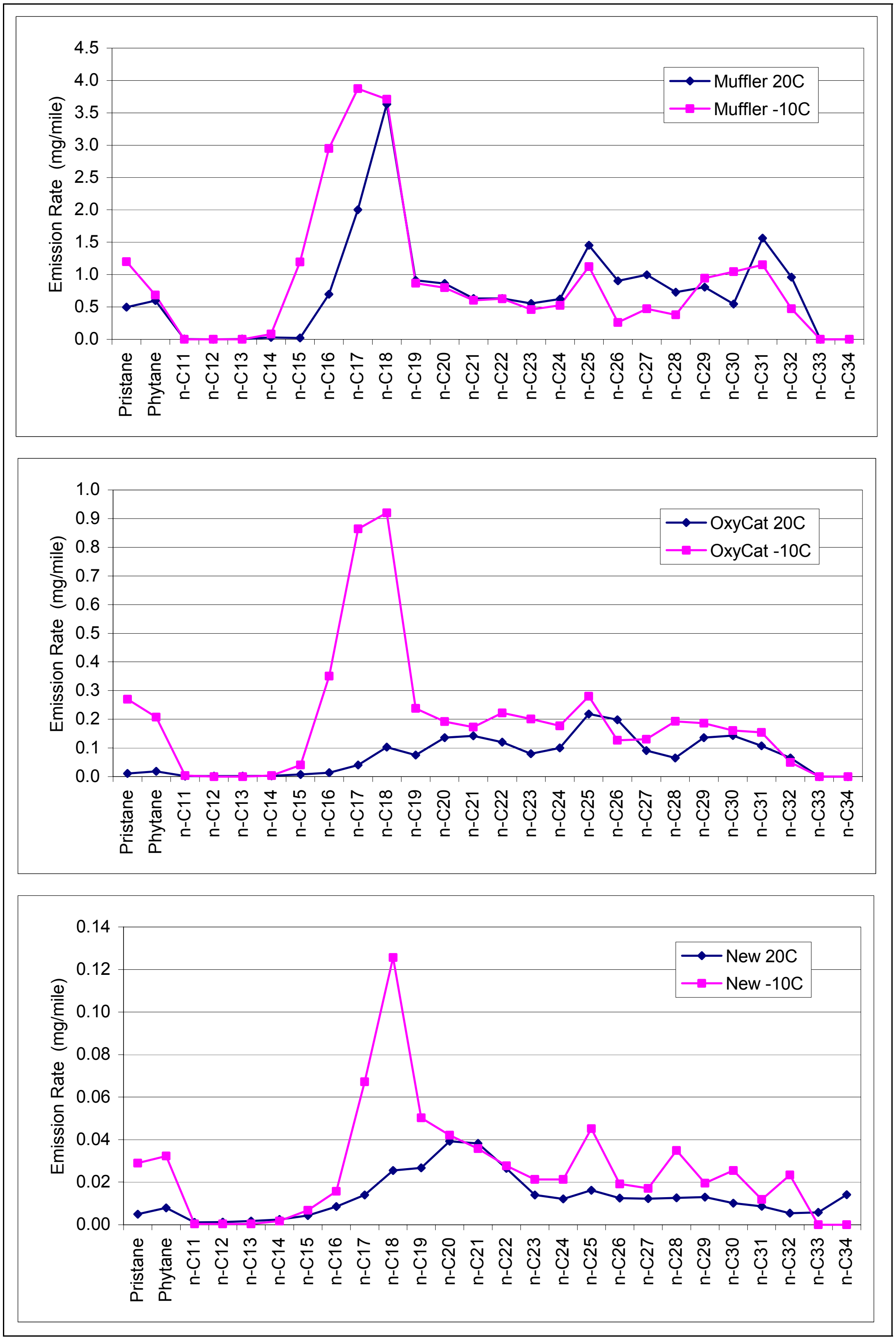


Figure 22. Comparison of alkylcyclohexane emission rates (mg/mile).

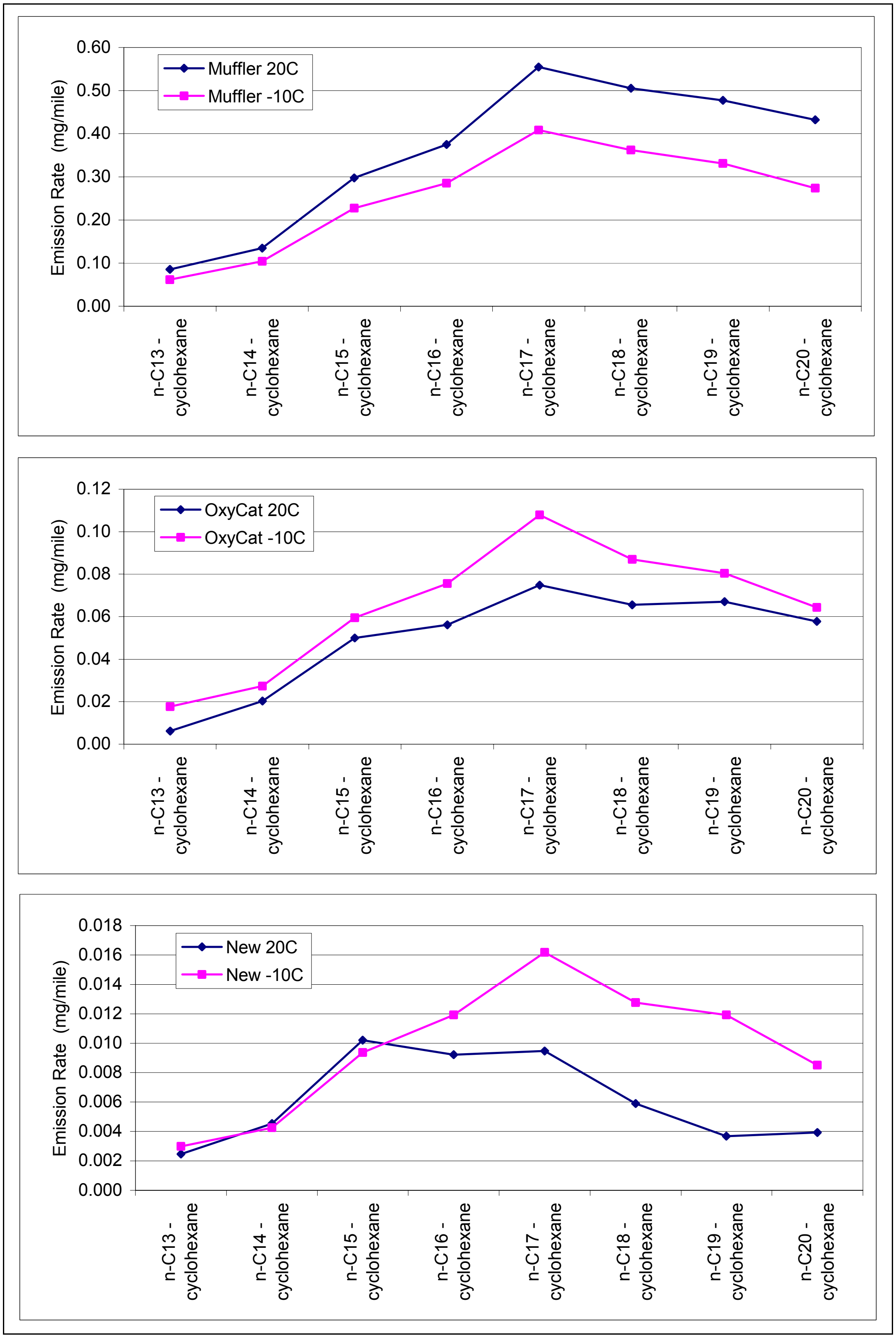


Figure 23. Comparison of petroleum biomarker emission rates (mg/mile).

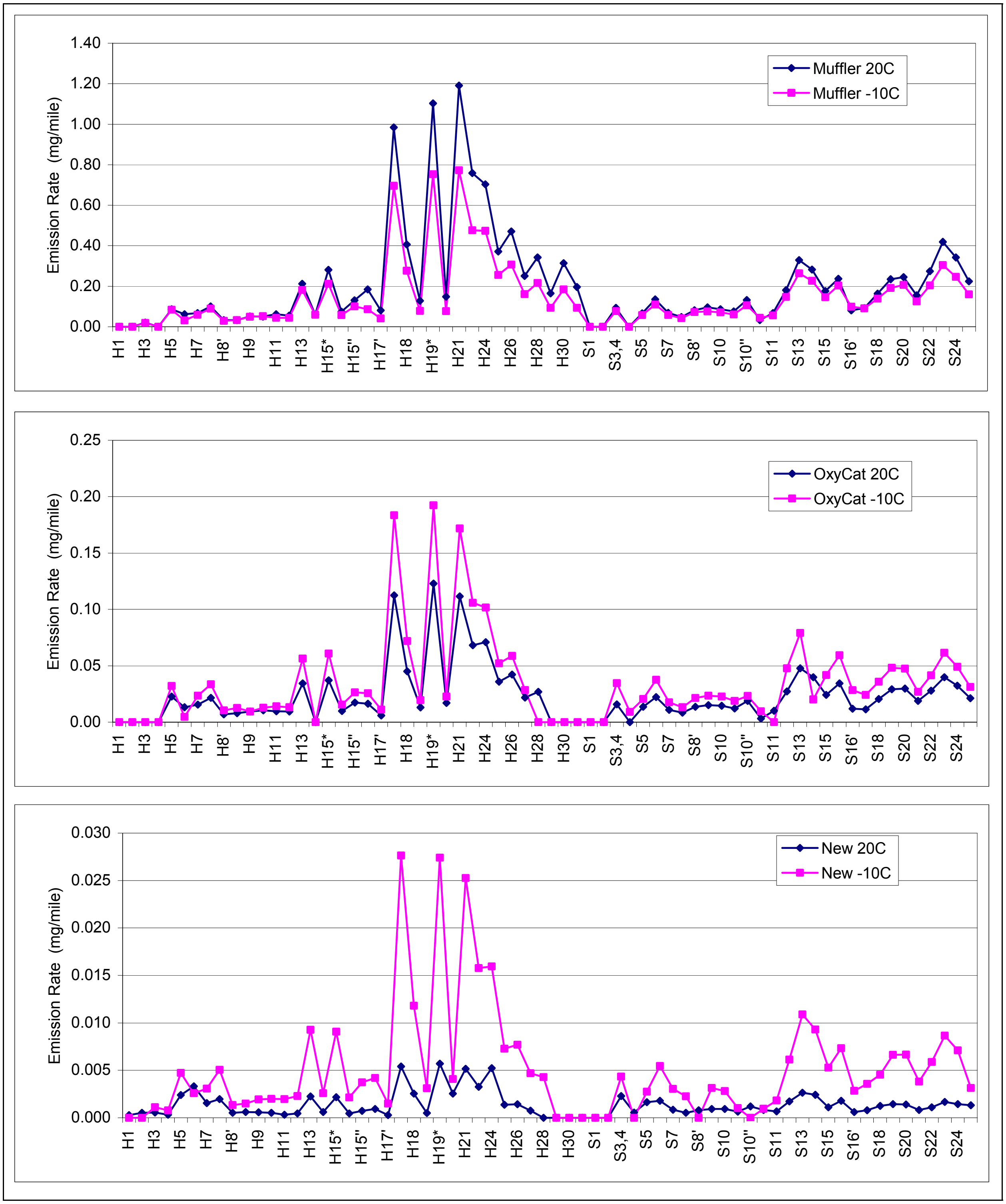


Figure 24. Comparison of PAH emission rates (mg/mile).

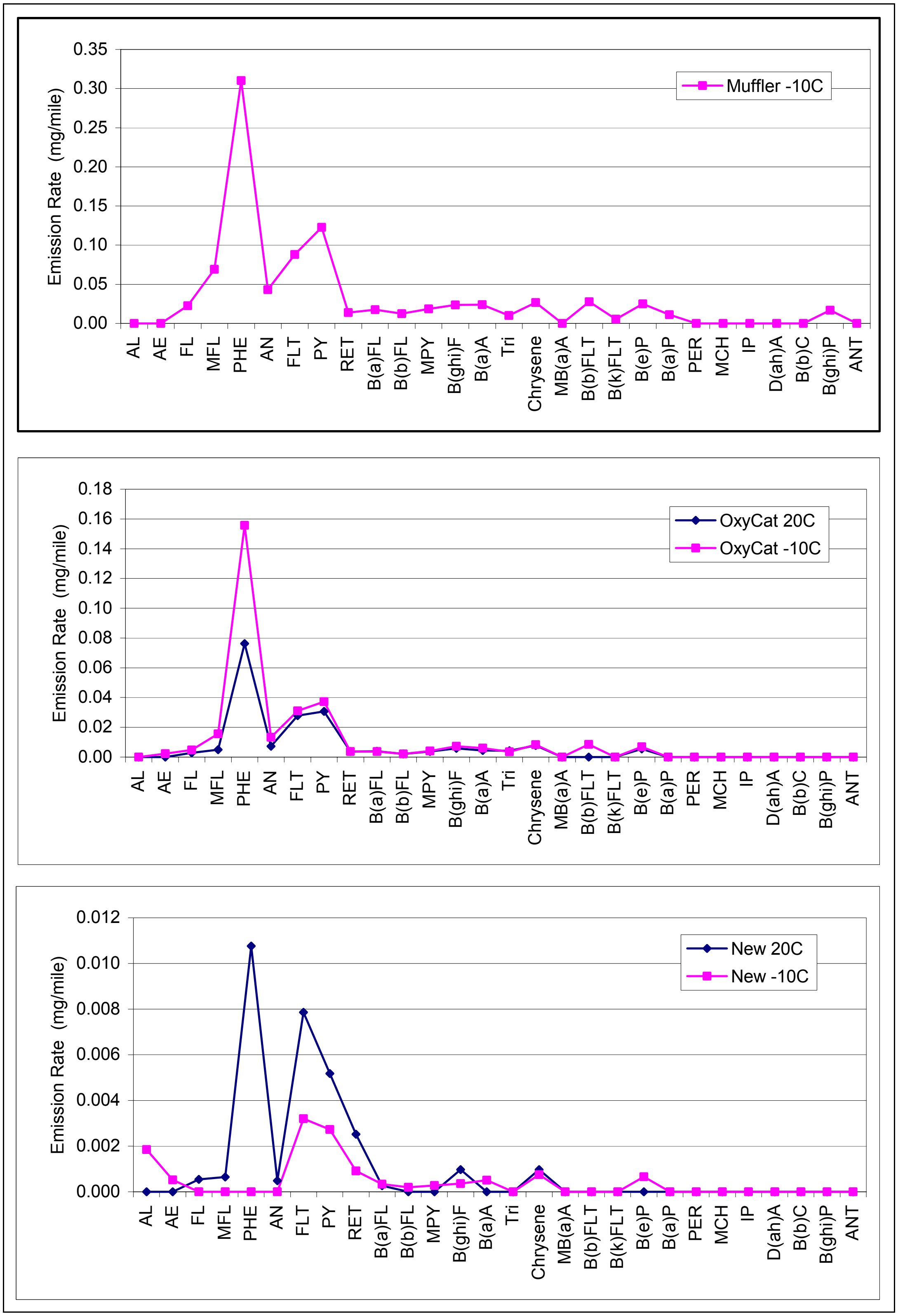


Figure 25. Comparison of PAsH emission rates (µg/mile).

Figure 26. Comparison of NO_2-PAH emission rates (µg/mile).

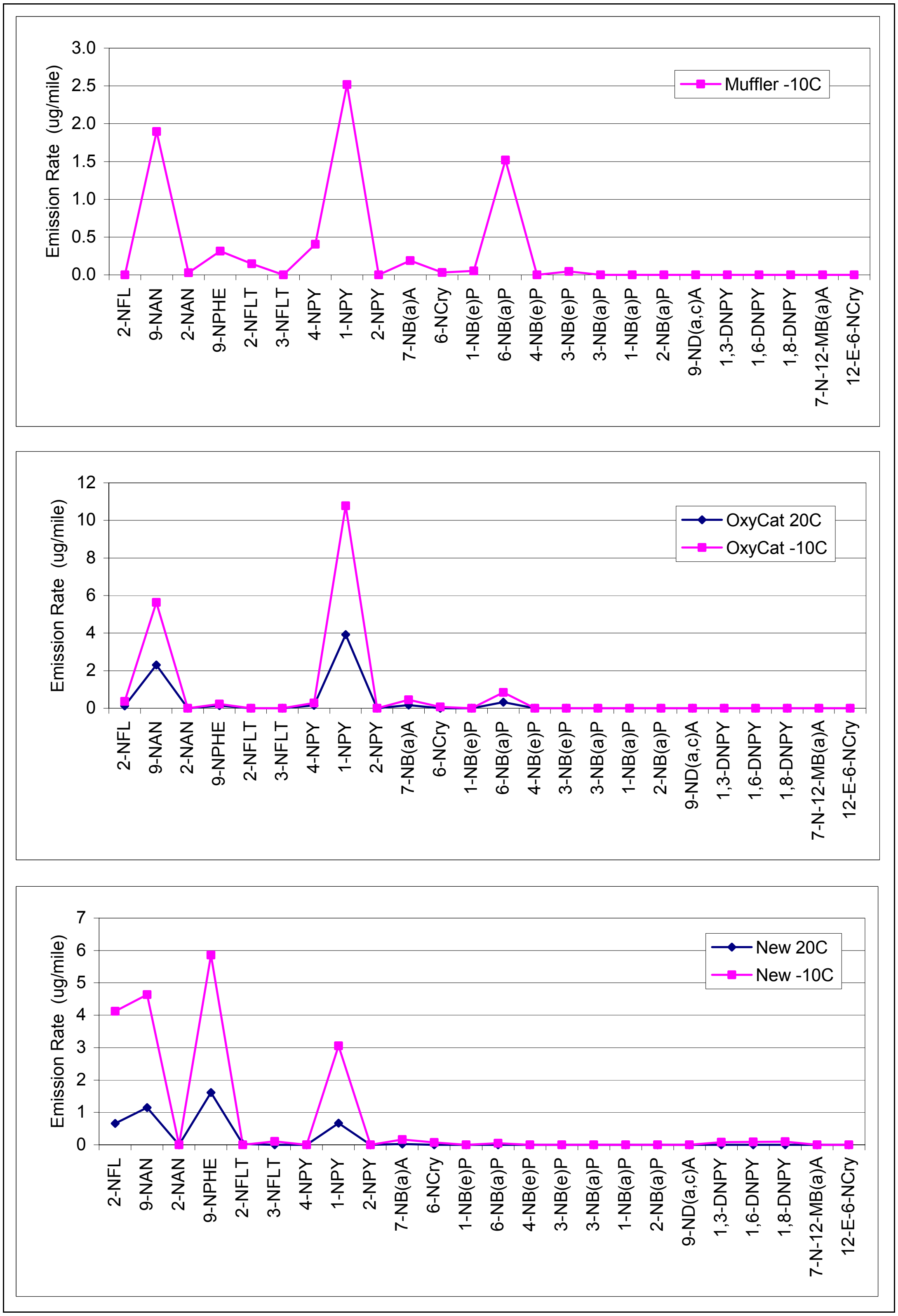


Figure 27. Comparison of lubrication oil and diesel fuel compositions (g/g).

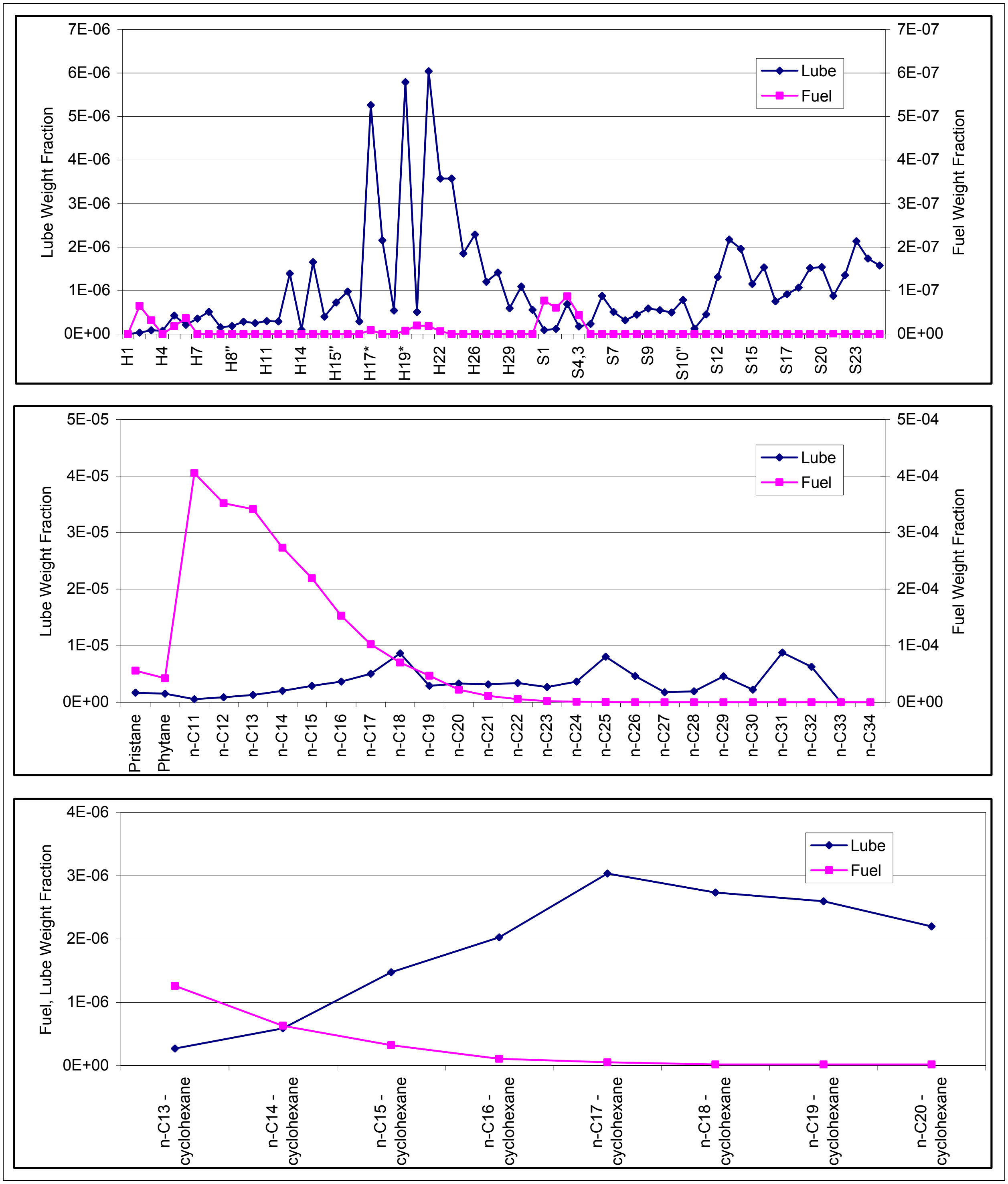
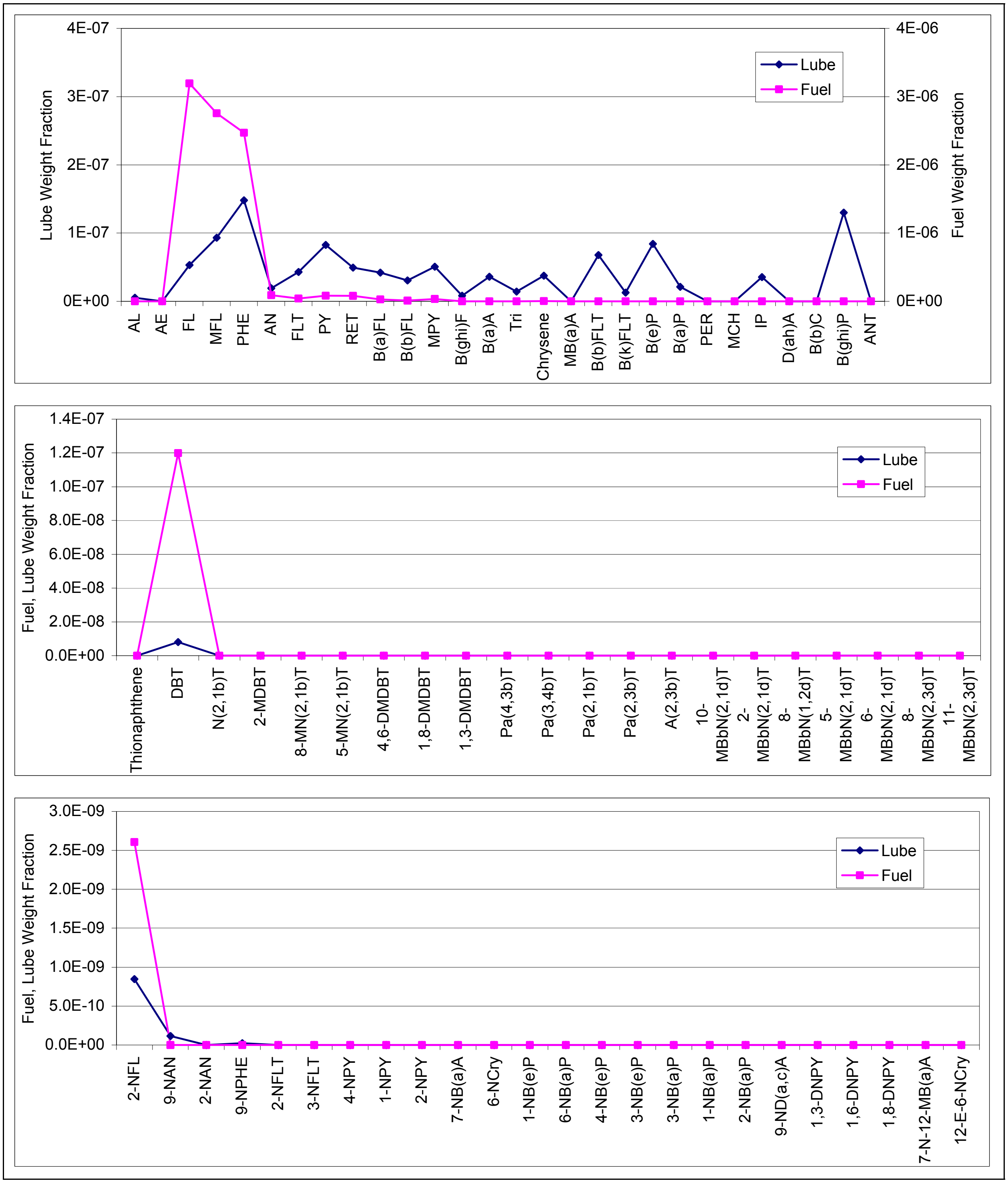


Figure 28. Comparison of lubrication oil and diesel fuel compositions (g/g).



These organic compounds are useful in source apportionment studies and so emission profiles expressed as fraction of (or normalized to) particle phase organic carbon emission rate are given in the Appendix in Table 41 through Table 46 and compared in Figure 29 and Figure 30.

There is considerable variation in the relative contributions of n-alkanes lighter than C_{19} due to operating temperature and to the presence or absence of exhaust aftertreatment. For the alkylcyclohexanes, there seems to be little difference in the emission profiles for the old technology bus with or without exhaust aftertreatment or with change in operating temperature. For the new technology bus, operating temperature appears to result in larger changes in emission profile. Since the absolute emission rates of these compounds are more than an order of magnitude less for the new technology bus than for the old technology bus, the difference may not be significant. For the petroleum biomarker compounds, the profiles for the old technology bus are similar with and without exhaust aftertreatment and regardless of operating temperature. The two new technology bus profiles are similar to one another, but different from the old technology bus. This difference may be attributable to the lube oil used, but since a sample was not collected for analysis, this cannot be confirmed. The comparison in Figure 29 might suggest that this explanation may not be correct. The largest differences in profiles appear with the heavier terpane compounds (H17*-H31; see Table 31 for compound names corresponding to the identifiers). The profiles are quite similar for the lighter terpanes and the full range of steranes.

To simplify the comparison of particulate matter composition with fuel and lubrication oil composition, an average of the normalized emission profiles was calculated. The comparisons are shown in Figure 31 and Figure 32. The similarities of the particulate matter profiles to the lubrication oil profiles are clearly visible. Influence from the fuel composition can be seen in the n-alkane profile (C_{15}-C_{19}), in the alkylcyclohexane profile (nC_{13}-cyclohexane – nC_{15}-cyclohexane), and in the PAH profile (fluoranthene – phenanthrene). The poor correlation of PM with lube oil or fuel composition for the PAsH is likely due to the lack of recovery correction for the lube oil and fuel samples.

Figure 33 illustrates the correlation of total named particle phase organic compound emission rates with organic carbon (OC) emission rates. The trends are qualitatively linear over several orders of magnitude.

Figure 29. Emission rate profiles as a fraction of organic carbon emission rate.

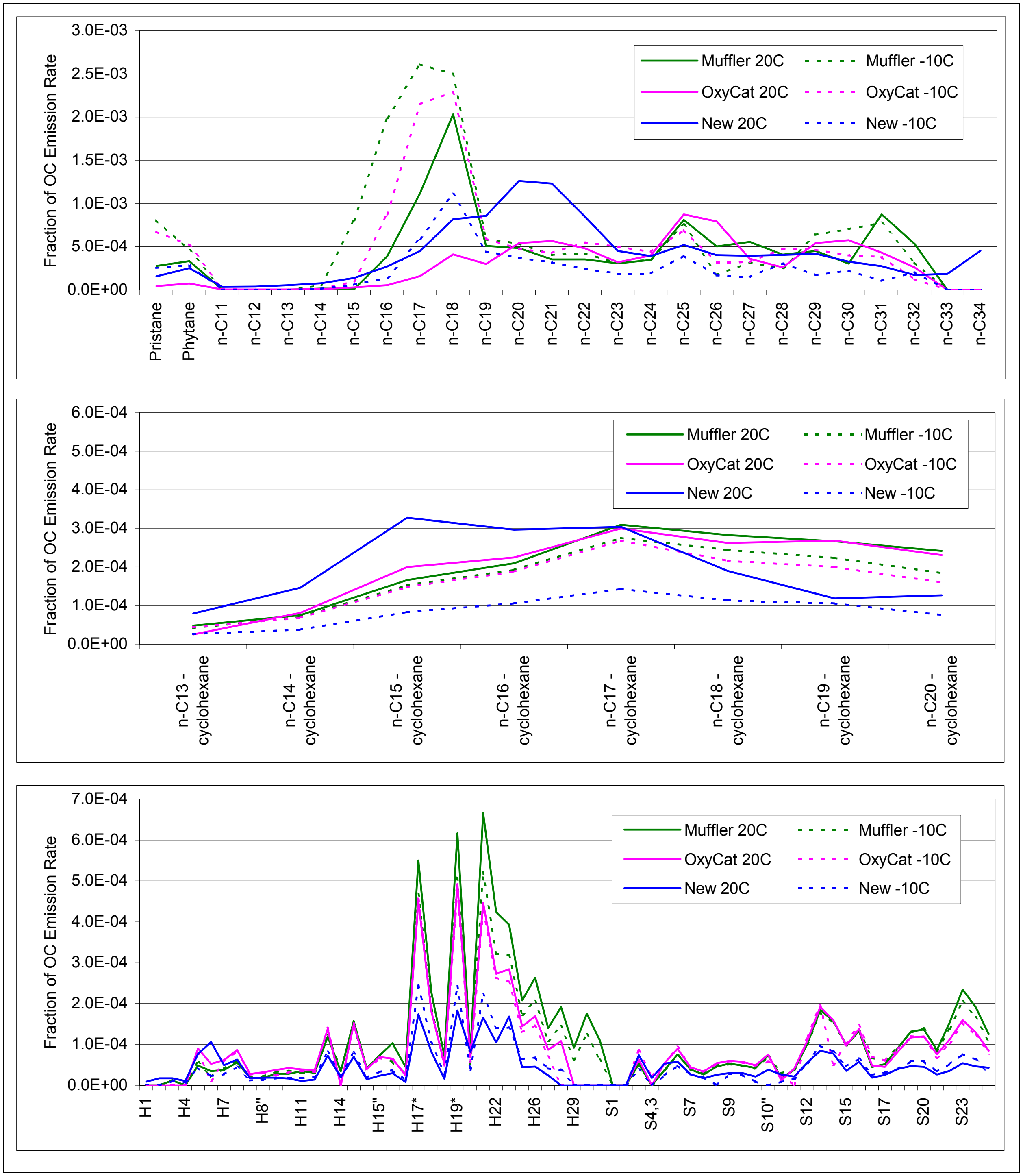


Figure 30. Emission rate profiles as a fraction of organic carbon emission rate.

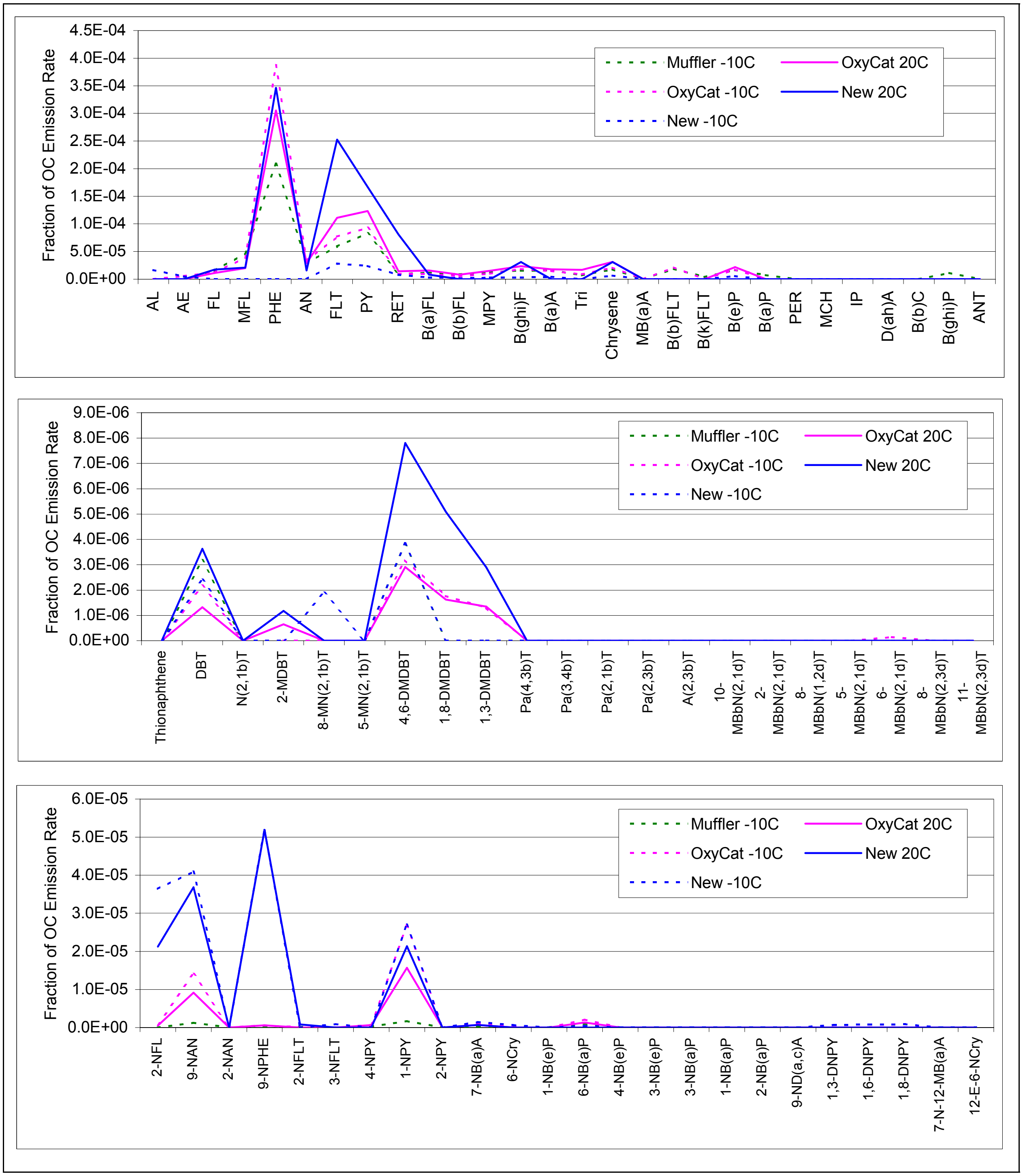


Figure 31. Comparison of particulate matter, lubrication oil and fuel compositions.

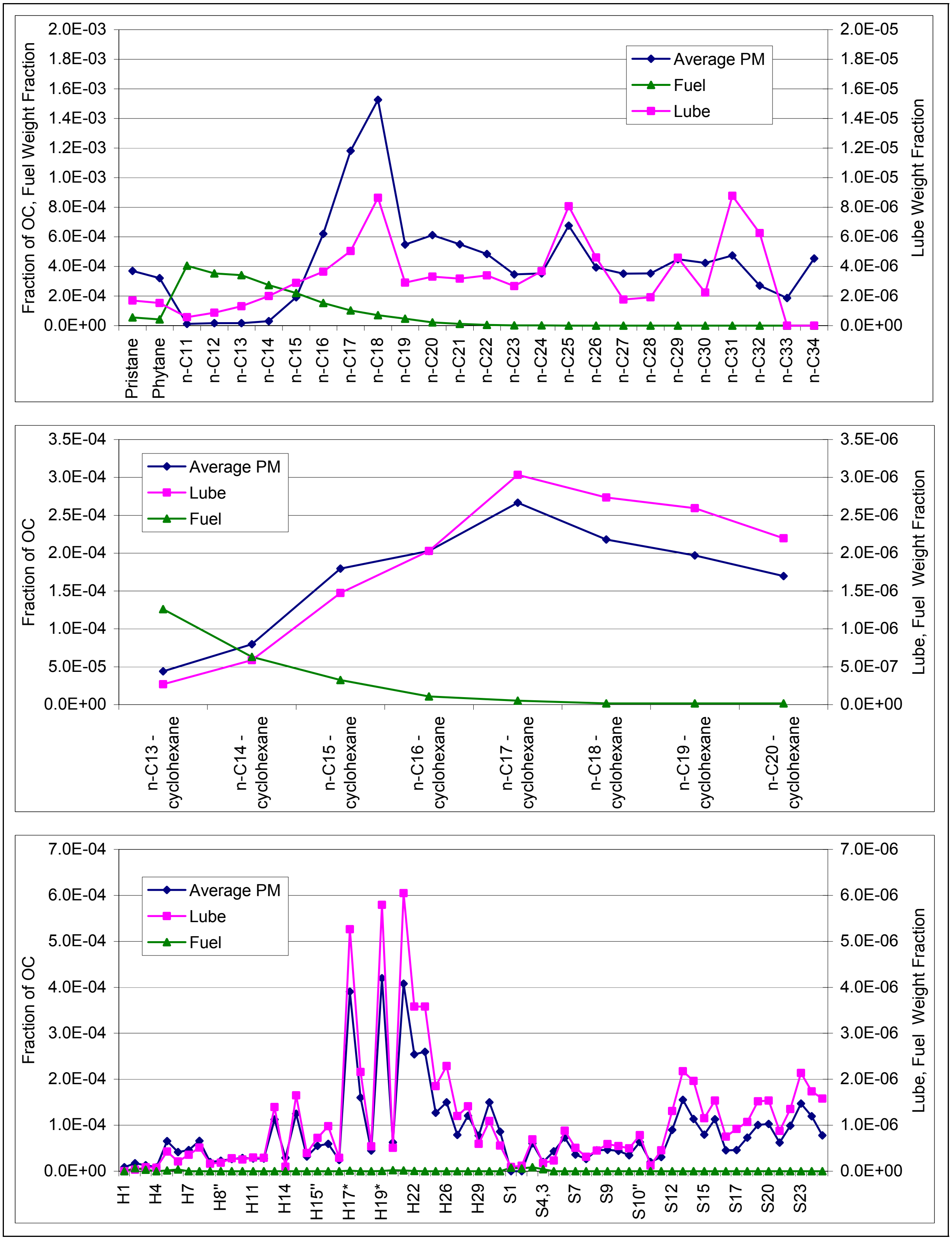


Figure 32. Comparison of particulate matter, lubrication oil and fuel compositions.

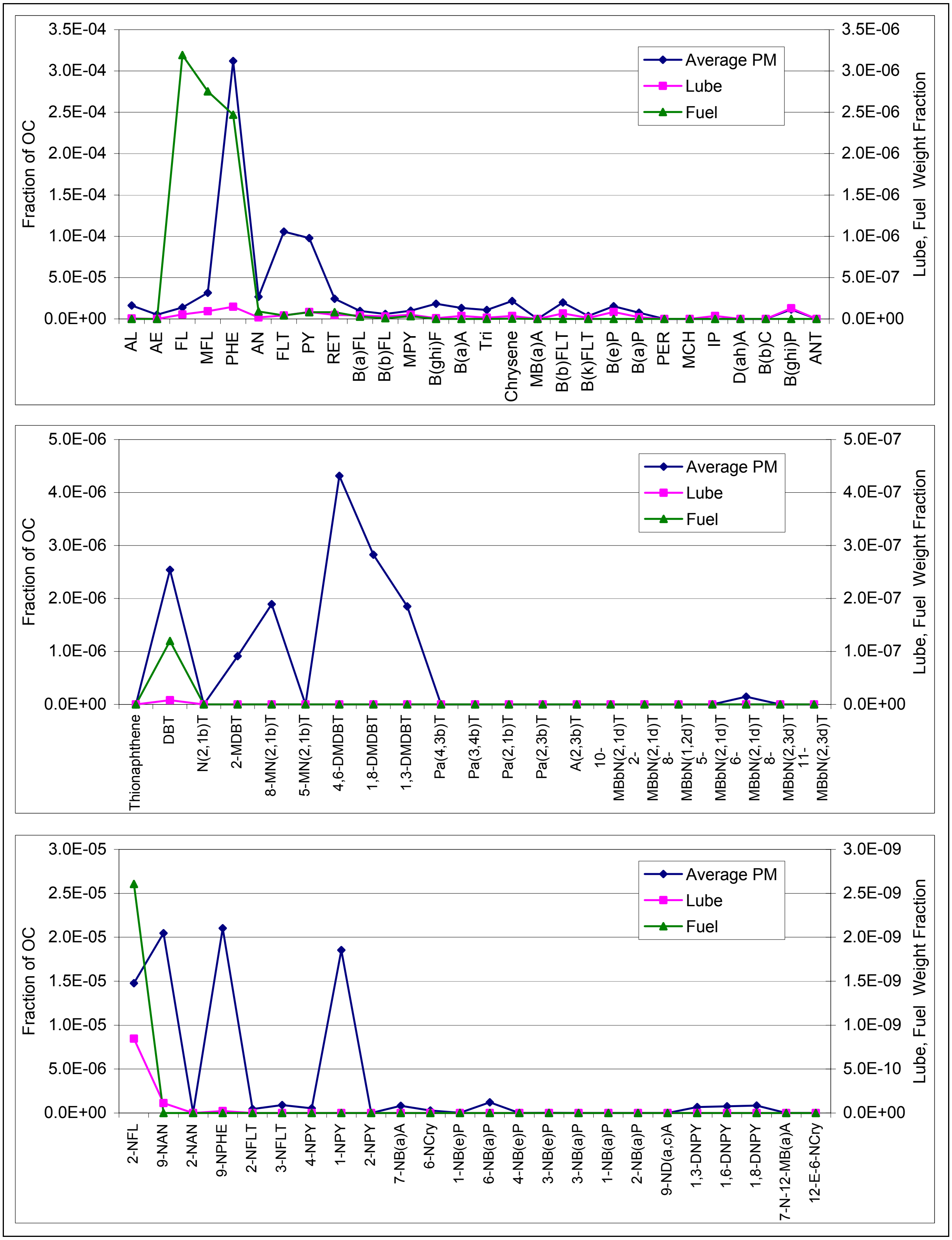
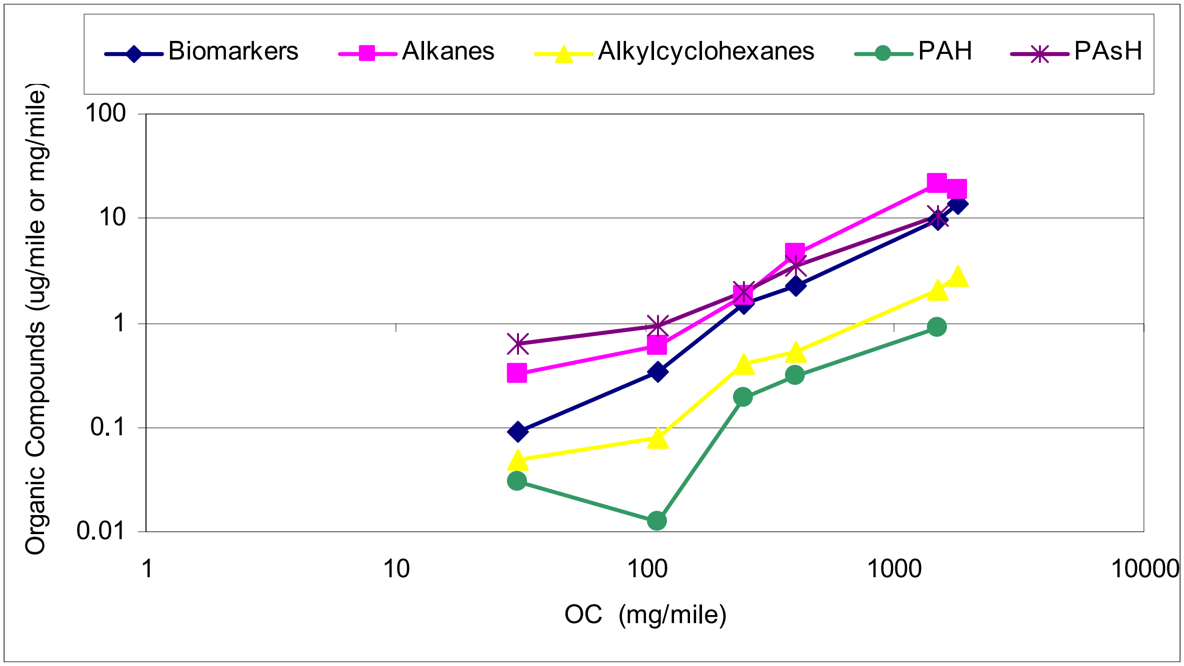


Figure 33. Correlation of total named particle phase organic compound emission rate with OC emission rate.



4. Conclusions

Two in-use urban buses were tested over the Central Business District cycle at two temperatures (20 ˚C and –10 ˚C). The old technology bus was equipped with a 2-stroke diesel engine and was tested in two configurations – with the OEM muffler and with a retrofit oxidation catalyst. This bus was certified to the 1988 heavy-duty diesel engine emission standards. The new technology bus was equipped with a 4-stroke diesel engine with a close-coupled oxidation catalyst and was certified to stringent 1998 urban bus emission standards.

Emission rates were determined for the gaseous criteria pollutants (CO, NO_X, THC), CO_2, methane and non-methane hydrocarbons, carbonyl compounds, vapour phase organic acids, SO_2, NH_3, $PM_{2.5}$ mass emissions, particle phase organic and inorganic ions, metals, organic and elemental carbon and for particle phase organic compounds.

At the test temperature of 20 ˚C, CO, NO_X and THC emission rates from the old technology bus with the muffler in place were the highest of all configurations. The use of the oxidation catalyst on the old technology bus resulted in a statistically significant decrease in both NO_X and THC emissions by 25% and 28% respectively, while the CO emissions remained essentially unchanged. It is possible that the catalyst was using the NO_2 in the exhaust to assist in oxidation of the hydrocarbons – both in the gas phase and particle bound. In comparing the new technology bus with the old technology bus with the oxidation catalyst, the new bus was found to have statistically lower CO and THC emission rates – 41% and 79% respectively. There was no difference in the NO_X emission rate. Both buses showed very similar CO_2 emission rates and fuel consumption rates.

Cold temperature operation reduced the effectiveness of the oxidation catalyst for both buses, but had no significant effect on the old bus with the muffler in place. NO_X emissions for both of the catalyst equipped bus actually increased with cold temperature operation. It may be that the catalyst was unable to take advantage of the NO_2 oxidation due to reduced operating temperatures. Further testing involving simultaneous before and after catalyst sampling would be necessary to confirm this hypothesis.

Non-methane hydrocarbon emissions were dominated by ethylene and propylene for all configurations. The n-alkane pattern typical of diesel fuel is readily apparent in the old technology bus emissions, and is less obvious in the new technology emissions. The trends discussed above with catalyst and temperature effects on THC emissions are paralleled in the NMHC profiles.

Toxic organic compound emissions (aromatic hydrocarbons and carbonyl compounds) were 8.5 times higher for the old technology bus with the muffler in place as compared to the new technology bus. The use of the oxidation catalyst on the old technology bus reduced this difference to 7.7 times.

The ozone specific reactivity (mg O_3/mg NMOG) for the new technology bus was slightly higher than for the old technology bus configurations – 5.35 for the new technology bus as compared to 4.34 for the old technology bus. Operation at cold temperature slightly decreased the specific reactivity for all configurations. When the magnitude of the NMOG emissions were considered, the ozone potential (mg O_3/mile) of the old technology bus with the muffler in place was 9.2 times greater than the new technology bus at standard temperature while the oxidation catalyst on the old technology bus reduced the ozone potential to only 7.1 times greater than the new technology bus.

Vapour phase organic acid emission rates were measured only for the old technology bus and were found to be of the same order of magnitude as the NMHC emission rates. Hydroxymethane sulphonic acid was found in the samples. This is an important finding since sulphur(IV) present in HMSA is more resistant to oxidation in the atmosphere by H_2O_2 and O_3 than is SO_2. This compound is formed by the reaction of aqueous SO_2 with aqueous formaldehyde under acidic conditions, and likely occurs in the condensed water vapour droplets present in cooled, diluted vehicle exhaust.

Particulate matter emissions from the old technology bus with the muffler in place were 15 times greater than the new technology bus. The oxidation catalyst reduced this difference to 5.6 times greater. At cold temperature, PM emissions from the old technology bus were statistically significantly lower (20% with muffler and 11% with oxidation catalyst) as compared to operation at standard conditions. There was no observed change in PM emissions with the new technology bus with operation at cold temperature. The composition of the PM emissions, however, changed significantly. At standard conditions, the old technology bus with the muffler in place had PM emissions that were 76% organic carbon by mass. The oxidation catalyst reduced the organic carbon composition to 24%.

The new technology bus had PM emissions that were 13% organic carbon. Operation at cold temperature caused an increase in the OC fraction 78%, 49% and 56% respectively for the old technology bus with the muffler, catalyst and the new technology bus.

Particle phase organic and inorganic ion emissions were low for all configurations (< 1 mg/mile) except for sulphate ion. The new technology bus had the highest sulphate emission rate. The ammonium ion emission rate was similarly increased. The oxidation catalyst on the old technology bus had little effect on the sulphate emission rates, likely because the temperature was not high enough to cause conversion of SO_2 to sulphate.

SO_2 emissions were different for the two buses, likely due to a difference in fuel sulphur content as they were tested nearly a year apart. Gas phase ammonia emissions were low for all configurations. Most of the ammonia was found in the particle phase due to reaction with particle phase sulphate ion. There was insufficient total ammonia to completely react with the sulphate ion in the particle phase. The sulphate conversion factor for the old technology bus was only about 0.7% while for the new technology bus was 5.7% at standard temperature and only 0.3% at cold temperature. When all oxidized species of sulphur were considered, the total conversion factor for the old technology bus increased from 0.7% to 14%. Results were not available for the new technology bus to compare.

Emissions of trace metals were also low. They were dominated by lube oil components (S, Zn, P, Ca). These emissions were higher with the old technology bus with its 2-stroke engine than with the new technology bus and its 4-stroke engine.

The particle phase organic compound emission rates were very low – mg/mile to μg/mile range, and paralleled the changes in OC content. Cold temperature operation increased the emission rates due to greater condensation on the particle phase. The emission profiles normalized to organic carbon emission rate showed strong similarity to the lube oil composition, and in some instances, influence from the fuel could be detected.

These results demonstrate quite convincingly that removing old technology buses from the road can have a dramatic effect on improving urban air quality.

Appendix

Table 26. Hydrocarbon emission rates (mg/mile).

Missing value indicates below detection limits, missing standard deviation indicates compound found in only one of two repeat samples.

ID#	Compound Name	Muffler 20C		Muffler -10C		OxyCat 20C		OxyCat -10C		New 20C		New -10C	
		avg	stdev	avg	stdev	avg	stdev	avg	stdev	avg	stdev	avg	stdev
1	methane	3.23	4.56			5.21	0.55	4.62	3.51				
2	ethylene	163.82	0.19	145.90	1.84	125.21	3.36	129.83	12.71	54.56	2.74	57.83	3.62
3	acetylene	30.52	0.67	28.34	1.48			5.36	1.15			3.11	4.40
4	ethane	0.86	0.01	2.25	0.15			2.27	0.03				
5	propylene	72.55	3.38	64.33	0.56	51.38	4.61	53.41	11.88	11.78	1.44	13.76	0.11
6	propane	0.59	0.84	0.15	0.21	1.87	2.65	0.27	0.38			21.10	29.83
7	propyne									0.13	0.02	0.53	0.01
8	isobutane					0.96	1.36						
9	isobutene/1-butene									0.86	0.35	2.72	0.89
10	13-butadiene	0.10	0.03	0.53	0.11	0.22	0.31	0.50	0.23	0.03	0.04	0.20	0.28
11	n-butane	0.61	0.52	0.65	0.12	0.12	0.16	0.71	0.01			0.16	0.01
12	t2-butene	0.47	0.03	1.37	0.05	1.82	0.41	1.57	0.39			0.41	0.01
13	22-dm-propane												
14	1-butyne	0.09	0.00	0.33	0.00	0.05	0.08	0.12	0.18				
15	c2-butene	0.19	0.01	0.94	0.06	1.14	0.08	1.01	0.20			0.31	0.03
16	12-butadiene												
17	3m1-butene	0.38	0.02	1.37	0.05	1.03	0.03	1.05	0.14	0.22	0.02	0.38	0.01
18	2m-butane	0.48	0.37	0.63	0.15	1.34	1.04	0.80	0.24	1.37	1.94	0.48	0.04
19	14-pentadiene			0.97	1.37					0.35	0.50	1.33	0.19
20	2-butyne					0.13	0.01						
21	1-pentene	1.31	0.09	4.52	0.27	3.52	0.25	3.30	0.54	0.15	0.07	1.10	0.01
22	2m1-butene					0.26	0.01						
23	n-pentane	0.24	0.17	0.45	0.06	1.10	0.39	0.56	0.19	0.24	0.34	0.05	0.01
24	2m-13-butadiene	0.41	0.04	1.27	0.06	0.89	0.06	0.74	0.06	0.10	0.14	0.46	0.21
25	t2-pentene	0.20	0.04	0.64	0.01	0.79	0.07	0.85	0.39			0.20	0.03
26	c2-pentene	0.10	0.01	0.33	0.00	0.37	0.02	0.33	0.07	0.04	0.05		
27	2m2-butene					0.19	0.00	0.18	0.02				
28	22-dm-butane									0.07	0.02	0.69	0.09
29	cyclopentene	0.14	0.02	0.71	0.04	0.69	0.02	0.63	0.10				
30	4m1 & 3m1-pentene	0.62	0.01	2.13	0.13	1.33	0.00	1.45	0.23	0.22	0.31	0.67	0.03
31	cyclopentane	0.10	0.05	0.59	0.11	0.35	0.15	0.35	0.01	0.12	0.16	0.40	0.00
32	23-dm-butane	0.08	0.02	0.08	0.11	0.16	0.01			0.03	0.04		
33	c/t-4m2-pentene	0.11	0.02	0.36	0.00	0.22	0.01	0.27	0.07				
34	2m-pentane	0.20	0.10	0.69	0.03	1.24	0.02	0.76	0.03	0.21	0.08	0.12	0.17
35	3m-pentane	0.31	0.09	1.08	0.10	0.60	0.01	1.39	0.14	0.37	0.01	0.66	0.08
36	2m1-pentene												
37	1-hexene	0.61	0.01	2.30	0.63	2.03	0.20	1.80	0.25	0.53	0.07	0.85	0.05
38	n-hexane	3.08	2.68	3.68	1.52	2.70	2.12	2.82	3.99	0.07	0.03	0.16	0.01
39	c/t-3-hexene												
40	t2-hexene	0.02	0.03			0.36	0.06	0.20	0.03				
41	2m2-pentene	0.09	0.01	0.40	0.07	0.33	0.02	0.30	0.05				
42	t-3m2-pentene			0.09	0.13	0.16	0.00						
43	c2-hexene					0.15	0.01						

ID#	Compound Name	Muffler 20C		Muffler -10C		OxyCat 20C		OxyCat -10C		New 20C		New -10C	
		avg	stdev	avg	stdev	avg	stdev	avg	stdev	avg	stdev	avg	stdev
44	c-3m2-pentene												
45	22-dm-pentane							0.13	0.18				
46	m-cyclopentane	6.64	0.65	3.72	3.44	1.24	0.55	0.68	0.29	0.12	0.03		
47	24-dm-pentane	0.04	0.01			0.19	0.06					0.29	0.12
48	223-tm-butane					0.08	0.02						
49	1m-cyclopentene					0.22	0.31						
50	benzene	27.53	0.11	27.42	3.15	21.90	0.80	26.01	3.19	1.88	0.33	2.54	0.02
51	33-dm-pentane					0.05	0.07						
52	cyclohexane	0.34	0.00	1.33	0.05	1.39	0.00	1.26	0.00	0.15	0.02	0.42	0.08
53	2m-hexane	0.21	0.02	0.82	0.11	1.12	0.11	0.90	0.04			0.11	0.15
54	23-dm-pentane	0.13	0.01	0.49	0.03	0.64	0.03	0.52	0.03			0.10	0.14
55	11-dm-cyP	0.02	0.03			0.23	0.01						
56	cyclohexene	0.11	0.00	0.41	0.04	0.37	0.04	0.36	0.01				
57	3m-hexane	0.31	0.02	1.18	0.13	4.90	4.96	14.02	0.93	0.24	0.03	0.39	0.13
58	c-13-dm-cyP	0.11	0.00	0.46	0.01	0.66	0.09	0.49	0.07				
59	3e-pentane/t-13-dm-cyP	0.15	0.00	0.59	0.02	0.69	0.00	0.59	0.01				
60	t-12-dm-cyP/1-heptene	9.18	0.56	10.58	0.30	1.47	0.09	4.33	4.28	0.57	0.08	0.66	0.00
61	224-tm-pentane												
62	t3-heptene												
63	n-heptane	10.08	1.86	10.00	1.58	7.80	0.31	9.99	2.19	0.33	0.03	0.27	0.00
64	c3-heptene					0.08	0.05						
65	t2-heptene					0.02	0.03						
66	c2-heptene												
67	m-cyclohexane/22-dm-hexane	1.28	0.05	5.19	0.30	5.60	0.02	4.98	0.02	0.34	0.05	0.44	0.01
68	12dm-cyH												
69	25&24&33-dm-C6/ctc124-tm&e-cyP/223-tm-C5	0.53	0.05	2.10	0.41	2.18	0.03	1.65	0.12				
70	ctc123-tm-cyP	0.21	0.01	0.84	0.03	0.86	0.01	0.77	0.01				
71	234-tm-pentane	0.06	0.01	0.09	0.13	0.19	0.00	0.09	0.12				
72	toluene/233-tm-pentane	30.09	0.08	26.81	1.04	20.42	0.51	24.09	2.64			1.23	0.08
73	23-dm-hexane	0.12	0.02	0.49	0.05	0.56	0.00	0.62	0.00				
74	112-tm-cyP/2m-3e-pentane	0.10	0.01	0.94	0.73	0.44	0.01	0.46	0.15			0.57	0.47
75	2m-heptane	6.53	0.32	2.17	0.62	2.73	0.36	6.02	4.33	0.48	0.26	0.25	0.36
76	4m-C7/3m3e-C5/1m-cyH/34-dm-hexane	0.27	0.00	1.20	0.13	1.14	0.47	1.13	0.01				
77	3m-heptane/3e-hexane/cct-124-tm-cyP/c-13-dm-cyH	1.27	0.12	5.06	0.91	5.88	0.36	5.16	0.11	0.63	0.06	0.73	0.06
78	t-13-dm-cyH	0.04	0.05	0.19	0.27	0.22	0.31						
79	t-14-dm-cyH	0.24	0.01	1.04	0.14	1.15	0.05	1.04	0.03				
80	225-tm-hexane					0.07	0.02						
81	11-dm-cyH/1-octene	5.83	0.06	6.26	0.60	0.58	0.01	0.48	0.00			0.20	0.01
82	1e1m-cyP/224-tm-hexane	0.10	0.02	0.33	0.00	0.35	0.02	0.34	0.00				
83	n-octane/t12-dm-cyH	51.22	1.59	50.83	3.84	47.07	3.99	50.54	5.28	0.72	0.16	0.71	0.05
84	t2-octene	0.10	0.00	0.40	0.01	0.46	0.04	0.39	0.03				
85	ccc-123-tm-cyP												
86	244-tm-hexane/ip-cyP	0.46	0.00	1.89	0.10	1.95	0.03	1.77	0.06				
87	c2-octene												
88	235-tm-hexane					0.25	0.02						
89	44&22-dm-heptane/26-dm-heptane/c12-dm-cyH	0.86	0.07	3.49	0.37	4.72	0.27	3.61	0.33	0.90	0.03	0.40	0.17
90	24-dm-heptane	0.25	0.01	1.02	0.06	1.23	0.01	1.04	0.01	0.15	0.21	0.20	0.28
91	np-cyP/e-cyH/ccc-135-tm-	9.00	0.65	11.80	1.45	8.48	3.58	8.31	4.91	0.52	0.10	0.44	0.01

ID#	Compound Name	Muffler 20C		Muffler -10C		OxyCat 20C		OxyCat -10C		New 20C		New -10C	
		avg	stdev	avg	stdev	avg	stdev	avg	stdev	avg	stdev	avg	stdev
	cyH												
92	25-dm-heptane/35-dm-heptane/33-dm-heptane	1.64	0.09	6.53	0.61	7.90	0.17	6.65	0.32	0.31	0.07	0.29	0.07
93	114-tm-cyH	0.34	0.02	1.36	0.13	1.69	0.05	1.37	0.06				
94	e-benzene	13.72	1.90	16.61	1.69	9.07	0.49	12.29	1.62	0.35	0.08	1.04	0.33
95	cct124-tm-cyH	20.46	1.45	29.32	8.08	9.48	1.33	16.47	1.23	0.25	0.02	0.10	0.15
96	23-dm-heptane	0.61	0.06	2.08	0.88	3.06	0.03	2.58	0.19	0.24	0.05		
97	m&p-xylene/34-dm-heptane	41.13	1.73	42.08	3.78	27.81	0.35	34.10	0.80	0.45	0.64	1.97	0.06
98	2m-octane	9.55	0.32	11.07	0.09	11.28	0.11	11.12	2.00	0.61	0.15	0.57	0.05
99	246-tm-hexane			0.32	0.06	0.37	0.03	0.12	0.17				
100	3m-octane/33-de-C5/3e-C7	17.27	0.05	19.07	3.14	18.18	1.06	20.01	2.96	0.56	0.09	0.53	0.14
101	ctc-124-tm-cyH	0.60	0.05	2.33	0.22	2.78	0.10	2.20	0.04	0.24	0.03	0.30	0.05
102	o-xylene & 112-tm-cyH	22.96	0.96	23.05	0.10	12.75	1.17	16.78	0.92	0.48	0.65	1.20	0.47
103	1-nonene	6.68	0.79	3.26	0.64	3.97	0.05	3.31	0.30	0.45	0.10	0.50	0.05
104	t3-nonene	0.51	0.04	1.98	0.11	2.37	0.07	1.90	1.01	0.18	0.01	0.24	0.09
105	c3-nonene/ib-cyP					0.67	0.06						
106	n-nonane	119.62	3.86	118.33	3.61	107.88	5.55	120.18	7.22	1.67	0.38	1.67	0.09
107	t2-nonene					0.14	0.02						
108	c2-nonene	0.27	0.01	5.93	2.05	3.05	2.64	4.37	0.50	0.39	0.09	0.33	0.03
109	ip-benzene	8.28	1.05	9.14	0.50	2.35	0.02	4.35	3.63				
110	22-dm-octane	0.45	0.04	1.71	0.67	2.47	0.09	1.96	0.30	0.09	0.13		
111	ip-cyH	1.75	0.25	5.68	0.45	9.25	0.21	8.18	0.89	1.02	0.13	0.87	0.00
112	nb-cyP	9.68	0.46	15.20	0.92	19.06	1.94	16.95	0.29	1.89	0.09	1.76	0.12
113	33-dm-octane	26.47	0.86	25.13	10.56	20.64	2.12	28.32	9.82				
114	n-propylbenzene	18.85	1.01	21.18	0.15	13.93	1.82	17.99	3.87	0.89	0.55	1.18	0.12
115	3e-toluene	36.32	1.25	35.43	0.37	18.46	1.30	24.48	4.80	0.92	0.40	1.12	0.11
116	4e-toluene/23-dm-octane	27.61	2.72	28.35	1.06	21.41	1.92	27.41	7.72	1.57	0.13	1.38	0.00
117	135-tm-benzene	22.34	2.16	21.97	0.94	15.79	1.57	20.20	2.40	2.40	0.27	2.66	0.01
118	2m-nonane	31.99	0.46	36.19	3.45	32.19	10.23	42.72	5.58	1.54	0.12	1.28	0.11
119	3e-octane	1.29	1.82	10.72	11.35	3.03	0.39	3.77	2.12	1.89	0.12	1.42	0.01
120	2e-toluene	41.02	1.17	40.84	1.19	29.66	0.19	35.83	0.43				
121	3m-nonane	26.32	1.61	26.74	1.47	24.28	1.36	26.49	3.00	1.85	0.16	1.69	0.00
122	124-tm-benz/tb-benz/1-decene	61.22	1.37	63.19	5.59	33.78	0.23	46.04	1.86	1.89	0.85	2.66	0.10
123	1b-cyH	17.34	0.54	18.86	0.85	17.15	0.96	18.20	2.10	1.83	0.48	0.69	0.24
124	n-decane	147.06	4.37	147.78	1.73	134.99	5.34	148.84	2.48	4.69	1.40	3.90	0.24
125	ib-benzene	0.47	0.67	2.20	1.37	3.88	0.48	3.81	1.84				
126	sb-benzene	12.78	1.43	12.44	3.11	8.84	2.93	12.30	3.27	0.33	0.47	0.53	0.02
127	3-ip-toluene	11.02	0.69	9.61	0.94	9.01	0.10	7.98	1.72	3.09	4.37		
128	123-tm-benzene					3.38	0.32			1.66	2.35	1.57	2.22
129	4-ip-toluene	7.04	1.08	2.63	3.73	2.79	0.49			2.12	0.69	1.71	0.08
130	indan	0.16	0.22										
131	2-ip-toluene	14.01	4.26	8.49	2.45	12.10	1.06	11.69	4.93	1.25	0.87	0.99	0.11
132	13-de-benzene			0.75	1.07	1.99	0.06	1.28	0.46	1.05	1.49		
133	14-de-benzene	0.30	0.18	0.70	0.99	1.04	1.47						
134	3-np-toluene	31.08	1.95	12.68	17.93	27.90	8.47	23.63	1.70	0.66	0.13	0.79	0.05
135	4-np-toluene/nb-benz/13dm5e-benzene	42.31	4.80	42.26	8.07	37.62	11.56	38.19	3.87			0.92	1.30
136	12de-benzene	14.33	3.72	16.17	2.52	17.94	1.75	15.68	3.33	0.95	0.13	1.00	0.20
137	2-np-toluene	17.15	0.52	17.86	1.58	7.94	2.33	12.45	0.65	0.99	0.23	1.03	0.06
138	14dm-2e-benzene	41.66	4.38	42.44	0.65	23.36	2.12	31.35	0.17	1.42	0.59	1.76	0.03
139	13dm-4e-benzene					1.32	1.86	0.59	0.83	0.64	0.90		

ID#	Compound Name	Muffler 20C		Muffler -10C		OxyCat 20C		OxyCat -10C		New 20C		New -10C	
		avg	stdev	avg	stdev	avg	stdev	avg	stdev	avg	stdev	avg	stdev
140	12dm-4e-benzene	16.82	2.79	16.11	0.75	2.24	1.46	9.62	0.22				
141	13dm-2e-benzene	26.89	3.55	16.10	14.87	18.86	1.74	22.74	0.89	0.77	0.06	0.29	0.42
142	n-undecane/12-dm-3e-&1245-ttm-benzene	161.99	6.94	150.53	4.06	125.22	10.80	144.97	0.21	3.22	0.34	2.88	0.44
143	2mb-benzene	12.65	0.18	8.41	7.37	17.19	2.65	21.01	3.06	2.41	0.82	2.94	0.23
144	tb-2m-benzene					0.55	0.03			1.09	0.12	0.96	0.06
145	1234-ttm-benzene									0.46	0.65	0.93	1.31
146	npentyl-benzene/t-1m-2-(4mp)CyP	10.57	14.96	5.23	7.39	0.85	0.33	16.50	4.18	0.92	0.19	0.42	0.59
147	tb-35dm-benzene	14.82	0.05	12.52	2.13	11.18	0.24	12.91	0.50	0.23	0.32	0.25	0.35
148	tb-4e-benzene	24.05	0.31	16.56	2.98	18.07	0.95	20.95	1.88				
149	naphthalene					1.40	0.72	7.39	10.46	5.89	3.15	6.95	2.97
150	n-dodecane					0.02	0.04	1.65	1.25	1.56	0.28	1.37	0.44
151	135-te-benzene	5.43	0.07	7.07	2.52								
152	124-te-benzene	70.39	3.97	62.40	3.35	39.33	5.74	49.39	14.32				
153	n-hexyl-benzene	46.39	7.42	23.56	3.52	20.93	0.63	16.43	5.73				
154	n-c13	70.39	3.97	62.40	3.35	39.33	5.74	49.39	14.32				
155	n-c14	46.39	7.42	23.56	3.52	20.93	0.63	16.43	5.73				
156	n-c15	17.55	9.62	3.23	4.57	8.94	1.16	5.05	7.14				
157	n-c16												
158	n-c17												
159	n-c18												
160	n-c19												
161	n-c20												
162	n-c21												
163	n-c22												
164	n-c23												
165	n-c24												
166	n-c25												
167	n-c26												

Table 27. Carbonyl compound emission rates (mg/mile).

Missing value indicates below detection limits, missing standard deviation indicates compound found in only one of two repeat samples.

Compound Nane	**Muffler 20C**		**Muffler -10C**		**OxyCat 20C**		**OxyCat -10C**		**New 20C**		**New -10C**	
	avg	**stdev**	**avg**	**stdev**	**avg**	**stdev**	**avg**	**stdev**	**avg**	**stdev**	**avg**	**stdev**
Formaldehyde	153.26	2.87	124.58	8.65	155.42	4.16	159.26	7.52	18.47	1.00	11.56	9.72
Acetaldehyde	48.68	2.21	45.80	2.72	61.73	0.68	72.64	6.14	17.25	1.52	17.31	0.42
2-3 butandione												
Acrolein	11.40	0.71	16.65	3.91	7.01	0.83	10.42	0.79	2.20	0.35	1.98	2.80
Acetone	15.26	1.19	14.26	2.86	26.72	0.92	27.23	5.82	6.07	0.47	7.57	0.23
Propionaldehyde	9.73	0.28	9.51	0.58	10.53	0.13	13.65	1.26	2.22	0.50	3.70	0.20
Methoxyacetone												
Crotonaldehyde	7.47	0.15	6.73	2.24	4.26	0.00	4.11	1.29	1.69	0.14	0.91	1.29
Methyl Vinyl Ketone												
Methacrolein	4.26	0.18	3.67	0.74	4.12	0.25	4.25	0.48	1.43	0.16	0.96	1.35
Methyl Ethyl Ketone	0.96	0.46	1.03	1.46	3.15	0.43	1.81	2.55				
Isobutyraldehyde & Butyraldehyde			3.58	5.06								
Benzaldehyde	6.39	0.34	3.32	0.78	2.95	0.42	3.51	0.35				
Isovaleraldehyde												
Trimethylacetaldehyde & 3m2-Butanone												
Valeraldehyde	8.21	1.38	4.77	1.60	5.31	0.19	5.55	1.02				
Acetophenone												
o-Tolualdehyde												
m&p-Tolualdehyde												
Methyl isobutyl Ketone												
Pinacolone												
Hexanaldehyde	2.66	0.51	2.90	0.43	1.58	0.16	2.30	0.36				
2,5-Dimethylbenzaldehyde												

Table 28. Emission rates for elements (mg/mile).

Missing values indicate element not detected. Zero values indicate element detected but below quantitation limits.

	20 °C						-10 °C					
	Muffler		OxyCat		New		Muffler		OxyCat		New	
	avg	stdev	avg	stdev	avg	stdev	avg	stdev	avg	stdev	avg	stdev
Na												
Mg	0.341	0.157	0.306	0.128			0.326	0.156	0.630	0.357		
Al	0.110	0.221	0.021	0.042			0.085	0.119	0.818	0.838		
Si	1.737	0.836	6.438	1.098	1.264	1.671	1.326	0.549	4.264	1.866	0.204	0.366
P	2.392	0.862	2.119	0.790	0.778	1.122	1.828	0.670	0.632	0.783	0.208	0.292
S	7.875	0.981	5.739	0.547	20.266	6.422	7.269	0.464	1.111	2.222	0.691	0.804
Cl	1.163	0.617	0.689	0.517			0.282	0.390				
K	0.062	0.074					0.079	0.159			0.009	0.011
Ca	3.700	0.413	4.492	0.691	0.761	0.283	3.947	0.506	3.985	0.566	0.755	0.202
Sc			0.179	0.129	0.177	0.288	0.043	0.052	0.068	0.083	0.170	0.155
Ti											0.043	0.085
V												
Cr	0.046	0.053									0.009	0.018
Mn	0.075	0.088	0.101	0.087	0.020	0.041	0.141	0.015	0.059	0.069	0.017	0.034
Fe					0.117	0.146					0.083	0.100
Co	0.003	0.006	0.007	0.013								
Ni			0.016	0.032			0.012	0.014			0.012	0.014
Cu	0.016	0.032	0.028	0.055					0.031	0.062		
Zn	1.931	0.153	1.780	0.124	0.355	0.143	1.795	0.147	1.581	0.155	0.366	0.045
Ga					0.000	0.001					0.004	0.005
Ge					0.003	0.003					0.012	0.012
As			0.000	0.001	0.001	0.001	0.001	0.001				
Se					0.007	0.003					0.005	0.003
Br	0.001	0.000	0.002	0.001	0.002	0.003	0.001	0.000	0.003	0.002	0.003	0.002
Rb	0.001	0.000	0.001	0.000	0.003	0.002	0.001	0.000	0.001	0.001	0.004	0.002
Sr	0.001	0.000	0.002	0.001	0.005	0.003	0.001	0.000	0.001	0.000	0.004	0.004
Y	0.001	0.000	0.001	0.000	0.003	0.001	0.001	0.000	0.001	0.001	0.005	0.003
Zr	0.001	0.000	0.001	0.001	0.007	0.004	0.001	0.001	0.002	0.002	0.007	0.004
Nb	0.001	0.000	0.002	0.002	0.008	0.006	0.001	0.000	0.002	0.001	0.006	0.003
Mo	0.002	0.001	0.003	0.002	0.009	0.005	0.001	0.000	0.002	0.002	0.009	0.005
Pd	0.009	0.017	0.004	0.009								
Ag	0.022	0.015			0.009	0.018	0.005	0.011	0.012	0.014	0.009	0.017
Cd	0.006	0.011	0.003	0.006					0.004	0.008		
In	0.030	0.023	0.011	0.014			0.022	0.015	0.008	0.011		
Sn	0.097	0.041	0.039	0.020	0.046	0.019	0.087	0.024	0.073	0.018	0.047	0.015
Sb	0.113	0.027	0.049	0.013			0.079	0.018	0.054	0.023		
Te	0.156	0.026	0.066	0.014			0.107	0.014	0.062	0.024		
I	0.227	0.054	0.094	0.064			0.169	0.009	0.061	0.071	0.009	0.018
Cs	0.386	0.036	0.115	0.083	0.045	0.015	0.263	0.038	0.152	0.063	0.026	0.010
Ba	0.397	0.050	0.179	0.048	0.051	0.043	0.285	0.044	0.176	0.072	0.069	0.045
La	0.405	0.014	0.197	0.034	0.036	0.009	0.305	0.059	0.158	0.079	0.048	0.019
Ce	0.275	0.031	0.150	0.034	0.055	0.011	0.242	0.050	0.131	0.040	0.046	0.021
Pr	0.172	0.052	0.084	0.018	0.050	0.022	0.166	0.032	0.099	0.054	0.052	0.009
Nd	0.045	0.018	0.043	0.030	0.070	0.029	0.050	0.006	0.035	0.016	0.047	0.035
W					0.541	0.218					0.598	0.173
Hg	0.001	0.001	0.001	0.001	0.032	0.025	0.001	0.001	0.001	0.001	0.011	0.007
Pb	0.002	0.002	0.002	0.003	0.014	0.011	0.001	0.001	0.004	0.005	0.021	0.017

Table 29. Particle phase n-alkane emission rates (mg/mile).

Compound	Muffler	Muffler	OxyCat	OxyCat	New	New
Name	20˚C	-10˚C	20˚C	-10˚C	20˚C	-10˚C
Pristane	0.498	1.198	0.011	0.270	0.0049	0.0289
Phytane	0.600	0.682	0.019	0.208	0.0079	0.0324
n-C11	0.004	NQ	0.002	0.003	0.0011	0.0004
n-C12	NQ	NQ	0.002	NQ	0.0012	0.0004
n-C13	0.004	NQ	0.002	NQ	0.0017	0.0004
n-C14	0.029	0.081	0.003	0.003	0.0025	0.0017
n-C15	0.022	1.194	0.008	0.040	0.0043	0.0068
n-C16	0.697	2.951	0.014	0.351	0.0085	0.0158
n-C17	2.002	3.872	0.041	0.864	0.0140	0.0673
n-C18	3.634	3.710	0.103	0.921	0.0254	0.1256
n-C19	0.909	0.867	0.075	0.238	0.0267	0.0502
n-C20	0.865	0.798	0.136	0.192	0.0392	0.0421
n-C21	0.632	0.601	0.142	0.172	0.0382	0.0358
n-C22	0.632	0.628	0.120	0.222	0.0264	0.0277
n-C23	0.555	0.458	0.080	0.201	0.0140	0.0213
n-C24	0.624	0.524	0.100	0.177	0.0122	0.0213
n-C25	1.452	1.121	0.218	0.280	0.0162	0.0451
n-C26	0.901	0.262	0.198	0.127	0.0125	0.0192
n-C27	0.995	0.470	0.091	0.130	0.0123	0.0170
n-C28	0.730	0.378	0.066	0.193	0.0127	0.0349
n-C29	0.807	0.944	0.136	0.187	0.0130	0.0196
n-C30	0.546	1.044	0.144	0.161	0.0102	0.0255
n-C31	1.562	1.152	0.108	0.154	0.0086	0.0119
n-C32	0.958	0.474	0.066	0.050	0.0054	0.0234
n-C33	NQ	NQ	NQ	NQ	0.0058	NQ
n-C34	NQ	NQ	NQ	NQ	0.0141	NQ
total	18.56	21.53	1.85	4.67	0.326	0.613

Table 30. Particle phase n-alkylcyclohexane emission rates (mg/mile).

Compound Name	Muffler	Muffler	OxyCat	OxyCat	New	New
	20°C	-10°C	20°C	-10°C	20°C	-10°C
n-C13 - cyclohexane	0.086	0.062	0.006	0.018	0.0025	0.0030
n-C14 - cyclohexane	0.135	0.104	0.020	0.027	0.0045	0.0043
n-C15 - cyclohexane	0.298	0.227	0.050	0.060	0.0102	0.0094
n-C16 - cyclohexane	0.375	0.285	0.056	0.076	0.0092	0.0119
n-C17 - cyclohexane	0.555	0.408	0.075	0.108	0.0095	0.0162
n-C18 - cyclohexane	0.506	0.362	0.066	0.087	0.0059	0.0128
n-C19 - cyclohexane	0.477	0.331	0.067	0.080	0.0037	0.0119
n-C20 - cyclohexane	0.432	0.274	0.058	0.064	0.0039	0.0085
total	2.863	2.054	0.398	0.520	0.049	0.078

Table 31. Particle phase petroleum biomarker emission rates (mg/mile).

ID	Compound Name	Muffler	Muffler	OxyCat	OxyCat	New	New
		20°C	-10°C	20°C	-10°C	20°C	-10°C
H1	C19 tricyclic terpane	NQ	NQ	NQ	NQ	0.0003	NQ
H2	C20 tricyclic terpane	NQ	NQ	NQ	NQ	0.0005	NQ
H3	C21 tricyclic terpane	0.022	0.019	NQ	NQ	0.0005	0.0011
H4	C22 tricyclic terpane	NQ	NQ	NQ	NQ	0.0003	0.0008
H5	C23 aB-dimethyl-a-butylpodocarpane	0.087	0.084	0.023	0.032	0.0024	0.0047
H6	C24 aB-dimethyl-a-methylbutylpodocarpane	0.062	0.031	0.013	0.005	0.0033	0.0026
H7	C25 tricyclic terpane	0.068	0.060	0.015	0.023	0.0015	0.0031
H8	C26 tricyclic terpane	0.100	0.090	0.022	0.034	0.0020	0.0051
H8'	C26 tricyclic triterpane 22R	0.032	0.029	0.007	0.011	0.0005	0.0014
H8"	C26 tricyclic triterpane 22S	0.033	0.033	0.008	0.013	0.0006	0.0015
H9	C27 tetracyclic terpane 22R	0.051	0.049	0.009	0.009	0.0006	0.0019
H10	C27 tetracyclic terpane 22S	0.050	0.053	0.011	0.013	0.0005	0.0020
H11	C28 tetracyclic terpane 22R	0.062	0.044	0.010	0.014	0.0003	0.0020
H12	C28 tetracyclic terpane 22S	0.055	0.044	0.009	0.013	0.0004	0.0023
H13	C27 aB-Trisnorneohopane	0.213	0.182	0.034	0.056	0.0022	0.0093
H14	C27 aaB-Trisnorhopane	0.061	0.060	NQ	NQ	0.0006	0.0026
H15*	Trisnorhopane	0.281	0.212	0.037	0.061	0.0022	0.0091
H15'	C30 Tricyclic terpane 22R	0.074	0.058	0.010	0.016	0.0005	0.0022
H15"	C30 Tricyclic terpane 22S	0.131	0.100	0.017	0.026	0.0007	0.0037
H16	C28 aaB-Bisnorhopane	0.185	0.087	0.016	0.026	0.0009	0.0042
H17'	C29 aB-25-norhopane	0.080	0.041	0.006	0.011	0.0003	0.0015
H17*	aB-norhopane	0.984	0.695	0.112	0.183	0.0054	0.0276
H18	C29 aB-Norneohopane	0.407	0.277	0.045	0.072	0.0025	0.0118
H17"	Ba-norhopane	0.128	0.078	0.013	0.019	0.0005	0.0031
H19*	aB-hopane	1.103	0.753	0.123	0.192	0.0057	0.0274
H20	Ba-hopane	0.148	0.077	0.017	0.023	0.0026	0.0041
H21	22S-aB-homohopane	1.191	0.773	0.111	0.172	0.0051	0.0253
H22	22R-aB-homohopane	0.759	0.477	0.068	0.106	0.0033	0.0158
H24	C32 22S-aB-bishomohopane	0.703	0.474	0.071	0.102	0.0052	0.0160
H25	C32 22R-aB-bishomohopane	0.372	0.255	0.036	0.052	0.0014	0.0073
H26	C33 22S-aB-trishomohopane	0.471	0.307	0.042	0.059	0.0014	0.0077
H27	C33 22R-aB-trishomohopane	0.251	0.161	0.022	0.028	0.0008	0.0047
H28	C34 22S-aB-tetrakishomohopane	0.342	0.216	0.027	NQ	NQ	0.0043
H29	C34 22R-aB-tetrakishomohopane	0.164	0.093	NQ	NQ	NQ	NQ
H30	C35 22S-aB-pentakishomohopane	0.314	0.184	NQ	NQ	NQ	NQ
H31	C35 22R-aB-pentakishomohopane	0.197	0.093	NQ	NQ	NQ	NQ

ID	Compound Name	Muffler	Muffler	OxyCat	OxyCat	New	New
		20°C	-10°C	20°C	-10°C	20°C	-10°C
S1	C20 aaa-sterane	NQ	NQ	NQ	NQ	NQ	NQ
S2	C21 Baa-sterane	NQ	NQ	NQ	NQ	NQ	NQ
S3,4	C21 aBB-sterane	0.093	0.077	0.016	0.035	0.0023	0.0043
S4,3	C21 aaa-sterane	NQ	NQ	NQ	0.009	0.0006	NQ
S5	C22 aBB-sterane	0.067	0.057	0.014	0.021	0.0016	0.0027
S6	C27 20S-Ba-diasterane	0.135	0.110	0.022	0.038	0.0018	0.0054
S7	C27 20R-Ba-diasterane	0.069	0.058	0.011	0.018	0.0008	0.0030
S8	C27 20S-aB-diasterane	0.048	0.042	0.008	0.013	0.0005	0.0023
S8'	C27 20R-aB-diasterane	0.082	0.073	0.014	0.021	0.0008	NQ
S9	C28 20S-Ba-diasterane	0.095	0.076	0.015	0.024	0.0009	0.0031
S10	C28 20R-Ba-diasterane	0.087	0.072	0.014	0.023	0.0009	0.0028
S10'	C28 20R/S?-Ba-diasterane	0.076	0.060	0.012	0.019	0.0007	0.0010
S10"	C28 20R/S?-Ba-diasterane	0.132	0.106	0.019	0.023	0.0012	NQ
S10"'	C28 20S-Ba-diasterane	0.033	0.045	0.003	0.010	0.0008	0.0009
S11	C27 20R-Baa-cholestane	0.068	0.056	0.010	NQ	0.0007	0.0018
S12	C27 20S-aaa-cholestane	0.181	0.147	0.027	0.048	0.0017	0.0061
S13	C27 20R-aBB-cholestane	0.329	0.264	0.048	0.079	0.0026	0.0109
S14	C27 20S-aBB-cholestane	0.283	0.226	0.040	0.020	0.0024	0.0093
S15	C27 20R-aaa-cholestane	0.176	0.145	0.024	0.042	0.0011	0.0053
S16	C29 20S-Ba-diasterane	0.238	0.203	0.034	0.059	0.0018	0.0073
S16'	C29 20S-Ba-diasterane	0.080	0.099	0.012	0.028	0.0006	0.0028
S17	C28 20S-aaa-methylcholestane	0.093	0.091	0.011	0.024	0.0008	0.0036
S18	C28 20R-aBB-methylcholestane	0.163	0.139	0.021	0.036	0.0012	0.0045
S19	C28 20S-aBB-methylcholestane	0.235	0.191	0.029	0.048	0.0015	0.0066
S20	C29 20R-aB-diasterane	0.245	0.206	0.030	0.047	0.0014	0.0066
S21	C28 20R-aaa-methylcholestane	0.155	0.125	0.019	0.027	0.0008	0.0038
S22	20S-aaa-ethylcholestane	0.275	0.205	0.028	0.041	0.0011	0.0059
S23	20R-aBB-ethylcholestane	0.419	0.304	0.040	0.061	0.0017	0.0086
S24	20S-aBB (20R-Baa)-ethylcholestane	0.342	0.246	0.032	0.049	0.0014	0.0071
S25	20R-aaa-ethylcholestane	0.225	0.160	0.021	0.031	0.0013	0.0031
	total named	13.60	9.77	1.51	2.27	0.090	0.335

Table 32. Particle phase PAH emission rates (mg/mile).

ID	Compound Name	Muffler	Muffler	OxyCat	OxyCat	New	New
		20C	-10C	20C	-10C	20C	-10C
AL	Acenaphthylene	NQ	NQ	NQ	NQ	NQ	0.0019
AE	Acenaphthene	NQ	NQ	NQ	0.002	NQ	0.0005
FL	Fluorene	NQ	0.023	0.003	0.005	0.0005	NQ
MFL	2-Me-Fluorene	NQ	0.069	0.005	0.016	0.0006	NQ
PHE	Phenanthrene	NQ	0.310	0.076	0.156	0.0108	NQ
AN	Anthracene	NQ	0.043	0.007	0.013	0.0005	NQ
FLT	Fluoranthene	NQ	0.088	0.028	0.031	0.0079	0.0032
PY	Pyrene	NQ	0.123	0.031	0.037	0.0052	0.0027
RET	Retene	NQ	0.014	0.004	0.004	0.0025	0.0009
B(a)FL	Benzo(a)Fluorene	NQ	0.017	0.004	0.004	0.0003	0.0003
B(b)FL	Benzo(b)Fluorene	NQ	0.013	0.002	0.002	NQ	0.0002
MPY	1-Me-Pyrene	NQ	0.019	0.004	0.004	NQ	0.0003
B(ghi)F	Benzo(g,h,i)Fluoranthene	NQ	0.023	0.006	0.007	0.0010	0.0004
B(a)A	Benzo(a)Anthracene	NQ	0.024	0.004	0.006	NQ	0.0005
Tri	Triphenylene	NQ	0.010	0.004	0.004	NQ	NQ
Chrysene	Chrysene	NQ	0.027	0.008	0.008	0.0010	0.0008
MB(a)A	7-Me-Benzo(a)Anthracene	NQ	NQ	NQ	NQ	NQ	NQ
B(b)FLT	Benzo(b)Fluoranthene	NQ	0.028	NQ	0.009	NQ	NQ
B(k)FLT	Benzo(k)Fluoranthene	NQ	0.006	NQ	NQ	NQ	NQ
B(e)P	Benzo(e)Pyrene	NQ	0.025	0.005	0.007	NQ	0.0007
B(a)P	Benzo(a)Pyrene	NQ	0.011	NQ	NQ	NQ	NQ
PER	Perylene	NQ	NQ	NQ	NQ	NQ	NQ
MCH	2-Me-Cholanthrene	NQ	NQ	NQ	NQ	NQ	NQ
IP	Indeno(1,2,3-cd)Pyrene	NQ	NQ	NQ	NQ	NQ	NQ
D(ah)A	Dibenzo(a,c)&(a,h)Anthracene	NQ	NQ	NQ	NQ	NQ	NQ
B(b)C	Benzo(b)Chrysene	NQ	NQ	NQ	NQ	NQ	NQ
B(ghi)P	Benzo(g,h,i)Perylene	NQ	0.017	NQ	NQ	NQ	NQ
ANT	Anthanthrene	NQ	NQ	NQ	NQ	NQ	NQ
	Total Identified	0	0.889	0.191	0.314	0.030	0.012

Table 33. Particle phase PAsH emission rates (µg/mile).

ID	Compound Name	Muffler	Muffler	OxyCat	OxyCat	New	New
		20C	**-10C**	**20C**	**-10C**	**20C**	**-10C**
Thionaphthene	thionaphthene	NQ	NQ	NQ	NQ	NQ	NQ
DBT	dibenzothiophene	NQ	4.715	0.330	0.871	0.113	0.272
N(2,1b)T	naphtho(2,1-b)thiophene	NQ	NQ	NQ	NQ	NQ	NQ
2-MDBT	2-methyldibenzothiophene	NQ	NQ	0.161	NQ	0.037	NQ
8-MN(2,1b)T	8-methylnaphtho(2,1-b)thiophene	NQ	NQ	NQ	NQ	NQ	0.214
5-MN(2,1b)T	5-methylnaphtho(2,1-b)thiophene	NQ	NQ	NQ	NQ	NQ	NQ
4,6-DMDBT	4,6-dimethyldibenzothiophene	NQ	5.680	0.726	1.281	0.243	0.435
1,8-DMDBT	1,8-dimethyldibenzothiophene	NQ	NQ	0.406	0.710	0.158	NQ
1,3-DMDBT	1,3-dimethyldibenzothiophene	NQ	NQ	0.338	0.522	0.090	NQ
Pa(4,3b)T	phenanthro(4,3-b)thiophene	NQ	NQ	NQ	NQ	NQ	NQ
Pa(3,4b)T	phenanthro(3,4-b)thiophene	NQ	NQ	NQ	NQ	NQ	NQ
Pa(2,1b)T	phenanthro(2,1-b)thiophene	NQ	NQ	NQ	NQ	NQ	NQ
Pa(2,3b)T	phenanthro(2,3-b)thiophene	NQ	NQ	NQ	NQ	NQ	NQ
A(2,3b)T	anthra(2,3-b)thiophene	NQ	NQ	NQ	NQ	NQ	NQ
10-MBbN(2,1d)T	10-methylbenzo(b)naphtho(2,1-d)thiophene	NQ	NQ	NQ	NQ	NQ	NQ
2-MBbN(2,1d)T	2-methylbenzo(b)naphtho(2,1-d)thiophene	NQ	NQ	NQ	NQ	NQ	NQ
8-MBbN(1,2d)T	8-methylbenzo(b)naphtho(1,2-d)thiophene	NQ	NQ	NQ	NQ	NQ	NQ
5-MBbN(2,1d)T	5-methylbenzo(b)naphtho(2,1-d)thiophene	NQ	NQ	NQ	NQ	NQ	NQ
6-MBbN(2,1d)T	6-methylbenzo(b)naphtho(2,1-d)thiophene	NQ	NQ	NQ	0.058	NQ	NQ
8-MBbN(2,3d)T	8-methylbenzo(b)naphtho(2,3-d)thiophene	NQ	NQ	NQ	NQ	NQ	NQ
11-MBbN(2,3d)T	11-methylbenzo(b)naphtho(2,3-d)thiophene	NQ	NQ	NQ	NQ	NQ	NQ
	Total Identified	0	10.395	1.960	3.442	0.641	0.921

Table 34. Particle phase NO_2-PAH emission rates (µg/mile).

ID	**Compound Name**	**Muffler**	**Muffler**	**OxyCat**	**OxyCat**	**New**	**New**
		20C	**-10C**	**20C**	**-10C**	**20C**	**-10C**
2-NFL	2- Nitrofluorene	NQ	NQ	0.13	0.36	0.66	4.12
	Total Nitro-C13*	**NQ**	**33.36**	**0.28**	**1.63**	**0.86**	**5.44**
9-NAN	9-Nitroanthracene	NQ	1.89	2.30	5.63	1.15	4.64
2-NAN	2-Nitroanthracene	NQ	0.03	NQ	NQ	NQ	NQ
9-NPHE	9-Nitrophenanthrene	NQ	0.31	0.15	0.23	1.62	5.86
	Total Nitro-C14*	**NQ**	**3.56**	**2.88**	**7.15**	**6.14**	**15.48**
2-NFLT	2-Nitrofluoranthene	NQ	0.15	NQ	NQ	0.02	NQ
3-NFLT	3-Nitorfluoranthene	NQ	NQ	NQ	NQ	NQ	0.10
4-NPY	4-Nitropyrene	NQ	0.41	0.16	0.29	NQ	NQ
1-NPY	1-Nitropyrene	NQ	2.52	3.92	10.78	0.67	3.06
2-NPY	2-Nitropyrene	NQ	NQ	NQ	NQ	NQ	NQ
	Total Nitro-C16*	**NQ**	**3.07**	**4.09**	**11.07**	**0.69**	**3.43**
7-NB(a)A	7-Nitrobenz(a)anthracene	NQ	0.19	0.17	0.45	0.02	0.17
6-NCry	6-Nitrochrysene	NQ	0.03	NQ	0.06	NQ	0.07
	Total Nitro-C18*	**NQ**	**0.33**	**0.17**	**0.51**	**0.02**	**0.27**
1-NB(e)P	1-Nitrobenzo(e)pyrene	NQ	0.05	NQ	NQ	NQ	NQ
6-NB(a)P	6-Nitrobenzo(a)pyrene	NQ	1.52	0.33	0.84	NQ	0.05
4-NB(e)P	4-Nitrobenzo(e)pyrene	NQ	NQ	NQ	NQ	NQ	NQ
3-NB(e)P	3-Nitrobenzo(e)pyrene	NQ	0.05	NQ	NQ	NQ	NQ
3-NB(a)P	3-Nitrobenzo(a)pyrene	NQ	NQ	NQ	NQ	NQ	NQ
1-NB(a)P	1-Nitrobenzo(a)pyrene	NQ	NQ	NQ	NQ	NQ	NQ
2-NB(a)P	2-Nitrobenzo(a)pyrene	NQ	NQ	NQ	NQ	NQ	NQ
	Total Nitro-C20*	**NQ**	**1.62**	**0.33**	**0.84**	**0.00**	**0.09**
9-ND(a,c)A	9-Nitrodibenzo(a,c)anthracene	NQ	NQ	NQ	NQ	NQ	NQ
	Total Nitro-C22*	**NQ**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
	Total Nitro-PAH (C13 to C22)	**NQ**	**45.01**	**11.83**	**32.28**	**7.72**	**24.71**
1,3-DNPY	1,3-Dinitropyrene	NQ	NQ	NQ	NQ	NQ	0.08
1,6-DNPY	1,6-Dinitropyrene	NQ	NQ	NQ	NQ	NQ	0.09
1,8-DNPY	1,8-Dinitropyrene	NQ	NQ	NQ	NQ	NQ	0.10
7-N-12-MB(a)A	7-Nitro-12-Methylbenzo(a)anthracene	NQ	NQ	NQ	NQ	NQ	NQ
12-E-6-NCry	12-Ethyl-6-Nitrochrysene	NQ	NQ	NQ	NQ	NQ	NQ

*Total Nitro- reported includes isomers not specifically identified

Table 35. Lubrication and fuel concentrations of n-alkanes (ug/g).

	Lubrication Oil	**Diesel Fuel**
Pristane	1.70	55.9
Phytane	1.53	42.6
n-C11	0.57	405
n-C12	0.88	352
n-C13	1.32	342
n-C14	2.00	274
n-C15	2.89	220
n-C16	3.65	153
n-C17	5.04	102
n-C18	8.64	70.2
n-C19	2.91	47.0
n-C20	3.30	22.2
n-C21	3.17	11.3
n-C22	3.40	5.50
n-C23	2.68	2.24
n-C24	3.67	0.88
n-C25	8.08	0.41
n-C26	4.61	0.14
n-C27	1.76	0.07
n-C28	1.91	NQ
n-C29	4.59	NQ
n-C30	2.23	NQ
n-C31	8.77	NQ
n-C32	6.25	NQ
n-C33	NQ	NQ
n-C34	NQ	NQ
total	**85.6**	**2107**

Table 36. Lubrication and fuel concentrations of alkylcyclohexanes (ug/g).

	Lubrication Oil	Diesel Fuel
n-C13 - cyclohexane	0.27	1.26
n-C14 - cyclohexane	0.59	0.63
n-C15 - cyclohexane	1.47	0.32
n-C16 - cyclohexane	2.03	0.11
n-C17 - cyclohexane	3.03	0.054
n-C18 - cyclohexane	2.74	0.018
n-C19 - cyclohexane	2.59	0.018
n-C20 - cyclohexane	2.20	0.018
total	**14.9**	**2.43**

Table 37. Lubrication and fuel concentrations of petroleum biomarker compounds (ug/g).

		Lubrication Oil	Diesel Fuel
H1	C19 tricyclic terpane	NQ	NQ
H2	C20 tricyclic terpane	0.04	0.065
H3	C21 tricyclic terpane	0.09	0.032
H4	C22 tricyclic terpane	0.08	NQ
H5	C23 aB-dimethyl-a-butylpodocarpane	0.44	0.018
H6	C24 aB-dimethyl-a-methylbutylpodocarpane	0.20	0.037
H7	C25 tricyclic terpane	0.36	NQ
H8	C26 tricyclic terpane	0.59	NQ
H8'	C26 tricyclic triterpane 22R	0.18	NQ
H8"	C26 tricyclic triterpane 22S	0.19	NQ
H9	C27 tetracyclic terpane 22R	0.28	NQ
H10	C27 tetracyclic terpane 22S	0.25	NQ
H11	C28 tetracyclic terpane 22R	0.31	NQ
H12	C28 tetracyclic terpane 22S	0.32	NQ
H13	C27 aB-Trisnorneohopane	1.39	NQ
H14	C27 aaB-Trisnorhopane	0.10	NQ
H15*	Trisnorhopane	1.66	NQ
H15'	C30 Tricyclic terpane 22R	0.39	NQ
H15"	C30 Tricyclic terpane 22S	0.73	NQ
H16	C28 aaB-Bisnorhopane	1.10	NQ
H17'	C29 aB-25-norhopane	0.30	NQ
H17*	aB-norhopane	5.34	0.009
H18	C29 aB-Norneohopane	2.19	NQ
H17"	Ba-norhopane	0.56	NQ
H19*	aB-hopane	5.93	0.008
H20	Ba-hopane	0.57	0.019
H21	22S-aB-homohopane	6.15	0.019
H22	22R-aB-homohopane	3.62	0.006
H24	C32 22S-aB-bishomohopane	3.64	NQ
H25	C32 22R-aB-bishomohopane	1.89	NQ
H26	C33 22S-aB-trishomohopane	2.37	NQ
H27	C33 22R-aB-trishomohopane	1.25	NQ
H28	C34 22S-aB-tetrakishomohopane	1.43	NQ
H29	C34 22R-aB-tetrakishomohopane	0.60	NQ
H30	C35 22S-aB-pentakishomohopane	1.13	NQ
H31	C35 22R-aB-pentakishomohopane	0.56	NQ
S1	C20 aaa-sterane	0.09	0.077
S2	C21 Baa-sterane	0.12	0.061
S3,4	C21 aBB-sterane	0.67	0.087
S4,3	C21 aaa-sterane	0.18	0.044
S5	C22 aBB-sterane	0.44	NQ
S6	C27 20S-Ba-diasterane	0.86	NQ
S7	C27 20R-Ba-diasterane	0.54	NQ
S8	C27 20S-aB-diasterane	0.32	NQ
S8'	C27 20R-aB-diasterane	0.43	NQ
S9	C28 20S-Ba-diasterane	0.58	NQ
S10	C28 20R-Ba-diasterane	0.55	NQ
S10'	C28 20R/S?-Ba-diasterane	0.49	NQ
S10"	C28 20R/S?-Ba-diasterane	0.75	NQ
S10'"	C28 20S-Ba-diasterane	0.13	NQ
S11	C27 20R-Baa-cholestane	0.44	NQ
S12	C27 20S-aaa-cholestane	1.34	NQ

		Lubrication Oil	**Diesel Fuel**
S13	C27 20R-aBB-cholestane	2.19	NQ
S14	C27 20S-aBB-cholestane	1.96	NQ
S15	C27 20R-aaa-cholestane	1.17	NQ
S16	C29 20S-Ba-diasterane	1.53	NQ
S16'	C29 20S-Ba-diasterane	0.76	NQ
S17	C28 20S-aaa-methylcholestane	0.80	NQ
S18	C28 20R-aBB-methylcholestane	1.08	NQ
S19	C28 20S-aBB-methylcholestane	1.53	NQ
S20	C29 20R-aB-diasterane	1.56	NQ
S21	C28 20R-aaa-methylcholestane	0.89	NQ
S22	20S-aaa-ethylcholestane	1.37	NQ
S23	20R-aBB-ethylcholestane	2.15	NQ
S24	20S-aBB (20R-Baa)-ethylcholestane	1.76	NQ
S25	20R-aaa-ethylcholestane	1.55	NQ
	Total	**74.5**	**0.48**

Table 38. Lubrication and fuel concentrations of PAH (ug/g).

		Lubrication Oil	**Diesel Fuel**
AL	Acenaphthylene	0.005	NQ
AE	Acenaphthene	NQ	NQ
FL	Fluorene	0.053	3.19
MFL	2-Me-Fluorene	0.093	2.75
PHE	Phenanthrene	0.148	2.47
AN	Anthracene	0.019	0.09
FLT	Fluoranthene	0.043	0.04
PY	Pyrene	0.083	0.08
RET	Retene	0.049	0.08
B(a)FL	Benzo(a)Fluorene	0.042	0.03
B(b)FL	Benzo(b)Fluorene	0.031	0.01
MPY	1-Me-Pyrene	0.051	0.03
B(ghi)F	Benzo(g,h,i)Fluoranthene	0.008	NQ
B(a)A	Benzo(a)Anthracene	0.036	NQ
Tri	Triphenylene	0.014	NQ
Chrysene	Chrysene	0.037	0.00
MB(a)A	7-Me-Benzo(a)Anthracene	NQ	NQ
B(b)FLT	Benzo(b)Fluoranthene	0.068	NQ
B(k)FLT	Benzo(k)Fluoranthene	0.013	NQ
B(e)P	Benzo(e)Pyrene	0.084	NQ
B(a)P	Benzo(a)Pyrene	0.021	NQ
PER	Perylene	NQ	NQ
MCH	2-Me-Cholanthrene	NQ	NQ
IP	Indeno(1,2,3-cd)Pyrene	0.035	NQ
D(ah)A	Dibenzo(a,c)&(a,h)Anthracene	NQ	NQ
B(b)C	Benzo(b)Chrysene	NQ	NQ
B(ghi)P	Benzo(g,h,i)Perylene	0.130	NQ
ANT	Anthanthrene	NQ	NQ
	Total	**1.07**	**8.79**

Table 39. Lubrication and fuel concentrations of PAsH (ug/g).

		Lubrication Oil	**Diesel Fuel**
Thionaphthene	thionaphthene	NQ	NQ
DBT	dibenzothiophene	0.0080	0.120
N(2,1b)T	naphtho(2,1-b)thiophene	NQ	NQ
2-MDBT	2-methyldibenzothiophene	NQ	NQ
8-MN(2,1b)T	8-methylnaphtho(2,1-b)thiophene	NQ	NQ
5-MN(2,1b)T	5-methylnaphtho(2,1-b)thiophene	NQ	NQ
4,6-DMDBT	4,6-dimethyldibenzothiophene	NQ	NQ
1,8-DMDBT	1,8-dimethyldibenzothiophene	NQ	NQ
1,3-DMDBT	1,3-dimethyldibenzothiophene	NQ	NQ
Pa(4,3b)T	phenanthro(4,3-b)thiophene	NQ	NQ
Pa(3,4b)T	phenanthro(3,4-b)thiophene	NQ	NQ
Pa(2,1b)T	phenanthro(2,1-b)thiophene	NQ	NQ
Pa(2,3b)T	phenanthro(2,3-b)thiophene	NQ	NQ
A(2,3b)T	anthra(2,3-b)thiophene	NQ	NQ
10-MBbN(2,1d)T	10-methylbenzo(b)naphtho(2,1-d)thiophene	NQ	NQ
2-MBbN(2,1d)T	2-methylbenzo(b)naphtho(2,1-d)thiophene	NQ	NQ
8-MBbN(1,2d)T	8-methylbenzo(b)naphtho(1,2-d)thiophene	NQ	NQ
5-MBbN(2,1d)T	5-methylbenzo(b)naphtho(2,1-d)thiophene	NQ	NQ
6-MBbN(2,1d)T	6-methylbenzo(b)naphtho(2,1-d)thiophene	NQ	NQ
8-MBbN(2,3d)T	8-methylbenzo(b)naphtho(2,3-d)thiophene	NQ	NQ
11-MBbN(2,3d)T	11-methylbenzo(b)naphtho(2,3-d)thiophene	NQ	NQ
	Total	**0.0080**	**0.120**

Table 40. Lubrication and fuel concentrations of NO_2-PAH (ug/g).

		Lubrication Oil	**Diesel Fuel**
2-NFL	2- Nitrofluorene	0.0008	0.003
	Total Nitro-C13*	0.0012	0.004
9-NAN	9-Nitroanthracene	0.0001	NQ
2-NAN	2-Nitroanthracene	NQ	NQ
9-NPHE	9-Nitrophenanthrene	0.0000	NQ
	Total Nitro-C14*	0.0004	0.000
2-NFLT	2-Nitrofluoranthene	NQ	NQ
3-NFLT	3-Nitorfluoranthene	NQ	NQ
4-NPY	4-Nitropyrene	NQ	NQ
1-NPY	1-Nitropyrene	NQ	NQ
2-NPY	2-Nitropyrene	NQ	NQ
	Total Nitro-C16*	0.0001	0.000
7-NB(a)A	7-Nitrobenz(a)anthracene	NQ	NQ
6-NCry	6-Nitrochrysene	NQ	NQ
	Total Nitro-C18*	0.0000	0.000
1-NB(e)P	1-Nitrobenzo(e)pyrene	NQ	NQ
6-NB(a)P	6-Nitrobenzo(a)pyrene	NQ	NQ
4-NB(e)P	4-Nitrobenzo(e)pyrene	NQ	NQ
3-NB(e)P	3-Nitrobenzo(e)pyrene	NQ	NQ
3-NB(a)P	3-Nitrobenzo(a)pyrene	NQ	NQ
1-NB(a)P	1-Nitrobenzo(a)pyrene	NQ	NQ
2-NB(a)P	2-Nitrobenzo(a)pyrene	NQ	NQ
	Total Nitro-C20*	0.0000	0.000
9-ND(a,c)A	9-Nitrodibenzo(a,c)anthracene	NQ	NQ
	Total Nitro-C22*	0.0000	0.000
	Total Nitro-PAH (C13 to C22)	0.0018	0.004
1,3-DNPY	1,3-Dinitropyrene	NQ	NQ
1,6-DNPY	1,6-Dinitropyrene	NQ	NQ
1,8-DNPY	1,8-Dinitropyrene	NQ	NQ
7-N-12-MB(a)A	7-Nitro-12-Methylbenzo(a)anthracene	NQ	NQ
12-E-6-NCry	12-Ethyl-6-Nitrochrysene	NQ	NQ

*Total Nitro- reported includes isomers not specifically identified

Table 41. Emission profile of n-alkanes as a fraction of organic carbon emission rate.

	Muffler	Muffler	OxyCat	OxyCat	New	New
	20C	-10C	20C	-10C	20C	-10C
Pristane	2.780E-04	8.073E-04	4.374E-05	6.724E-04	1.581E-04	2.560E-04
Phytane	3.349E-04	4.595E-04	7.498E-05	5.164E-04	2.530E-04	2.861E-04
n-C11	2.279E-06	NQ	6.248E-06	8.004E-06	3.557E-05	3.764E-06
n-C12	NQ	NQ	6.248E-06	NQ	3.953E-05	3.764E-06
n-C13	2.279E-06	NQ	6.248E-06	NQ	5.534E-05	3.764E-06
n-C14	1.595E-05	5.451E-05	1.250E-05	8.004E-06	7.905E-05	1.506E-05
n-C15	1.208E-05	8.047E-04	3.124E-05	1.003E-04	1.383E-04	6.022E-05
n-C16	3.896E-04	1.988E-03	5.623E-05	8.730E-04	2.727E-04	1.393E-04
n-C17	1.119E-03	2.609E-03	1.625E-04	2.150E-03	4.506E-04	5.947E-04
n-C18	2.030E-03	2.500E-03	4.124E-04	2.290E-03	8.182E-04	1.110E-03
n-C19	5.081E-04	5.841E-04	2.999E-04	5.925E-04	8.577E-04	4.441E-04
n-C20	4.830E-04	5.374E-04	5.436E-04	4.765E-04	1.261E-03	3.726E-04
n-C21	3.532E-04	4.050E-04	5.686E-04	4.284E-04	1.229E-03	3.162E-04
n-C22	3.532E-04	4.231E-04	4.811E-04	5.524E-04	8.498E-04	2.447E-04
n-C23	3.099E-04	3.089E-04	3.187E-04	5.003E-04	4.506E-04	1.882E-04
n-C24	3.486E-04	3.530E-04	3.999E-04	4.403E-04	3.913E-04	1.882E-04
n-C25	8.111E-04	7.554E-04	8.748E-04	6.965E-04	5.218E-04	3.990E-04
n-C26	5.035E-04	1.765E-04	7.935E-04	3.161E-04	4.032E-04	1.694E-04
n-C27	5.560E-04	3.167E-04	3.624E-04	3.241E-04	3.953E-04	1.506E-04
n-C28	4.079E-04	2.544E-04	2.624E-04	4.799E-04	4.071E-04	3.086E-04
n-C29	4.511E-04	6.360E-04	5.436E-04	4.646E-04	4.190E-04	1.731E-04
n-C30	3.053E-04	7.035E-04	5.748E-04	4.003E-04	3.281E-04	2.258E-04
n-C31	8.727E-04	7.762E-04	4.311E-04	3.842E-04	2.767E-04	1.054E-04
n-C32	5.354E-04	3.193E-04	2.624E-04	1.242E-04	1.739E-04	2.070E-04
n-C33	NQ	NQ	NQ	NQ	1.858E-04	NQ
n-C34	NQ	NQ	NQ	NQ	4.546E-04	NQ

Table 42. Emission profile of alkylcyclohexanes as a fraction of organic carbon emission rate.

	Muffler	Muffler	OxyCat	OxyCat	New	New
	20C	-10C	20C	-10C	20C	-10C
n-C13 - cyclohexane	4.785E-05	4.153E-05	2.499E-05	4.406E-05	7.905E-05	2.635E-05
n-C14 - cyclohexane	7.519E-05	7.009E-05	8.123E-05	6.808E-05	1.463E-04	3.764E-05
n-C15 - cyclohexane	1.663E-04	1.532E-04	1.999E-04	1.481E-04	3.281E-04	8.281E-05
n-C16 - cyclohexane	2.096E-04	1.921E-04	2.249E-04	1.881E-04	2.965E-04	1.054E-04
n-C17 - cyclohexane	3.099E-04	2.752E-04	2.999E-04	2.682E-04	3.044E-04	1.430E-04
n-C18 - cyclohexane	2.825E-04	2.440E-04	2.624E-04	2.162E-04	1.897E-04	1.129E-04
n-C19 - cyclohexane	2.666E-04	2.232E-04	2.687E-04	2.000E-04	1.186E-04	1.054E-04
n-C20 - cyclohexane	2.415E-04	1.843E-04	2.312E-04	1.601E-04	1.265E-04	7.528E-05

Table 43. Emission profile of petroleum biomarkers as a fraction of organic carbon emission rate.

		Muffler	Muffler	OxyCat	OxyCat	New	New
		20C	-10C	20C	-10C	20C	-10C
H1	C19 tricyclic terpane	NQ	NQ	NQ	NQ	8.626E-06	NQ
H2	C20 tricyclic terpane	NQ	NQ	NQ	NQ	1.709E-05	NQ
H3	C21 tricyclic terpane	1.204E-05	1.292E-05	NQ	NQ	1.734E-05	9.926E-06
H4	C22 tricyclic terpane	NQ	NQ	NQ	NQ	1.032E-05	6.788E-06
H5	C23 aB-dimethyl-a-butylpodocarpane	4.834E-05	5.635E-05	9.036E-05	7.992E-05	7.701E-05	4.183E-05
H6	C24 aB-dimethyl-a-methylbutylpodocarpane	3.465E-05	2.099E-05	5.265E-05	1.130E-05	1.062E-04	2.298E-05
H7	C25 tricyclic terpane	3.783E-05	4.051E-05	6.199E-05	5.832E-05	4.953E-05	2.715E-05
H8	C26 tricyclic terpane	5.597E-05	6.063E-05	8.681E-05	8.372E-05	6.307E-05	4.477E-05
H8'	C26 tricyclic triterpane 22R	1.814E-05	1.932E-05	2.775E-05	2.612E-05	1.701E-05	1.195E-05
H8"	C26 tricyclic triterpane 22S	1.847E-05	2.193E-05	3.151E-05	3.142E-05	1.905E-05	1.332E-05
H9	C27 tetracyclic terpane 22R	2.855E-05	3.315E-05	3.768E-05	2.351E-05	1.870E-05	1.716E-05
H10	C27 tetracyclic terpane 22S	2.820E-05	3.569E-05	4.211E-05	3.157E-05	1.651E-05	1.762E-05
H11	C28 tetracyclic terpane 22R	3.449E-05	2.957E-05	3.879E-05	3.482E-05	1.071E-05	1.737E-05
H12	C28 tetracyclic terpane 22S	3.071E-05	2.990E-05	3.761E-05	3.274E-05	1.413E-05	2.030E-05
H13	C27 aB-Trisnorneohopane	1.190E-04	1.224E-04	1.379E-04	1.404E-04	7.231E-05	8.194E-05
H14	C27 aaB-Trisnorhopane	3.396E-05	4.014E-05	NQ	NQ	1.952E-05	2.300E-05
H15*	Trisnorhopane	1.571E-04	1.431E-04	1.482E-04	1.512E-04	6.980E-05	8.013E-05
H15'	C30 Tricyclic terpane 22R	4.143E-05	3.876E-05	3.936E-05	3.859E-05	1.472E-05	1.905E-05
H15"	C30 Tricyclic terpane 22S	7.315E-05	6.762E-05	6.975E-05	6.568E-05	2.337E-05	3.297E-05
H16	C28 aaB-Bisnorhopane	1.032E-04	5.835E-05	6.563E-05	6.360E-05	2.949E-05	3.693E-05
H17'	C29 aB-25-norhopane	4.485E-05	2.763E-05	2.389E-05	2.785E-05	8.447E-06	1.329E-05
H17*	aB-norhopane	5.499E-04	4.685E-04	4.501E-04	4.564E-04	1.737E-04	2.444E-04
H18	C29 aB-Norneohopane	2.272E-04	1.868E-04	1.808E-04	1.787E-04	8.165E-05	1.043E-04
H17"	Ba-norhopane	7.166E-05	5.279E-05	5.226E-05	4.835E-05	1.569E-05	2.746E-05
H19*	aB-hopane	6.162E-04	5.073E-04	4.922E-04	4.783E-04	1.832E-04	2.424E-04
H20	Ba-hopane	8.280E-05	5.165E-05	6.828E-05	5.635E-05	8.202E-05	3.622E-05
H21	22S-aB-homohopane	6.657E-04	5.209E-04	4.464E-04	4.270E-04	1.655E-04	2.234E-04
H22	22R-aB-homohopane	4.238E-04	3.213E-04	2.727E-04	2.636E-04	1.050E-04	1.394E-04
H24	C32 22S-aB-bishomohopane	3.929E-04	3.192E-04	2.840E-04	2.532E-04	1.684E-04	1.411E-04
H25	C32 22R-aB-bishomohopane	2.076E-04	1.719E-04	1.440E-04	1.300E-04	4.390E-05	6.428E-05
H26	C33 22S-aB-trishomohopane	2.632E-04	2.072E-04	1.688E-04	1.459E-04	4.575E-05	6.810E-05
H27	C33 22R-aB-trishomohopane	1.400E-04	1.088E-04	8.696E-05	7.083E-05	2.427E-05	4.144E-05
H28	C34 22S-aB-tetrakishomohopane	1.912E-04	1.452E-04	1.079E-04	NQ	NQ	3.792E-05
H29	C34 22R-aB-tetrakishomohopane	9.170E-05	6.261E-05	NQ	NQ	NQ	NQ
H30	C35 22S-aB-pentakishomohopane	1.755E-04	1.242E-04	NQ	NQ	NQ	NQ
H31	C35 22R-aB-pentakishomohopane	1.098E-04	6.255E-05	NQ	NQ	NQ	NQ
S1	C20 aaa-sterane	NQ	NQ	NQ	NQ	NQ	NQ
S2	C21 Baa-sterane	NQ	NQ	NQ	NQ	NQ	NQ
S3,4	C21 aBB-sterane	5.192E-05	5.194E-05	6.324E-05	8.616E-05	7.348E-05	3.829E-05
S4,3	C21 aaa-sterane	NQ	NQ	NQ	2.248E-05	1.798E-05	NQ
S5	C22 aBB-sterane	3.739E-05	3.836E-05	5.457E-05	5.122E-05	5.290E-05	2.420E-05
S6	C27 20S-Ba-diasterane	7.545E-05	7.389E-05	8.929E-05	9.338E-05	5.759E-05	4.815E-05
S7	C27 20R-Ba-diasterane	3.858E-05	3.898E-05	4.395E-05	4.377E-05	2.690E-05	2.680E-05
S8	C27 20S-aB-diasterane	2.655E-05	2.844E-05	3.345E-05	3.286E-05	1.717E-05	2.003E-05
S8'	C27 20R-aB-diasterane	4.575E-05	4.894E-05	5.426E-05	5.325E-05	2.577E-05	NQ
S9	C28 20S-Ba-diasterane	5.321E-05	5.118E-05	6.028E-05	5.860E-05	2.973E-05	2.773E-05
S10	C28 20R-Ba-diasterane	4.846E-05	4.818E-05	5.779E-05	5.612E-05	3.000E-05	2.500E-05
S10'	C28 20R/S?-Ba-diasterane	4.259E-05	4.068E-05	4.858E-05	4.706E-05	2.108E-05	9.115E-06
S10"	C28 20R/S?-Ba-diasterane	7.373E-05	7.120E-05	7.562E-05	5.802E-05	3.825E-05	NQ
S10"'	C28 20S-Ba-diasterane	1.848E-05	2.999E-05	1.252E-05	2.420E-05	2.673E-05	8.276E-06
S11	C27 20R-Baa-cholestane	3.797E-05	3.751E-05	4.064E-05	NQ	2.129E-05	1.610E-05
S12	C27 20S-aaa-cholestane	1.014E-04	9.904E-05	1.091E-04	1.187E-04	5.549E-05	5.421E-05
S13	C27 20R-aBB-cholestane	1.841E-04	1.782E-04	1.917E-04	1.966E-04	8.458E-05	9.628E-05
S14	C27 20S-aBB-cholestane	1.580E-04	1.525E-04	1.598E-04	5.008E-05	7.761E-05	8.219E-05
S15	C27 20R-aaa-cholestane	9.824E-05	9.798E-05	9.693E-05	1.036E-04	3.507E-05	4.665E-05
S16	C29 20S-Ba-diasterane	1.327E-04	1.367E-04	1.375E-04	1.478E-04	5.759E-05	6.469E-05
S16'	C29 20S-Ba-diasterane	4.473E-05	6.655E-05	4.822E-05	7.037E-05	1.904E-05	2.502E-05
S17	C28 20S-aaa-methylcholestane	5.175E-05	6.146E-05	4.510E-05	6.020E-05	2.538E-05	3.147E-05
S18	C28 20R-aBB-methylcholestane	9.123E-05	9.398E-05	8.243E-05	8.906E-05	3.996E-05	4.020E-05
S19	C28 20S-aBB-methylcholestane	1.312E-04	1.290E-04	1.170E-04	1.202E-04	4.682E-05	5.861E-05
S20	C29 20R-aB-diasterane	1.367E-04	1.390E-04	1.195E-04	1.178E-04	4.504E-05	5.877E-05
S21	C28 20R-aaa-methylcholestane	8.652E-05	8.394E-05	7.587E-05	6.696E-05	2.675E-05	3.361E-05
S22	20S-aaa-ethylcholestane	1.536E-04	1.379E-04	1.119E-04	1.031E-04	3.536E-05	5.201E-05
S23	20R-aBB-ethylcholestane	2.343E-04	2.050E-04	1.594E-04	1.529E-04	5.403E-05	7.637E-05

		Muffler	Muffler	OxyCat	OxyCat	New	New
		20C	-10C	20C	-10C	20C	-10C
S24	20S-aBB (20R-Baa)-ethylcholestane	1.912E-04	1.660E-04	1.295E-04	1.220E-04	4.623E-05	6.271E-05
S25	20R-aaa-ethylcholestane	1.255E-04	1.078E-04	8.474E-05	7.790E-05	4.271E-05	2.780E-05

Table 44. Emission profile of PAH as a fraction of organic carbon emission rate.

		Muffler	Muffler	OxyCat	OxyCat	New	New
		20C	-10C	20C	-10C	20C	-10C
AL	Acenaphthylene	NQ	NQ	NQ	NQ	NQ	1.640E-05
AE	Acenaphthene	NQ	NQ	NQ	5.517E-06	NQ	4.577E-06
FL	Fluorene	NQ	1.533E-05	1.115E-05	1.173E-05	1.751E-05	NQ
MFL	2-Me-Fluorene	NQ	4.665E-05	2.013E-05	3.888E-05	2.075E-05	NQ
PHE	Phenanthrene	NQ	2.091E-04	3.053E-04	3.874E-04	3.463E-04	NQ
AN	Anthracene	NQ	2.900E-05	2.934E-05	3.310E-05	1.556E-05	NQ
FLT	Fluoranthene	NQ	5.924E-05	1.112E-04	7.717E-05	2.528E-04	2.829E-05
PY	Pyrene	NQ	8.265E-05	1.231E-04	9.270E-05	1.666E-04	2.407E-05
RET	Retene	NQ	9.334E-06	1.457E-05	9.340E-06	8.092E-05	8.056E-06
B(a)FL	Benzo(a)Fluorene	NQ	1.172E-05	1.573E-05	9.043E-06	8.440E-06	2.942E-06
B(b)FL	Benzo(b)Fluorene	NQ	8.510E-06	8.434E-06	5.185E-06	NQ	1.694E-06
MPY	1-Me-Pyrene	NQ	1.259E-05	1.504E-05	1.013E-05	NQ	2.407E-06
B(ghi)F	Benzo(g,h,i)Fluoranthene	NQ	1.583E-05	2.371E-05	1.809E-05	3.112E-05	3.121E-06
B(a)A	Benzo(a)Anthracene	NQ	1.604E-05	1.778E-05	1.483E-05	NQ	4.458E-06
Tri	Triphenylene	NQ	6.925E-06	1.710E-05	8.860E-06	NQ	NQ
Chrysene	Chrysene	NQ	1.794E-05	3.134E-05	2.090E-05	3.112E-05	6.644E-06
MB(a)A	7-Me-Benzo(a)Anthracene	NQ	NQ	NQ	NQ	NQ	NQ
B(b)FLT	Benzo(b)Fluoranthene	NQ	1.871E-05	NQ	2.123E-05	NQ	NQ
B(k)FLT	Benzo(k)Fluoranthene	NQ	3.742E-06	NQ	NQ	NQ	NQ
B(e)P	Benzo(e)Pyrene	NQ	1.675E-05	2.198E-05	1.739E-05	NQ	5.869E-06
B(a)P	Benzo(a)Pyrene	NQ	7.415E-06	NQ	NQ	NQ	NQ
PER	Perylene	NQ	NQ	NQ	NQ	NQ	NQ
MCH	2-Me-Cholanthrene	NQ	NQ	NQ	NQ	NQ	NQ
IP	Indeno(1,2,3-cd)Pyrene	NQ	NQ	NQ	NQ	NQ	NQ
D(ah)A	Dibenzo(a,c)&(a,h)Anthracene	NQ	NQ	NQ	NQ	NQ	NQ
B(b)C	Benzo(b)Chrysene	NQ	NQ	NQ	NQ	NQ	NQ
B(ghi)P	Benzo(g,h,i)Perylene	NQ	1.143E-05	NQ	NQ	NQ	NQ
ANT	Anthanthrene	NQ	NQ	NQ	NQ	NQ	NQ

Table 45. Emission profile of PAsH as a fraction of organic carbon emission rate.

		Muffler	**Muffler**	**OxyCat**	**OxyCat**	**New**	**New**
		20C	**-10C**	**20C**	**-10C**	**20C**	**-10C**
Thionaphthene	thionaphthene	NQ	NQ	NQ	NQ	NQ	NQ
DBT	dibenzothiophene	1.367E-08	3.177E-06	1.322E-06	2.165E-06	3.626E-06	2.406E-06
N(2,1b)T	naphtho(2,1-b)thiophene	NQ	NQ	NQ	NQ	NQ	NQ
2-MDBT	2-methyldibenzothiophene	8.297E-09	NQ	6.428E-07	NQ	1.180E-06	NQ
8-MN(2,1b)T	8-methylnaphtho(2,1-b)thiophene	NQ	NQ	NQ	NQ	NQ	1.891E-06
5-MN(2,1b)T	5-methylnaphtho(2,1-b)thiophene	NQ	NQ	NQ	NQ	NQ	NQ
4,6-DMDBT	4,6-dimethyldibenzothiophene	NQ	3.827E-06	2.907E-06	3.186E-06	7.803E-06	3.847E-06
1,8-DMDBT	1,8-dimethyldibenzothiophene	NQ	NQ	1.624E-06	1.766E-06	5.092E-06	NQ
1,3-DMDBT	1,3-dimethyldibenzothiophene	NQ	NQ	1.353E-06	1.297E-06	2.898E-06	NQ
Pa(4,3b)T	phenanthro(4,3-b)thiophene	NQ	NQ	NQ	NQ	NQ	NQ
Pa(3,4b)T	phenanthro(3,4-b)thiophene	NQ	NQ	NQ	NQ	NQ	NQ
Pa(2,1b)T	phenanthro(2,1-b)thiophene	NQ	NQ	NQ	NQ	NQ	NQ
Pa(2,3b)T	phenanthro(2,3-b)thiophene	NQ	NQ	NQ	NQ	NQ	NQ
A(2,3b)T	anthra(2,3-b)thiophene	NQ	NQ	NQ	NQ	NQ	NQ
10-MBbN(2,1d)T	10-methylbenzo(b)naphtho(2,1-d)thiophene	NQ	NQ	NQ	NQ	NQ	NQ
2-MBbN(2,1d)T	2-methylbenzo(b)naphtho(2,1-d)thiophene	NQ	NQ	NQ	NQ	NQ	NQ
8-MBbN(1,2d)T	8-methylbenzo(b)naphtho(1,2-d)thiophene	NQ	NQ	NQ	NQ	NQ	NQ
5-MBbN(2,1d)T	5-methylbenzo(b)naphtho(2,1-d)thiophene	NQ	NQ	NQ	NQ	NQ	NQ
6-MBbN(2,1d)T	6-methylbenzo(b)naphtho(2,1-d)thiophene	NQ	NQ	NQ	1.449E-07	NQ	NQ
8-MBbN(2,3d)T	8-methylbenzo(b)naphtho(2,3-d)thiophene	NQ	NQ	NQ	NQ	NQ	NQ
11-MBbN(2,3d)T	11-methylbenzo(b)naphtho(2,3-d)thiophene	NQ	NQ	NQ	NQ	NQ	NQ

Table 46. Emission profile of NO_2-PAH as a fraction of organic carbon emission rate.

		Muffler	**Muffler**	**OxyCat**	**OxyCat**	**New**	**New**
		20C	**-10C**	**20C**	**-10C**	**20C**	**-10C**
2-NFL	2- Nitrofluorene	NQ	NQ	5.224E-07	8.946E-07	2.121E-05	3.644E-05
	Total Nitro-C13*	1.318E-07	2.248E-05	1.116E-06	4.055E-06	2.776E-05	4.811E-05
9-NAN	9-Nitroanthracene	5.206E-08	1.277E-06	9.199E-06	1.401E-05	3.686E-05	4.099E-05
2-NAN	2-Nitroanthracene	NQ	1.917E-08	NQ	NQ	NQ	NQ
9-NPHE	9-Nitrophenanthrene	NQ	2.109E-07	5.902E-07	5.604E-07	5.193E-05	5.182E-05
	Total Nitro-C14*	6.833E-08	2.400E-06	1.152E-05	1.779E-05	1.975E-04	1.368E-04
2-NFLT	2-Nitrofluoranthene	NQ	9.773E-08	NQ	NQ	7.980E-07	NQ
3-NFLT	3-Nitorfluoranthene	NQ	NQ	NQ	NQ	NQ	9.062E-07
4-NPY	4-Nitropyrene	NQ	2.736E-07	6.332E-07	7.157E-07	NQ	NQ
1-NPY	1-Nitropyrene	NQ	1.697E-06	1.570E-05	2.682E-05	2.139E-05	2.705E-05
2-NPY	2-Nitropyrene	NQ	NQ	NQ	NQ	NQ	NQ
	Total Nitro-C16*	2.115E-08	2.068E-06	1.637E-05	2.753E-05	2.219E-05	3.030E-05
7-NB(a)A	7-Nitrobenz(a)anthracene	NQ	1.272E-07	6.937E-07	1.113E-06	7.182E-07	1.469E-06
6-NCry	6-Nitrochrysene	NQ	2.062E-08	NQ	1.590E-07	NQ	6.384E-07
	Total Nitro-C18*	0.000E+00	2.234E-07	6.937E-07	1.272E-06	7.182E-07	2.409E-06
1-NB(e)P	1-Nitrobenzo(e)pyrene	NQ	3.451E-08	NQ	NQ	NQ	NQ
6-NB(a)P	6-Nitrobenzo(a)pyrene	NQ	1.024E-06	1.303E-06	2.090E-06	NQ	4.498E-07
4-NB(e)P	4-Nitrobenzo(e)pyrene	NQ	NQ	NQ	NQ	NQ	NQ
3-NB(e)P	3-Nitrobenzo(e)pyrene	NQ	3.067E-08	NQ	NQ	NQ	NQ
3-NB(a)P	3-Nitrobenzo(a)pyrene	NQ	NQ	NQ	NQ	NQ	NQ
1-NB(a)P	1-Nitrobenzo(a)pyrene	NQ	NQ	NQ	NQ	NQ	NQ
2-NB(a)P	2-Nitrobenzo(a)pyrene	NQ	NQ	NQ	NQ	NQ	NQ
	Total Nitro-C20*	0.000E+00	1.089E-06	1.303E-06	2.090E-06	0.000E+00	7.812E-07
9-ND(a,c)A	9-Nitrodibenzo(a,c)anthracene	NQ	NQ	NQ	NQ	NQ	NQ
	Total Nitro-C22*	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
	Total Nitro-PAH (C13 to C22)	2.733E-07	3.307E-05	5.964E-05	9.910E-05	3.811E-04	3.782E-04
1,3-DNPY	1,3-Dinitropyrene	NQ	NQ	NQ	NQ	NQ	6.865E-07
1,6-DNPY	1,6-Dinitropyrene	NQ	NQ	NQ	NQ	NQ	7.755E-07
1,8-DNPY	1,8-Dinitropyrene	NQ	NQ	NQ	NQ	NQ	8.544E-07
7-N-12-MB(a)A	7-Nitro-12-Methylbenzo(a)anthracene	NQ	NQ	NQ	NQ	NQ	NQ
12-E-6-NCry	12-Ethyl-6-Nitrochrysene	NQ	NQ	NQ	NQ	NQ	NQ

*Total Nitro- reported includes isomers not specifically identified

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